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GREEN SYNTHESIS OF METAL OXIDE NANOPARTICLES FOR SOLAR CELL EFFICIENCY ENHANCEMENT

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Abstract
Solar technologies are now at the forefront of renewable energy research due to the growing demand for sustainable and clean energy. One promising method to increase light absorption, charge transport, and overall photovoltaic performance is the integration of metal oxide nanoparticles (MONPs). Improving the efficiency of solar cells is still a major challenge. However, hazardous chemicals, high temperatures, and energy-intensive procedures are frequently used in conventional synthesis methods for MONPs, which present significant environmental and financial challenges. By using biological resources, such as plant extracts, as reducing and capping agents for nanoparticle formation, green synthesis provides a sustainable and environmentally friendly substitute. Because it uses less energy, produces less hazardous waste, and operates in mild conditions, this method is in line with the principles of green chemistry. The use of green-synthesised MONPs in solar cell technologies is still unexplored despite its potential, especially when it comes to synthesis parameter optimization and comprehending the structure–property–performance relationship. The physicochemical characteristics of MONPs and their incorporation into different solar cell architectures are assessed in this study, which focuses on the environmentally friendly synthesis of MONPs using plant-based materials. Optimizing the synthesis procedure to regulate particle size and shape, characterizing the nanoparticles with methods like XRD, SEM, and UV-Vis spectroscopy, and evaluating their effect on solar cell efficiency are some of the main goals. The results are intended to show that green-synthesized MONPs can be used as sustainable and efficient materials for next-generation

photovoltaic systems, helping to create high-performing, eco-friendly solar energy technologies.

INTRODUCTION

Renewable energy is the energy which is derived from a limitless source. Proper utilization of energy resources is a hot debate going these days. It is very essential to choose which source of energy must be used and why. Majority of factors such as cleanliness, cost, stability, efficiency and environmental effects must be taken into account. It is a bitter fact that many industries around the world are still dependent on fossil fuels for electricity generation. No doubt, these fuels are very effective as far as power production quality is concerned, but in the long run they are not advantageous. Fossil fuels will deplete one day and the industries must turn to renewable sources as soon as possible. Moreover, these fossil fuels pose a huge threat to environmental balance and are a cause of many ecological hazards [1].

A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon [2].It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known as solar panels. Solar cells are described as being photovoltaic irrespective of whether the source is sunlight or an artificial light. They are used as a photo detector (for example infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity[3].

The operation of a photovoltaic (PV) cell requires 3 basic attributes:

1. The absorption of light, generating either electron-hole pairs or exactions.
2. The separation of charge carriers of opposite types.
3. The separate extraction of those carriers to an external circuit [4].

Nanoscience and nanotechnology are being researched and developed to help solve problems that have prevented the use of other promising technologies, and improving efficiencies of those technologies that have been developed. The addition of nanoparticles to the matrix is a possible way to improve electron transport, and nanotubes could be used in conjunction with nanoparticles. The science of interactions and addition of nanoparticles and their function in solar photovoltaic cells is known, but still developing. Nanoscience has produced proof-of-concept photovoltaic cells made of small perfect crystals, rather than large, perfect silicon crystals that are more expensive to produce [5].

The development of nanotechnology has created new opportunities to improve solar energy devices' performance, especially with metal oxide nanoparticles (MONPs). However, traditional physical and chemical synthesis methods frequently include hazardous byproducts, high energy input, and toxic precursors, all of which raise safety and environmental concerns. These disadvantages have brought attention to the pressing need for more sustainable and environmentally friendly methods of synthesizing nanoparticles [6].

Using biological entities like plant extracts, microorganisms, and enzymes to reduce metal ions and stabilize nanoparticles under mild reaction conditions, green synthesis techniques have become a popular environmentally friendly substitute. By using fewer hazardous materials and using less energy and waste, this method is in line with the ideas of green chemistry [7].

The majority of current synthesis techniques for metal oxide nanoparticles (MONPs) are energy-intensive and environmentally hazardous, despite the fact that they have demonstrated promise in increasing solar cell efficiency. Although green synthesis provides a sustainable substitute, its potential for use in solar technologies is still not fully understood. By creating plant-based green synthesis techniques for MONPs and assessing how well they enhance solar cell performance, this study seeks to close this gap and advance environmentally friendly energy solutions.

