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Polymer-Based Nanocomposite Coatings for Enhancing Solar Photovoltaic Panel Efficiency

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Abstract

Environmental factors such as dust deposition, ultraviolet (UV) radiation, and surface reflection significantly reduce the performance of solar photovoltaic (PV) modules. This study investigates the development and performance evaluation of polymer-based nanocomposite coatings designed to improve the optical and surface properties of PV panel glass. A hybrid nanocomposite coating containing TiO_2 and SiO_2 nanoparticles dispersed in a polymethyl methacrylate (PMMA) matrix was synthesized using the sol–gel technique and deposited through spin coating. The coatings were characterized in terms of optical transmittance, surface wettability, and photovoltaic performance under standard test conditions (AM 1.5, 1000 W/m², 25°C). The coated PV modules exhibited improved optical transmission and enhanced hydrophobic behavior compared to uncoated glass. The efficiency of solar photovoltaic panels is affected by various environmental parameters such as dust accumulation, high operating temperatures, and optical losses. The present work proposes the development of polymer-based nanocomposite coatings for the enhancement of the efficiency and lifespan of solar photovoltaic systems. The incorporation of nanomaterials such as metal oxide and carbon-based materials in the polymer matrix enables the formation of multifunctional coatings with improved optical transmission, thermal dissipation, and anti-soiling properties. The performance of the developed coatings has been investigated in terms of transparency, thermal dissipation, and surface wettability. The results reveal the effectiveness of the proposed nanocomposite coatings in improving the efficiency and lifespan of solar photovoltaic systems. The proposed approach has the potential to be used in the development of advanced solar panels in the coming days. Experimental results indicate an improvement of approximately 3–5% in power output due to reduced reflection losses and improved surface self-cleaning characteristics. The findings suggest that polymer nanocomposite coatings can be a promising approach for improving photovoltaic module performance.

Keywords: TiO_2, SiO_2, self-cleaning coatings, polymer nanocomposites, solar photovoltaics, surface coating, optical transmission, and renewable energy.

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INTRODUCTION

The world is now shifting toward renewable energy, so further study is needed on how to make solar photovoltaic (PV) systems work better as well as last longer. Solar energy is now becoming the leading renewable source as it is massively available and can be used in many different ways. One more reason behind it is that more and more people want clean and sustainable energy. But the efficiency of commercial PV panels is usually between 15% and 22%, which is still inadequate because the number of outside and inside issues, like dust buildup, surface reflection, thermal deterioration, and aging caused by UV light. In

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order to minimise these losses, researchers worked on new ways to change the surface of materials. Polymer-based nanocomposite coatings are one of the most capable ways to enhance efficiency. This material used in coating can change its optical properties as well as clean itself. The addition of nanoscale fillers like TiO_2, SiO_2, ZnO, and graphene oxide (GO) to polymer material makes them more transparent, water-repellent, and resistant to UV light. The performance of PV in real-world applications is enhanced. A PMMA-based nanocomposite coating augmented with TiO_2 and SiO_2 nanoparticles for photovoltaic glass surfaces is expressed and assessed in this research. The effects of these coatings on optical transmission, surface characteristics, and power output efficiency under simulated solar radiation are emphasized. Although several studies have investigated nanomaterial coatings for photovoltaic applications, many of them focus on single nanoparticle systems or inorganic coatings. The novelty of the present work lies in the development of a hybrid TiO_2–SiO_2 nanocomposite embedded in a PMMA polymer matrix specifically designed for photovoltaic glass surfaces. Solar power has become one of the most important solutions for efficient and eco-friendly power production. However, there are many challenges faced by solar panels due to environmental and operational factors. The presence of dust on solar panels affects the amount of solar irradiance incident on the panel surface. Moreover, high temperatures affect the efficiency of solar panels. Prolonged exposure to UV rays affects the panel surface as well. In order to overcome these challenges faced by solar panels, scientists have developed efficient coating technologies to improve the properties of solar panels. Polymer nanocomposites have become one of the most important coating solutions due to their flexibility and robustness. These nanocomposites can be formulated to achieve high transparency, high thermal conductivity, and self-cleaning properties as well. This article aims to discuss the importance of polymer nanocomposites in improving solar panel efficiency.The hybrid structure aims to combine the anti-reflective characteristics of SiO_2 with the photocatalytic and UV-resistant properties of TiO_2, while maintaining good mechanical adhesion through the PMMA matrix. This approach provides a balanced combination of optical enhancement, durability, and surface self-cleaning capability. Polymer Nanocomposite Coatings refer to advanced functional coatings that are formed by combining polymer-based matrices such as PMMA, PDMS, or epoxy with nanoscale fillers (1–100 nm) like TiO_2, SiO_2, ZnO, or graphene oxide. Unlike traditional coatings (polymer-based or inorganic coatings), the advantages of polymer nanocomposite coatings include: Multifunctionality (optical+ thermal+self-cleaning), Greater optical clarity due to nanoscale distribution of fillers, Higher strength & UV resistance, Refractive index tuning to make the coating anti-reflective, Surface improvements (hydrophobic or self-cleaning), Whereas traditional coatings typically: Are not multifunctional, Offer limited control over optical performance, Lack sufficient strength/UV resistance. Hence, polymer nanocomposite coatings offer the best of both worlds - polymers and nanoparticles together.

