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Mitigating UV-Induced Degradation in Solar Panels through ZnO Nanocomposite Coatings

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Abstract: This study explores the enhancement of silicon-based solar cell performance and durability through the application of zinc oxide (ZnO) nanocomposite film coatings. Utilizing the sol–gel method, ZnO nanorods were synthesized and dispersed within a polyvinyl butyral (PVB) matrix, resulting in uniform nanocomposite films. Comprehensive characterization using X-ray Diffraction (XRD), Fourier-Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), UV-Visible spectroscopy, and contact angle measurements confirmed the effective integration and desirable properties of ZnO within the PVB matrix. The ZnO coatings demonstrated superior UV absorptivity, significantly blocking UV radiation at 355 nm while maintaining high transparency in the visible range. This led to improvements in key photovoltaic parameters, including short circuit current (J_{sc}), open-circuit voltage (V_{oc}), efficiency (η), and fill factor (FF). Although a minor reduction in J_{sc} was observed due to the ZnO layer's influence on the light absorption spectrum, the overall efficiency and fill factor experienced notable enhancements. Furthermore, the thermal load on the solar cells was effectively reduced, mitigating UV-induced degradation and thereby prolonging the operational lifespan of the solar panels. Under damp heat conditions, the coated solar panels exhibited remarkable durability compared to their uncoated counterparts, underscoring the protective advantages of ZnO films. These findings highlight the potential of ZnO nanocomposite coatings to significantly boost the efficiency, reliability, and longevity of silicon-based solar panels, making them more viable for long-term deployment in diverse environmental conditions.

Keywords: solar panels; PVB; ZnO nanoparticles; adhesive yellowing; UV blocking



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1. Introduction

The escalating global demand for renewable energy sources has driven a rapid expansion in various energy conversion technologies, including thermoelectric and solar photovoltaic (PV) technology. This expansion positions solar panels as a pivotal component of the transition towards a more sustainable energy landscape, highlighting their significance alongside other advanced energy conversion methods [1,2]. As the solar energy sector grows, it becomes increasingly imperative to optimize the longevity and performance of solar panels, ensuring they remain efficient over extended periods [3,4]. One significant impediment to this goal is the degradation of the adhesive materials used in solar panels, which manifests as a yellowing phenomenon over time [5–7]. The efficiency of solar cells decreases significantly if the adhesive degrades [8,9]. The degradation of adhesive materials in solar panels is a multifaceted problem arising from exposure to a combination of environmental stressors [10–12]. Ultraviolet (UV) radiation, a constant presence in sunlight, plays a central role in initiating chemical reactions within the adhesive materials that contribute to yellowing [13–15]. Additionally, temperature fluctuations, moisture exposure, and other

environmental factors can exacerbate the degradation process, leading to a decline in both the aesthetic appeal and functional integrity of solar panels [16–18]. In the quest to address the yellowing issue in solar panels, a considerable body of literature has emerged, exploring diverse strategies and materials.

Many researchers suggested that zinc oxide (ZnO) is employed as a UV-resistant material in thin films for solar panels due to its wide bandgap of around 3.3 eV, effectively absorbing and blocking harmful ultraviolet radiation [19–22]. Its transparency in the visible range allows sunlight to reach underlying semiconductor layers for efficient energy conversion. ZnO's chemical stability ensures long-term durability, protecting against environmental degradation. Moreover, ZnO's compatibility with thin film deposition techniques, such as spraying and casting, makes it a practical choice for manufacturing processes, contributing to the overall performance and reliability of solar panels in the presence of UV radiation [23–26]. Several studies have specifically explored the efficacy of zinc oxide (ZnO) coatings in preventing yellowing in solar panel adhesive materials. Various researchers conducted extensive experiments on different types of adhesives commonly used in solar panels, applying varying thicknesses of the coatings [24,25]. Their results showcased a significant reduction in yellowing, with thicker layers exhibiting superior protective effects [27,28]. These findings reinforce the potential of such coatings as a reliable solution for enhancing the durability of solar panels [27,29]. Adding ZnO to adhesive is a choice for manufacturers; however, for the already installed solar panels, the only possible way is to coat externally with ZnO-based coatings. A compatible matrix and cost-effective deposition processing are required to make external ZnO-based coatings effective [30–33]. Uniform ZnO dispersion in a polymer matrix is important for formulating a dense and functional coating. Various polymers such as poly (vinyl alcohol) (PVA), poly (vinyl butyral) (PVB), polystyrene (PS), and ethylene vinyl acetate (EVA) have proven suitable for incorporating ZnO particles. This is because matching the refractive indices of these polymers with the refractive index of ZnO will make it easy to process transparent coatings. Not only this, but the wetting characteristics of ZnO in these aforementioned polymers is also advantageous for the generation of uniform coatings [34,35].

PVB and EVA serve different purposes in the context of solar cells. While PVB is commonly used as an encapsulant to protect solar cell components, EVA is typically employed as a layer in the lamination process. In a typical photovoltaic module, the solar cells are encapsulated between layers of EVA, and the entire assembly is often further protected by a layer of glass on the front [36]. PVB is known for its UV-blocking properties and its ability to encapsulate solar cells, protecting environmental factors [37–39]. However, when it comes to protecting EVA specifically, the primary role of PVB is to contribute to the overall encapsulation and protection of the entire solar cell structure. The encapsulation helps prevent moisture ingress, dust, and other environmental elements from reaching and potentially damaging the solar cells and their connections [40,41].

This study focuses on the development of coatings using PVB with varying concentrations of zinc oxide (ZnO) nanoparticles dispersed in the solution. Solar panels already exposed to UV radiation face serious issues of degradation, such as discoloration and a decrease in fill factor and efficiency over time. ZnO, when blended with PVB and made into composite films, can protect against photo-degradation and yellowing (discoloration) of the adhesive, thereby enhancing the lifespan of solar panels. The experimental approach involves preparing PVB-ZnO solutions, followed by depositing thin films onto solar panels using a spray coating technique. The aim is to investigate the impact of different ZnO concentrations to observe various solar cell performance parameters, with a primary focus on their ability to resist yellowing under prolonged exposure to sunlight.

