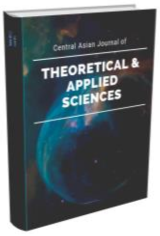

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Article

Study of the Interaction Between Optical Materials and Solar Energy Cells to Enhance Energy Conversion Efficiency

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Abstract: In light of the increasing demand for clean and sustainable energy, solar cells have become one of the most promising solutions to meet global energy needs. However, the primary challenge lies in improving the efficiency of these cells to ensure the maximum conversion of solar energy into electrical energy. Optical materials emerge as a key factor in this context, possessing the ability to enhance light absorption and reduce loss due to reflection.This research aims to study the interaction between optical materials and solar energy cells to understand how efficiency can be enhanced and significant progress achieved in energy conversion technology. By focusing on the unique properties of these materials and their integration into cell design, the study seeks to fabricate a dye-sensitized solar cell using ZnO semiconductors as photoanodes, a conductive electrode (cathode), and an electrolyte solution of (I2/KI). The ZnO semiconductors include ZnO nanoparticles (coated on glass). The conductive electrodes involve carbon also placed on glass. The dye used: Azo dye. The dye was characterized by infrared spectroscopy, with the azo group absorption observed around 1550 cm^{-1} and the C=N group absorption around 1630 cm^{-1}. The dye's absorption spectrum was also characterized by UV-Vis spectroscopy, which indicated that it absorbs light at 620 nm. Electrical measurements were carried out on the fabricated cell only.

Keywords: Dye-Sensitized Solar Cell (DSSC), Optical Materials Efficiency, ZnO Nanoparticles and Azo Dye Characterization

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1. Introduction

Solar cells are among the most important inventions of the modern age, enabling humanity to secure a significant portion of its daily energy needs by converting solar energy into electrical energy, either directly or indirectly. The idea of solar cells dates back to 1939, when the French scientist Edmond Becquerel discovered that exposing an electrode to light while submerged in a conductive solution produces an electric current. Later, in 1941, American inventor Russell Ohl succeeded in producing the first silicon-based solar cell[1].

Solar cells are usually made from chemically treated silicon, arranged in layers along with other materials and conductive wires in a specific geometric system. When these cells are exposed to ordinary light or sunlight, electrons are released and transmitted through the conductive wires, allowing their use in powering electrical devices or lighting electric lamps. Photovoltaic solar cells have been extensively utilized in various aspects of daily life, and they have played a major role in generating the electricity needed to power satellites in space and spacecraft launched to explore planets and celestial bodies[1].

These cells are considered an ideal source of electrical energy because they do not cause environmental harm or produce toxic chemical waste or gases. Therefore, research into their development and utilization has been widely supported in various fields and across the globe.

However, the high cost of producing solar cells remains one of the biggest obstacles to their widespread use[2].

Scientists have thus realized that the greatest challenge lies in increasing the conversion efficiency of solar cells, their ability to convert solar energy into electrical energy ,while reducing their production costs. Some studies suggest that a satisfactory level of conversion efficiency has been achieved, with a conversion rate of incoming solar energy into electricity. Many researchers believe it is possible to reach a conversion rate of up to 48%. Such an increase in solar cell conversion efficiency would lead to a reduction in the size of these cells, an increase in the amount of electricity produced, and ultimately, lower production costs It, in turn, will play an important role in reducing global warming and combating environmental pollution, which has become the foremost threat to humanity at present[2].

The first practical photovoltaic cell was developed in 1954 at Bell Laboratories. The modern solar cell was first created by two researchers, Daryl, Calvin Fuller Sawyer, and Gerald Pearson, using silicon. Initially, solar cells were designed for purposes such as PN junction toys in 1954 and other minor applications, as the cost of the electricity they produced was relatively high. Solar cells were saved from obscurity by the proposal to add them to the "Vanguard" satellite, which was launched in 1950[3].

Solar Cells

A solar cell, or photovoltaic cell (PV Photovoltaics), allows the direct conversion of sunlight into electricity through solid-state technology. These cells are made of silicon (sand), which is abundantly available on Earth. While other materials are used in solar cells, silicon remains the primary foundation. Generally, the materials of these cells are either thick crystalline substances like crystalline silicon or thin amorphous materials such as amorphous silicon. Some cells use layered materials deposited on semiconductor substrates, like gallium arsenide (GaAs)[4].