LITERATURE REVIEW

It has been shown by the study of recent research papers that the use of polymer-based nanocomposite coatings on solar photovoltaic (PV) modules has come forward as a potential way to reduce optical losses, surface damage, and dust buildup. The key purpose of these coatings is to increase transmittance, lower reflection, and make the surface more durable when it is exposed to environmental factors like UV radiation and changes in temperature for an extensive time. The following properties improve the transparency and anti-reflectance characteristics of nanofillers like SiO_2 and TiO_2. 1. Matching of Refractive Index (Anti-Reflection) : Low refractive index of SiO_2 (~1.45), Provides a layer of variable refractive index between air and glass, Reduces the loss due to Fresnel Reflection. 2. Nanoscale Dispersion : Even dispersing of particles prevents light scattering, Optical transmittance is thus increased (90%-93%). 3. Surface Nanostructuring : Surface structuring is provided by nanoscopic structures, Light absorption is improved by capturing the incident light 4. Photocatalysis (TiO_2) : Photo-catalysis effect on organic pollutants in TiO_2, Ensures Optical Clarity for an extended period. The composite TiO_2-SiO_2 system provides a hybrid optical film with improved optical transmission and anti-reflection characteristics. A lot of research has been conducted into TiO_2-based nanocomposite coatings since better blocking of light and photocatalytic properties are provided by them. It is expressed by Chen *et al*. [1] that TiO_2 coatings made from sol–gel could improve the PV power output by over

