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1. Introduction

Energy has had an enormous impact on the development of technology and is a main factor in humans' advancement towards an evolved society. Nevertheless, nonrenewable energy resources – which are the most effective in everyday application - have led to changes in the climate, environment, human health, and the world in general [1], which has encouraged researchers to switch to the use of renewable energy sources.

Solar Cells are one of the most effective resources that rely on renewable energy. They come in a variety of types, operation methods, and efficiency as shown in Figure 1, including Dye-Sensitized Solar Cells (DSSC), which, inspired by photosynthesis in plants, uses photo-sensitive dye to capture sunlight and generate electricity. DSSCs were proved to have generated a great deal of interest and are one of the most promising solar cells among third-generation PV technologies, due to their low cost, simple preparation, good performance, and environmental friendliness compared to conventional photovoltaic devices [3]. However, their efficiency is quite insufficient for everyday use.

Previous studies proved that Tandem DSSCs – which are two dye-sensitized cells stacked on top of each other – are able to enhance cell performance. The light absorption range of a tandem cell is increased because the bottom cell behind the top one absorbs and uses the incident light that was not absorbed by it [4]. It operates as shown in Figure 2, where the light photons excite the electrons of the dye molecules. The electrons are then transported to the FTO (conductive glass) by the semiconductor, which is used in the figure as TiO₂ nanoparticles. The electrons pass through the circuit to perform the work, then move to the counter electrode (shown as Platinum). They are then transported by the electrolyte (I⁻/I₃⁻) back to the dye molecules, and the process is repeated.

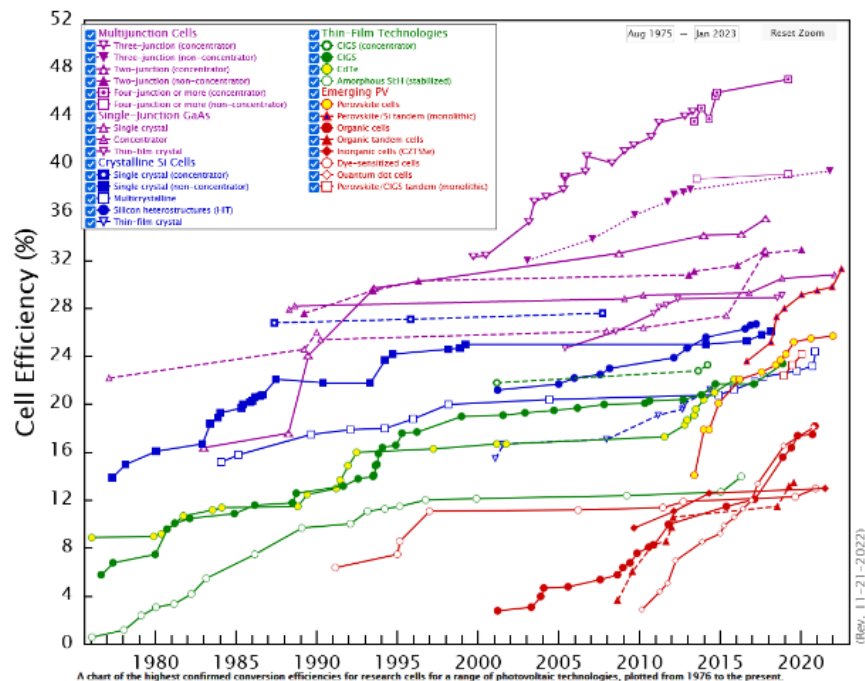


Figure 1. Cell Efficiency Chart [2]

