

Enhancement in Power Conversion Efficiency of Dye Sensitized Solar Cell by Using Nanocomposite Photoanode Material TiO_2 - ZnO

*Savita Rambhau Nemade, Purnima Swarup Khare

Department of School of Nanotechnology, Rajiv Gandhi Prodyogiki Vishwavidyalaya (RGPV) Bhopal, State Technological University, 462033, India

*Corresponding Author

DOI : <https://doi.org/10.51583/IJLTEMAS.2025.140400019>

Received: 13 April 2025; Accepted: 18 April 2025; Published: 01 May 2025

Abstract: This study represents the important role of dye sensitizer selection for best photovoltaic response and the photo anode thickness of semiconducting layer for determining the efficiency of dye-sensitized solar cells (DSSCs). For obtaining these objectives we employ an ex-situ methodology to prepare the composite materials. So we prepare nanocomposite by adding 20 wt.% of ZnO nanoparticles into TiO_2 nanoparticles (20TZ). We fabricate dye sensitized solar cell by using the doctor blade technique. Furthermore our key findings are to extends the duration of dye loading, highlighting its significant influence on DSSC performance. The research also encompasses variations in the thickness of the semiconducting layer, providing critical insights into DSSC efficiency. Significance of present research work represent , photoanode thickness of 300-micron 20TZ-based DSSC, sensitized with 3% of N749 dye for a 2-hour loading period, achieves an impressive power conversion efficiency of 15.1%. The stability of 20TZ-based DSSCs was evaluated under continuous light illumination, revealing a minimal decrease in power conversion efficiency of 1.61% over 240 hours. Significance of present study is that we achieve power conversion efficiency 15.1% for the assemble dye sensitized solar cell and its stability duration time.

Keywords: Photovoltaic; Dye Sensitized Solar Cell; Nanocomposite; N749 dye; TiO_2 nanoparticles

I. Introduction

Current work is related to 3rd generation solar cell technology known as Dye-sensitized solar cells (DSSCs). It emerged as a promising photovoltaic technology, offering an innovative approach to harnessing solar energy amidst the ever-increasing demand for energy derived from fossil fuels, which exacerbates the emission of greenhouse gases, particularly carbon dioxide (CO_2), leading to global warming [1]. Because silicon- solar cell has limited application in space industry that are only used for domestic and commercial use and also not environmental friendly because during production of this solar cell pollution is created due to harmful gases. So there is damage of public health. So researcher's are focus on the production of environment friendly dye sensitized solar cell

These cells operate on the principle of light absorption by a sensitizer dye, followed by the injection of electrons into a semiconductor material, and subsequent transport to an external circuit. Among the critical components of DSSC, the choice of sensitizer dye plays a pivotal role in determining their efficiency and performance. In recent years, extensive research has focused on the development and optimization of various dye molecules to enhance DSSC efficiency [2, 3].

The effectiveness of a DSSC critically depends on the sensitizer dye ability to efficiently capture sunlight across the solar spectrum and convert it into electrical energy. Dye molecules have distinctive absorption profiles, making them well-suited for different regions of the solar spectrum. Understanding how various dyes, such as N3, N719, N749, and Z907, influence the performance of DSSCs is essential for tailoring these devices to different applications and improving their overall efficiency [4, 5].

The thickness of the semiconductor layer is another crucial parameter that significantly influences the performance of DSSCs. The thickness of the semiconductor layer in a DSSC is a critical parameter that significantly impacts its performance [6]. The semiconductor layer, typically composed of materials like titanium dioxide (TiO_2) or zinc oxide (ZnO), is responsible for absorbing light and generating electron-hole pairs [7]. The thickness of this layer determines how effectively it can absorb photons from incident sunlight. An optimal thickness ensures that the maximum amount of light is absorbed, leading to higher photon-to-electron conversion efficiency. The thickness of the semiconductor layer directly influences the short-circuit current generated by the DSSC. Also, the thickness of the semiconductor layer affects the transport of charge carriers (electrons and holes) within the cell. A too-thin layer may limit charge transport, causing recombination losses, while an excessively thick layer may increase electron transport distances, leading to increased resistive losses. Further, the thickness of the semiconductor layer can influence the rate of electron-hole recombination. A thinner layer may lead to faster recombination, reducing the efficiency of the DSSC. In contrast, an optimal thickness can minimize recombination losses and enhance charge collection efficiency.

The thickness of the semiconductor layer in a DSSC plays a crucial role in determining its efficiency, current output, and overall performance. Finding the right balance between absorbing maximum light and optimizing charge carrier transport is essential for achieving high-performance DSSCs for practical solar energy conversion applications [8, 9].

Elmorsy et al developed a series of innovative metal-free dyes (TMS-1-4) by incorporating triphenylamine (TPA) and carbazole (Cz) as strong donor species and evaluated for their potential application in DSSCs. These dyes exhibited strong absorption in the wavelength range of 686 nm to 730 nm, indicative of their robust light-harvesting capabilities. The study further explored the photovoltaic conversion efficiencies of TMS-1-4, along with a reference dye (N719). The PCE rankings were as follows: TMS-2 (8.81%)>TMS-4 (8.03%)>N719 (7.60%)>TMS-3 (6.85%)>TMS-1 (6.51%). This research underscores the potential of these metal-free dyes (TMS-1-4) as promising candidates for enhancing the performance of DSSCs [10]. Ahmad et al investigated the bi-functional role of molybdenum diselenide (MoSe₂)-flowers as both an electro-catalyst for DSSCs applications. A counter electrode for DSSCs using MoSe₂-flowers, achieved power conversion efficiency of approximately 4.8%. These findings highlight the potential of MoSe₂-flowers as potential materials for energy conversion [11]. Abdulrahman et al study focused on the experimental testing of DSSCs, utilizing four distinct natural dyes derived from *Mentha* leaves, *Helianthus annuus* leaves, *Fragaria*, and a combination of these extracts in equal proportions as sensitizers for TiO₂ films. The outcomes of the study demonstrated the successful conversion of solar energy into electrical power, highlighting the viability of employing these natural dyes in DSSC applications. Remarkably, DSSCs employing mixtures of these dyes exhibited superior performance compared to those employing single dyes. The reported efficiency reached 0.714%, with an impressive fill factor of 83.3% for the cell area. This research provides valuable insights into the utilization of natural dyes as sensitizers for DSSCs, presenting a sustainable and eco-friendly approach to harnessing solar energy with promising efficiency and cost-effectiveness [12]. Selopal et al presents the synthesis and characterization of novel metal-free organic dyes, specifically B18, BTD-R, and CPTD-R, designed with the D- π -A concept for DSSC application. The study evaluated the photovoltaic performance of these dyes when integrated into two distinct photoanodes: a conventional TiO₂ mesoporous photoanode and a ZnO photoanode constructed from hierarchically assembled nanostructures. The results revealed that the B18 dye exhibited superior photovoltaic properties compared to the other two dyes, BTD-R and CPTD-R. This study offers valuable insights into the development of metal-free organic dyes designed for DSSCs, with the B18 dye showing exceptional promise as a light harvester. The integration of hierarchical ZnO nanostructures and blocking layers demonstrates further avenues for enhancing DSSC efficiency and performance [13]. Roy et al studied the photo-physical surface characteristics associated with the sensitization of Ru(II) polypyridyl dye (N719) and its subsequent performance in DSSCs. The findings reveal notable variations in DSSC performance based on sensitization temperature. The highest recorded power conversion efficiency of 2.25% was achieved at a temperature of 40 °C, accompanied by a commendable open-circuit voltage of 0.87 V. This research sheds light on the potential of DSSCs to thrive in diverse solution sensitization temperature environments, offering valuable insights for future advancements in solar cell technology [14]. Siddika et al studied the impact of two distinct fabrication methods, Doctor's blade and Screen print, for the production of photoanodes in DSSCs. Additionally, the influence of three ruthenium-based dyes (N3, N749, and Z907), as well as a mixed dye combination, on DSSC performance is explored. The research reveals that the screen-printed film exhibits several advantages, including an increased effective surface area and reduced densification compared to the Doctor's blade method. The overall power conversion efficiencies of the DSSCs fall within the range of 1.26% to 1.61%. Remarkably, the screen-printed film with the mixed dye configuration demonstrates the highest efficiency among the tested setups [15]. Salau et al. conducted research on a double-layer structured dye-sensitized solar cell (DSSC), wherein composite photoanodes comprising ZnO and TiO₂ were fabricated on FTO substrates. Various characterization techniques, including IV measurements, were utilized to evaluate the performance of the solar cell. The experimental results demonstrate a considerable enhancement in current generation upon the combination of ZnO and TiO₂, resulting in significant alterations in the IV characteristics. Furthermore, the study observed that the current density in TiO₂ exhibits variations with electrode thickness, peaking at a thickness of 10 μ m. Optimizing the thickness ensures that the active layer absorbs as much sunlight as possible, thereby maximizing the generation of electron-hole pairs and improving overall photocurrent. This study contributes valuable insights into improving DSSC performance through the combination of ZnO and TiO₂, as well as by optimizing electrode thickness, offering potential advancements in solar cell technology [16].

In this research paper, we aim to elucidate the critical role of sensitizer dye selection and semiconductor layer thickness in determining the performance of DSSCs. Our investigation delves into how the choice of dyes, including N3, N719, N749, and Z907, and the optimization of dye loading concentration, dye loading time and semiconductor layer thickness impact the key parameters of DSSCs, such as their current-voltage characteristics and power conversion efficiency. By addressing these fundamental aspects, we endeavor to address the urgent need for efficient and sustainable solar energy utilization, thereby contributing to the development of more effective DSSCs and fostering a greener and more energy-efficient future.

The present research stands out due to the comprehensive and systematic exploration of the impact of three critical parameters namely dye concentration, dye loading time and semiconducting layer thickness on the performance of DSSCs. Unlike previous studies that often focus on a single parameter, present work evaluates all three under the same experimental conditions, offering a holistic understanding of their combined effects on DSSC efficiency. In conclusion, present study not only provides a robust framework for optimizing DSSC performance but also offers valuable insights that pave the way for future research and development in highly efficient and sustainable solar energy conversion technologies.

II. Experimental

Reagents and Materials

All the chemicals and reagents utilized in this research were procured from sources in India, specifically from SD Fine.