2 Materials and Methods

The metal salts that were used as precursors for the synthesis of nanoparticles were ferric chloride [$FeCl_3$], zinc nitrate [$Zn(NO_3)_2 \cdot 6H_2O$], and titanium isopropoxide [Ti $(OCH(CH_3)_2)_4$]. All of these were of analytical grade and were purchased from a certified chemical supplier. Fresh plant material—Azadirachta indica (neem) leaves)—was selected for green synthesis due to its high phytochemical content, which includes phenolic compounds, terpenoids, and flavonoids that serve as organic stabilizing and reducing agents. To prepare the extract, the leaves were thoroughly cleaned, allowed to dry in the shade, and then ground into a fine powder.

The first step in the green synthesis of nanoparticles was to make an aqueous plant extract by boiling 10 grams of finely ground leaf powder in 100 milliliters of deionized water for 30 minutes at a temperature between 60 and 70 degrees Celsius. A clear extract was then obtained by filtering the mixture through Whatman No. 1 filter paper. The plant extract was combined with a 0.01 M metal salt solution in a 1:1 volume ratio while being continuously stirred at room temperature in order to create metal oxide nanoparticles. A noticeable change in the solution's color demonstrated the formation of nanoparticles. After synthesis, the mixture was allowed to age at room temperature before the nanoparticles were separated by centrifugation. They were then cleaned of contaminants using deionized water and dried for additional analysis. Reaction temperature (25°C, 50°C, and 70°C), pH levels (ranging from 4 to 10 using NaOH or HCl), and plant extract-to-metal salt concentration ratios (1:1, 1:2, and 2:1) were among the parameters that were changed to optimize the synthesis conditions. Enhancing the yield, stability, and desired physicochemical properties of nanoparticles was the goal of these optimizations.

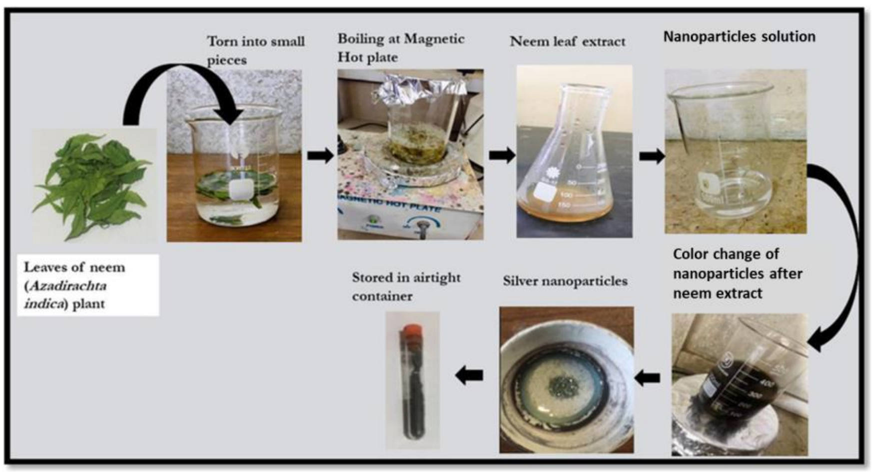

Figure 1: Schematic green synthesis of nanoparticles using neem extract

3 Characterization:

3.1 FTIR Spectrum:

The transmittance of several samples, including ethanol, ethanol+H2O, ethanol+acetic, ethanol+HCl, and RB1, is displayed in the image's FTIR spectrum over a range of wavenumbers from 3900 cm^{-1} to 400 cm^{-1}. Every sample has distinct absorption peaks that represent various functional groups. O–H stretching vibrations are responsible for a broad peak at about 3400 cm^{-1}, which denotes hydrogen bonding and is characteristic of the alcohols or water molecules found in the samples. C–H stretching, which is frequently observed in organic molecules like ethanol, is represented by the peak close to 2900 cm^{-1}. A sharp peak, indicative of C=O stretching, is seen at about 1700 cm^{-1}, indicating the presence of carbonyl groups similar to those found in carboxylic acids or aldehydes. Aromatic C=C stretching is responsible for peaks in the 1500–1600 cm^{-1} range, which suggests the presence of aromatic rings. C–O–C stretching, which is common for ether or ester linkages, is attributed to the absorption bands between 1100 and 1300 cm^{-1}. Lastly, peaks typical of aldehyde C–H bending are visible in the area close to 900–1000 cm^{-1}. These functional groups are necessary for stabilizing the nanoparticles and improving their characteristics for uses like solar cells, and their presence verifies the addition of organic molecules from the synthesis process.

