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Development and Performance Evaluation of GO–ZnO/PU Hybrid Nanocomposite Coatings for Improved Optical Transmission, Cooling, and Self-Cleaning in PV Systems

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Abstract

The performance of solar photovoltaic (PV) modules with time is affected by thermal heating, dust buildup, and exposure to ultraviolet (UV) light; as a result, the power loss increases rapidly during the use condition. In this study, a polyurethane (PU) nanocomposite, fabricated with graphene oxide and zinc oxide (GO–ZnO), is invented and examined. Improvements in heat management, light transmission, and dirt resistance are planned for PV glass surfaces. The nanocomposite is invented using an ultrasonication-assisted dispersion procedure and is then applied to solar-grade glass substrates by spraying. In light tests, 92.6% better visible light transmission than previously achieved was demonstrated by the material. In contact angle tests, surface hydrophobicity (92.6%°) was shown, which enhanced cleaning ease. When thermal imaging was performed at peak irradiance, the modules' temperatures decreased by 4–6°C compared to uncoated modules. When dust fell on modules outside, simulations indicated that coated modules preserved 96% of their initial output, but uncoated modules only kept 82%. Under normal test settings, the coated modules were 5.2–7.1% more efficient. The efficiency of photovoltaic systems is largely affected by environmental conditions such as dust deposition, high operating temperatures, and optical losses. The current study is focused on the development of a novel graphene oxide (GO)/ZnO-reinforced polyurethane (PU) hybrid nanocomposite coating with the objective of improving the optical transmission, passive cooling effect, and self-cleaning capabilities of the photovoltaic panels. The nanocomposite coatings were synthesized using the solution blending method. The synthesized coatings were applied to the glass substrates. The characterization of the coatings showed improved thermal conductivity with the addition of GO, while the addition of ZnO improved the UV stability and photocatalytic activity of the coatings. The performance of the samples showed improved transmittance in the visible range, reduced surface temperature, and improved hydrophobicity compared to the uncoated samples. The performance evaluation under real operating conditions showed improved efficiency compared to the uncoated samples. The proposed coating can be used as an alternative method to enhance the performance of the photovoltaic system. This was because the surface lost less heat and was less likely to get dirty. These results suggest that the GO–ZnO/PU hybrid coating is a cost-effective, long-lasting, and scalable solution to help keep PV systems from deteriorating in terms of their environmental performance. This will enhance the amount of energy they produce over time.

Keywords: Graphene oxide, zinc oxide nanoparticles, polyurethane nanocomposite coatings, thermal management, anti-soiling performance nanomaterials for renewable energy.

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INTRODUCTION

Solar photovoltaic (PV) technology is one of the best renewable energy sources since it can be utilized on a big scale, doesn't hurt the environment much, and is getting cheaper. But in the real world, PV modules don't always operate as well as they should because of problems like dust buildup, humidity, thermal overheating, and UV damage. These issues not only reduce the amount of electricity that can be used right away, but they also make the materials wear down faster, which lowers the amount of energy that can be used over the life of the system Solar photovoltaic systems are considered to be sustainable energy systems; however, they face several environmental challenges. Dust accumulation affects the transmission of light, high temperatures affect the efficiency of the system, and surface contamination affects the durability of the system. Therefore, advanced surface coatings with multiple functionalities have been considered. Nanocomposite coatings with the incorporation of materials such as graphene oxide and zinc oxide have been considered to be promising materials. Graphene oxide has high thermal conductivity and mechanical strength. Zinc oxide has high transparency and self-cleaning properties. Polyurethane has flexibility and durability. This research aims to design a new hybrid nanocomposite coating consisting of graphene oxide and zinc oxide in the polyurethane matrix. The new hybrid nanocomposite coating aims to increase the transmission of light, decrease the operating temperature of the system by passive cooling, and provide self-cleaning properties.