Preparation of ZnO and TiO₂ Nanoparticles

ZnO Nanoparticle

To begin with, 5 grams of KOH were placed in a separate beaker containing 30 milliliters of ethanol and subjected to magnetic stirring for 30 minutes. Simultaneously, 0.03294 gm of zinc acetate dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$) were placed in another beaker containing 150 mL of ethanol. The solutions in both containers underwent ultrasonication for one hour at room temperature to ensure proper dispersion of the compounds. Following this, the KOH solution was gradually added drop by drop to the zinc acetate dihydrate solution. Subsequently, the mixture of both solutions was left for magnetic stirring for one hour to facilitate the reaction between the compounds. As a final step, 6 mL of ethyl acetate were introduced into the solution to precipitate the ZnO nanoparticles. The resulting solution was then rinsed multiple times with additional ethanol to remove impurities. Finally, the washed solution was dried in an oven at 60°C. This method yielded the ZnO nanoparticles as a result of the investigation.

TiO₂ Nanoparticle

To prepare the TiO₂ nanoparticles, the process began by taking 10 mL of titanium isopropoxide ($\text{C}_{12}\text{H}_{28}\text{O}_4\text{Ti}$) and placing it in a beaker containing 20 milliliters of ethanol. This beaker was left under magnetic stirring for 30 minutes. Following this initial step, an aqueous ethanol solution was gradually added drop by drop into the titanium isopropoxide solution while maintaining magnetic stirring for another hour. Subsequently, the resulting solution was heated to 100°C and kept at that temperature for 6 hours. After this, the final solution was subjected to a washing process using both water and ethanol. A mixture of ethanol and water was added to the precipitate, and this mixture was filtered multiple times through filter paper to eliminate impurities. The washed precipitate was then left to dry overnight at 50°C to remove any remaining moisture. Subsequently, the dried precipitate was collected and subjected to calcination at a temperature of 600°C for a duration of 5 hours. This step was aimed at stabilizing the TiO₂ nanoparticles.

Preparation of Composites

In this study, an ex-situ approach was employed to create composite materials. These composites were crafted by incorporating ZnO nanoparticles into TiO₂ nanoparticles in specific weight percentages (wt.%). The wt.% stoichiometry was calculated using relation [17],

$$\text{wt. \%} = \frac{X}{(X+Y)} \times 100$$

where X (ZnO) and Y (TiO₂) are constituents of composite.

To prepare the TiO₂-ZnO nanocomposite with 20 wt.% ZnO loading, the requisite quantity of ZnO nanoparticles was placed in a beaker containing 30 mL of ethanol and subjected to magnetic stirring for 30 minutes. Simultaneously, TiO₂ nanoparticles were also placed in a separate beaker containing 30 mL of ethanol and stirred magnetically for the same duration.

After the magnetic stirring, the suspension containing ZnO nanoparticles was added drop by drop into the suspension of TiO₂ nanoparticles while maintaining magnetic stirring. The resulting suspension was then left to stir magnetically for an additional hour. Subsequently, the suspension was subjected to heating at 60°C to facilitate drying.

Characterization Techniques

The structural analysis of both the pure and nanocomposite materials was conducted through X-ray diffraction (XRD). XRD measurements were performed using a Rigaku Miniflex-XRD instrument, employing X-rays with a wavelength of 1.5406 Å, a scan step of 0.02°, a scan rate of 0.01 s/step, and a scan range of 20–80°. The morphology and structure of the sample was examined using a transmission electron microscope (TEM) and selected area electron diffraction (SAED), using the TecnaiTM G2 F30 S-TWIN instrument at an acceleration voltage 300 kV. The Fourier-Transform infrared spectroscopy (FTIR) spectra of the nanocomposites were obtained utilizing a BRUKER ALPHA Platinum ATR-IR instrument. To investigate the optical properties of the nanocomposites, ultraviolet-visible (UV-VIS) absorption spectra were recorded using an Agilent Cary 60 UV-VIS spectrophotometer. The photoluminescence (PL) spectra of the nanocomposites were measured with an FL Spectrophotometer, specifically the HITACHI F-7000 model. In this study, a laser with a wavelength of 325 nm was employed to excite the electrons within the sample.

Fabrication of

The photovoltaic (PVDSSCs) cells were produced using the doctor blade technique [18]. In this procedure, the nanocomposite material was positioned between a cleaned ITO (Indium Tin Oxide) plate, serving as the transparent electrode, and an aluminum foil, functioning as the metallic electrode within the PV cell architecture. The ITO plate used in this study had dimensions of 25mm×25mm and was procured from Techinstro (ITO-SE-011), India. To facilitate the deposition of the nanocomposite onto the ITO electrode, a temporary binder was employed, which was prepared using a mixture of 3% ethyl cellulose and 97% butyl digol. The thickness of the active nanocomposite material was consistently maintained at around 100 µm, utilizing the transparency sheets of 100 µm thickness using doctor blade technique. To optimize the thickness of the PV cell, we employed the doctor blade technique

with various thickness transparency sheets, ranging from 100 μm to 500 μm , including increments of 100 μm . The constructed PV cell was subsequently allowed to dry at 50°C for 1 hour to aid in the evaporation of volatile organic compounds present in the composite material. A visual representation of the PV cell, along with its dimensions and other pertinent details, is depicted in Figure 1. Before conducting PV cell testing, the nanocomposite layer within the PV cell was sensitized with a ruthenium-based red dye known as N3 for a duration of 1 hour. This sensitization process was accomplished through capillary action.

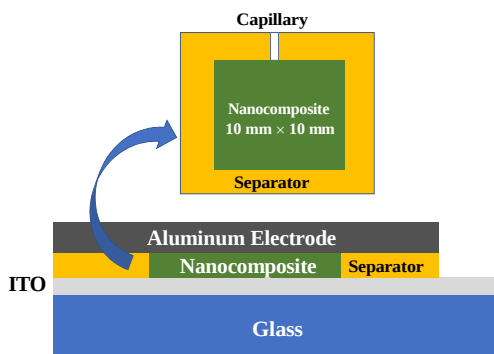


Figure 1. Pictorial representation of PV Cell architecture.

Solar Cell Characterization

The current-voltage measurements were conducted with a Keithley 2400 source/meter under PC control, all while being exposed to simulated sunlight at 100 mW/cm^2 with AM 1.5G spectrum using a Newport 91160 solar simulator. Key diode characteristics such as open circuit voltage (V_{OC}), short circuit current (I_{SC}), fill factor (FF), and power conversion efficiency (η) were determined by following method. The FF of PV cell computed using relation [19],

$$FF = \frac{I_{MAX} \times V_{MAX}}{I_{SC} \times V_{OC}}$$

whereas, power conversion efficiency (η) of PV cell were calculated using the relation,

$$\% \eta = \left(\frac{I_{SC} \times V_{OC} \times FF}{P_{in}} \right) \times 100$$

where, P_{in} is power incidence.

III. Results and Discussion

XRD Analysis

Figure 2 (a) displays the XRD pattern of anatase TiO_2 , revealing distinct peaks within its pattern. In the case of anatase TiO_2 , these prominent peaks are typically observed at approximately 25.3°, 37.8°, 48.1°, 54.1°, 62.7°, and 75.0°. These peak positions in the XRD pattern correlated with the crystallographic planes of anatase TiO_2 (JCPDS card no. 21-1272). The most intense peak, often occurring at around 25.3° (2θ position), corresponds to the (101) crystal plane of anatase TiO_2 . Similarly, other peaks at 37.8°, 48.1°, 54.1°, 62.7°, and 75.0° are assigned to the (004), (200), (105), (211), and (204) crystal planes, respectively.

Figure 2 (b) illustrates the XRD pattern of ZnO nanoparticles. The recorded XRD pattern within the range of 20 to 80 degrees reveals prominent peaks at 2θ values of 31.84°, 34.52°, 36.38°, 47.64°, 56.7°, 63.06°, 68.1°, and 69.18°, corresponding to crystal planes (100), (002), (101), (102), (110), (103), (112), and (201), respectively. All these peaks can be indexed as characteristic peaks and crystal planes of zinc oxide, as indicated by the JCPDS Card No: 36-1451. The XRD analysis for both TiO_2 and ZnO confirms that the synthesized nanopowder is devoid of impurities and does not exhibit any impurity peaks.

Figure 2 (c) displays the X-ray diffraction (XRD) patterns of 20 wt.% ZnO loaded TiO_2 (20TZ) system. The XRD patterns offer valuable insights into the crystal structures and phase composition of the composite material. The XRD pattern of the TiO_2 -ZnO composite reveals characteristic peaks corresponding to both TiO_2 and ZnO. For TiO_2 , the typical peaks are observed at approximately 25.3°, 37.8°, 48.1°, 54.1°, 62.7°, and 75.0°, corresponding to its characteristic crystal planes mentioned earlier. Similarly, the XRD pattern of the composite exhibits strong peaks at 31.7°, 34.4°, 36.3°, 47.6°, 56.6°, 62.9°, and 67.9°, representing its crystallographic planes. The relative intensities of the TiO_2 and ZnO peaks in the XRD pattern provide information about the composition of the composite. The presence of distinct peaks for both TiO_2 and ZnO confirms the coexistence of these two phases within the composite [20].

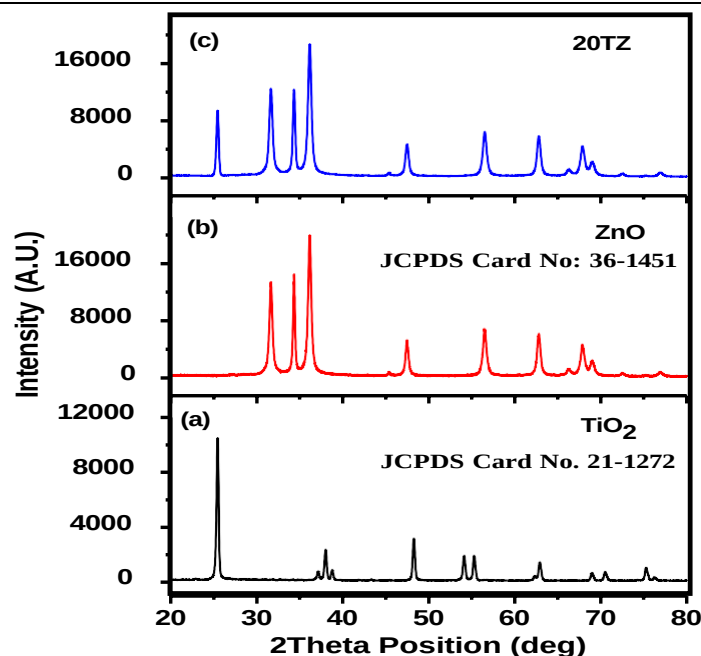


Figure 2. XRD pattern of (a) TiO_2 , (b) ZnO and (c) 20TZ nanocomposite system.