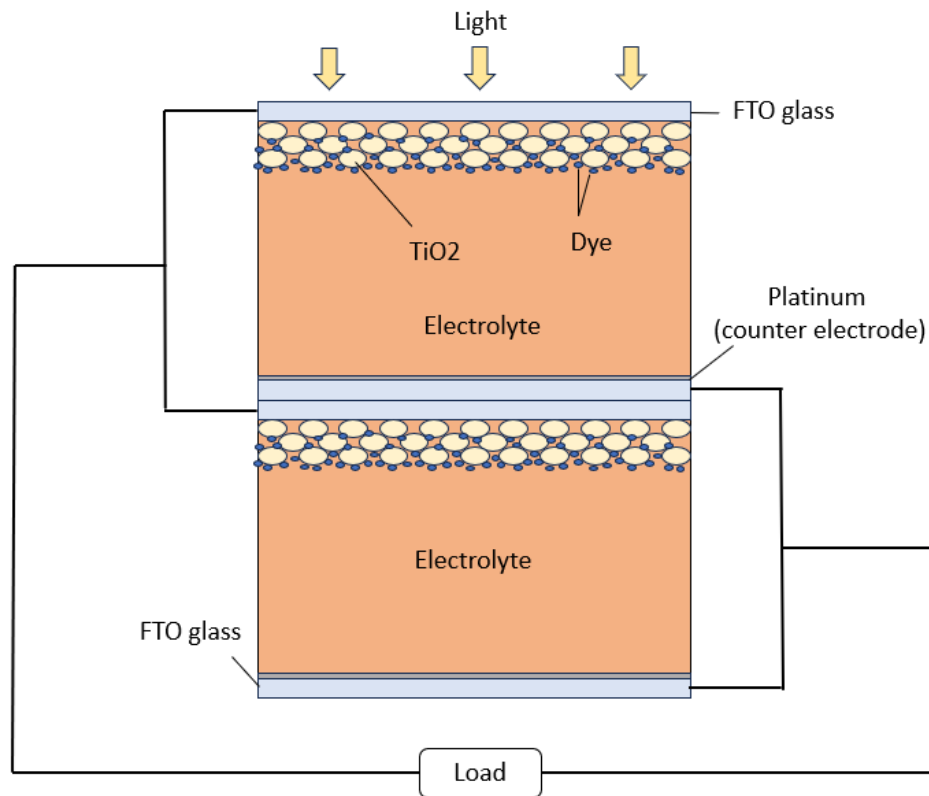


Figure 2. Structure of Tandem Dye-Sensitized Solar Cells

2. Literature Review

In literature, ruthenium-based dyes have been vastly studied. In the DSSC community, ruthenium-based complex dyes with a variety of structures, excellent stability, and high efficiency have drawn a lot of interest [5]. An article mentioned that the dye's structure has the ability to influence and promote electron infusion into the conduction band of titanium dioxide [6], and that a few fundamental conditions have been met by the standard dyes N3 and N719 as well as the dark dye N749 in previous DSSC studies. Another paper elaborated on these conditions, stating that **(1)** dyes should be able to absorb large amounts of light in the visible spectrum as well as the near-infrared region (NIR) and ultraviolet–visible (UV–vis) regions [7], **(2)** Both the ground state and the excited state of the dye—after absorbing the incident light—should be stable, **(3)** The highest occupied molecular orbital's (HOMO) energy should be lower than the semiconductor's minimum conduction band for n-type DSSCs. Additionally, the energy of the HOMO should be substantially less than that of the electrolyte redox couple, **(4)** As for p-type dye-sensitized solar cells, the dye's HOMO should be considerably lower than the semiconductor's maximum valence band in order to increase the driving force for hole injection, while the lowest unoccupied molecular orbital (LUMO) energy ought to be higher than that of the redox shuttle energy, as in the case of n-type dye-sensitized solar cells, where LUMO energy needs to be near yet greater than the conduction band's minimum, **(5)** To guarantee the dye's long-term stability when in contact with the electrolyte and the surroundings, its outermost atoms as well as rest groups must be hydrophobic, **(6)** Strong dye-to-

semiconductor interaction and effective transfer of charges between the two should be made possible by anchoring groups.

Regarding semiconductors in DSSCs, a paper highlights both ZnO and TiO₂. For ZnO, it is thought to be an excellent photoanode material for DSSCs since it has a greater carrier mobility compared to TiO₂ and a similar work function and conduction band edge [8], but unfortunately, ZnO's performance is diminished by its instability in acidic environments and the dye's aggregate formation on its surface. In the case of TiO₂, it claims that, due to TiO₂ nanoparticles' combined advantages in dye absorption, porosity, transfer of charges, and transport of electrons, the most effective DSSCs to date have been based on them. Another paper provided a chart that demonstrated the band gaps of different semiconductors as shown in Figure 3.