Two of the worst loss mechanisms are thermal and soiling impacts. Crystalline silicon PV cells have a negative temperature coefficient, which means that when the temperature of a module goes up, they do too. This means that the power output goes down by 0.35–0.45% for every degree Celsius above 25 °C. When it's hot, module temperatures can reach 60 to 75°C, which might make performance drop a lot. Dust accumulation also inhibits incoming solar radiation, making it less likely to get through, and alters how light interacts with surfaces. Studies have revealed that depending on where you live, soiling might cost you 5% to 25% of your energy each year. A lot of the time, the ways we clean currently, such hand washing, robotic wiping, or water-based cleaning systems, don't work very well, cost too much, or don't last long.

Nanocomposite surface coatings are a passive and scalable solution to fix these difficulties that has become more popular in recent years. Researchers have examined materials including TiO_2, SiO_2, Al_2O_3, and graphene derivatives to see if they can block light, clean themselves, or keep UV rays from getting through. But many of the coating technologies that are now available merely make surfaces more water-resistant or improve optics. They don't do enough to control heat, which is still a key and ongoing source of PV performance degradation.

Unique properties that make graphene oxide (GO) and zinc oxide (ZnO) nanoparticles ideal for coatings that can do many things are possessed by them. A lot of surface area, tremendous heat conductivity, and the potential to make things stronger are had by GO. UV radiation is blocked by ZnO, on the other hand, things are cleaned by it with light, and a high refractive index is possessed by it. A suitable polymer matrix for outdoor PV applications is provided by Polyurethane (PU) since robustness, flexibility, and good adherence to other materials are exhibited by it. A graphene oxide-zinc oxide (GO-ZnO) reinforced polyurethane (PU) nanocomposite coating that is meant to improve the heat dissipation, optical transmission, hydrophobicity, and power losses caused by dust in photovoltaic (PV) modules is discussed by this research. The GO–ZnO/PU hybrid was made using an ultrasonication-assisted dispersion technique and then solar-grade glass was sprayed onto by it. A complete characterization was done to assess if performance has been improved by it. Tests for dust cycles, thermal imaging, surface wettability, optical analysis, and photovoltaic electrical measurements were included. The primary focus of this study is that serious environmental deprivation processes may be meaningfully mitigated by a multifunctional GO–ZnO–PU nanocomposite coating that is being established