Solar energy is considered environmentally friendly and clean because it operates without producing polluting waste, noise, or radiation, nor does it require fuel, as these photovoltaic cells work silently. However, their initial cost is high compared to other energy sources. Solar cells generate direct, continuous electricity, similar to liquid and standard dry batteries[4].

The intensity of their current depends on sunlight brightness, solar radiation levels, and the efficiency of the photovoltaic cell itself. Solar cells can provide hundreds of volts of DC electricity when connected in series. This generated voltage can be stored in lead-acid batteries or nickel-cadmium alkaline batteries. Additionally, DC current can be converted into AC current using inverters for electrical equipment and devices in households and industries[5].

The term "photovoltaics" means directly generating electricity from light using solar cells made of semiconductor materials like silicon, which generates electric current when exposed to sunlight. The largest solar power plant currently operating is located in Carrizo Plain, California, producing 5 megawatts. Other stations in Germany generate up to 18 megawatts. Since 1968, solar cells have been effectively utilized on satellites, operating efficiently in all weather conditions, including cloudy days when sunlight is scarce. This is achieved by storing the generated energy in batteries[6].

The overall efficiency of solar cells for electricity generation is calculated based on both sunny and cloudy days. Frequent cloudy conditions can reduce the system's efficiency. One major advantage is the absence of moving parts, minimizing failure, which allows solar cells to operate efficiently in satellites. Furthermore, they require no maintenance, repairs, or fuel, functioning silently. However, dirt or dust accumulation on photovoltaic cells due to pollution can reduce their efficiency, necessitating periodic cleaning[6].

Solar Cell Efficiency

Conversion efficiency is considered one of the most important characteristics of solar panels (photovoltaic panels PV). Global companies invest billions of dollars annually to improve the efficiency of their products, but what does cell conversion efficiency mean? Conversion efficiency is defined as the ratio of the energy received from sunlight that the photovoltaic effect is capable of converting into electrical energy. Efficiency is calculated by dividing the electrical energy produced by the conversion by the energy of the light incident on the cell [7].

Cell Conversion Efficiency = Electrical Energy Produced by Conversion / Light Energy Incident on the Cell

Technically and simply, photons reaching the absorption layer stimulate the carriers of negative and positive charges. High-efficiency solar panels require less energy from light to free a negative electron and a positive hole, enabling the electron to pass through the insulating region to the negative wafer. Therefore, if the same amount of light is shone on two photovoltaic panels with different efficiencies—one with 28% efficiency and the other with 15%—one square meter of the 28%-efficient panel would free more electrons and produce more electrical energy than one square meter of the 15%-efficient panel[8].

Calculating solar cell efficiency is a crucial step in designing solar systems, as it measures the amount of solar radiation incident on the surface of solar cells that is converted into electrical energy. With ongoing developments over the years, panel efficiency has increased from 15% to 22%, the highest efficiency achieved by some companies specializing in solar cell manufacturing. There are now solar panels with a power capacity of 488 watts and 22% efficiency, produced by Sun Power. The higher the efficiency and capacity with less surface area, the better[8].

Dye-Sensitized Solar Cells (DSSC)

Dye-sensitized solar cells (DSSCs) are classified as third-generation organic solar cells because they provide additional functionalities such as flexibility and transparency, which are not offered by the first two generations of devices designed with monocrystalline silicon (first generation) or thin-film (second generation). DSSCs mimic the process of photosynthesis, where light absorbed by a green dye, chlorophyll, induces electron transfer and generates energy (starch). The molecule absorbing light and subsequently generating a charge produces the photovoltaic (PV) effect[7].

DSSCs are referred to as dual-functional solar cells due to their transparency and flexibility, allowing them to be used as windows in buildings and vehicles while simultaneously generating electrical current. Furthermore, DSSCs can be manufactured at low cost, in various colors, on transparent glass, and on visible substrates, which gives them enormous potential in the commercial market, especially for low-density applications such as rooftop solar collectors and other small electronic tools[6], [8].