In the case of 20TZ nanocomposite system, even if the concentration of TiO_2 is higher than ZnO in the composite, the intensity of the ZnO peak may still be higher due to several reasons [21-23]:

- ZnO may have a higher crystallinity that is more conducive to XRD analysis compared to TiO_2 . This means that ZnO nanoparticles may form well-defined crystalline structures that produce sharper and more intense XRD peaks.
- The grain size of ZnO nanoparticles may be smaller than that of TiO_2 nanoparticles in the composite. Smaller grain sizes can lead to broader XRD peaks, but they may also result in higher peak intensities due to increased scattering from smaller crystallites.
- ZnO nanoparticles may exhibit a preferred orientation that enhances the intensity of specific XRD peaks. This can happen if the nanoparticles tend to align themselves in a particular direction during the synthesis process.
- The presence of dopants or defects in ZnO nanoparticles can influence their XRD peak intensities. Certain dopants or defects may enhance the scattering of X-rays, leading to higher peak intensities.
- In the composite with a TiO_2 : ZnO ratio of 80:20, the synergistic effects between TiO_2 and ZnO may also contribute to the higher intensity of the ZnO peak. The presence of ZnO nanoparticles could influence the crystallization behaviour or structure of TiO_2 , leading to enhanced XRD peak intensity for ZnO .
- For higher concentration of TiO_2 within the 20TZ nanocomposite system results in increased intensity of ZnO peaks. This phenomenon is ascribed to the presence of both uniform and non-uniform strains within the composite material, coupled with the mismatch in ionic radii between Zn (0.75 Å) and Ti (0.61 Å) ions.

The higher intensity of the ZnO XRD peak in TiO_2 - ZnO composite despite the higher concentration of TiO_2 can be attributed to differences in crystallinity, grain size, preferred orientation, and synergistic effects between the two materials. These factors collectively contribute to the observed XRD diffraction pattern for TiO_2 - ZnO composite.

The observation that the ZnO peak intensity in the 20TZ composite slightly matches with pure ZnO can be attributed to the highly crystalline nature of ZnO nanoparticles. ZnO has a strong scattering factor due to its higher electron density, which can lead to prominent peaks even at lower concentrations when compared to TiO_2 . The slight decrease in TiO_2 peak intensity in the 20TZ composite is likely due to the partial coverage of TiO_2 surfaces by ZnO nanoparticles. This coverage can cause a slight reduction in the exposure of TiO_2 crystalline planes to the X-ray beam, leading to a lower observed intensity.

TEM and SAED Study

To investigate key aspects of the 20TZ composite, TEM analysis was employed to visualize the surface morphologies of the composites. Figure 3 displays TEM image corresponding to the 20TZ systems. Inset of Figure 3 also exhibits the SAED pattern of the 20TZ system. From the TEM image, the average particle size of 20TZ composite is 72.3 nm. Some degree of the agglomeration of particles with different shapes was observed in this TEM images. Furthermore, the SAED pattern of the TiO_2 - ZnO composite reveals crystal planes identified for both ZnO and TiO_2 .

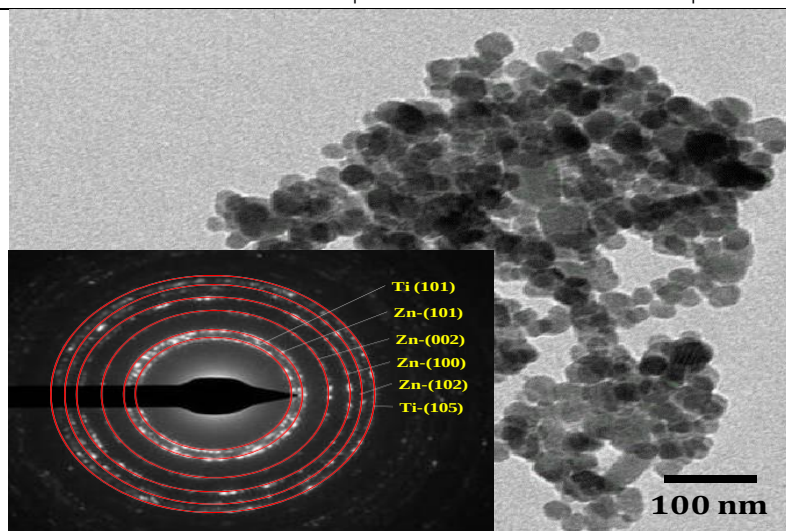


Figure 3. TEM image of 20TZ nanocomposite system and inset images shows the selected area electron diffraction (SAED) pattern.

UV-Vis, PL and FTIR Analysis

gh7

Figure 4 shows UV-Visible spectra of (a) Pure ZnO and ZnO Sensitized by (b) N3, (c) N719, (d) N749 and (e) Z907. Among all the dyes, N749 exhibited superior results due to its excellent optical properties, making it highly suitable for DSSC applications. N749 dye stands out due to its superior optical properties. The UV-Visible spectrum exhibits strong and broad absorption peaks spanning a wider range of the visible spectrum, particularly around 560 nm. This broad absorption is critical for capturing more sunlight and converting it into electrical energy efficiently. In conclusion, among the dyes tested, N749 demonstrated superior optical properties and significantly enhanced the performance of DSSCs. Its broad absorption range and efficient electron injection capabilities make it a promising sensitizer for high-efficiency DSSCs.

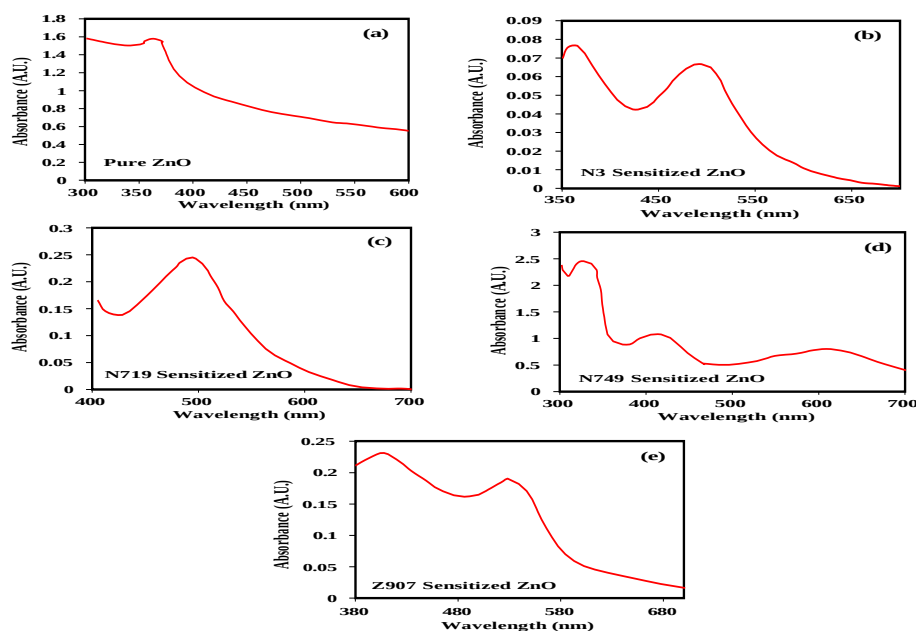


Figure 4. UV-Visible spectra of (a) Pure ZnO and ZnO Sensitized by (b) N3, (c) N719, (d) N749 and (e) Z907.

Figure 5 shows the UV-Visible spectra of (a) Pure TiO_2 and TiO_2 sensitized by (b) N3, (c) N719, (d) N749, and (e) Z907 were meticulously analyzed to evaluate their optical properties and effectiveness as sensitizers for DSSCs. The analysis revealed significant insights into the optical behavior of these dyes when combined with TiO_2 . In this case N719 dye sensitized TiO_2 shows improved absorption characteristics, with broader absorption peaks. The broader absorption spectrum indicates better utilization of the visible light spectrum, contributing to improved DSSC performance. Among the dyes tested, N749 demonstrated superior optical properties and significantly enhanced the performance of DSSCs. Its broad absorption range and efficient electron injection capabilities make it a promising sensitizer for high-efficiency DSSCs.

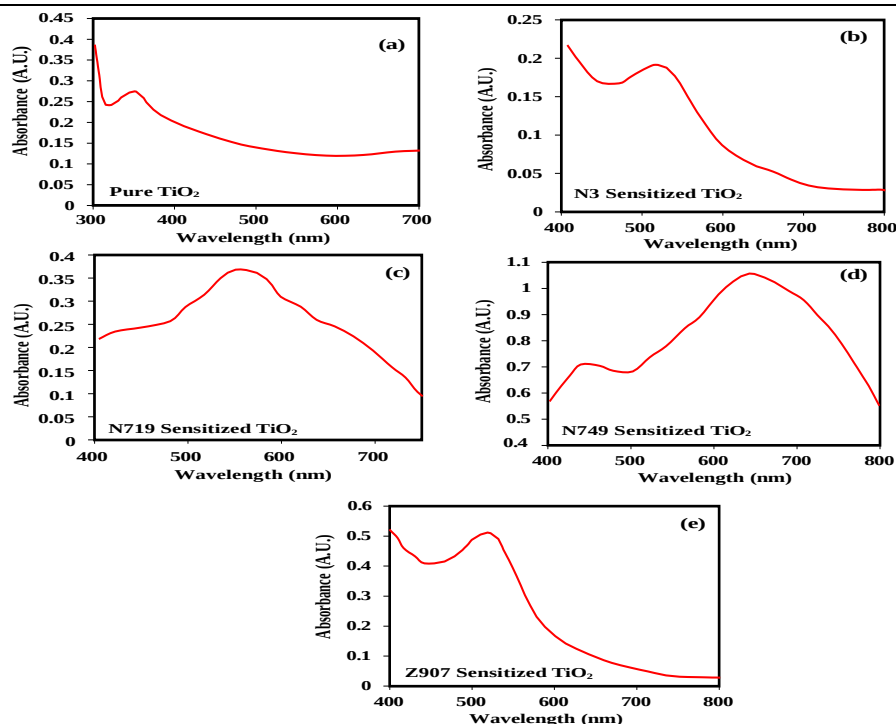


Figure 5. UV-Visible spectra of (a) Pure TiO_2 and TiO_2 Sensitized by (b) N3, (c) N719, (d) N749 and (e) Z907.