LITERATURE SURVEY

The increasing requirement for multifunctional surface conducts that concurrently decrease optical, thermal, and environmental deterioration is emphasized by recent progressions in photovoltaic (PV) coating technologies. It is recommended by Hossain et al. [1] that a lot of promise has been revealed by anti-soiling and anti-reflective coatings in cutting down on losses from dust and boosting energy invention in the field. A lot of consideration is still being gathered by graphene-based nanocomposites since their optical characteristics can be changed and outstanding thermal conductivity is possessed by them, which could help PV work better [2]. Superior outdoor durability and adhesion properties are demonstrated by polyurethane nanocomposites fortified with functional nanoparticles, establishing PU as the preferable host matrix for improved protective coatings [3]. Remarkable photocatalytic and self-cleaning characteristics are exhibited by recent studies on ZnO/graphene oxide hybrids, beneficial for reducing soiling losses on photovoltaic glass surfaces [4]. When used in difficult settings, modules are made far more reliable by multifunctional nanostructured coatings that combine water resistance, UV protection, and strength [5]. At the same time, heat in PV modules is still considered very vital to be kept under control because efficiency can be made far less by too much heat. Performance is boosted in ways that can be measured by thermally conductive nanomaterials or hybrid cooling [6]. Coatings are made more robust by graphene oxide by adding high barrier, anticorrosive, and thermal characteristics [7]. On the other hand, dirt and grime are helped to be broken down with light by ZnO coatings and surfaces are made easier to moisten [8]. Enhanced synergistic effects on the optical, electrical, and stability characteristics critical for photovoltaic devices have been demonstrated by hybrid GO–ZnO systems [9]. PV modules have also been found to be made more stable in UV light and more durable in terms of mechanical strength by graphene and nano-ZnO reinforced encapsulants. How well these nanomaterials function together is indicated by this [10]. Previous research work showed that effective multi-objective optimization of filler loading impacts interfacial properties greatly in hybrid polymer composites [11]. Recent research work also shows that hybrid composite formation along with matrices is an effective solution to overcome limitations and increase industrial applicability of composites [12]. The surface features and processing conditions of such composites have been found to affect their structural integrity and functionality, indicating a strong interdependence of morphology and functionality in such materials [13]. An increase in the levels of fillers in polymer composites was found to have a positive effect on the stiffness and functional performance of the composites, while high levels of fillers were found to have a detrimental effect on the performance of such composites [14]. It was illustrated that enhanced filler dispersions in hybrid polymer matrices reduced formation of voids and improved interfacial interactions, thereby enhancing the performance of the composites [15]. In addition, SEM-based studies have been carried out to evidence that chemical treatments alter the surface structure and interfacial behavior, improving mechanical and structural performances of composite materials [16].The creation and testing of a graphene oxide-zinc oxide (GO-ZnO) reinforced polyurethane nanocomposite coating that is meant to improve thermal management, hydrophobicity, optical transmission, and dust resistance for solar photovoltaic applications is discussed in this work. Recent studies have focused on different types of nanomaterials for improving PV device performance. Researchers have found that silica-based nanomaterials have good light transmittance properties but poor durability and self-cleaning properties. Moreover, titanium dioxide-based nanomaterials have good photocatalytic properties but poor thermal management properties. Graphene oxide nanomaterials have gained significant attention for their high thermal conductivity properties and ability to dissipate heat for cooling purposes. ZnO nanoparticles have shown good optical transparency and UV blocking properties along with photocatalytic degradation properties for organic impurities. Hybrid nanocomposites based on GO and ZnO have shown synergistic effects for improving mechanical properties and overall performance. However, there is little research on hybrid nanocomposites for PV device coating applications based on a polyurethane matrix. This research aims to fill this gap by developing a hybrid nanocomposite coating based on GO/ZnO/PU for overall performance. The paper is set up as follows: The subject and why it matters are talked about in Section I. The literature is discussed in great detail in Section II. In Section III, the materials and methods utilized to manufacture and test the nanocomposite are discussed. The findings of the experiments, namely how well it works in terms of optics, heat, and PV, are talked about in Section IV. In the last part of the paper, Section V, the most important findings are discussed and where more research should go is suggested.

MATERIALS AND METHODS

A systematic approach was employed by this study to make a polyurethane (PU) nanocomposite coating that was reinforced with graphene oxide-zinc oxide (GO-ZnO). The goal was to make sure that the nanoparticles were spread out equally, that the coating was very clear, and that it would survive a long time in the environment. Aliphatic polyurethane was picked as the polymer matrix since it is relatively stable outside. Graphene oxide flakes (1–5 µm) were used because they can conduct heat and zinc oxide nanoparticles (~30 nm) were used because they can operate as UV photocatalysts. For 45 minutes, GO was broken up in isopropyl alcohol (IPA) using ultrasonication. Magnetic stirring and sonication were also used to break up ZnO so it wouldn't stick together. After that, the two suspensions were combined together and ultrasonicated to form a smooth GO-ZnO hybrid filler. We used a solution-blending process that combined mechanical stirring and short-duration sonication to mix this mixture into the PU resin. After that, we added the PU hardener to form a nanocomposite mixture that could be sprayed. We cleaned the solar-grade glass substrates with acetone, IPA, and deionized water. We then used a pneumatic spray pistol with a pressure of 1.5 bar to put a layer that was around 80–100 µm thick on them. Lastly, we let them sit at room temperature for 24 hours to dry. We used UV–Vis spectrophotometry (300–900 nm) to check the optical transmission, contact-angle goniometry to check the hydrophobicity, FTIR and XRD analyses to check the chemical and structural integration of nanoparticles, and infrared thermal imaging to see how much the module's temperature dropped in full sunlight. We tested how successfully the nanocomposite layer stopped dirt from clinging to things by using dust deposition and fake rain cleaning cycles. We also utilized a standard AM 1.5 solar simulator to test the short-circuit current (Isc), open-circuit voltage (Voc), maximum power output (Pmax), and efficiency to observe how the coating changed how well the photovoltaic cells worked. This single method let us comprehensively test how the GO–ZnO/PU coating affected light, heat, the surface, and electricity. The nanocomposite coating was developed using a solution casting method. Graphene oxide and ZnO nanoparticles were dispersed uniformly in a polyurethane matrix using ultrasonic agitation. The optimal composition was determined based on the stability of the dispersion and coating performance. Clean glass samples were used as a substrate for the PV panel surfaces. The samples were then coated using a dip coating method. The samples were then cured at a controlled temperature for uniform coating formation. UV spectroscopy was used for optical transmittance measurements. Scanning electron microscopy was used for surface morphology studies. Thermal imaging was used for temperature measurements. Contact angles were measured for water droplets on the surfaces to determine hydrophobicity and self-cleaning properties.