The findings of this study may pave the way for developing advanced protective coatings, ensuring prolonged and efficient operation of solar panels in diverse environmental conditions. Given the global emphasis on sustainability and renewable energy, enhancing the durability of solar panels is critical. By extending the operational lifespan and maintaining the efficiency of solar panels, this work directly contributes to reducing electronic

waste and promoting more sustainable energy practices. The use of ZnO nanoparticles as a protective measure is not only innovative but also crucial in the context of sustainable energy solutions, as it potentially reduces the need for frequent replacements and lowers the overall environmental impact. This novel approach to utilizing ZnO for solar panel protection underlines the importance of combining materials science with environmental sustainability, positioning this study as a significant contribution to the field.

2. Materials and Methods

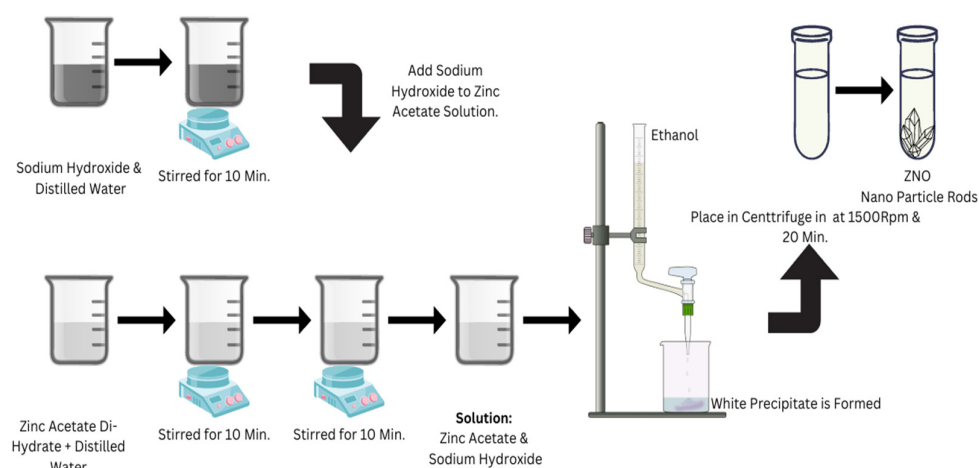
2.1. Materials

Sigma-Aldrich (St. Louis, MO, USA) supplied zinc acetate (purity 99.8%), sodium hydroxide (purity 99.5%), and polyvinyl butyl (PVB) (purity > 98%). Khurram Scientific Center (Karachi, Pakistan) supplied toluene (purity 99%) and ethanol (purity 99.5%). The solar panels used in this research were purchased from Blue Solaria, Dongguan, China. The purchased solar panels were polycrystalline type, having model No. BSP-004.

2.2. Methods

2.2.1. Synthesis of ZnO Nano-Powder

The synthesis ZnO particles in this study involved the utilization of high-purity zinc precursor materials and the scheme of processing steps is shown in Figure 1. Zinc salts, such as zinc acetate or zinc nitrate, were employed as the primary sources of zinc ions. These salts were carefully dissolved in a suitable solvent, typically water, to form a precursor solution. The addition of a hydroxide source or base, such as sodium hydroxide or ammonium hydroxide, facilitated the controlled precipitation of zinc hydroxide, which subsequently underwent thermal decomposition or calcination to yield the desired ZnO particles. The process was conducted under controlled temperature conditions to ensure the formation of crystalline ZnO with well-defined morphological features. The choice of reagents and reaction parameters played a critical role in determining the purity, size, and structure of the ZnO particles, ensuring their suitability for subsequent applications in composite materials [42,43].



Sol Gel Technique for Production of Zinc Nano Particle Rods.

Figure 1. Schematic diagram showing the steps involved in the preparation of ZnO nanoparticles.

The synthesis of zinc oxide (ZnO) through a combination of zinc acetate and sodium hydroxide in distilled water involves a straightforward process. Initially, zinc acetate is dissolved in distilled water to form a clear solution. Simultaneously, sodium hydroxide is added to this solution under stirring conditions, promoting the formation of zinc hydroxide through a precipitation reaction. The resulting mixture undergoes a hydrolysis and condensation process, eventually leading to the formation of a gel-like substance. After

drying, the gel is subjected to calcination, where heating removes organic components and transforms the zinc hydroxide into crystalline ZnO particles. This combination of zinc acetate and sodium hydroxide in distilled water provides a convenient route for the sol-gel synthesis of ZnO, offering control over particle size and morphology, with the potential for applications in various technological fields [44].

Two g of zinc acetate was mixed with 15 mL of distilled water, labeled as solution A. Solution A was placed on a magnetic stirrer for 3 h and 40 min at room temperature. Then, 8 g of sodium hydroxide was mixed with 10 mL of distilled water, labeled as solution B. Solution B was placed on a magnetic stirrer for around 4 h. The PH of both solutions was checked. Solution A was acidic with a PH of 6 (confirmed with Whatman filter paper) and Solution B was basic with a PH of 12 (confirmed with Whitman filter paper). Now both the solutions were mixed and drop-wise ethanol was added to make a milky solution known as solution C. Solution C, found to have a PH of 7, was maintained and put on a magnetic stirrer for 2 h at 50 °C. After the final solution was placed in the oven for heating at 250 °C for 8 h, it resulted in white nanoparticles of ZnO powder.

2.2.2. Synthesis of PVB/ZnO-Based Nanocomposite Films

A solution was made by dissolving 10% PVB in toluene for 3 h at room temperature with magnetic stirring at 700 rpm and a clear solution was obtained. ZnO particles in concentrations of 0.1%, 0.3%, and 0.5% (wt%) were added to produce a variety of PVB-ZnO films. This solution was then stirred on a magnetic stirrer for 1 h at room temperature. The resultant solution was sprayed on a PET substrate and solar panels. Films coated on PET substrate were peeled off and were used for film characterizations, whereas coated solar panels were tested for their stability under accelerated aging conditions.

3. Characterization Techniques

In this section, various characterization techniques that were used for the characterization of nanoparticles, films, and solar panel stability are described.