2. Materials and Methods

The topic of improving solar cell efficiency has received significant attention due to its contribution to better utilization of solar energy compared to other energy sources. Key studies in this field include:

Hammil A.S: Worked on increasing the efficiency of solar cells by reducing light reflection from the cell surface, achieving an 81% reduction in reflectivity. This increased light absorption and minimized energy losses in the metallic top grid by using innovative grid designs, such as regular and irregular pyramidal shapes[9].

Murad S.M: Developed a monocrystalline silicon solar cell by adding surface folds. This modification resulted in an increase in cell efficiency from 4.1% to 5.5%[10].

Shyu R. et al.: Created thin lens systems that act as solar concentrators, based on a high aspect ratio design[11].

Ruggiero W.C: Enhanced the surface of silicon solar cells by designing semi-circular or parabolic shapes. This optimized light path tracking through grooves in slanted and parallel manners using the Zemax software[12].

Geetha M: Improved solar cell efficiency by studying groove models for solar cells with varying aspect ratios. The study also utilized Zemax software to enhance efficiency[13].

Hamdani A: Designed and built a new dual-mirror trough concentrator and studied its effects on silicon solar cell performance. In cases without a cooling system, cell efficiency increased from 11.94% to 15.46%, while with cooling, efficiency improved from 13.3% to 16.40%. He also investigated the integration of different Fresnel lenses with this concentrator, achieving an optimal efficiency of 24% without cooling and 26.6% with cooling[14].

Zaidan Y: Manufactured a solar cell with nanostructures by producing porous silicon layers from n-p silicon wafers in hydrofluoric acid. This process employed both electrochemical and photoelectrochemical etching, and the prepared solar cell exhibited superior electrical properties, such as lower resistivity and higher current flow[15].

Jason H. Karp, Eric J. Tremblay, and Joseph E. Ford: Developed a model for solar concentrators with a waveguide to improve solar cell efficiency by employing an array of convex-flat lenses[16].

Bader A: Designed solar concentrators featuring an array of thin lenses and a waveguide to enhance the efficiency of solar cells[17].

In 2021, Atwator H., a professor of applied physics and materials science at Howard Hughes University, demonstrated that silicon can absorb only a specific portion of the light spectrum, while the remaining wavelengths pass through it as if it were a transparent material. He also found that when a simple solar panel is placed on any residential surface, silicon absorbs only part of the spectrum. The remaining light spectrum is not converted into electrical energy but instead heats the surface of the house[18].

In 2022, Lindner S. studied the properties of pure and impure silicon, highlighting the benefits of silicon doping in solar cells[19].

Practical Part

The aim of the research is to synthesize a new azo compound and evaluate its efficiency in dye-sensitized solar cells.

Steps for Synthesis of Azo Dye:

1. Dissolving the Base Compound:

Dissolve 0.004 mol of 2-amino benzimidazole in 25 ml of distilled water, Add 6 ml of concentrated hydrochloric acid to the solution, and cool the mixture to 0°C.

2. Preparing Sodium Nitrite Solution:

Dissolve 0.002 mol of sodium nitrite in 6 ml of distilled water, Place the solution in an ice bath and cool it to 0°C.

3. Combining Aminobenzimidazole and Sodium Nitrite Solutions:

Gradually add the sodium nitrite solution to the aminobenzimidazole solution, resulting in a color change to yellow.

4. Dissolving 2-Chlorotoluene:

Dissolve 0.003 mol of 2-chlorotoluene in 10 ml of ethanol.

Add 10 ml of 10% sodium hydroxide solution to the mixture and cool it to 0°C.

5. Reacting Diazotized Salt with 2-Chlorotoluene:

Gradually add the diazotized salt solution to the 2-chlorotoluene solution, this results in the solution turning a deep maroon color.

6. Filtration and Drying:

Leave the solution overnight, then filter it and dry it in air to obtain the final product with a yield of 55%.