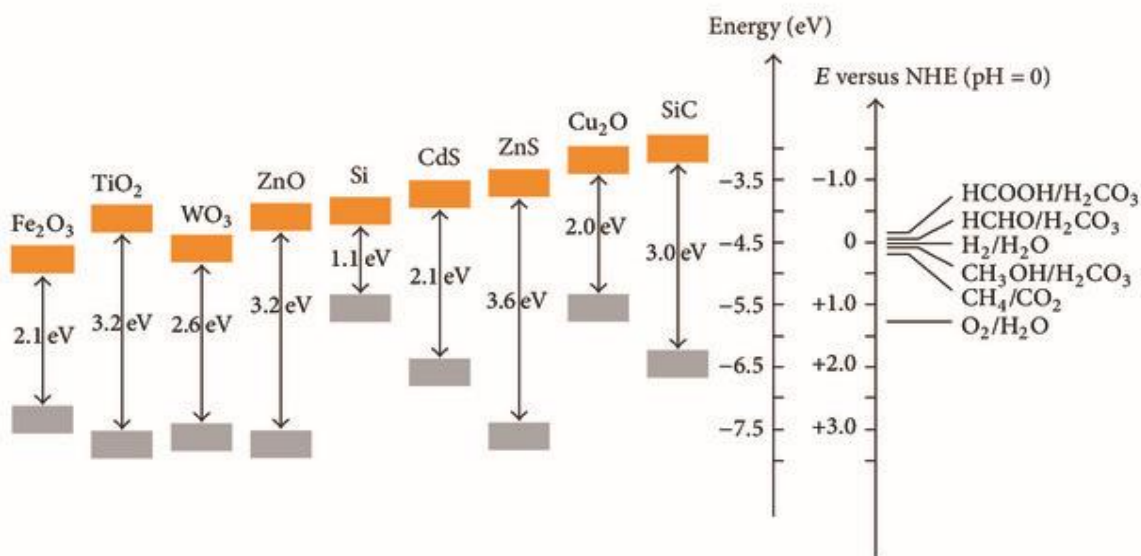


Figure 3. Band Gaps of Different Semiconducting Materials [9]

As for electrolytes, an article claims that every electrolyte in a DSSC needs to meet a number of requirements [10]. In summary, it requires the ability to transfer charge carriers within the cell, allow for faster charge carrier diffusion, long-term stability, and there shouldn't be any noticeable absorption of visible light by the electrolyte.

An article claims that DSSCs would be a good application for "Indoor Light Harvesting", since - compared to Silicon-based solar cells - they are more effective in low-light conditions [11].

3. Objectives and Hypothesis

Aiming to solve the issue of low DSSC efficiency, this research paper offers a novel method of enhancing tandem DSSC performance by comparing different types of dyes and semiconductors used in tandem dye-sensitized solar cells towards enhancing the efficiency of DSSCs.

This project's hypothesis states that:

- 1- if each dye in asymmetric and symmetric tandem cells cover varying positions of the wavelength, the cell's absorbance rate is higher, therefore resulting in higher power conversion efficiency (PCE).
- 2- if the photoanode material (TiO₂) is combined with CdS and WO₃, the band gap between that of the dye and semiconducting material is smaller, therefore enhancing the absorbance rate and photovoltaic efficiency of the tandem DSSC.

4. Methodology and Procedures

4.1 Materials

4.1.1 Asymmetric and Symmetric Tandem DSSC: The materials that were utilized to allow the success of this part of the project were: A set of Fluorine-doped Tin Oxide (FTO) glasses, ethanol for cleaning, and TiO₂ paste as photoelectrode. Z-50 formed an electrolyte to transport Msonication, BRANSON 3510 was used. Hotplate to dry the pastes (TiO₂ and Pt) was used as well. Three types of ruthenium-based dyes: N3, N719, and Z907, were used to compare the efficiency of each cell. IV Rider and UV computerized programs were important for obtaining the cells' PCE.

4.1.2 Semiconducting Material: The items required for this part of the project were: TiO₂ powder, CdS powder, and WO₃ powder as semiconductors. Mettler Toledo scale was utilized for measuring the weight of each sample's powder. PTFE magnetic beads were used to help the combining process of the samples. Vials were used for storing the samples, and ethanol, along with BRANSON 3510 device were used for insuring the sanitization of all tools. De-ionized (DI) water was used for easier mixing of the photoanode materials, and Pulsed Laser Ablation in liquid (PLAL) laser machine was essential to convert the sample's particles into nanoparticles for high-quality combination. A filtration funnel and filter paper were utilized to separate the DI water and the semiconductors, and an oven was used to dry the samples. UV testing was important for obtaining the absorbance rate of the materials and band gaps.