3.1. Scanning Electron Microscopy (SEM)

The SEM (Model: JSM-6387) images were taken from the JEOL (Tokyo, Japan) manufacturer with an accelerated voltage of 20 kv and magnification of 1000 $\times$ and 4500 $\times$. SEM was utilized to capture the micrographs at various magnifications. In addition, SEM-EDS (energy-dispersive X-ray spectroscopy) was also utilized to better understand the chemical composition of the sample.

3.2. X-ray Diffraction (XRD)

XRD spectra were taken from Expert Pro, using an XRD machine manufactured by Panalytical company (made in Eindhoven, The Netherlands) with working conditions of 30 mA and 40 kv.

3.3. Fourier-Transform Infrared (FTIR) Spectroscopic Analysis

A Fourier-Transform Infrared (FTIR) spectrophotometer (Bruker Alpha-P, Bruker Corporation, Billerica, MA, USA) operated with OPUS 7.2 software was used to capture IR spectra in ATR mode. Spectra were acquired by performing 128 scan summations at a resolution of 4 cm⁻¹.

3.4. Ultraviolet-Visible (UV-Vis) Spectroscopic Analysis

The ultraviolet-visible spectra of the produced thin film were determined using a double-beam UV-Vis spectrometer (pharma Spec UV-1700, Shimadzu, Kyoto, Japan). Absorbance was measured at wavelengths ranging from 200 to 800 nm.

3.5. Contact Angle Measurements

Water droplets were used to measure the contact angle with a contact angle goniometer, SL200A, from KINO Scientific Instrument Inc. in Boston, MA, USA.

3.6. Solar Panel Stability Testing

Solar panels were subjected to two types of accelerated aging conditions, i.e., solar irradiation and damp heat conditions. A solar simulator was used to irradiate the panels with 1000 W/cm^2 with test conditions of 60°C while maintaining 0% RH. For damp heat, solar panels were placed in a humidity chamber with test conditions of 65°C and 65% RH. The working parameters of the solar panels such as short-circuit current (J_{sc}), open-circuit voltage (V_{oc}), efficiency(η), and fill factor (FF) were recorded with the help of an in-house-built AI and IoT-based ThinkSpeak software version 2.0.

4. Results and Discussion

4.1. Morphological Analysis

The morphological characteristics of the ZnO nanoparticles were meticulously examined using SEM and the results are shown in Figure 2a,b. The SEM analysis provided a detailed insight into the surface topography, size distribution, and shape of the ZnO particles, crucial parameters governing their effectiveness in solar panel protection [45].

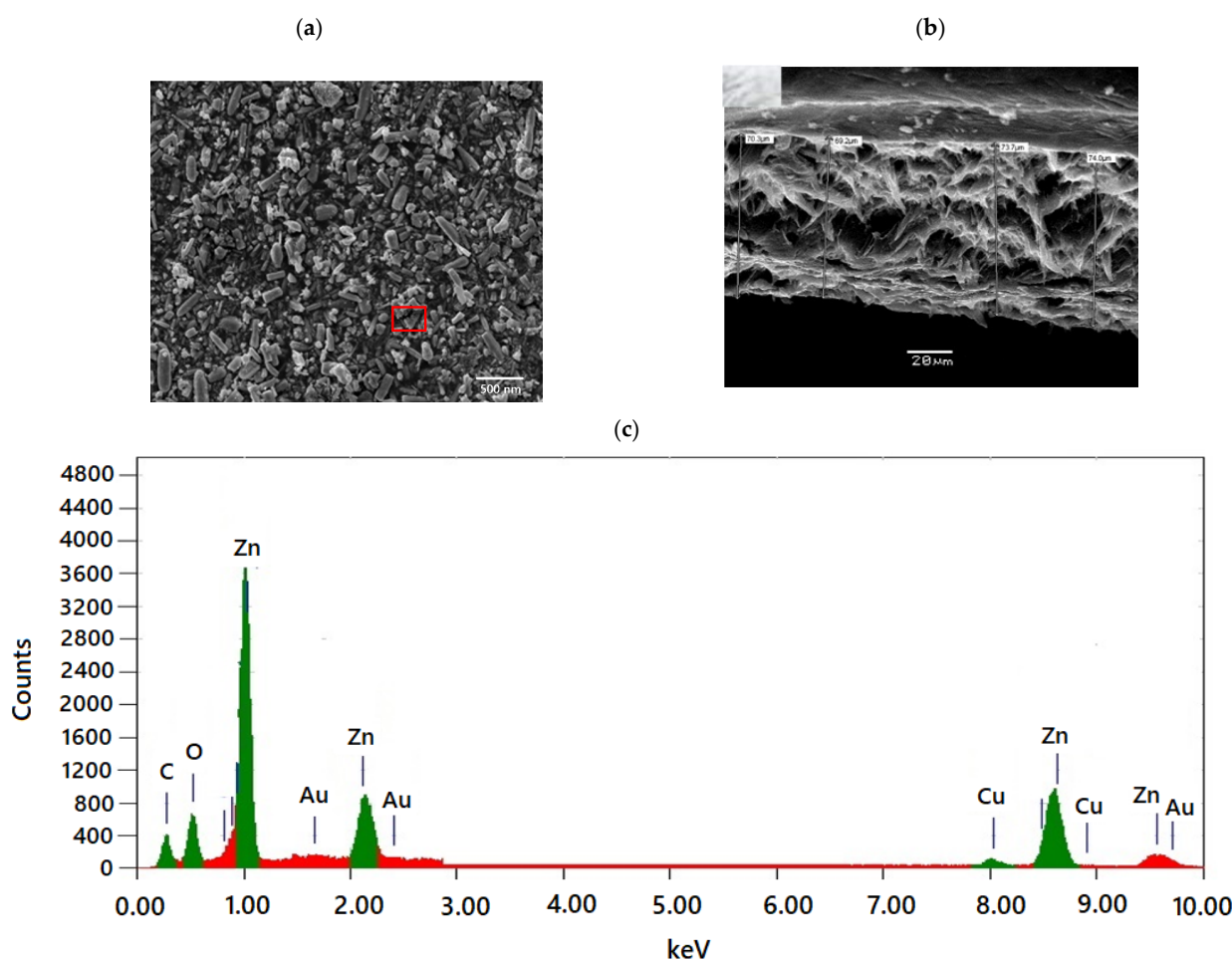


Figure 2. SEM analysis of synthesized ZnO NPs and corresponding PVB films, where (a) represents SEM image of ZnO nanoparticles, (b) represents cross-sectional view of PVB matrix embedded with ZnO, and (c) represents spot analysis of EDX of ZnO NPs, and the corresponding spot is the marked red box in (a).