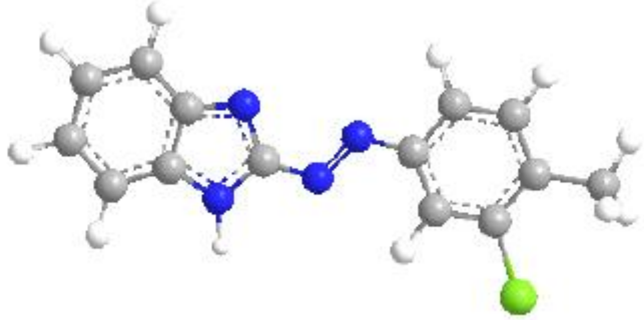

Figure 1. The spatial and structural formula of the prepared dye.

Figure 2. Pictures of the dye preparation.

Figure 3. The shape of the manufactured dye-based solar cell.

3. Results and Discussion

Electronic Transitions of the Prepared Dye:

The UV-Visible spectrum of the prepared dye clearly indicates strong absorption covering a wide range of the visible spectrum, reaching up to 673 nanometers. This aids in absorbing sunlight even under cloudy conditions, where the dye-sensitized cell can capture specific wavelengths of sunlight. The UV-Visible spectrum of the prepared dye demonstrates this effective absorption capability.

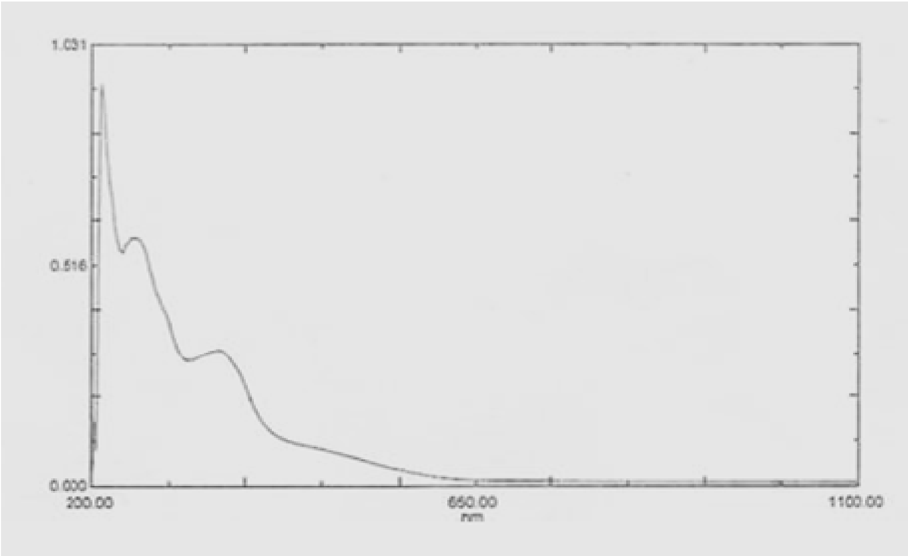

Figure 4. UV-vis spectrum of the prepared dye.

Infrared Spectrum of the Prepared Dye

The infrared spectrum of the prepared dye indicates absorption of the azo group at approximately 1550 cm⁻¹ and absorption of the CN group at around 1630 cm⁻¹. This is the infrared spectrum of the azo dye.