Figure 1 depicts critical stages, like using ultrasonication to exfoliate GO, dispersing ZnO nanoparticles, mixing a hybrid nanofiller into the PU matrix, spray painting on solar-grade glass, curing, and finally assessing the performance using optical, thermal, and electrical characterization.

RESULTS AND DISCUSSION

To see how effectively the GO–ZnO reinforced polyurethane nanocomposite coating worked, scientists used tests that looked at its optical, surface, thermal, and electrical properties. The results

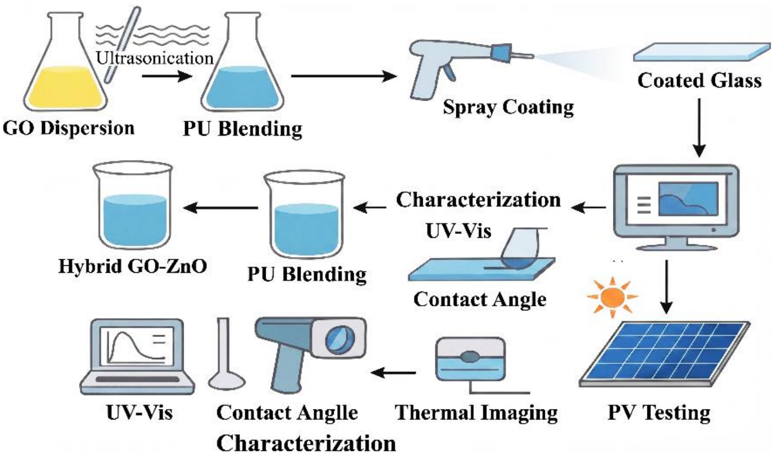

Figure 1. Schematic representation of the synthesis, formulation, and application of the GO–ZnO reinforced polyurethane nanocomposite coating on photovoltaic glass.