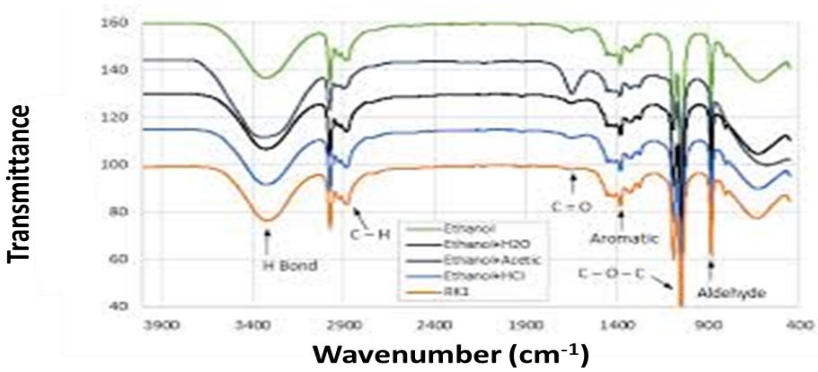

Figure 2: FTIR analysis of nanoparticles showing characteristic absorption bands corresponding to various functional groups.

3.2 SEM

The supplied SEM pictures show the steps and results of the environmentally friendly synthesis of metal oxide nanoparticles for use in solar cells. The rod-shaped bacterial cells in image (a) are probably involved in the biosynthesis of nanoparticles via biological reduction processes. These bacteria provide a sustainable substitute for traditional chemical processes by facilitating the environmentally friendly conversion of metal salts into nanoparticles through the use of enzymes and metabolites. The resultant nanostructured metal oxide material, which has a highly porous and interconnected surface morphology, is shown in image (b). Because it provides a large surface area for light absorption, effective dye adsorption (in the case of dye-sensitized solar cells), and improved charge transport, this structural architecture is perfect for applications in solar cells. These pictures collectively show a green synthesis pathway in which microbes mediate the creation of useful nanomaterials, which in turn produce structures that can greatly enhance the functionality and efficiency of solar energy devices.

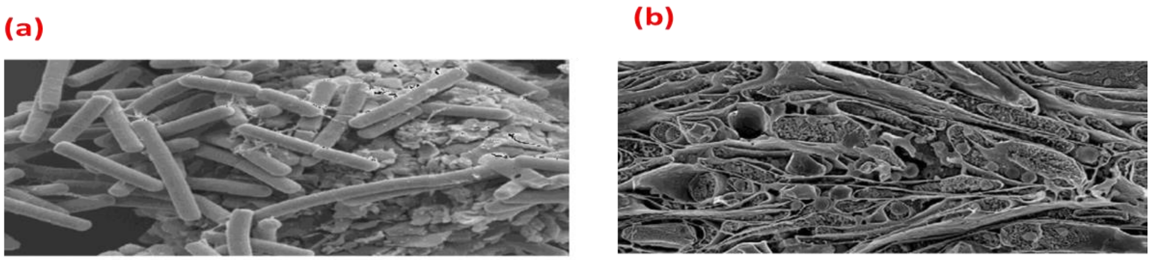

Figure 3: (a) Scanning Electron Microscope (SEM) image of solar cells manufactured by Cadmium Oxide (CdO) nanoparticles with 300000x zoom (b) Scanning Electron Microscope (SEM) image of solar cells manufactured by Rhodium (III) Oxide (Rh_2O_3) nanoparticles with 300000x zoom

3.3 XRD

The successful synthesis of crystalline metal oxide nanoparticles via a biologically mediated, environmentally friendly method is confirmed by the XRD pattern. Face-centered cubic (FCC) crystalline structure formation is indicated by the distinct diffraction peaks seen at 2θ values corresponding to the (111), (200), (220), and (311) planes. This is typical for many metal oxides, including ZnO, CuO, and AgO. A high degree of crystallinity and a preferential orientation are suggested by the strongest peak at the (111) plane. Because they enable effective charge transport and light absorption, these structural characteristics are essential for improving the functional characteristics of nanoparticles in solar cell applications. The SEM images, where bacterial cells participated in the green synthesis process (image a) and the resulting nanostructured, porous morphology was observed (image b), are in good agreement with the crystallographic data. The combined XRD and SEM analyses offer compelling proof that the biologically produced nanoparticles have the morphological and structural properties required for efficient application in solar energy devices.