In Figure 6, the PL spectra of pure ZnO and ZnO sensitized with various dyes—N3, N719, N749, and Z907 are provided. The PL properties of ZnO sensitized with N749 dye stand out significantly among all these dyes. The enhanced PL properties observed in ZnO sensitized by N749 indicate its superior performance and potential for use in DSSCs. This suggests that the interaction between ZnO and N749 dye leads to more efficient charge separation and transfer processes, which are crucial for high-performance DSSCs. Thus, ZnO sensitized with N749 is particularly promising for DSSC applications, offering improved efficiency and stability compared to other dyes.

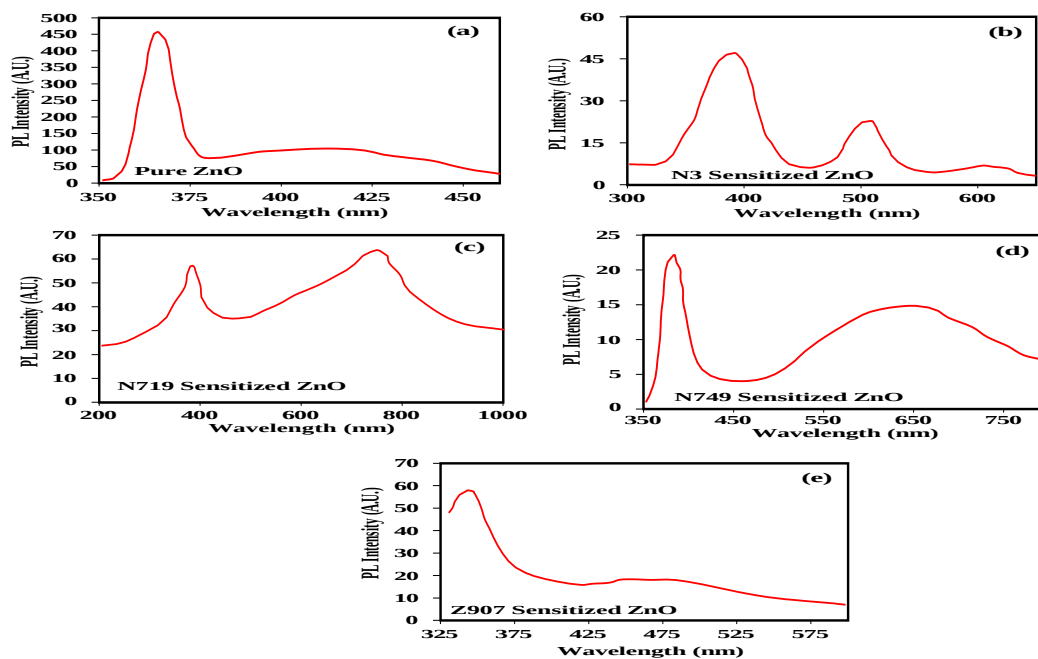


Figure 6. PL spectra of (a) Pure ZnO and ZnO Sensitized by (b) N3, (c) N719, (d) N749 and (e) Z907.

In Figure 7, the PL spectra of pure TiO_2 and TiO_2 sensitized with various dyes—N3, N719, N749, and Z907—are presented. Among these, the PL properties of TiO_2 sensitized with N749 dye exhibit superior performance, indicating its enhanced suitability for DSSCs. The PL enhancement in TiO_2 sensitized by N749 suggests efficient charge transfer and reduced recombination rates, which

are critical for optimizing DSSC efficiency. Consequently, TiO_2 sensitized with N749 emerges as a highly promising material for DSSC applications, demonstrating notable improvements over the other tested dyes.

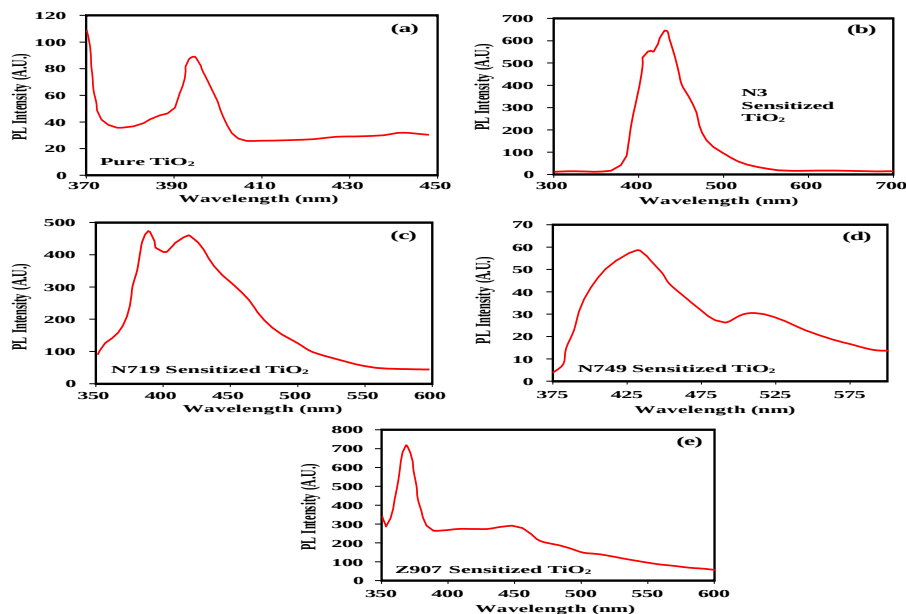


Figure 7. PL spectra of (a) Pure TiO_2 and TiO_2 Sensitized by (b) N3, (c) N719, (d) N749 and (e) Z907.

In the PL studies of ZnO and TiO_2 sensitized by N3, N719, N749, and Z907 (Figures 6 and 7), it is observed that the PL intensity of ZnO and TiO_2 sensitized with N749 dye is significantly reduced. A higher PL intensity for the other dye combinations indicates a higher rate of radiative recombination of photo-generated electron-hole pairs. In the context of DSSCs, high PL intensity can be detrimental as it suggests that a significant portion of the generated charge carriers recombine before contributing to the photocurrent. Conversely, lower PL intensity is generally preferred for DSSCs, as it implies reduced recombination and more efficient charge separation, leading to higher photocurrent and improved cell efficiency. The reduced PL intensity observed in ZnO and TiO_2 sensitized with N749 dye aligns with the results of this study, which are discussed in subsequent sections.

Figure 8 (a) presents UV-VIS spectroscopy data for 20TZ nanocomposite systems. This data provides essential insights into their optical characteristics and bandgap energy, which are crucial for potential applications in photovoltaic cells. Typically, both TiO_2 and ZnO nanoparticles exhibit strong absorption in the UV region, with TiO_2 having an absorption range of 320–400 nm and ZnO ranging from 280–400 nm [24, 25]. Understanding the relationship between ZnO concentration and the optical bandgap in TiO_2 -ZnO nanocomposites is crucial for tailoring their optical properties for photovoltaic applications [26, 27]. The absorption spectrum of 20TZ nanoparticle appears at the wavelength 378 nm which corresponds to the band gap value 3.28 eV.

Further, the energy band gap of 20TZ was determined using the widely recognized Tauc's relation. By extrapolating the linear portion of the plot of $(\alpha h\nu)^2$ on the y-axis against photon energy ($h\nu$) on the x-axis, the energy band gap value was obtained, as illustrated in Figure 8(b), yielding a result of 3.28 eV.

Figure 8 (c) illustrates the photoluminescence (PL) spectra for the 20TZ systems. These PL analyses offer valuable insights into the suitability of TiO_2 -ZnO nanocomposites for photovoltaic applications. In the PL spectra of the TiO_2 -ZnO composites, emission peaks are observed at 525 nm wavelengths, utilizing an excitation wavelength of 325 nm at room temperature. Generally, ZnO exhibits a higher concentration of defect states when compared to TiO_2 [28]. The excitation wavelength of 325 nm falls within the UV range, which is suitable for exciting both TiO_2 and ZnO, as they have band gaps in the UV region. Exciting the composite material with this wavelength can lead to electron transitions within both TiO_2 and ZnO components. The emission peak observed at 525 nm corresponds to green light, falling within the visible range of the electromagnetic spectrum. This emission is somewhat unusual for TiO_2 and ZnO individually, as they typically exhibit emissions in the UV range due to their wide band gap energies. However, in a composite material like TiO_2 -ZnO, the presence of defects, surface states, or interface interactions between TiO_2 and ZnO phases could lead to the observed emission in the visible range [29].

In composite phases, the proximity of different components can lead to quenching effects, where the energy transfer between the components results in the loss of luminescence intensity. This can happen due to various mechanisms such as charge transfer, energy transfer, or surface defects that can act as non-radiative recombination centers. Aggregation can alter the electronic structure and increase non-radiative decay pathways, thereby reducing the emission intensity. Interfaces and surfaces within the composite phase can introduce defects or traps that promote non-radiative recombination of excitons, reducing the overall luminescence intensity. Incorporation of TiO_2 and ZnO into a composite phase can induce structural changes in the material, altering its electronic properties and affecting its PL intensity. The decrease in PL intensity in composite phases compared to individual components can

be influenced by a combination of factors related to interactions between different components, changes in the local environment, and alterations in the material properties [30, 31].

Figure 8 (d) shows the FTIR spectrum of the 20TZ nanocomposite system revealed several characteristic peaks, facilitating peak assignments. The Zn–O vibration appeared at 467 cm^{-1} , indicative of the Zn–O bonding. The presence of Zn–OH groups was confirmed at 705 cm^{-1} . The stretching vibrations of Ti–O in TiO_2 were observed within the range of 474 to 800 cm^{-1} . The Ti–O–C group exhibited a peak at 1047 cm^{-1} , while the C=O bond of zinc acetate was identified at 1352 cm^{-1} . Furthermore, the C=C bond of zinc acetate appeared at 1487 cm^{-1} , and the stretching vibration of C–H in zinc acetate was evident at 1577 cm^{-1} . The stretching vibration of the C=O bond in titanium carboxylate, arising from the use of titanium isopropoxide and ethanol as precursors, was noted at 1627 cm^{-1} . Hydrogen bonding was confirmed by the O–H bond at 3294 cm^{-1} , while the stretching vibration of the hydroxyl group (–OH), representing moisture, was observed in the range of 3000 – 3400 cm^{-1} . These assignments provide valuable insights into the structural and chemical composition of the TiO_2 –ZnO nanocomposite system [32].