The micrographs reveal ZnO rod-like structures exhibiting uniform morphology and well-defined dimensions, which indicate successful synthesis, as shown in Figure 2a. The rod-like formations are consistently distributed. Detailed analysis of the micrographs shows that the ZnO rods possess smooth surfaces and uniform widths. Moreover, elemental analysis conducted concurrently with the SEM analysis demonstrated the elemental homogeneity and uniformity of the ZnO particles. The SEM results underscore the morphological attributes of the ZnO particles, portraying them as nanoscale entities with well-defined rods [46]. These SEM findings lay the foundation for understanding the microstructural features of the ZnO particles, critical for elucidating their subsequent influence on the properties of the composite thin films [34].

The cross-sectional view shows critical insights into the morphology and distribution of zinc oxide (ZnO) nanoparticles within a PVB matrix. Several key observations can be made from the SEM cross-sectional image (Figure 2b). Firstly, the SEM image reveals a homogeneous and dense structure of the films. This gives a clear impression that the addition of ZnO nanoparticles did not experience any de-wetting problem, and they are well dispersed throughout the matrix. The soft PVB matrix does not withstand the heat generated by the electron beam and melts, thereby covering the edges and making it very hard to distinguish between the matrix and nanoparticles in the SEM image [47]. However, the dense structure of the films without any significant porosity clearly supports the homogeneous distribution of the nanoparticles in the PVB matrix. Secondly, the cross-sectional view allows for the measurement of the thickness of the composite film (around 70 microns, μm) providing important information for applications where precise film thickness is critical. Additionally, the SEM image enables the visualization of the interface between the ZnO nanoparticles and the PVB matrix. A close examination of this interface reveals details about the interfacial adhesion, where there is no evidence of the presence of the defects such as voids or imperfections that could potentially lead to failure of the films.

The energy-dispersive X-ray spectroscopy (EDS) analysis of the ZnO sample (as shown in Figure 2c reveals the presence of multiple elements, including carbon (C), oxygen (O), sodium (Na), copper (Cu), zinc (Zn), and gold (Au). The prominent peaks corresponding to Zn and O confirm the successful synthesis of ZnO, indicating that these elements are the primary constituents. The presence of C may be attributed to surface contamination or the use of carbon-based materials during sample preparation. Sodium (Na) and copper (Cu) signals could be due to residual impurities from the synthesis process or contamination from handling and equipment. The peak for Au is because of its coating to make the sample conductive. Despite these additional elements, the main composition of ZnO remains evident, with Zn and O being the dominant peaks in the spectrum. This comprehensive EDS profile provides a detailed understanding of the elemental composition and potential impurities within the ZnO sample.

Furthermore, the elemental composition determined an atomic percentage of 19.27% for zinc (Zn) and 21.73% for oxygen (O), resulting in a Zn atomic ratio of approximately 0.887:1. This ratio is notably close to the ideal stoichiometric ratio of 1:1, which is important for optimizing the structural and optical properties of ZnO nanoparticles. Achieving a ratio near to 1:1 ensures that the nanoparticles can retain excellent UV-blocking capabilities, essential for protecting solar panels from photo-degradation and enhancing their longevity. The close-to-ideal Zn ratio in our samples underscores the effectiveness of our synthesis process in producing high-quality ZnO nanoparticles suitable for UV protection applications.

4.2. XRD X-ray Diffraction (XRD) Analysis

The XRD pattern of ZnO rods shown in Figure 3 (red curve) exhibited distinct diffraction peaks at 2θ values corresponding to well-defined crystal planes, indicative of the crystalline nature of ZnO. The prominent diffraction peaks observed at approximately 31.68° , 34.38° , 36.08° , 44.8° , 47.53° , 56.68° , 62.66° , 67.91° , 69.2° , 72.22° , and 77.03° , which correspond to (hkl) indices of (010), (002), (011), (012), (110), (013), (020), (112), (012), (004),

and (022), were in excellent agreement with the characteristic peaks of the hexagonal wurtzite crystal structure of ZnO [46]. The reference spectra (standard PDF card number 96-900-44182) of pure wurtzite ZnO is also plotted in Figure 3 (black lines). The high intensity and sharpness of these peaks underscore the crystalline purity and integrity of the ZnO particles and it is evident that impurity-free ZnO rods were successfully prepared and are ready to be incorporated with the PVB matrix for the formation of nanocomposite films. The absence of extraneous diffraction peaks in the XRD pattern confirmed the absence of impurities or secondary phases, affirming the high phase purity of the ZnO particles. This high phase purity is a critical attribute ensuring the reliability and consistency of the ZnO particles in conferring desirable characteristics to the resultant PVB thin films [48,49].