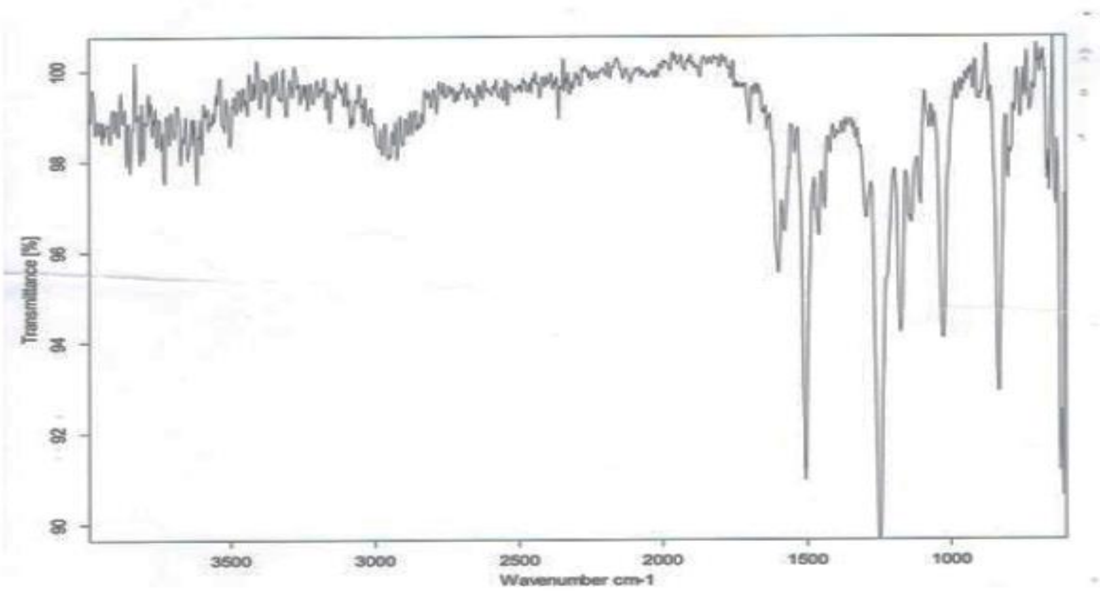

Figure 5. Infrared spectrum of azo dye.

Voltage-Current Characteristics of the Dye-Sensitized Solar Cell:

The table below shows the electrical measurements of the manufactured cell, represented by the voltage and current readings. The Y-axis represents current density measurements, while the X-axis represents voltage measurements.

The diagram illustrates positive voltage in the forward bias, whereas negative voltage represents reverse bias. Additionally, the curve demonstrates the current density of the manufactured cell.

Table 1. Electrical measurements of the manufactured cell.

Voltage (mV)	Current density (mA/cm²)
-0.3	-0.2
-0.2	-0.1
-0.1	0.15
0	0.3
+0.1	0.35
0.2	0.37
0.3	0.4
0.4	0.43
0.5	0.46
0.6	0.49
0.7	0.51
0.8	0.54
0.9	0.55
1	0.56

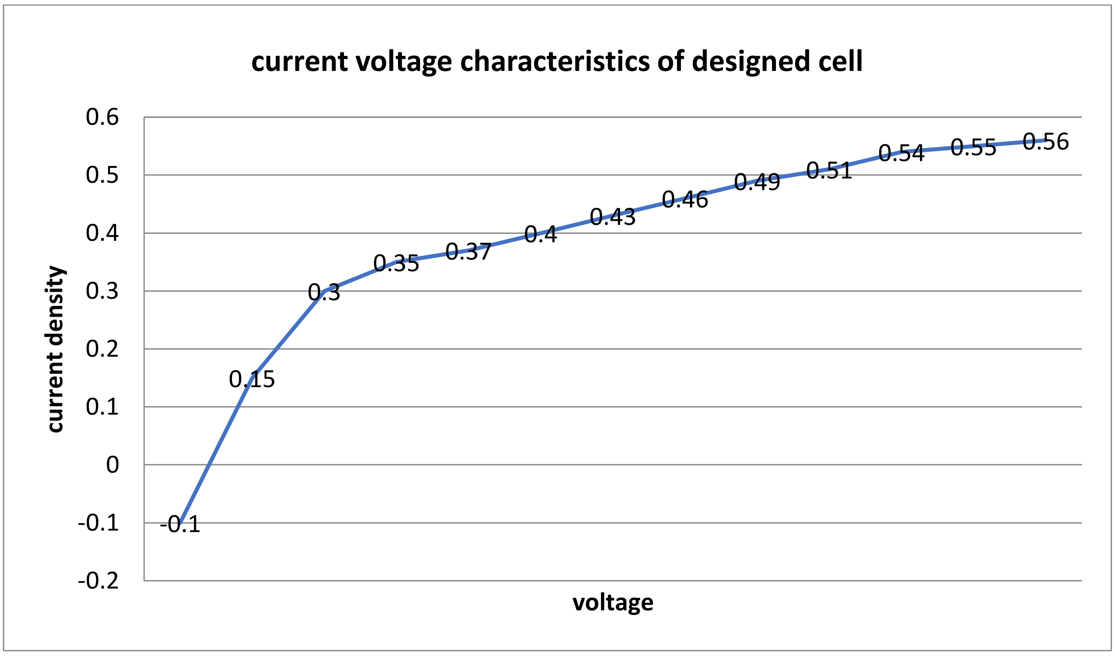

Figure 6. Current-voltage characteristics of the designed cell.