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4% by decreasing the reflection losses and cleaning themselves with light. Singh [8] also observed that TiO_2 thin films retain spin coating and institute that they provide a better optical transmission (400–800 nm), which allows the better flow of the short-circuit current in crystalline silicon solar cells. SiO_2 nanoparticles, which have the properties of a low refractive index and high transmittance. These properties act as an add-on to provide the surface smoother and more durable. Patel *et al*. [2] shaped hybrid SiO_2–PMMA films that were very robust and allow more than 92% of light to pass through. Their research authenticated that the use of SiO_2 nanoparticles enhances the abrasion resistance and UV stability, which are very much important for photovoltaic applications whom the exposure to sunlight leads to surface degradation. Hybrid nanocomposites that mix TiO_2 and SiO_2 have become a lot of interest recently as they combine the UV protection of TiO_2 with the optical clarity of SiO_2, which provides increase in the performance in a balanced way [3]. The refractive index gradient produced by TiO_2–SiO_2 hybrids decreases light reflection at the air–glass contact, and attractive more photon transmission to the solar cell surface. How to choose a polymer matrix becomes very important as it will decide that how flexible, sticky, and clear the coating will it provide. Polymethyl methacrylate (PMMA) and polydimethylsiloxane (PDMS) are the polymers that are applied and used mostly to the most of surface to become them clear, can stand up to the weather, and are easy to work. Yadav and Mehta [7] inspected several polymer nanocomposites applied in renewable energy systems and determined that polymeric coatings suggested a versatile medium for integrating inorganic nanoparticles while maintaining optical clarity. Adding nanoparticles like ZnO, Al_2O_3, or graphene oxide (GO) to polymer matrices together provide them much robust and more valuable. Gupta and Singh [4] observed a PMMA-based hybrid composite using TiO_2–GO nanofillers, noting enhanced hydrophobicity and better photovoltaic output in real-world applications. Li *et al*. [6] demonstrated that nanoparticle fillers reduce surface reflectance by generating a nano-roughened surface topology, efficiently trapping incident light on coating layer. Current studies also highlight the importance of hybrid polymer–inorganic films provide better environmental stability. Banerjee and Chattopadhyay [11] investigated that multilayered TiO_2–SiO_2–PMMA coatings can retain more than 95% of their optical clarity even when the weather is not good in term of sunlight. They also investigated that they are good for large-scale photovoltaic integration. A number of research works have been carried out to explore the application of nanocomposite coatings in enhancing the PV system. Silica-based coatings have been found to offer excellent transmission capabilities due to the anti-reflective properties. Additionally, TiO2-based coatings offer self-cleaning capabilities due to the photocatalytic properties. However, such coatings have been found to have limitations in durability and thermal stability. Graphene and carbon nanotubes have been found to offer excellent thermal conductivity, thus facilitating the dissipation of heat from the PV panel. ZnO and Al2O3 metal oxide nanoparticles offer excellent protective capabilities against UV exposure. Polyurethane and epoxy matrices have been found to offer excellent binders to the coatings. Recent research has focused on the application of hybrid nanocomposite coatings, where different nanoparticles are mixed to offer multifunctional capabilities. Such coatings have been found to offer excellent transmission capabilities and dust resistance. Additionally, the coatings offer excellent thermal management capabilities. However, challenges have been encountered in optimizing the coating composition. The reason for the lower efficiency is the accumulation of dust on PV systems. The dust particle blocks some of the sunlight that reaches the solar cells. With the addition of hydrophobic or superhydrophobic coatings can decrease this problem by allowing water droplets roll off and gross dust away. Kumar [5] shows a full assessment of self-cleaning coatings and exposed that the integration of TiO_2 nanoparticles within a polymer matrix can yield a contact angle beyond 100°. This will reduce the deposition of dust particles. Sharma *et al*. [9] highlight that the breadth of the coating play a very significant role for performance. Coatings that are moreover thick will scatter light and lesser transmission, while coatings that are too thin can miffed surface coverage and strength. So, to get the most power out of a PV system, it's imperative to find the right equilibrium between thickness, nanoparticle loading, and surface energy. Epoxy composites reinforced with hybrid kenaf and banana fibers show improved wear behavior because of better loading capacity and lower rates of surface deterioration in [12]. In addition, such composites withstand moisture attacks without losing their mechanical properties, including tensile strength and flexural strength, which is an

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indication that they are suitable for use in humid conditions [13]. The mechanical characteristics of the hybrid polymer composites have been greatly improved because of the increased interfacial bond strength between the reinforcing fibers and the matrix and the reduction of the structural defects. The developed hybrid composite mixture displays excellent tensile, flexural, and impact strength, and it proves the efficiency of using bio-based materials as fillers [14]. The flexural properties of composites made from recycled polypropylene and filled with waste manhole cover flour and MDF sawdust have been found to increase with an increase in the amount of filler. In addition, the water absorption rate and thermal stability of these composites are relatively low, making them viable engineering materials [15]. The composites of Areca catechu fiber reinforced with epoxy have better mechanical behavior owing to their high cellulose content. Maximum performance is obtained with controlled amounts of fillers. The addition of silicon carbide provides increased hardness and strength, but beyond a certain optimum level (10 wt%), there is a reduction in performance due to agglomeration [16]. Natural fiber-reinforced composite materials have received considerable attention as environmentally friendly substitutes for traditional artificial fiber composites because of their light weight, bio-degradable qualities, and excellent mechanical properties. Their abundance, environmental benefits, and utility in fields like construction, automobiles, and packaging demonstrate their suitability for developing environmentally sustainable engineering solutions [17]. The summery of the reviewed article on polymer nanocomposite is tabulated in Table 1.