4.2 Process

4.2.1 Fabricating Asymmetric and Symmetric Tandem DSSCs:

4.2.1.1 Preparation: Initially, FTO glasses were prepared and cleansed with ethanol and sonicated using BRANSON for 15 minutes. The device produced sound waves of a high frequency in the ultrasonic range, which allowed the ethanol particles to move in a manner that enhanced the cleaning process. Pencil was used to determine the conductive side of the pieces of glass and draw an outline for the cell area, forming approximately 0.25 cm². The glasses were then secured on top of the table using duct tape, which was attached to surround the cell area.

4.2.1.2 Applying TiO₂: TiO₂ was utilized to coat the clear area (cell area) of conductive glasses and serve as a semiconductor. A small rod was then used to spread the titanium dioxide across the highlighted area. As soon as the FTOs were coated, the duct tapes were removed to set the samples on a hotplate to dry the TiO₂. The temperature of the hotplate was set between 120-130

degrees Celsius for approximately 10 minutes. When the first layer of TiO₂ was dried, the same process was repeated twice. For the third and final time, the samples were placed on hotplate, and the temperature was set to 200 degrees Celsius for a duration of 10 minutes, then the heat was increased every minute until it reached nearly 450 degrees Celsius. The FTOs were then left to heat for 25 minutes before shutting the hotplate off. Throughout this process, the TiO₂ darkened occasionally, then transformed to an off-white color.

4.2.1.3 Applying Platinum: Platinum was employed to the untouched glasses and went through the same process. These glasses were going to act as counter electrode layers for the cell. The samples were put on hotplate and set for the same process as the final TiO₂ coating. By the end of this process, the Pt became quite transparent. The samples were left on top of the hotplate to cool off.

4.2.1.4 Dyes: The TiO₂ coated cells were divided into three containers; the first contained N3, the second N719, and the third Z907. Parafilm was later secured on top of each container to prevent the ethanol decomposed in dye from evaporating, and aluminum was rolled around them to prevent photovoltaic reactions. The cells were left to absorb the dye for a duration of 24 hours.

4.2.1.5 Fabricating Cells: The dried photoanode glasses were paired with the Pt coated ones. Each pair was secured using strong glue and Z-50 electrolyte was applied to move charge carriers and maintain the cell's electrochemical equilibrium. Each cell was tested individually to determine their efficiency before fabricating the tandem cells.

Fabricating tandem DSSCs was the next step. Each cell was paired with another that contained a different type of dye (asymmetric cells):

- 1- Z907+N3
- 2- N719+N3
- 3- Z907+N719

Next, each cell was paired with another that contained the same type of dye (symmetric cells):

- 1- Z907+Z907
- 2- N719+N719
- 3- N3+N3

4.2.2 Semiconducting Material:

4.2.2.1 Preparation: For this part of the project, 3 vials were cleansed with ethanol and sonicated with BRANSON 3510. Then, 300mg of TiO₂ and 300mg of WO₃ powders were measured using Mettler Toledo scale and added to the first vial. 300mg of TiO₂ and CdS were added to the second vial, and 150mg of WO₃, 150mg of CdS, and 300mg of TiO₂ were put in the third vial.

4.2.2.2 PLAL Mixing: The second step was adding DI water to each samples to allow the particles to move freely and combine, as well as adding a metal bead for achieving that goal as well. Each sample went through 4 rounds in the PLAL laser device, and each round was set for nearly 20 minutes. The device helped degrade the particles of the materials into nanoparticles through laser beam.

4.2.2.3 Extracting Samples: Once the samples were thoroughly mixed, they were poured onto a filtering paper and a funnel to separate the DI water from the semiconducting nanocomposites. As soon as that was achieved, the three samples were set to dry in an oven for approximately an

hour on a temperature of 110 Celsius. Finally, the resulted powders of the samples were transported to small containers.

5. Results and Analysis

5.1 Asymmetric and Symmetric Tandem DSSCs:

Results were obtained using IV Rider software as shown in Figure 3 and 4. Figure 3 illustrates the individual DSSC characteristics. Z907, which is shown as the black line, appears to have gained the lowest energy percentage. The results indicated that cells coated with Z907 have formed nearly 6.6%. N719 coated DSSCs are negligibly higher, featuring 6.8%. DSSCs coated with N3, on the other hand, have exceeded the percentage of them by 1%, gaining approximately 7.8 PCE.