The absence of peaks corresponding to acetate and carbon in the XRD patterns despite their presence in the FTIR analysis can be attributed to the differences in sensitivity and detection limits between these two analytical techniques. XRD may not be as sensitive to the presence of amorphous or low-concentration phases, especially if they are present in small amounts or dispersed within the crystalline matrix. The preservation of absorption bands corresponding to acetate and carbon in the FTIR analysis suggests the presence of these substances in the composite material, possibly in an amorphous or dispersed form [33, 34].

In conclusion, the presence of acetate groups on the ZnO surface, as observed in the FTIR study, suggests that these organic groups are adsorbed onto the ZnO nanoparticles. While these acetate groups can influence the surface chemistry, their impact on the XRD peak intensity is minimal. This is because the XRD technique primarily detects crystalline structures and is less sensitive to surface-bound organic molecules.

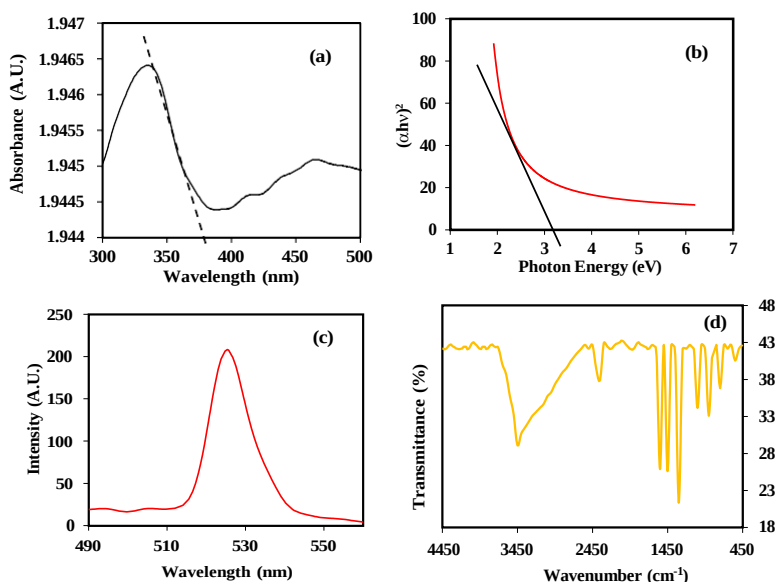


Figure 8. (a) UV-Vis spectra, (b) Tauc's plots for the calculation of band gap, (c) PL spectra and (d) FTIR Spectra of 20TZ nanocomposite system.

PV Response

Effect of Dye Loading Concentration

Figure 9 (a-d) illustrates the current-voltage (I–V) characteristics of DSSC based on the 20TZ nanocomposite system. These DSSCs were sensitized with different dyes, namely N3, N719, N749, and Z907, at loading concentrations ranging from 1% to 5% with an interval of 1%. The sensitization process involved capillary action, where the nanocomposite encountered the respective dye. Table 1 provides essential parameters for these photovoltaic (PV) cells. Notably, these PV cells demonstrated stable photovoltaic performance, indicating consistent and minimal deviation in their readings over time. The data related to the I–V characteristics represent the average of five measurement sets, taken at hourly intervals, and showed negligible variations.

According to the information in Table 1, the DSSC labeled as "3N749" (20TZ-based DSSC sensitized with 3% of N749 dye) achieved the highest power conversion efficiency. This DSSC exhibited the following values: $I_{\text{max}} = 3.497\text{ mA}$, $V_{\text{max}} = 0.535\text{ V}$, $I_{\text{sc}} = 4.153\text{ mA}$, $V_{\text{oc}} = 0.856\text{ V}$, $\text{FF} = 0.38$, and $\eta\% = 13.7$. It is worth noting that the power conversion efficiency appears to be sensitive to the composition of the dye used in the sensitization process. Here are some reasons why N749 dye sensitized 20TZ show higher efficiency compared to the others [35]:

- N749 dye likely has an absorption spectrum that matches well with the solar spectrum. This means it can efficiently absorb a broad range of wavelengths from sunlight, maximizing the amount of light it can harvest.
- The absorption spectrum of the 20TZ nanoparticle, showing a peak at 378 nm corresponding to a band gap energy of 3.28 eV, indicates its suitability for absorbing photons in the UVA region. In the case of the N749 dye, its absorption spectrum likely overlaps well with the absorption spectrum of the TiO₂-ZnO composite, indicating effective light harvesting and electron injection. This favourable alignment of energy levels between the dye and the semiconductor can lead to efficient charge separation and collection, resulting in high DSSC efficiency [36].
- The energy levels of the dye molecule should be well-matched with the energy levels of the semiconductor material used in the DSSC (20TZ in present study). This ensures efficient electron transfer from the dye to the semiconductor. N749 dye may have favorable energy level alignment with 20TZ material.
- The stability of the dye molecule is crucial for long-term performance. N749 dye may have better stability under the operating conditions of a DSSC, leading to consistent performance over time.

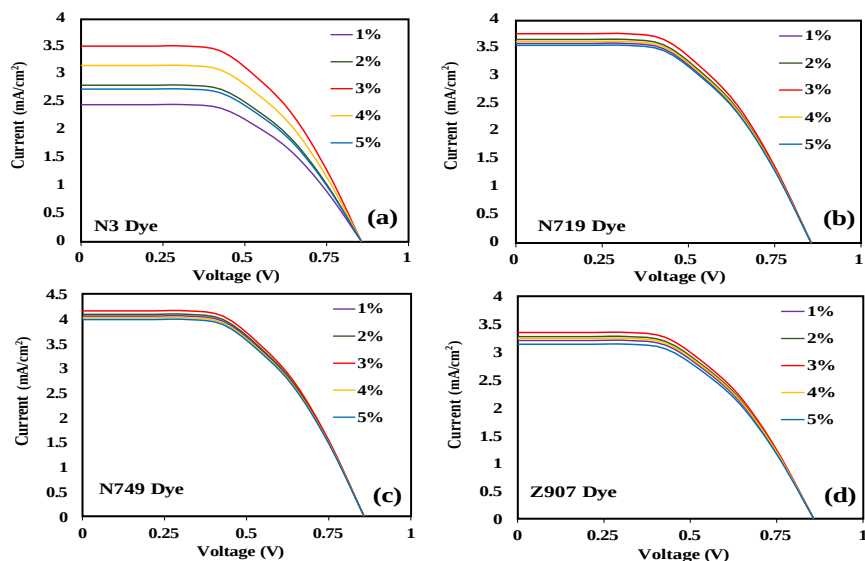


Figure 9. I-V characteristics of 20TZ nanocomposite system-based PV cell sensitized with various dyes (a) N3, (b) N719, (c) N749 and (d) Z907 with loading concentration 1% to 5% with an interval of 1%.

Table 1. PV Parameters of 20TZ nanocomposite system-based PV cell sensitized with various dyes (N3, N719, N749 and Z907).

Sample	I_{max} (mA/cm ²)	V_{max} (V)	I_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
N3 Dye						
1N3	2.074	0.535	2.463	0.856	0.38	8.1
2N3	2.371	0.535	2.815	0.856	0.38	9.3
3N3	2.964	0.535	3.519	0.856	0.38	11.6
4N3	2.667	0.535	3.167	0.856	0.38	10.4
5N3	2.312	0.535	2.745	0.856	0.38	9.1
N719 Dye						
1N719	3.023	0.535	3.59	0.856	0.38	11.8
2N719	3.082	0.535	3.66	0.856	0.38	12.1
3N719	3.171	0.535	3.766	0.856	0.38	12.4
4N719	3.053	0.535	3.625	0.856	0.38	12.1
5N719	2.993	0.535	3.555	0.856	0.38	11.7
N749 Dye						
1N749	3.408	0.535	4.047	0.856	0.38	13.3
2N749	3.438	0.535	4.083	0.856	0.38	13.5

3N749	3.497	0.535	4.153	0.856	0.38	13.7
4N749	3.379	0.535	4.012	0.856	0.38	13.2
5N749	3.349	0.535	3.977	0.856	0.38	13.1
Z907 Dye						
1Z907	2.697	0.535	3.203	0.856	0.38	10.6
2Z907	2.756	0.535	3.273	0.856	0.38	10.8
3Z907	2.815	0.535	3.343	0.856	0.38	11.1
4Z907	2.727	0.535	3.238	0.856	0.38	10.7
5Z907	2.638	0.535	3.132	0.856	0.38	10.3

Optimizing the dye loading in DSSCs is crucial for achieving maximum efficiency as it directly impacts light absorption, charge generation, and charge injection processes. The observation in Table 1, where samples with a 3% dye loading exhibit the highest efficiency, particularly with sample 3N749 achieving the highest value, underscores the importance of discussing the correlation between dye loading and DSSC efficiency.

Increasing dye loading enhances light absorption within the active layer of the DSSC. At lower dye loadings, insufficient dye molecules may result in underutilization of incident photons. Conversely, excessively high dye loadings may lead to dye aggregation, reducing the effective light-absorbing surface area and causing self-quenching effects. Proper dye loading ensures an adequate density of dye molecules to efficiently generate electron-hole pairs upon light absorption. Insufficient dye loading can lead to fewer generated charge carriers, limiting photocurrent generation. Conversely, excessive dye loading may result in increased recombination losses due to overcrowding of dye molecules, reducing charge generation efficiency.

The optimal dye loading facilitated efficient injection of photoexcited electrons from the dye molecules into the conduction band of the 20TZ semiconductor material. This process is crucial for initiating charge transport and collection. The rate of dye diffusion and the potential for dye aggregation can also be influenced by dye loading. Higher dye loadings may impede mass transport of redox species within the electrolyte and increase the likelihood of dye aggregation, both of which can negatively impact device performance [37-39].

Effect of Dye Loading Time Concentration

Figure 10 presents the IV characteristics of DSSCs based on the 20TZ nanocomposite system, sensitized with N749 dye over various loading durations ranging from 1 hour to 5 hours with a 1-hour interval. The sensitization process involved capillary action, where the nanocomposite encountered the N749 dye for the specified time durations.

Table 2 offers crucial parameters for these PV cells. Notably, these PV cells displayed consistent and stable photovoltaic performance, indicating minimal deviation in their readings over time. The data related to the I-V characteristics represent the average of five measurement sets taken at hourly intervals and exhibited negligible variations.