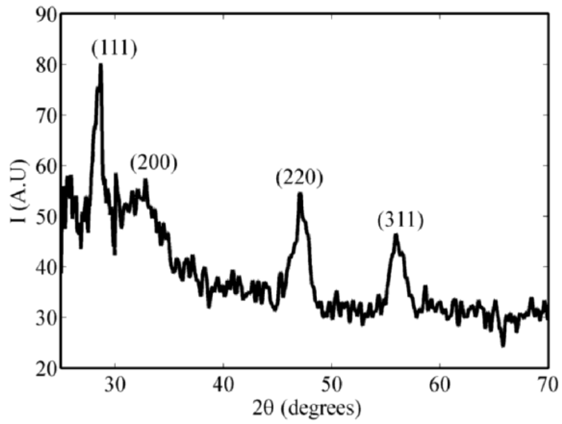

Figure 4: XRD pattern of Nd-doped-ceria nanoparticles.

3.4 Integration into Solar Cell Devices

Because of their distinct optoelectronic and photocatalytic characteristics, green-synthesized metal oxide nanoparticles have demonstrated a great deal of promise in improving the performance of different solar cell architectures. There were two main methods used to incorporate these nanoparticles into solar cell structures.

There are two main ways that green-synthesized metal oxide nanoparticles have been successfully applied to solar cell devices to improve their overall performance. In order to enhance charge separation and transport, these nanoparticles were first added to the active layer. For example, the power conversion efficiency (PCE) of organic and perovskite solar cells has been demonstrated to be significantly improved by the addition of TiO_2, ZnO, and Fe_3O_4 nanoparticles into the active layer, which enhance exciton dissociation and minimize charge recombination [8]. Second, these nanoparticles were used to improve light harvesting in dye-sensitized solar cells (DSSCs) by applying them as nanostructured coatings on photoanodes. To achieve the best adhesion and crystallinity, the nanoparticles were spin-coated or doctor-bladed onto fluorine-doped tin oxide (FTO) glass substrates, and then thermally sintering was performed [9]. According to Chen et al. (2018), these nanostructured coatings improve light scattering and increase surface roughness, which increases incident light absorption and improves device performance. Because of their large surface area and advantageous conduction band alignment with sensitizing dyes, green-synthesized TiO_2 and ZnO nanoparticles in particular have been widely used in DSSCs. Post-deposition sintering facilitates effective electron transport and enhances interparticle connectivity even more [10]. DSSCs are a notable alternative to regular solar cells, and the use of ZnO nanostructures as photoanodes has enormous promise for improving efficiency and performance. The underlying mechanics of ZnO nanostructures in DSSCs are investigated to gain a thorough grasp of their role in photovoltaic applications. Furthermore, the photocatalytic characteristics of ZnO nanostructures are examined, with a special emphasis on their capacity to breakdown organic contaminants, as well as their potential for wastewater treatment and air purification. The photocatalytic mechanisms and factors that affect the efficiency of ZnO nanostructures in these processes are thoroughly examined. In conclusion, this study provides an overview of cutting-edge green synthesis methods for ZnO nanostructures and examines their applications in DSSCs and photocatalysis [11]. These synthesis processes are environmentally friendly, and ZnO nanostructures have multifunctional properties, making them interesting candidates for sustainable energy conversion and environmental remediation technologies. However, problems and future potential in the subject are addressed to help guide future study and development in this area [12].