Table 1. Summary of reviewed studies on polymer nanocomposite coatings for photovoltaic applications.

Study	**Material System**	**Technique**	**Key Findings**	**Efficiency Gain**
Chen *et al.* (2021) [1]	TiO_2 sol–gel	Spin coating	Enhanced anti-reflective property	4.2%
Patel *et al.* (2020) [2]	SiO_2–PMMA	Sol–gel	High transmittance and UV stability	3.5%
Kim *et al.* (2022) [3]	TiO_2–fluoropolymer	Spray coating	Maintained 90% efficiency post exposure	4.5%
Gupta & Singh (2023) [4]	PMMA–TiO_2–GO	Spin coating	Improved hydrophobicity & PV output	5.6%
Kumar (2020) [5]	TiO_2–PDMS	Dip coating	Superhydrophobic surface ($\theta = 108°$)	4.8%
Li *et al.* (2022) [6]	TiO_2–SiO_2 hybrid	Sol–gel	Reduced reflection & UV degradation	5.1%
Yadav & Mehta (2021) [7]	Review	—	Highlighted flexible energy coatings	—
Sharma *et al.* (2021) [9]	PMMA–TiO_2	Spray coating	Thickness-dependent optical response	3.7%
Zhang *et al.* (2023) [10]	TiO_2–SiO_2 polymer film	UV curing	Stable under prolonged UV exposure	6.0%

MATERIALS AND METHODS

The author used polymethyl methacrylate (PMMA) as the foundation polymer as it provides better performance in bad weather conditions. This polymer also works well with inorganic fillers. Nanoparticles of titanium dioxide (TiO_2) and silicon dioxide (SiO_2) (average size: 20–50 nm) are used as they provide a surface harder, defend against UV rays, and reduce glare. The employment of an analytical-grade ethanol, acetone, and ammonium hydroxide as solvents and catalysts for enhancing the working and reducing losses. The commercial solar-grade glass (3 mm thick) is chosen as the base of the coating. TiO_2 and SiO_2 nanoparticles were dispersed with ethanol using ultrasound to ensure they were evenly distributed. At room temperature, PMMA pellets are dissolved in acetone, and the nanoparticle dispersion is slowly added. The combination was left to be settled for 24 hours to make sure that the hydrolysis and condensation process is complet and it will generate a homogeneous hybrid solution. To compare, we made TiO_2-only, SiO_2-only, and TiO_2–SiO_2 hybrid coatings to investigate how the composition of the nanoparticles enhances the performance. Before the coating process started, glass