Based on the information in Table 2, the 20TZ-based DSSC identified as "2H:N749" (a 20TZ-based DSSC sensitized with 3% of N749 dye for a 2-hour loading time) achieved the highest power conversion efficiency. This specific DSSC exhibited the following values: $I_{\max}=3.812$ mA, $V_{\max}=0.535$ V, $I_{SC}=4.527$ mA, $V_{OC}=0.856$ V, FF = 0.38, and $\eta\% = 14.9$. It is noteworthy that the power conversion efficiency appears to be influenced by the duration of dye loading.

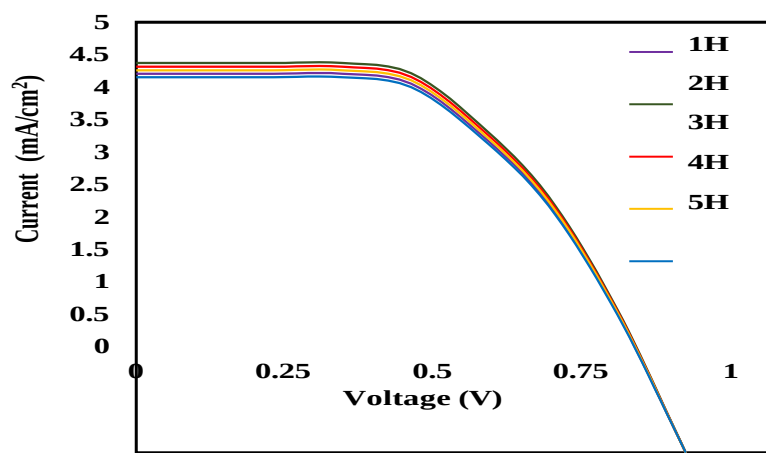


Figure 10. IV characteristics of 20TZ nanocomposite system-based PV cell sensitized with N749 for various dipping time (a) 1 Hour, (b) 2 Hours, (c) 3 Hours, (d) 4 Hours and (e) 5 Hours.

Table 2. PV Parameters of 20TZ nanocomposite system-based PV cell sensitized with N749 for various dipping times (1 Hour, 2 Hours, 3 Hours, 4 Hours and 5 Hours).

Sample	$I_{\max}$ (mA/cm ²)	$V_{\max}$ (V)	I_{sc} (mA/cm ²)	V_{oc} (V)	FF	$\eta(\%)$
N749 Dye (Dipping Time)						
1H:N749	3.707	0.535	4.402	0.856	0.38	14.5
2H:N749	3.812	0.535	4.527	0.856	0.38	14.9
3H:N749	3.777	0.535	4.485	0.856	0.38	14.8
4H:N749	3.742	0.535	4.444	0.856	0.38	14.7
5H:N749	3.672	0.535	4.361	0.856	0.38	14.4

The optimal dye loading time of 2 hours for the 20TZ-based DSSC sensitized with N749 dye resulted in the highest power conversion efficiency due to several interconnected factors:

Optimal Dye Coverage: A 2-hour loading time likely allows for an optimal amount of dye molecules to be adsorbed onto the surface of the 20TZ nanocomposite. This provides sufficient light-absorbing molecules to enhance the generation of electron-hole pairs without oversaturating the surface.

Effective Electron Injection: At 2 hours, the dye molecules are sufficiently close to each other to facilitate efficient electron injection from the dye to the semiconductor, enhancing the current (ISC) without causing excessive aggregation that might impede the process.

Minimized Aggregation: Longer loading times can lead to dye aggregation, where dye molecules stack on top of each other rather than spreading evenly across the surface. Aggregation can reduce the effective surface area for light absorption and hinder electron transfer, leading to lower performance. The 2-hour duration strikes a balance by maximizing dye coverage while minimizing aggregation.

Stable Dye-Semiconductor Interface: The interaction between the dye and the semiconductor surface needs to be strong enough to ensure good electron transfer but not so prolonged that it causes dye desorption or weak binding. The 2-hour loading time seems to provide the most stable interface, contributing to consistent and high performance.

Uniform Penetration: The capillary action during the 2-hour period may allow for uniform penetration of the dye throughout the porous structure of the nanocomposite, ensuring that all active sites are adequately sensitized.

In conclusion, the 2-hour dye loading time provides an optimal balance between sufficient dye coverage, minimal aggregation, and stable dye adsorption, resulting in the highest power conversion efficiency for the 20TZ-based DSSC sensitized with N749 dye.

Effect of Thickness

Figure 11 shows the IV characteristics of DSSCs based on the 20TZ nanocomposite system. These DSSCs were sensitized with 3% of N749 dye for a 2-hour loading time and examined with various thicknesses ranging from 100 microns to 500 microns. This investigation aimed to assess the impact of thickness on the power conversion efficiency of the DSSC.

Table 3 offers essential parameters for these PV cells. Remarkably, these PV cells demonstrated stable photovoltaic performance, indicating a consistent and minimal deviation in their readings over time. The data concerning the IV characteristics represent the average of five measurement sets taken at hourly intervals and displayed negligible variations.

As per the data in Table 3, the 300-micron thickness 20TZ-based DSSC sensitized with 3% of N749 dye for a 2-hour loading time achieved the highest power conversion efficiency. This specific DSSC exhibited the following values: $I_{\max} = 3.850$ mA, $V_{\max} = 0.535$ V, $I_{sc} = 4.572$ mA, $V_{oc} = 0.856$ V, FF = 0.38, and $\eta\% = 15.1$. It is important to note that the power conversion efficiency appears to be influenced by the thickness of the semiconducting layer of 20TZ.

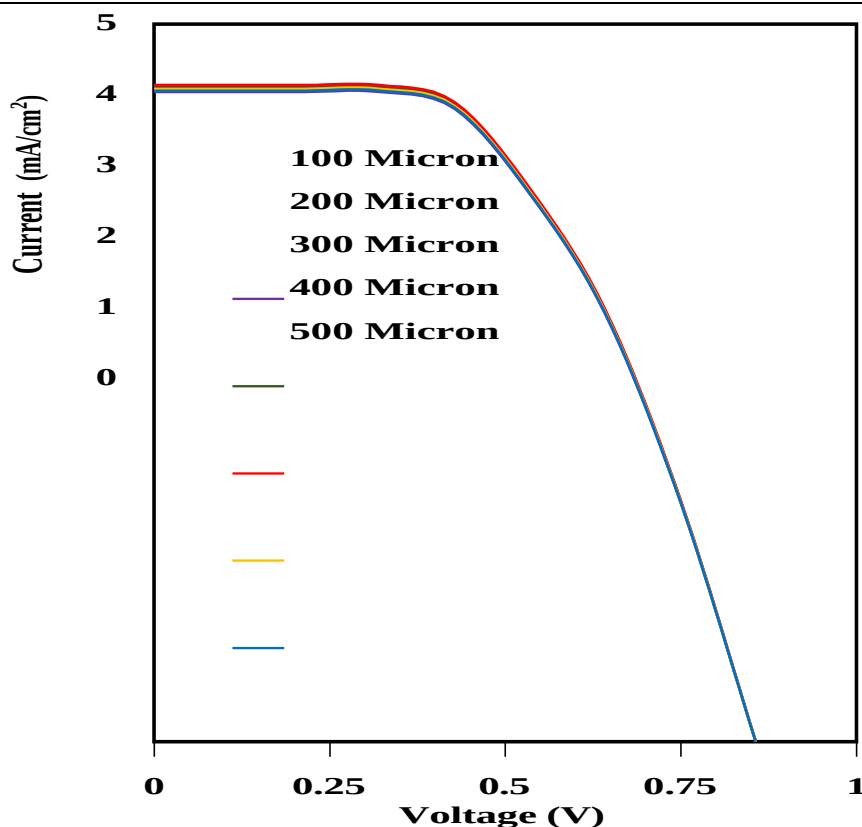


Figure 11. IV characteristics of 20TZ nanocomposite system-based PV cell sensitized with N749 for 2 Hours dipping time and tested at different thickness (a) 100 micron, (b) 200 micron, (c) 300 micron, (d) 400 micron and (e) 500 micron.

Table 3. PV Parameters of 20TZ nanocomposite system-based PV cell sensitized with N749 for 2 Hours dipping time and tested at different thickness (100 micron, 200 micron, 300 micron, 400 micron and 500 micron).

Sample	$I_{\max}$ mA/cm ²	$V_{\max}$ (V)	I_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
2H:N749:100	3.812	0.535	4.527	0.856	0.38	14.9
2H:N749:200	3.843	0.535	4.563	0.856	0.38	15
2H:N749:300	3.850	0.535	4.572	0.856	0.38	15.1
2H:N749:400	3.831	0.535	4.550	0.856	0.38	15
2H:N749:500	3.820	0.535	4.536	0.856	0.38	14.9

Figure 12 shows the variation of power conversion efficiency with error bars for 20TZ nanocomposite at thicknesses of 100 microns, 200 microns, 300 microns, 400 microns, and 500 microns. This study investigates the effect of varying thicknesses (100 μ m, 200 μ m, 300 μ m, 400 μ m, and 500 μ m) on the power conversion efficiency (PCE) of a 20TZ nanocomposite-based photovoltaic (PV) cell sensitized with N749 dye for a 2-hour dipping time. The results indicate that the changes in PCE are minimal across the different thicknesses, suggesting that the thickness variation is insignificant within the experimental error range.

The power conversion efficiency of a photovoltaic cell is influenced by several factors, including the thickness of the active layer. In this study, the thickness of the 20TZ nanocomposite active layer was varied (100 μ m, 200 μ m, 300 μ m, 400 μ m, and 500 μ m) to observe its impact on power conversion efficiency. The results indicated that the variations in power conversion efficiency were minimal across these different thicknesses.

As the active layer thickness increases, the potential for charge carrier recombination also increases due to longer travel distances for the carriers. However, if the material intrinsic properties, such as high carrier mobility and long carrier lifetime, effectively moderate recombination, the overall power conversion efficiency might remain relatively unchanged with thickness variation.

The minimal variation in power conversion efficiency could also be attributed to high precision and consistency in the experimental setup and measurements. The reported power conversion efficiency values may include measurement errors, which can overshadow the minor differences caused by thickness variations.