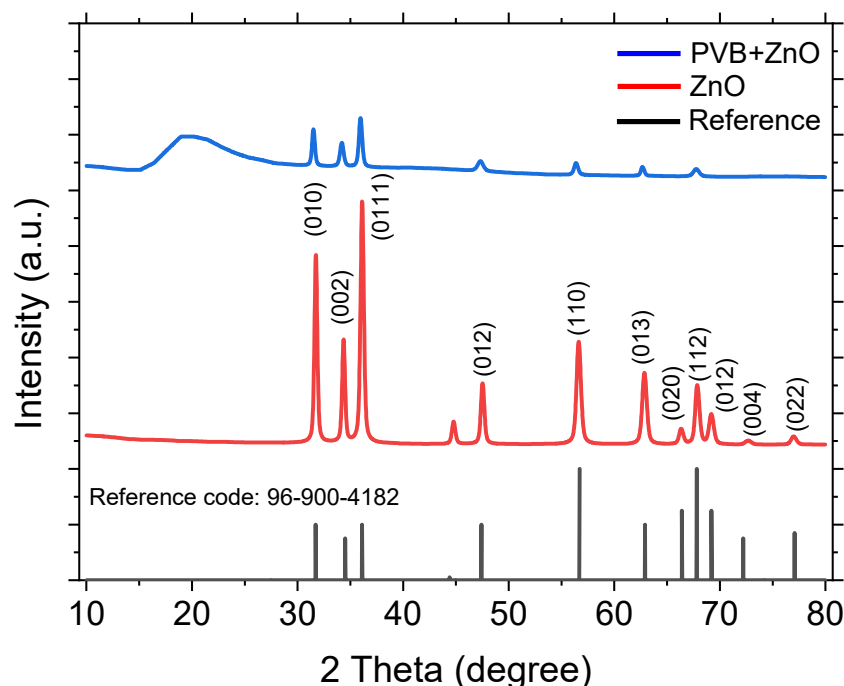


Figure 3. XRD Spectra for prepared ZnO NPs (red curve) along with films of PVB filled with ZnO NPs (blue curve) and standard reference code 96-900-4182 (black lines).

The diffraction spectrum of PVB containing ZnO is also shown in Figure 3 (blue curve), which exhibits characteristic peak at 19.81° , which suggests that PVB is semi-crystalline. It can also be noticed that there are many XRD peaks such as 31.43° , 34.21° , 36.01° , 47.48° , 56.36° , 62.66° , and 67.78° . This behavior indicates that the original structure of the ZnO particles remained unaltered and the results are in accordance with the literature [34,46,50–53].

4.3. Fourier-Transform Infrared (FTIR) Spectroscopic Analysis

The molecular vibrational characteristics and surface functionalities of the ZnO particles were examined through FTIR spectroscopy. This analytical approach allows for the identification of chemical bonds and provides valuable insights into the composition and bonding configurations of the ZnO particles.

The FTIR spectra of ZnO, PVB, and PVB containing ZnO are shown in Figure 4. The strong and broad absorption peaks found at the wave number of 1334 cm^{-1} , 536 cm^{-1} , and 413 cm^{-1} are attributed to the characteristic stretching vibrations of the Zn-O bond in the wurtzite crystal structure. The presence of this peak confirms the successful synthesis and preservation of the hexagonal ZnO phase [54–56].

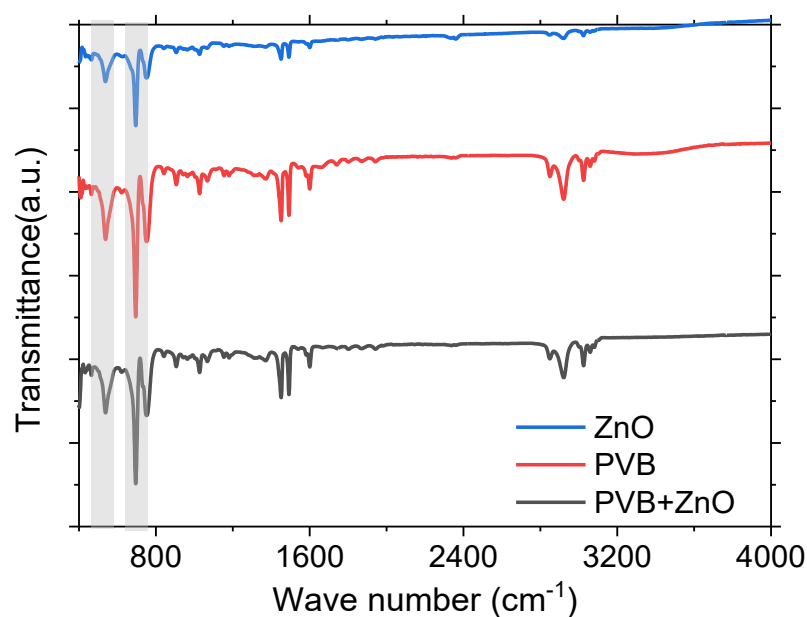


Figure 4. FTIR of prepared ZnO and its composite film (PVB with ZnO embedded).

Figure 4 demonstrates that the strong peak at 665 to 750 cm^{-1} indicates a C=C bond, and weak bending is observed at 1450 to 1500 cm^{-1} indicating the presence of a C-H bond. Another weak peak is shown in the curve for 2700 to 3200 cm^{-1} indicating stretching of O-H bonds. The presence of these peaks clearly indicates the successful mixing of ZnO with PVB [57,58].

4.4. Ultraviolet-Visible Light (UV-Vis) Spectroscopic Analysis

The optical characteristics and absorbance behavior of zinc oxide (ZnO) particles, integral components of PVB thin films, were explored through UV-Vis spectroscopy. This analytical approach provides critical insights into the electronic transitions within the ZnO particles, offering a comprehensive understanding of their absorption properties relevant to solar radiation and potential applications in photo-protective coatings [59,60]. The UV-Vis absorption spectrum of the ZnO particles suspended in aqueous solutions (as shown in Figure 5, blue curve) exhibited a distinct absorption edge in the ultraviolet region, characterized by a sharp onset at approximately 400 nm. This spectral feature corresponds to the bandgap absorption of ZnO, reflecting the transition of electrons from the valence band to the conduction band. In order to show a significance of the UV absorption of the ZnO-based coatings on top of the solar panel, a bare encapsulating glass of the solar panel was also analyzed for the UV absorption and the result is shown in Figure 5 (black curve). The glass did not exhibit any capacity to block radiation in the UV range. This means most of the harmful radiation can effectively interact with the encapsulating adhesive and may lead to UV-induced degradation in it. In addition to that, when the encapsulating glass was coated with a PVB film containing ZnO in it, a significant UV blocking effect was observed. The film effectively blocks all the radiation having wavelengths below 380 nm. The different absorption peaks for ZnO nanoparticles in suspension and in PVB films are mainly due to changes in the surface environment and interactions with the surrounding medium [61]. Furthermore, the absence of discernible absorption peaks in the visible region of the spectrum suggests that the ZnO particles are transparent within this wavelength range. This transparency in the visible spectrum is desirable for preserving the overall transparency of PVB thin films, ensuring minimal interference with the visible light spectrum and, consequently, the efficient utilization of solar energy [62].