The generated energy or output energy

Estimated by multiplying the values of current and voltage. The energy represents the amount of energy (in the form of electricity) produced by the solar cell, measured in watts. Figure 7 illustrates the average energy generated by the manufactured organic solar cell. During the initial phase of experimental work, as solar radiation increased, the value of generated energy rose and reached its peak at 14:00 (2:00 PM). The average generated energy value changes depending on solar radiation and time.

The efficiency of a solar cell is the ratio of energy generated by it to the energy supplied to it. It reflects the organic solar cell's ability to utilize the maximum amount of solar energy. This criterion is crucial for indicating the thermal performance of a solar cell.

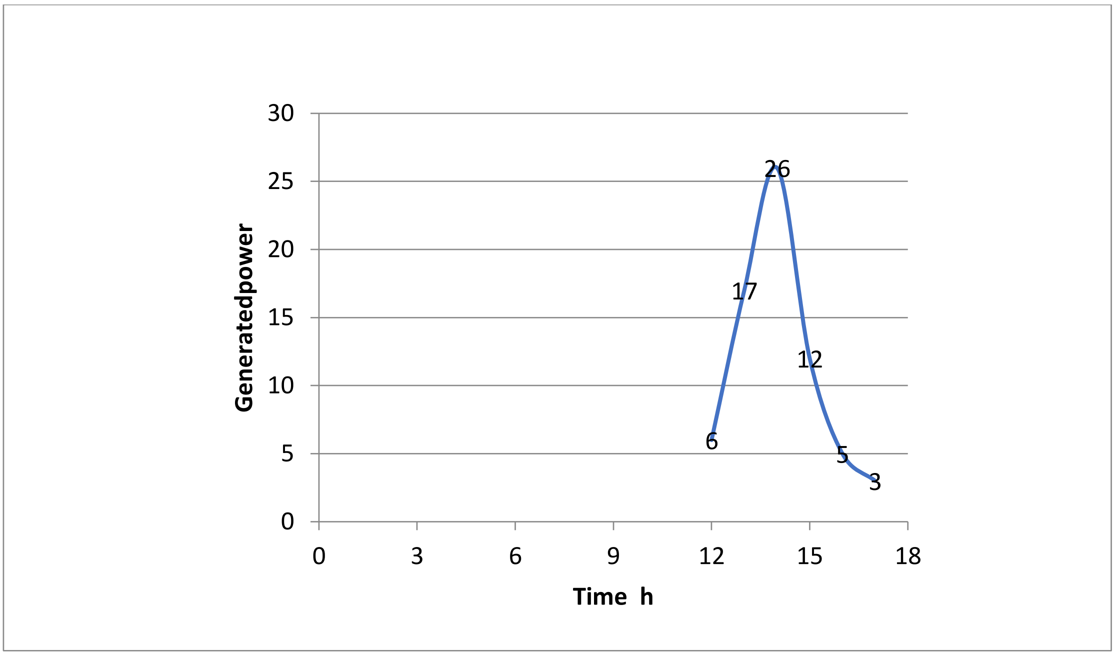

Figure 7. The average energy generated by the manufactured organic solar cell.

4. Conclusion

An effective chemical method was developed for producing the dye, achieving a production efficiency of 60%. The dye demonstrated the ability to absorb light across a wide range, up to 670 nm, making it effective at capturing sunlight even under cloudy conditions—a beneficial feature for dye-sensitized solar cells, Voltage and current characteristics were measured using the (I-V) curve, showing good response in both forward and reverse bias, with excellent current density.

The results indicate that the dye possesses optical and electrical properties, making it a cost-effective and efficient option for applications in dye-sensitized solar cells.

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