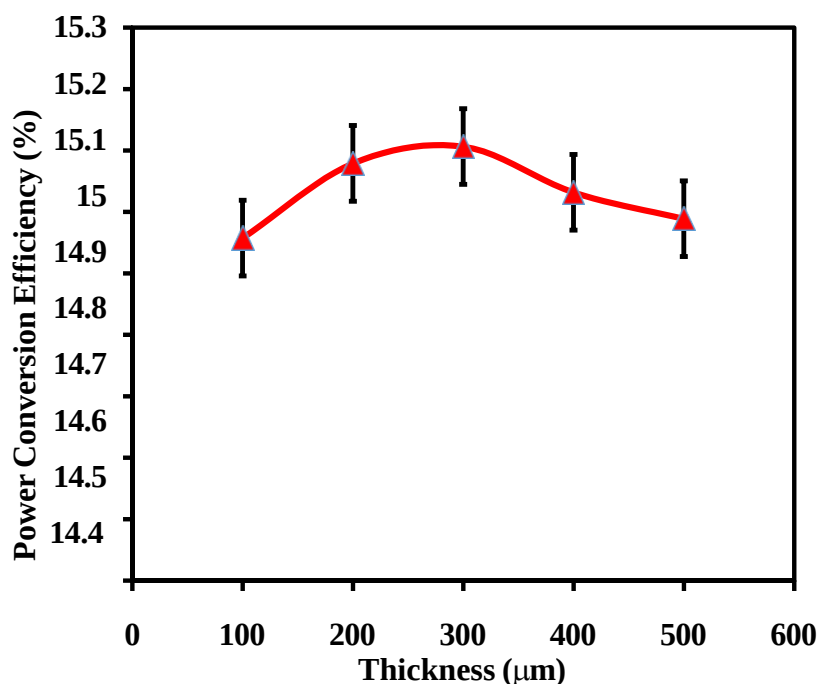


Figure 12. Variation of Power Conversion Efficiency with error bars for 20TZ nanocomposite at thicknesses of 100 microns, 200 microns, 300 microns, 400 microns, and 500 microns.

Figure 13 shows the schematic diagram of the electron transfer mechanism in the 20TZ nanocomposite-based DSSC. In the 20TZ nanocomposite-based DSSC, incorporating ITO and N749 dye, the charge transfer mechanism involves several key steps. When light is absorbed by the N749 dye, it gets excited from its ground state to an excited state. The excited electrons from the N749 dye are then injected into the conduction band of ZnO, which is slightly lower in energy than the conduction band of TiO₂. These electrons subsequently transfer from the ZnO conduction band to the TiO₂ conduction band, facilitating efficient charge transport. The electrons are finally collected by the ITO (Indium Tin Oxide) electrode, which serves as the anode. In bare TiO₂, recombination can occur either between the injected electron in the TiO₂ conduction band and the oxidized dye or between the injected electron and the electrolyte. However, the presence of ZnO in the system lowers the probability of these recombination events, as ZnO enhances electron injection and transfer to TiO₂, thereby reducing electron-hole recombination with the dye and electrolyte. The oxidized N749 dye is then regenerated by the electrolyte, which donates an electron to the dye, completing the circuit and enabling continuous electricity generation. The integration of ZnO into the TiO₂ matrix thus results in lower recombination resistance, higher recombination rates, and improved overall performance of the DSSC.

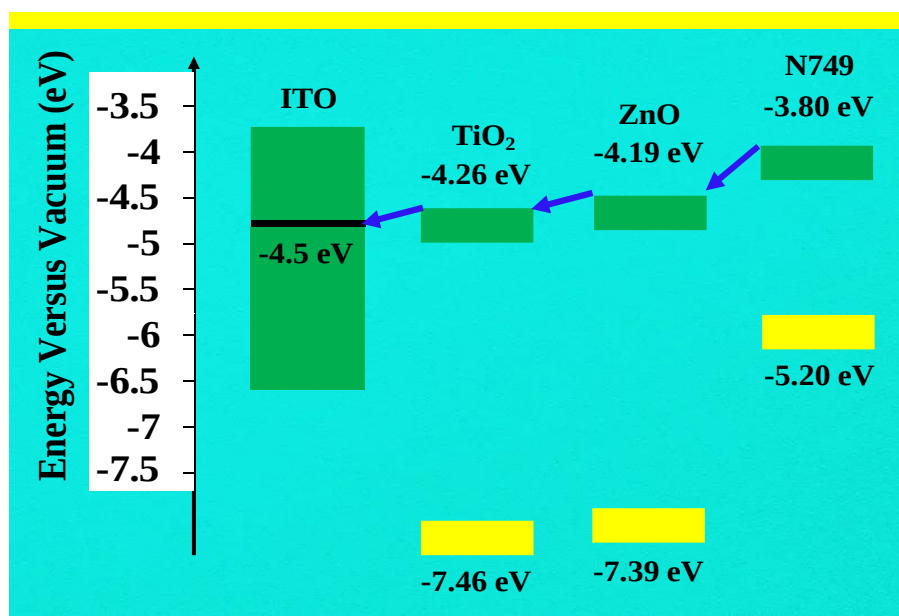


Figure 13. Schematic diagram of electron transfer mechanism in 20TZ DSSC Sensitized by N749 Dye.

Incident Photon Current Efficiency (IPCE) Analysis

IPCE was measured to analyze the photocurrent behavior in the devices. As depicted in Figure 14, the IPCE for the 20TZ-DSSC displays a broad peak spanning from 320 nm to 540 nm, primarily attributed to the band gap of the 20TZ nanocomposite. The overlap between the band gap of the 20TZ nanocomposite and the absorption spectrum of the N749 dye occurs within this wavelength range. This overlap facilitates enhanced photon absorption by both the semiconductor material and the dye molecules, consequently leading to an increase in photocurrent generation. Consequently, the IPCE spectrum demonstrates a broad peak across this range, showcasing the efficient utilization of incident photons by the composite system.

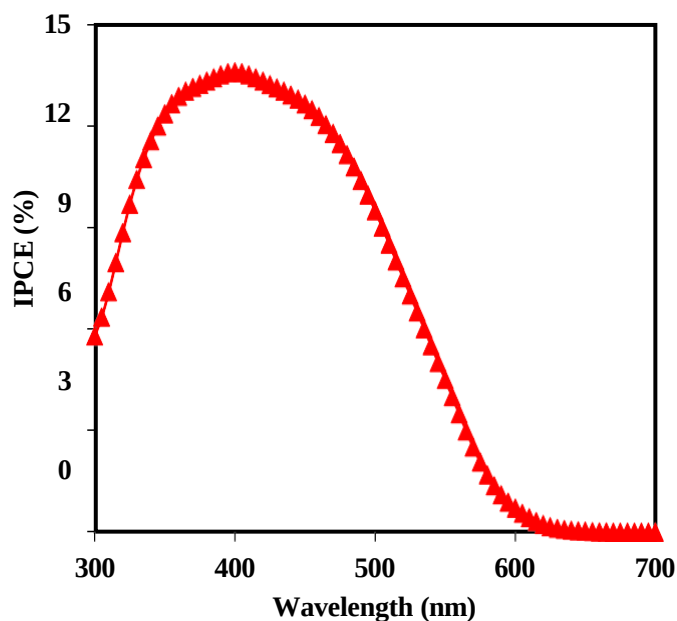


Figure 14. Incident Photon Current Efficiency of 20TZ-DSSC.

Initially, during the dye optimization process, an efficacy of 13.7% was achieved using dye N749 at a concentration of 3%. Subsequently, the optimization focused on dye loading time, resulting in an increased efficiency value of 14.9% when the loading time was set to 2 hours for Dye N749. Finally, in the thickness optimization phase, utilizing a sample with a thickness of 300 microns and a 2-hour dipping time for dye N749, the overall study yielded an efficiency of 15.1%. Table 4 shows the change in efficiency of PV cell with the optimization parameter. The change in efficiency values listed in table 4 estimated over the dye concentration optimization step. In the optimization process, from dye loading time to thickness optimization, the observed change in efficiency is merely 0.885%. Therefore, the IV characteristics in the PV cell during the thickness optimization study exhibit striking similarities to each other.

Table 4. Change in efficiency of PV cell with the optimization parameter.

SN	Optimization Parameter	Efficiency Obtained (%)	Efficiency Change (%)
01	Dye Concentration	13.7	-
02	Dye loading time	14.9	9.0
03	Thickness optimization	15.1	9.8 %

In the optimization process, the overall efficiency of a cell with a thickness of 300 microns and a 2-hour dipping time for Dye N749 was determined to be 15.1%. This efficiency represents a notable improvement of 9.8% compared to the cell optimized using dye concentration alone, which achieved an efficiency of 13.7%.

Stability Test of 20TZ DSSC

The stability test, conducted under light illumination for a duration ranging from 0 to 240 hours, is illustrated in Figure 15. The photovoltaic performance remained unchanged during the first 168 hours of light irradiation. However, a slight decrease in power conversion efficiency of 1.61% was observed under light illumination for 20TZ based DSSC. This slight change in the power conversion efficiency % of the 20TZ-based DSSC indicates that further improvements are necessary to enhance the stability of 20TZ composite-based DSSCs for long-term, high-performance device applications.

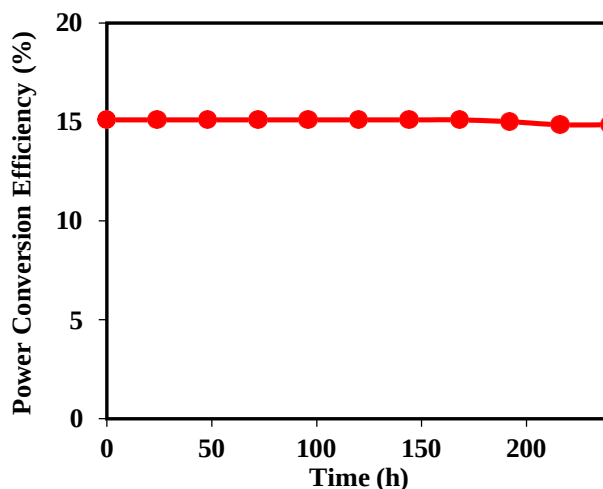


Figure 15. Stability test of 20TZ DSSC.

IV. Conclusions

This research has systematically explored the critical factors influencing the performance of DSSCs. The goal of present study is to assemble DSSC which has more potential, efficient and used to produce sustainable solar energy conversion to electricity. Also the study emphasizes the significant impact of dye sensitizer selection, semiconducting layer thickness, and dye loading duration are key parameters of the power conversion efficiency improvement in DSSCs. Through an ex-situ approach used to prepare nanocomposite materials. For this we incorporating ZnO nanoparticles into TiO₂ nanoparticles, enabling a detailed investigation of their structural, morphological, and optical properties. The research explores the influence of varying thicknesses of the semiconducting layer, revealing a direct correlation between layer thickness and DSSC efficiency. The 300-micron thickness 20TZ-based DSSC sensitized with 3% of N749 dye for a 2-hour loading time emerged as the most efficient configuration, achieving a remarkable power conversion efficiency of 15.1%. Thus, while 20TZ-based DSSCs exhibit promising initial stability under light illumination, further optimizations are essential to achieve long-term durability and maintain high performance in practical applications.