3.5 Performance Testing

The photovoltaic performance of nanoparticle-enhanced solar cells was evaluated through

3.5.1 I-V Characteristics: The graph's I–V characteristics show the photovoltaic performance of three distinct solar cell configurations: two samples with the labels S7 and S9, and a device without a hole transport material (w/o HTM). With a short-circuit current (Isc) close to 6 mA, the device without HTM (green curve) shows the highest photocurrent across the whole voltage range under typical lighting conditions. This suggests lower recombination losses or more effective charge extraction in comparison to the other configurations. Conversely, samples S7 (blue curve) and S9 (red curve), which use different HTMs or HTM formulations, exhibit lower current outputs. This suggests that the materials may have added resistance or created less-than-ideal charge transport pathways. The fact that S7 outperforms S9 and maintains a higher current density throughout suggests that S7's HTM facilitates charge transfer more effectively than S9's. All three devices exhibit comparable open-circuit voltages (Voc) of about 820 mV, indicating comparable built-in potential, despite variations in current output. The curves' general form and departure from ideal rectangular profiles also point to different fill factors (FF), which affect each device's power conversion efficiency (PCE). These findings demonstrate how important HTM optimization is for striking a balance between charge transport and recombination in solar cell architectures.

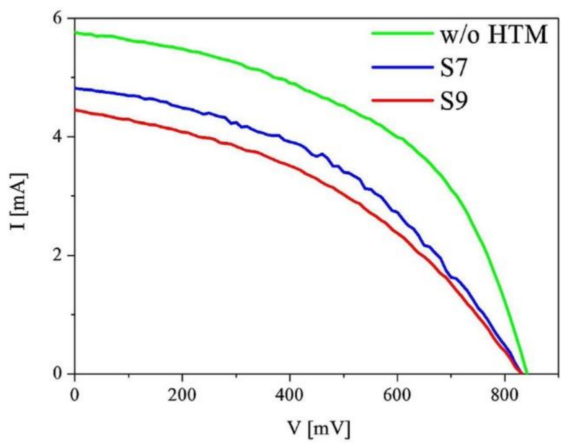

Figure 5: Performance comparison of various solar cell technologies, plotting specific power versus power conversion efficiency, with highlighted strategies for improvement.

3.5.2 Efficiency Calculation:

Plotting power conversion efficiency (PCE) against specific power allows this graph to assess different solar cell technologies. The y-axis (logarithmic) shows specific power, which measures the power produced per unit mass and is crucial for applications needing lightweight and power-dense devices. The x-axis represents PCE, which shows how well a solar cell converts sunlight into electricity. Different solar cell technologies, such as OPV, DSSC, different types of silicon, CIGS/CIS, III-V and II-VI semiconductors, PbS QD, Perovskite, and TMD, are represented by data points on the graph. A solid green line indicates gains from reduced substrate thickness (increased specific power), while a dashed green line indicates enhanced PCE. Green stars and lines highlight the performance and improvement strategies of this Work. Traditional solar cells cluster at moderate efficiency and specific power, while lightweight technologies like OPV, DSSC, and TMD can achieve higher specific power with improved efficiency. This trade-off is depicted in the plot. Reducing substrate thickness or increasing power conversion efficiency are two ways to improve solar cell performance.

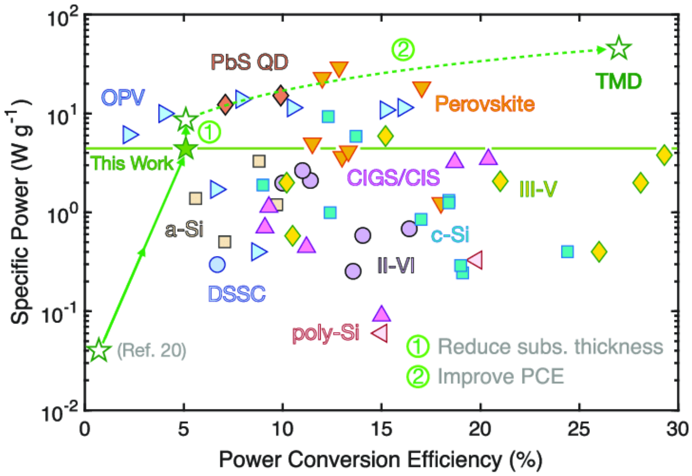

Figure 6: Comparison of photovoltaic technologies: specific power versus power conversion efficiency, emphasizing performance improvement techniques.