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substrates were cleaned with acetone, ethanol, and deionized water using ultrasound. After the coating process they are dried at 60°C. The hybrid nanocomposite sol was spin-coated at 1500 rpm for 60 seconds. The TiO_2 and SiO_2 nanoparticles with an average particle size of 20–50 nm were used in concentrations of 1 wt% and 0.5 wt%, respectively. PMMA was dissolved in acetone to form a 5 wt% polymer solution. The nanoparticle dispersion was prepared using ultrasonic agitation for 30 minutes to ensure uniform distribution. The nanocomposite solution was deposited on solar-grade glass substrates using a spin coating technique at 1500 rpm for 60 seconds. After deposition, the coated substrates were dried at 60°C for 2 hours to ensure proper film formation. The polymer-based nanocomposite coating material was developed employing a solution mixing method. Particular nanoparticles were mixed into a polymer matrix using mechanical stirring and ultrasonication methods for uniform dispersion. The formulation was adjusted to attain a balance between transparency and functionality. Clean glass substrates were coated employing a dip coating method and then cured at specified temperatures to obtain a uniform thin film. The coated samples were then characterized employing various characterization methods. Optical transmittance measurements were carried out employing UV-Vis spectroscopy. Thermal performance characterization was conducted employing infrared thermography. Dust deposition tests were performed to assess anti-soiling properties. Contact angle measurements were used to assess surface wettability. It should be highlighted that the fabrication approach has a direct impact on such parameters as the film thickness, homogeneity, adhesion, and performance of nanocomposites. It should be noted that among all the approaches, the spin-coating method results in uniform and thin films, allowing achieving precise control of film thickness, which makes it especially preferable for laboratory-scale applications in photovoltaics. The dip-coating method is considered rather cheap and easy but provides an uneven thickness of the film due to withdrawal speed, while spray coating is fast and scalable but causes relatively high surface roughness. Furthermore, sol-gel synthesis of materials allows obtaining a homogeneous dispersion of nanoparticles in the polymer matrix, which positively impacts adhesion and optical transparency. As a consequence, the choice of the fabrication technique has a strong influence on such parameters as optical transmission, roughness, stability of the coating, and photovoltaic performance. In the current work, the application of sol-gel synthesis and spin coating leads to obtaining uniform dispersion of nanoparticles and controllable film thickness. Fig. 1 exhibits the schematic representation of TiO_2–SiO_2/PMMA nanocomposite coating on solar photovoltaic glass.

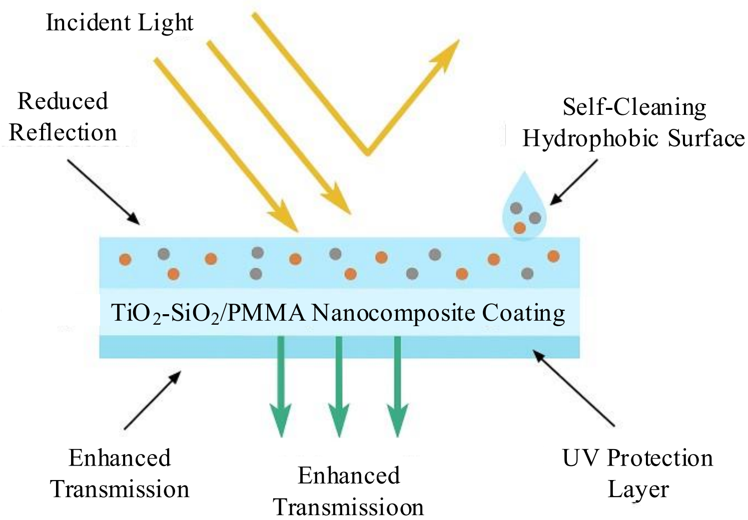

Figure 1. Schematic representation of TiO_2–SiO_2/PMMA nanocomposite coating on solar photovoltaic glass.

The author inspected both coated and uncoated 10 W monocrystalline PV modules under real-world settings by means of an AM 1.5 solar simulator (1000 W/m², 25°C). They used an accuracy source meter and recorded the value of current-voltage (I–V) characteristics. A comparative analysis has been

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conducted across uncoated, single-component, and hybrid-coated panels to assess the impact of the nanocomposite layer in order to enhance the power output and efficiency. Optical transmittance of the coated and uncoated samples was measured using a UV–Vis spectrophotometer in the wavelength range of 300–800 nm. Surface wettability was evaluated using a contact angle goniometer. Photovoltaic performance was measured using a solar simulator operating under standard test conditions (AM 1.5, 1000 W/m², 25°C). The current–voltage characteristics were recorded using a digital source meter.