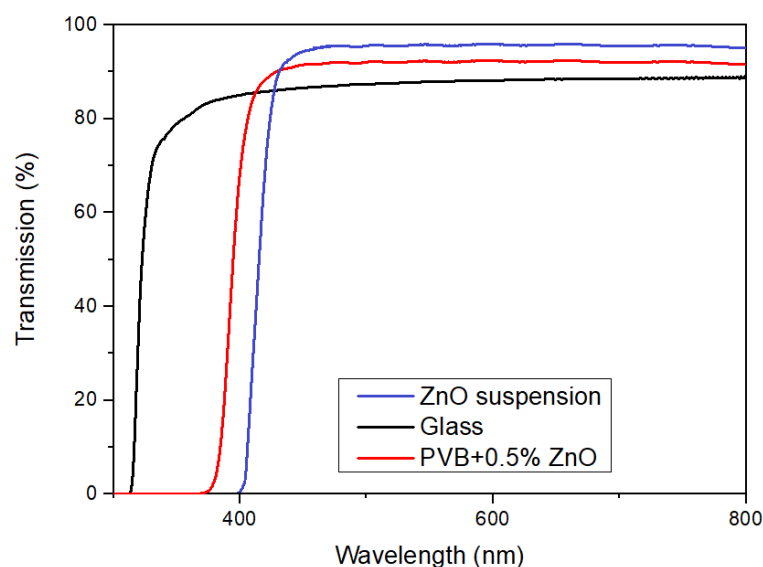


Figure 5. UV-Vis of ZnO nanoparticles, where blue curve represents ZnO NPs suspended in aqueous solution, the black curve represents the absorption capacity of encapsulating glass, and the red curve represents the PVB film containing 0.5% of the ZnO NPs.

In summary, the presence of a well-defined absorption band in the UV region is advantageous for solar protection applications, as it indicates the effective absorption of harmful ultraviolet (UV) radiation [63], thereby protecting the encapsulating adhesive underneath. The protection of the adhesive is highly beneficial for the overall performance and life of the solar panel [64].

4.5. Contact Angle Measurements

The characterization of the hydrophobic nature of the PVB + ZnO-based nanocomposite film coating was effectively demonstrated through contact angle measurements, demonstrated in Figure 6. Initially, the bare glass of the solar module was tested and it exhibited a contact angle of 92.56° , indicating a moderately hydrophobic surface. Upon application of the PVB + ZnO nanocomposite film, a significant increase in the contact angle to 110.23° was observed when the coating was applied to the glass of the solar module. This substantial enhancement in the contact angle illustrates the superior hydrophobic properties imparted by the nanocomposite coating. The increase in hydrophobicity can be attributed to the intrinsic properties of the ZnO nanoparticles, which, when uniformly dispersed within the PVB matrix, reduce surface energy and form a more water-repellent surface. The contact angle measurement serves as a crucial quantitative indicator, confirming the effective modification of the glass surface and the successful development of a hydrophobic coating. This improvement in hydrophobicity is critical for applications requiring water-resistant surfaces, thus highlighting the potential of PVB + ZnO nanocomposite films in advanced coating technologies.

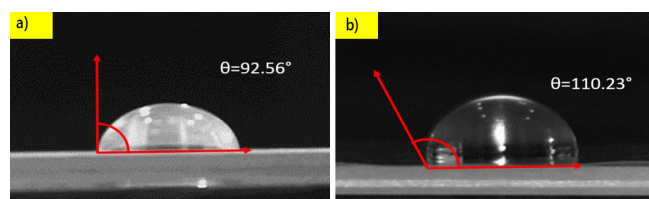


Figure 6. (a) Contact angle on glass. (b) Contact angle over coated glass.

4.6. Solar Cell Performance (Sun Test)

The final thin composite film of PVB with different concentrations of ZnO was prepared successfully and sprayed onto solar panel surfaces directly to prevent UV blocking and enhance the thermal efficiency of the cell, and the process is schematically shown in Figure 7. Films were uniformly distributed over solar panel surfaces.

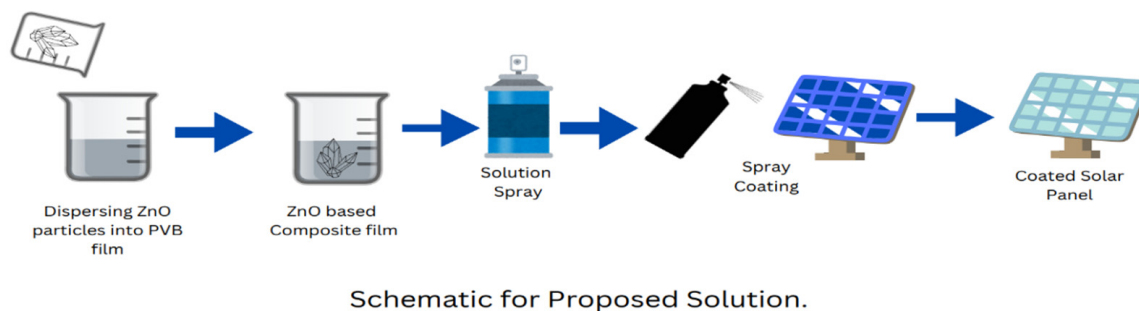


Figure 7. Schematic of synthesizing and applying ZnO-PVB nanocomposite solution via spray coating on solar panels.

A series of solar panels were subjected to solar exposure to check the performance and longevity of the panel to 5000 h at the intensity of 1000 W/m^2 with Air Mass AM = 1.5. Solar panels were inclined at an angle equal to Karachi's latitude of 24.84°N . Solar panels were coated with different concentrations like PVB, PVB + 0.1% ZnO, PVB + 0.3% ZnO, and PVB + 0.5% ZnO and were subjected to lifetime tests, and the corresponding results are shown in Figure 8. The performance of a solar cell is measured by evaluating its open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), efficiency, and fill factor (FF), which together provide a comprehensive assessment of its electrical output and overall effectiveness. All data were recorded with different time intervals on ThinkSpeak (AI and IoT) software and curves were plotted to analyze solar performance parameters, as shown in Figure 8.