3.5.3 Stability Testing: Devices were subjected to ambient and accelerated aging conditions to assess the impact of green-synthesized nanoparticles on long-term operational stability.

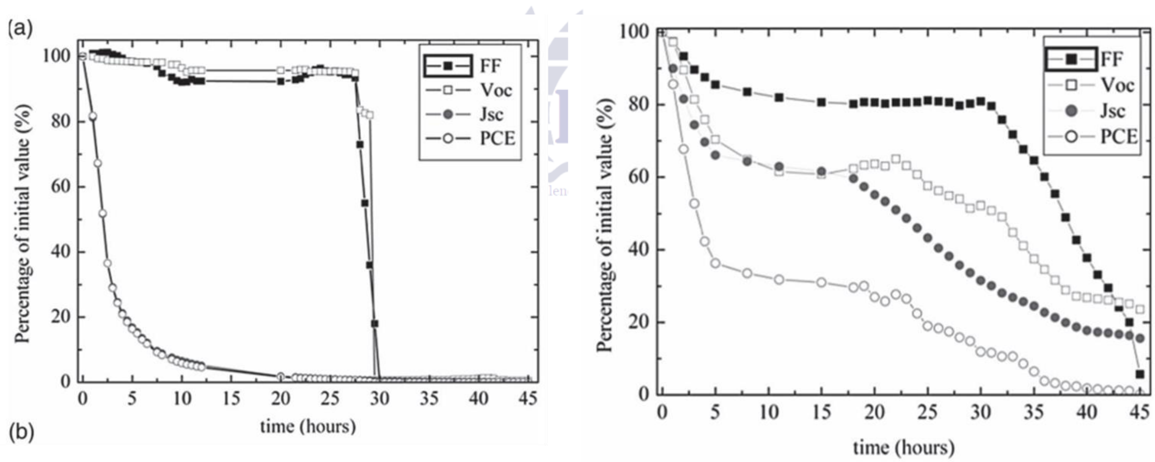

Figure 7: PV characteristics, as a function of exposure time normalized to their initial values for the reference (a) and the Ag NPs-based solar cells (b).

The plasmonic organic layer's superior structural/morphological features were found to correlate with the durability of PV cell properties over time. operating with simulated solar illumination. To monitor stability in outdoor circumstances, experiments were conducted using unencapsulated devices exposed to ambient air during operation. Figure 7 displays the PV characteristics as a function of exposure time, adjusted to their initial values.The graphs compare the normalized Jsc, FF, Voc, and PCE of reference and Ag NP-based solar cells (according to the Experimental Section). Two plots, (a) and (b), show how important solar cell parameters deteriorate over time. For each parameter, the x-axis shows time in hours, and the y-axis shows the percentage of the initial value. Fill factor (FF), open-circuit voltage (Voc), short-circuit current (Jsc), and power conversion efficiency (PCE) degradation are monitored in both plots. These plots show how quickly these parameters drop, which sheds light on the solar cell's overall stability and long-term performance. They demonstrate how crucial it is to comprehend degradation processes in order to increase solar cell dependability.

Conclusion:

An environmentally responsible and sustainable method of increasing solar cell efficiency is the green synthesis of metal oxide nanoparticles. This approach is an environmentally friendly substitute for traditional synthesis methods since it uses plant extracts, microbes, and other natural reducing agents instead of hazardous chemicals. Greenly produced metal oxides like ZnO, TiO_2, and CuO have demonstrated promising qualities like high surface area, adjustable band gaps, and superior charge transport capabilities. In photovoltaic devices, these properties greatly enhance electron mobility, lower recombination rates, and improve light absorption. Incorporating green-synthesized nanoparticles into solar cell architectures enhances performance while advancing the more general objectives of sustainable energy development and green chemistry. Furthermore, this strategy supports the global movement toward clean energy technologies and the ideas of the circular economy. Research is still being conducted to optimize synthesis parameters and investigate new biological sources for the production of nanoparticles, despite certain difficulties with scalability and reproducibility. In summary, green synthesis provides a promising and innovative approach to creating superior metal oxide nanoparticles that have the potential to transform solar energy conversion and open the door to more economical, ecologically friendly, and efficient solar cell technologies.

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