Figure 4 presents the obtained PCE of asymmetric tandem DSSCs. Tandem coated with Z907 and N719 were the least efficient compared to the rest, being only 6.3%. Z907+N3 and N719+N3 tandems proved to have gained a higher power conversion efficiency, forming 8.2% and 9.2% respectively.

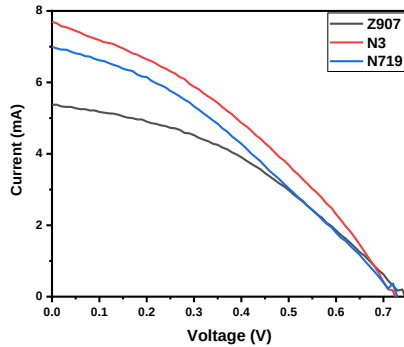


Figure 3. Individual DSSC IV Characteristics

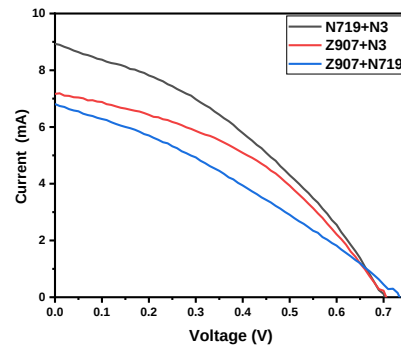


Figure 4. Asymmetric Tandem DSSC IV Characteristics

Results for symmetric tandem DSSCs, as shown in Figure 5, indicate that tandems coated with N719 gained the highest efficiency rate of nearly 10.4%. Lower were N3 coated tandem DSSCs, which reached approximately 8.2%, and negligibly less than that were Z907 coated tandems, which only resulted in 7.8 PCE.

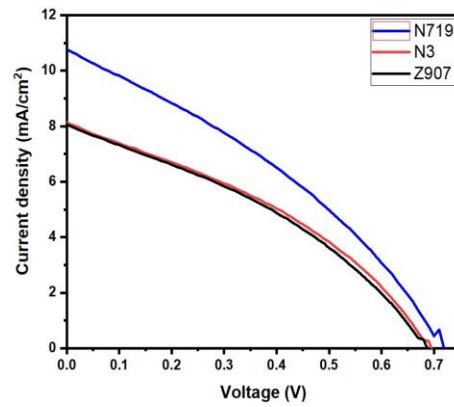


Figure 5. Symmetric Tandem DSSC IV Characteristics

Figure 6 illustrates the UV spectra of the dyes' absorption. The individual DSSCs have been tested, along with the Tandem N719+N3 DSSC – since it earned the highest efficiency rate. It could be extracted from the chart that the wavelengths of the individual N719 and N3 dyes covered different positions according to the wavelength axis, and close absorbance rates. Furthermore, when these two dyes were joined together, their absorbance rate increased. Finally, the Z907 spectrum shows that it absorbs the light, but there are no significant concentrating peaks as in N3 and N719 to absorb more light in exact wavelength. Figure 7 demonstrates the UV spectra of the dyes' absorption when added along with TiO₂ in a DSSC. It could be seen that TiO₂ hindered the absorbance rates of N3 and Z907 individual dyes, while in contrast, being very efficient when added with N719 individual dye. In N3+N719 tandem DSSCs, the TiO₂ affected the dyes' absorbance rates by decreasing the absorbance of individual N719 dye and increasing the absorbance of individual N3 dye. Figure 8 summarizes each cell's power conversion efficiency.