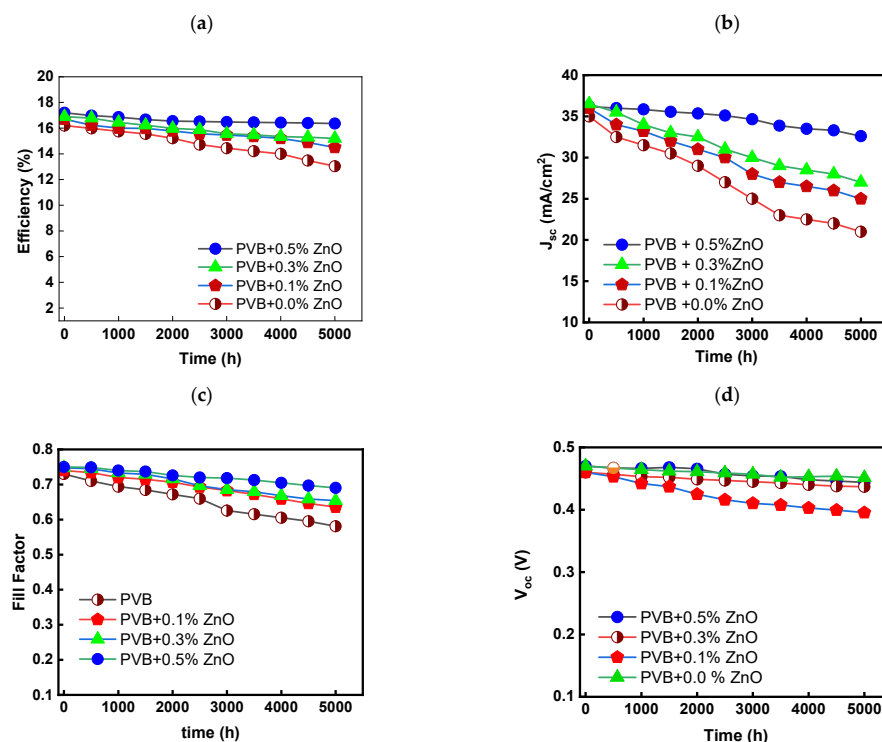


Figure 8. Analysis of solar performance parameters exposed to sun directly. (a) Efficiency with time, (b) is J_{sc} , (c) is FF, and (d) is V_{oc} .

Efficiency is a critical performance metric for solar cells, representing the ratio of the electrical power output to the incident light power input. It is influenced by both the open-circuit voltage V_{oc} and J_{sc} , as well as the fill factor (FF). Figure 8a shows the effect on the efficiency with time elapsed for different coatings of PVB, PVB + 0.1% ZnO, PVB + 0.3% ZnO, and PVB + 0.5% ZnO. The coated solar cell with the highest concentration of ZnO (0.5%) in the composite film results in a better performance and exhibited an efficiency loss of around 1%. Modules coated with 0.3% ZnO, 0.1% ZnO, and pristine PVB exhibited efficiency losses of 3%, 4%, and 7% respectively. The drop in efficiencies is mainly because of the loss of J_{sc} in all coatings. Coatings with 0.5% ZnO, 0.3% ZnO, 0.1% ZnO, and pristine PVB showed the J_{sc} loss of 10%, 27%, 30%, and 40%, respectively. Furthermore, FF and V_{oc} remained relatively stable. The possible reasons for this could be the UV radiation degradation of the adhesive, which may have created paths for the diffusion of oxygen through them and the resulting oxidation of Si, whereas the coating with 0.5% ZnO protected the adhesive and did not allow any degradation and thus efficiency remained almost stable [65]. When exposed to UV radiation, the encapsulating adhesive used to encapsulate the solar panel with glass can undergo photochemical reactions that break down its polymer structure. This process, known as photodegradation, results in the formation of free radicals and other reactive species, which further attack the polymer chains. Over time, this leads to a loss of mechanical properties, causing the adhesive to become brittle and less effective at sealing and protecting the panel's performance. The degradation of the adhesive compromises the integrity of the encapsulation, which is essential for protecting the photovoltaic cells from environmental factors like moisture, oxygen, and temperature fluctuations. As the adhesive deteriorates, these harmful elements can penetrate the encapsulation, leading to further degradation of the solar cells. This is the reason that the solar panels degraded in terms of reduced efficiency and lower power output, which ultimately leads to a shorter lifespan [66].

4.7. Solar Cell Performance (Damp Heat Test)

Solar panels were tested in a temperature/humidity chamber at 65% RH and 65 °C for an uninterrupted cycle of 5000 h, as shown in Figure 9 below. All solar performance parameters were taken into account under this test. The type of this test is considered to be an over 25~30-year equivalent in the harshest climate and outdoor exposure [67].



Figure 9. (a) shows panels subjected to 65 °C and 65% RH. (b) Temperature and humidity chamber placed in lab. (c) shows inside view of solar panels placed under damp heat conditions.

Figure 10a shows the efficiency (%) over the period of 5000 h for the samples coated with PVB, PVB + 0.1% ZnO, PVB + 0.3% ZnO, PVB + 0.5%. It is evident from the figure that the modules remained stable for the given set of time and no degradation in efficiency was seen. This is because almost all parameters of the solar cell remained intact and did not show any degradation. No significant change in any of the parameters like efficiency, J_{sc} , fill factor, and V_{oc} was observed. This test yielded very stable solar cells compared to the sun test. The possible reason could be that the damp heat only provides the heat and that heat does not leave any negative impact on the performance of the solar cell. All

parameters, including efficiency (Figure 10a), J_{sc} (Figure 10b), fill factor (Figure 10c), and V_{oc} (Figure 10d) did not change with time. The possible reason could be the absence of UV light, which means the damp heat controlling system only provides heat and relative humidity, which seems to suite the performance of a solar cell. Obtained results conclude that the damp heat is not causing any negative effect on the adhesive and this is evident from the stable performance of the solar modules, whereas under the sun test, the solar panels degraded, confirming the cause of degradation is UV light, which severely damages the adhesive.