RESULTS AND DISCUSSION

The study observes that at the optical transmittance spectra of glass substrates that were not coated and those that were in the region of 300 to 800 nm. The PMMA–TiO_2–SiO_2 nanocomposite coating allows 91–93% of light, while the uncoated glass only allows 70% of light. The addition of SiO_2 nanoparticles twisted a graded refractive index layer in between air and glass, due to which the glass became more transparent. The nano-scale dispersal of TiO_2 additionally decreases reflection losses by sprinkling incoming photons more efficiently, which makes a easy way to collect the photon by the solar cell. The surface contact angle goes up to 65° for uncoated glass to 108° for coated glass. These demonstrations show that the performance changed from hydrophilic to hydrophobic. This enhanced hydrophobicity provides better self-cleaning, as rainwater may wash away dirt and dust. After examining the simulation result shows the reduced dust deposition, coated panels improve 97% of their original power output for the coated surface, but the uncoated panels provide 85% of the original power output. This reveals the usefulness of the coating's dust-repelling surface. This coating also lasts up to numerous temperature cycles between 25°C and 80°C without cracking, which shows that it works well in real PV module conditions. **Table 2.** Comparison of photovoltaic performance parameters for uncoated and coated solar panels under standard test conditions (AM 1.5, 1000 W/m², 25°C). Each experiment was repeated three times to ensure repeatability, and the reported values represent the average of the measurements with a standard deviation of ±0.2%. The nanocomposite coatings demonstrated high transparency in the visible region of the solar spectrum. This ensures the maximum possible incident solar radiation is not lost. The incorporation of thermally conductive nanomaterials demonstrated a significant reduction in surface temperature. This factor is critical in the efficiency of the PV device.

Surface analysis of the nanocomposite coatings demonstrated improved hydrophobicity. This resulted in reduced dust accumulation. The cumulative benefits of the nanocomposite coatings resulted in an increase in the efficiency of the PV device. This study has demonstrated the benefits of using polymer-based nanocomposite coatings in the enhancement of the efficiency of solar panels.

Table 2.Performance comparison of uncoated, TiO_2-coated, and TiO_2–SiO_2-coated surfaces.

Parameter	Uncoated Panel	TiO_2 Coated	TiO_2–SiO_2 Coated
Short-circuit current (Isc)	0.58 A	0.60 A	**0.61 A**
Open-circuit voltage (Voc)	21.4 V	21.5 V	**21.6 V**
Maximum power output (Pmax)	9.85 W	10.21 W	**10.43 W**
Efficiency (η)	19.7%	20.4%	**20.9%**

Table 2 provides a detailed comparison for the uncoated, TiO_2 coated and TiO_2–SiO_2–coated for the short circuit current, open circuit voltage, maximum power output, and efficiency. Result show the better result achieved for the TiO_2–SiO_2–coated surface. The TiO_2–SiO_2 coated module demonstrated an efficiency of 20.9%, compared to 19.7% for the uncoated module, indicating an approximate relative improvement of 3–4%.

CONCLUSION

This study investigated the development of a PMMA-based TiO_2–SiO_2 nanocomposite coating for photovoltaic glass surfaces. The results indicate that the hybrid coating improves optical transmission

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and surface hydrophobicity, which contributes to enhanced photovoltaic performance. The coated PV modules showed an improvement of approximately 3–4% in power output compared to uncoated modules. The TiO_2–SiO_2 synergy functioned effectively to achieve the desired refractive index and enhance optical transmission, while also blocking UV light. The contact angle varies from 65° to 108°, which makes the surface hydrophobic and self-cleaning, which helps decrease the dust formation. The coating enhanced PV efficiency by an average of 20.9%, mostly by reducing reflection losses and also it easier for light to be absorbed. The coating's mechanical strength and resistance to UV light ensure that it remains effective for a long time, as well as in adverse weather conditions. It is demonstrated by this study that polymer nanocomposite coatings can be an inexpensive, scalable, and lifelong way for solar PV systems to last longer and yield more energy. Further work is required to evaluate the long-term durability and large-scale applicability of the proposed coating under outdoor environmental conditions. The application of polymer-based nanocomposite coatings has the potential to enhance the efficiency of photovoltaic devices. This is because the application of nanomaterials in polymer matrices has the capability to provide multifunctional coatings. The developed coatings have the capability to reduce temperature, prevent soiling, and retain transparency. These coatings have the potential to be implemented in the future to assess their viability.

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