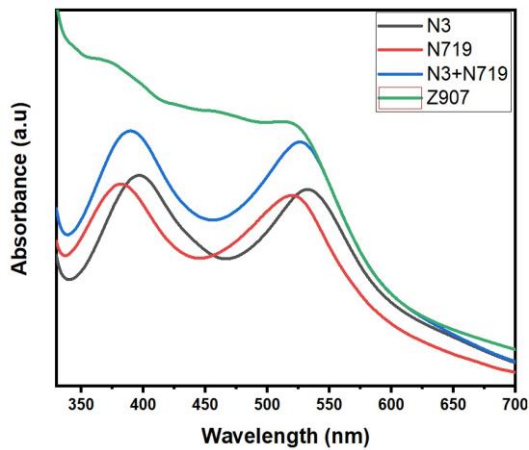


Figure 6. UV Spectra of Dyes' Absorption

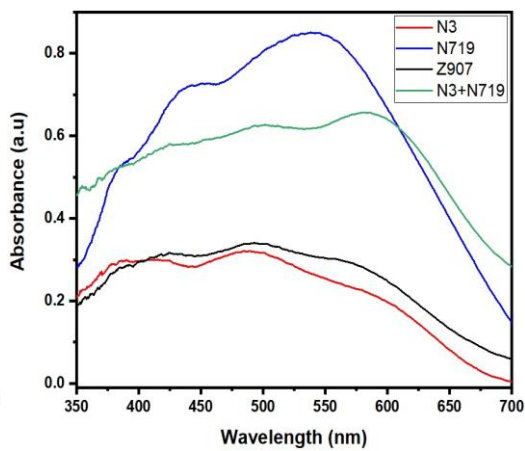


Figure 7. UV Spectra of Dyes' Absorption (with TiO₂)

Cell	PCE (%)
Z907	6.6
N719	6.8
N3	7.8
N719+N3	9.2
Z907+N3	8.2
Z907+N719	6.3

Figure 8. Power Conversion Efficiency Summary

5.2 Semiconducting Material:

Results acquired from the UV test are as shown in Figures 9 and 10. Figure 9 demonstrates the UV spectra of the semiconductor's absorption rate. Sample 3, which represents pure CdS, gained the highest absorption rate. Samples 5 and 6, which are TiO₂+CdS and TiO₂+WO₃+CdS, respectively, followed shortly and gained very close absorbance rates, with TiO₂+CdS being slightly higher. Pure WO₃'s absorption was less than samples 5 and 6 and higher than sample 4, which represents TiO₂+WO₃. Finally, it could be noticed that pure TiO₂ (sample 1) absorbed the least amount of the wavelength out of all samples.

Figure 10 highlights the UV spectra of the semiconductors' band gaps. The band gap of individual TiO₂ is shown to reach 3.33. When joined with WO₃, however, the band gap decreased to approximately 3.25. It could be noticed that when TiO₂ is associated with CdS, and with both WO₃ and CdS, shown respectively as samples 5 and 6, the band gap declined even more to arrive at 3.18. Pure WO₃ was shown in the graph to be 2.7. Finally, CdS formed the lowest band gap, which is demonstrated in the graph to be nearly 2.18.

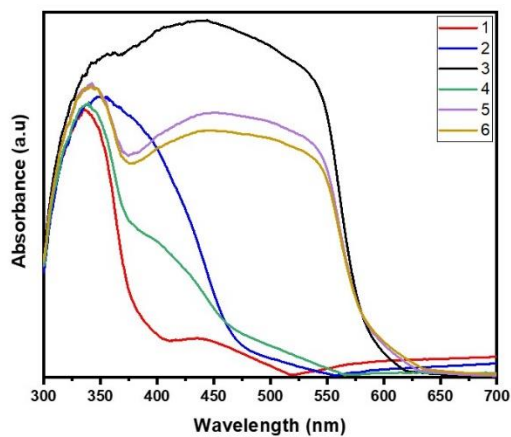


Figure 9. UV Spectra of Semiconductors' Absorbance

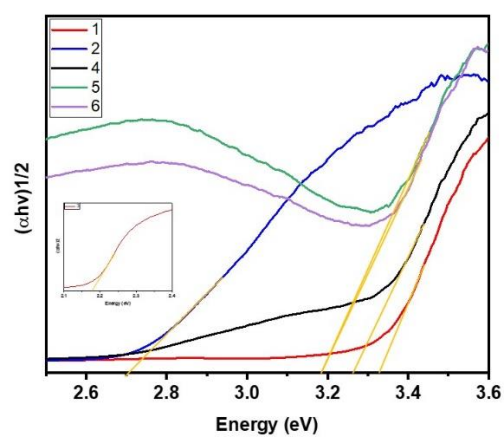


Figure 10. UV Spectra of Semiconductors' Band Gap

The following graph illustrates the XRD characterization of each material used throughout this part of the project (TiO₂, WO₃, CdS, TiO₂+WO₃, TiO₂+CdS, TiO₂+WO₃+CdS).