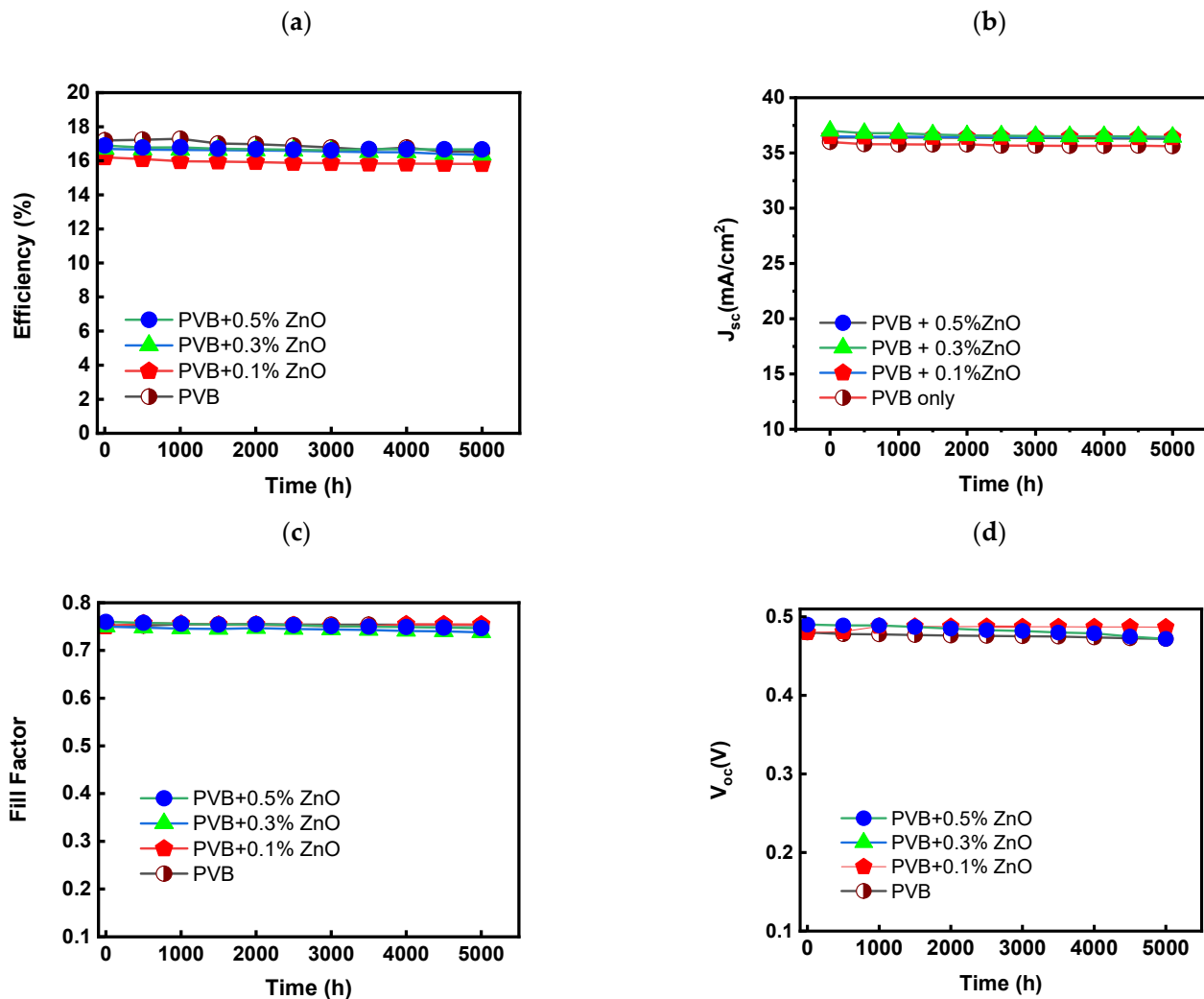


Figure 10. Analysis of solar performance parameters under damp heat conditions. (a) J_{sc} with time elapsed. (b) V_{oc} with time elapsed. (c) Efficiency with time passed. (d) FF varying with time.

5. Conclusions

This study demonstrates the significant advantages of incorporating ZnO nanocomposite film coatings into silicon-based solar cells. The high band gap energy (3.37 eV) and excellent electro-optical properties of ZnO, combined with its exceptional UV absorptivity and transparency in the visible range, make it an ideal material for enhancing solar cell performance and longevity. The sol-gel method successfully produced ZnO nanorods, which were dispersed in a PVB matrix to create uniform nanocomposite films. Characterization through various techniques, including X-ray Diffraction (XRD), FTIR, SEM, UV-Vis spectroscopy, and contact angle measurements, confirmed the effective integration of ZnO within the PVB matrix. This integration provided significant UV blocking at 380 nm, improving the short-circuit current (J_{sc}), open-circuit voltage (V_{oc}), efficiency (η), and fill

factor (FF) of the solar cells. Although a slight decrease in J_{sc} was observed due to the ZnO layer's impact on the light absorption spectrum, the overall efficiency and fill factor saw remarkable enhancements. The ZnO coatings effectively reduced the thermal load on the solar cells by absorbing and dissipating UV radiation, thus enhancing their performance. Moreover, the coated solar panels demonstrated superior durability under damp heat conditions compared to those exposed solely to sunlight. This increased resistance to degradation in damp heat underscores the protective advantages of ZnO films, ensuring extended operational life and consistent performance of solar cells. This also confirmed that the main degradation source in the solar module is the UV light that deteriorates the adhesive, thus causing the shortening of the panel's life. The findings of this study strongly support the potential of ZnO nanocomposite coatings to significantly enhance the efficiency, reliability, and longevity of silicon-based solar panels, making them more viable for long-term applications in various environmental conditions.

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