Future scope of present study provides valuable insights in optimizing DSSC performance through proper dye selection and precise control of photoanode layer thickness of dye sensitized solar cell. The findings offer a promising avenue for the development of highly efficient and sustainable solar energy conversion technologies by the use of dye sensitized solar cell which contribute in production of green energy and also globally more energy-efficient future.

Author Contributions

In this work, material preparation, experiments, data collection and analysis were performed by SRN. The first draft of the manuscript was written by PSK. The authors read and approved the final manuscript.

Funding

No funding received for this research work.

Data availability

The authors declare that the datasets and results obtained and/or analyzed during the current study are available from the corresponding author on reasonable request. All data generated or analyzed during this study are included in this published article.

Declarations

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent for Publication

The manuscript was only submitted to the journal named as “Journal of Materials Science: Materials in Electronics.” The authors have certified that this manuscript was not submitted to any journal for simultaneous consideration. The authors declare that the submitted results in the manuscript are original and any part of them had not been published elsewhere in any form or language (partially or in full), and this study was not split up into several parts for increasing publication number. The authors endorsed that all results introduced in this study were presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Research Involving Human and Animal Participants

This study did not involve any experiments on animals or humans.

References

1. Raza W, Ahmad K. Artificial photosynthesis system for the reduction of carbon dioxide to value-added fuels. *Handbook of Greener Synthesis of Nanomaterials and Compounds*. Elsevier. 2021;917-938.
2. Arjmand F, Ranjbar ZR, Fatemi H. Effect of dye complex structure on performance in DSSCs; An experimental and theoretical study. *Heliyon*. 2022;8:11692.
3. Bachtiar MI, Agustina MNP, Hariyani LW, Nurosyid F. Effect of dye variation on DSSC efficiency. *Journal of Physics Conference Series*. 2019;1153:012097.
4. Pratiwi DD, Nurosyid F, Supriyanto A, Suryana R. Performance improvement of dye-sensitized solar cells (DSSC) by using dyes mixture from chlorophyll and anthocyanin. *Journal of Physics: Conference Series*. 2017;909:012025.
5. Hossain MK, Pervez MF, Mia MNH, Mortuza AA, Rahaman MS, Karim MR, et al. Effect of dye extracting solvents and sensitization time on photovoltaic performance of natural dye sensitized solar cells. *Results in Physics*. 2017;7:1516.
6. Abdel-Galeil MM, Kumar R, Matsuda A, El-Shater RE. Investigation on influence of thickness variation effect of TiO₂ film, spacer and counter electrode for improved dye-sensitized solar cells performance. *Optik*. 2021;227:166108.
7. Raza W, Ahmad K. ZnO Nanostructures for Photocatalytic Dye Degradation Under Visible Light Irradiation. *Environmental Nanotechnology for Water Purification*. Wiley-Scrivener. 2020.
8. Rahman MF, Hidayat A, Diantoro M. The influence of TiO₂ film thickness in Dye-Sensitized Solar Cells (DSSC) performance based on TiO₂/Ag@TiO₂-ZnO. *J. Phys.: Conf. Ser.* 2020;1572:012079.
9. Kao MC, Chen HZ, Young SL, Kung CY. The effects of the thickness of TiO₂ films on the performance of dye-sensitized solar cells. *Thin Solid Films*. 2009;517:5096.
10. Elmorsy MR, Badawy SA, Abdel-Latif E, Assiri MA, Ali TE. Significant improvement of dye-sensitized solar cell performance using low-band-gap chromophores based on triphenylamine and carbazole as strong donors. *Dyes and Pigments*. 2023;214:111206.
11. Ahmad K, Kim H. MoSe₂-nanoflowers as bi-functional electro-catalyst: An efficient counter electrode material for dye-sensitized solar cells and electrode modifier for hydrazine sensor. *Materials Chemistry and Physics*. 2023;296:127260.
12. Abdulrahman ZH, Hachim DM, Al-murshedi ASN, Kamil F, Al-Manea A, Yusaf T. Comparative performances of natural dyes extracted from Mentha Leaves, Helianthus Annuus Leaves, and Fragaria Fruit for dye-sensitized solar cells. *Designs*. 2022;6:100.
13. Selopal GS, Wu H, Lu J, Chang Y, Wang M, Vomiero A, et al. Metal-free organic dyes for TiO₂ and ZnO dye-sensitized solar cells. *Scientific Reports*. 2016;6:18756.
14. Roy A, Sundaram S, Mallick TK. Effect of dye sensitization's temperature on ZnO-based solar cells. *Chemical Physics Letters*. 2021;776:138688.
15. Siddika, Sultana M, Bashir MS, Tabassum S, Aziz S, Shaikh MAA. Improved performance of dye sensitized solar cell by exploration of photoanode and ruthenium-based dye. *Optical Materials*. 2022;125:112042.
16. Salau AO, Olufemi AS, Oluleye G, Owuoye VA, Ismail I. Modelling and performance analysis of dye-sensitized solar cell based on ZnO compact layer and TiO₂ photoanode. *Materials Today: Proceedings*. 2022;51:502.
17. Nemade KR, Dudhe PV, Tekade P. Enhancement of photovoltaic performance of polyaniline/graphene composite-based dye-sensitized solar cells by adding TiO₂ nanoparticles. *Solid State Sciences*. 2018;83:99.
18. Nemade KR, Tekade PV, Dudhe PV. Strengthening of photovoltaic and supercapacitive properties of graphene oxide-polyaniline composite by dispersion of α -Al₂O₃ nanoparticles. *Chemical Physics Letters*. 2018;706:647.
19. Salmi T, Bouzguenda M, Gastli A, Masmoudi A. MATLAB/Simulink based modelling of photovoltaic cell. *International Journal of Renewable Energy Research*. 2012;2:213.
20. Behara DK, Tammineni J, Maheswari MS. TiO₂/ZnO: Type-ii heterostructures for electrochemical crystal violet dye degradation studies. *Macedonian Journal of Chemistry and Chemical Engineering*. 2020;39:1.
21. Baitha PK, Manam J. Luminescence properties of ZnO/TiO₂ nanocomposite activated by Eu³⁺ and their spectroscopic analysis. *Bulletin of Material Science*. 2016;39:1233.
22. Upadhyay GK, Rajput JK, Pathak TK, Kumar V, Purohit LP. Synthesis of ZnO:TiO₂ nanocomposites for photocatalyst application in visible light. *Vacuum*. 2019;160:154.
23. Pezhooli N, Rahimi J, Hasti F, Maleki A. Synthesis and evaluation of composite TiO₂@ZnO quantum dots on hybrid nanostructure perovskite solar cell. *Scientific Reports*. 2022;12:9885.
24. Li S, Wang Y, Li T, Ma P, Zhang X, Xia B, et al. Skin bioinspired anti-ultraviolet melanin/TiO₂ nanoparticles without penetration for efficient broad-spectrum sunscreen. *Colloid and Polymer Science*. 2021;299:1797.
25. Aldalbahi A, Alterary S, Almoghaim R, Awad MA, Aldosari NS, Alghannam SF, et al. Greener Synthesis of Zinc Oxide Nanoparticles: Characterization and Multifaceted Applications. *Molecules*. 2020;25:4198.
26. Sridevi KP, Prasad LG, Sangeetha B, Sivakumar S. Structural and optical study of ZnO-TiO₂ nanocomposites. *Journal of Ovonic Research*. 2022;18:453.

27. Giannakopoulou T, Todorova N, Giannouri M, Yu J, Trapalis C. Optical and photocatalytic properties of composite TiO₂/ZnO thin films. *Catalysis Today*. 2014;230:174.
28. Mazabuel-Collazos A, Gomez CD, Rodriguez-Paez JE. ZnO-TiO₂ nanocomposites synthesized by wet-chemical route: Study of their structural and optical properties. *Materials Chemistry and Physics*. 2019;222:230.
29. Pant A, Ojha GP, Kuk Y, Kwon OH, Park YW, Park M. Synthesis and Characterization of ZnO-TiO₂/Carbon Fiber Composite with Enhanced Photocatalytic Properties. *Nanomaterials*. 2020;10:1960.
30. Mitric J. Rare-Earth-Activated Phosphors: Chemistry and Applications. Elsevier - Health Sciences Division. 2022;43-58.
31. Shi L, Wang F, Wang Y, Wang D, Zhao B, Zhang L, et al. Photoluminescence and photocatalytic properties of rhombohedral CuGaO₂ nanoplates. *Scientific Reports*. 2016;6:21135.
32. Pezhooli N, Rahimi J, Hasti F, Maleki A. Synthesis and evaluation of composite TiO₂@ZnO quantum dots on hybrid nanostructure perovskite solar cell. *Scientific Reports*. 2022;12:9885.
33. Klug HP, Alexander LE. X-Ray Diffraction Procedures: For Polycrystalline and Amorphous Materials (2nd Edition). Wiley Publication. 1974.
34. Griffiths PR, de Haseth JA. Fourier Transform Infrared Spectrometry. Wiley Publication. 2006.
35. Younas M, Harrabi K. Performance enhancement of dye-sensitized solar cells via co-sensitization of ruthenium (II) based N749 dye and organic sensitizer RK1. *Solar Energy*. 2020;203:260.
36. Tahir M, Ud Din I, Zeb M, Aziz F, Wahab F, Gul Z, et al. Thin Films Characterization and Study of N749-Black Dye for Photovoltaic Applications. *Coatings*. 2022;12:1163.
37. Arslan BS, Ozturk N, Gezgin M, Sevindik S, Yilan D, Kumbasar RA, et al. Optimization of fabrication parameters for efficient dye-sensitized solar cells based on dyes containing benzothiadiazole, indoline, and their co-sensitization. *Electrochimica Acta*. 2023;458:142523.
38. Sharma GD, Angaridis PA, Pipou S, Zervaki GE, Nikolaou V, Misra R, et al. Efficient co-sensitization of dye-sensitized solar cells by novel porphyrin/triazine dye and tertiary aryl-amine organic dye. *Organic Electronics*. 2015;25:295.
39. Sharma K, Sharma V, Sharma SS. Dye-Sensitized Solar Cells: Fundamentals and Current Status. *Nano Research Letter*. 2018;13:381.