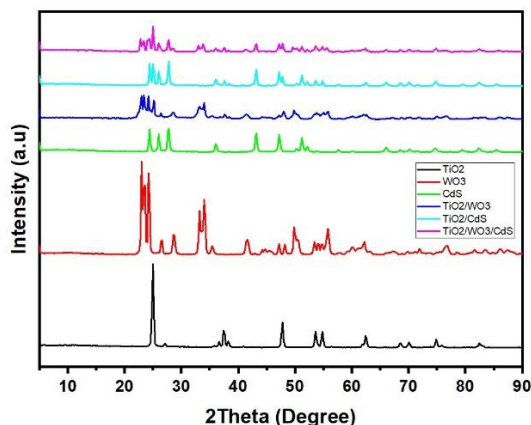


Figure 11. XRD Material Characterization

Figure 12 highlights the IV results of each semiconducting material used in DSSC. It could be seen that, for individual cells, TiO₂+WO₃ was the least efficient in power conversion, reaching only 4.9% of PCE. TiO₂+CdS shortly followed, reaching a PCE of 6.5%. Highest of all out of the individual cells was TiO₂+WO₃+CdS, arriving at 7.3%. In the case of tandem DSSCs, TiO₂+CdS joined with TiO₂+WO₃ proved to be the least effective, forming only 5.2. TiO₂+CdS joined with TiO₂+CdS (symmetric) was negligibly higher by only 0.1%, reaching 5.3%. On the other hand, TiO₂+CdS joined with TiO₂+CdS+WO₃, as well as symmetrically coated tandem cells by TiO₂+CdS+WO₃, were extremely close in PCE, both arriving at approximately 8%. Figure 13 summarized the results mentioned above.

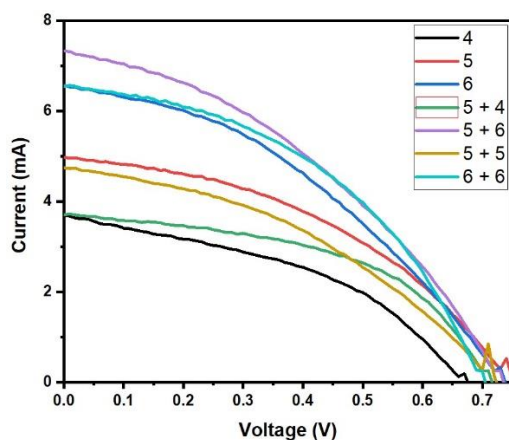


Figure 12. Semiconducting Nanocomposites IV Characteristics

Cell	Power Conversion Efficiency (PCE (%))
4	4.9
5	6.5
6	7.3
5+4	5.2
5+6	8.2
5+5	5.3
6+6	8

Figure 13. Semiconducting Nanocomposites PCE Summary

6. Interpretation and Conclusion

6.1 Individual Dyes:

It could be concluded from the results that N3 produces greater PCE, especially when paired with N719. The two dyes together proved the first hypothesis of this research. The N3+N719 tandem DSSC increased compared to each one individually, since individual N3 and N719 DSSCs have covered different wave positions. Therefore, the more wavelengths the two dyes cover in a tandem DSSC, the greater PCE it produces.

6.2 Dyes in DSSCs (The effect of TiO₂):

It is concluded that N719 in DSSCs absorbed the greatest amount of light and gained the highest PCE. The analysis shows that, when applied with TiO₂ on a DSSC, the absorbance rate of N719 is increased. On the other hand, TiO₂ has proved to hinder the absorbance of Z907 and N3.

6.2 Semiconducting Materials:

The test results concluded that TiO+CdS+WO₃ proved to be the most efficient regarding absorbance, since CdS and WO₃ helped decrease the band gap of TiO₂. Compared with individual TiO₂, however, the results were almost the same. This proves

7. Future Works

This project is ongoing. Later research will be based on:

- 1- Utilizing natural dyes and comparing them with organic dyes in tandem DCCSs.
- 2- Fabricating a new dye for absorption enhancement.

8. References

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In this study, the students developed an energy conversion layer consisting of $\text{TiO}_2/\text{CdS}/\text{WO}_3$ and ruthenium-based dyes, including N3, N719, and Z907. The development of tandem cells is also discussed. The results indicate that the dual N3-containing DSSCs exhibit the highest efficiency. While the research is valuable, the students should address several points more thoroughly: (1) the chemical structure of the dyes and their impact on energy conversion; (2) a detailed discussion of the factors influencing the tandem cell results; and (3) potential strategies for improving efficiency. Overall, the report is well-written, and the students' hard work and dedication to the research are commendable.