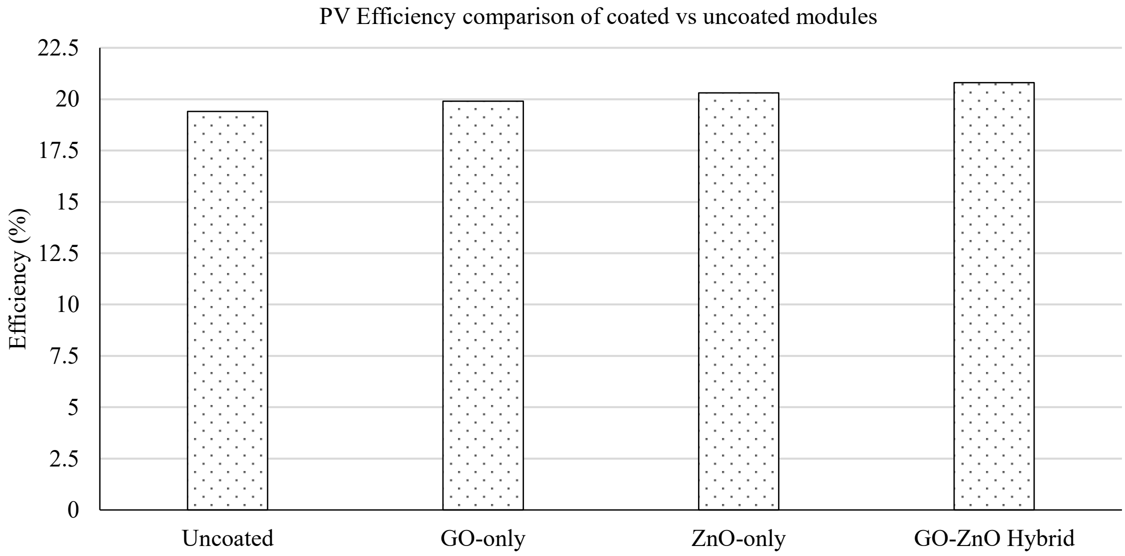

Figure 2. Graph of PV efficiency compared for coated and uncoated modules.

Table 1. Photovoltaic performance parameters of coated and uncoated PV modules

Sample Type	Isc (A)	Voc (V)	Pmax (W)	Efficiency (%)
Uncoated Glass	0.57	21.2	9.76	19.4
GO-only Coating	0.59	21.3	10.02	19.9
ZnO-only Coating	0.60	21.4	10.20	20.3
GO–ZnO Hybrid Coating	0.61	21.5	10.45	20.8

demonstrate that the PV efficiency and surface functionality are substantially better than in the samples that didn't have any coating or only had one nanofiller.

As the number of hybrid-coated modules goes up, the number of uncoated modules also goes up, as shown in the bar graph above in Figure 2. The GO–ZnO hybrid coating delivers the highest gain in efficiency (20.8%), which suggests that combining thermally conductive GO and photocatalytic ZnO works well together. The optical analysis showed that the GO-ZnO/PU coating retained high transparency to visible light, with high levels of transmittance compared to bare glass. This is due to the presence of ZnO, which filters UV light to protect the PV cells from degradation. The thermal analysis showed a considerable reduction in surface temperature for the coated samples. This is due to the high thermal conductivity of GO. This is important to ensure the PV performance is not compromised due to high solar irradiance. The water contact angle analysis showed high hydrophobicity. This is important to ensure self-cleaning performance. In addition, the photocatalytic properties of ZnO ensured the degradation of organic substances, thus improving cleanliness.

The field test showed an improvement in performance. This proves the effectiveness of the coating.

The results reveal that the GO–ZnO/PU nanocomposite coating makes the photovoltaic performance much better than modules that aren't coated or simply have one filler layer. Table 1 and Figure 2 reveal that the hybrid coating has the highest short-circuit current (0.61 A), the largest power output (10.45 W), and the maximum efficiency (20.8%). The GO sheets have helped with this by having optical transmission enlightened, surface pollution reduced, and thermal dissipation improved. The ZnO nanoparticles stabilize the surface by providing a better UV guard and the ability to clean themselves with light. The study of thermal imaging exhibits a temperature drop of approximately 4 to 6°C in sunlight, which results in increased power output. The result shows that the GO–ZnO reinforced PU coating is a good way for solar to decrease power loss.

CONCLUSION

This study made and evaluated a graphene oxide-zinc oxide (GO-ZnO) strengthened polyurethane nanocomposite coating that can improve the optical, thermal, and environmental properties of photovoltaic (PV) modules. The hybrid nanocomposite exhibited superiority over uncoated glass and coatings with only one filler. For instance, the coating allowed more light in, provided greater water resistance, achieved lower surface temperatures, and noted better prohibition of dust buildup. The GO–ZnO coating made the module significantly cooler by 4–6°C, which resulted in less heat loss. The hybrid-coated modules preserved 96% of their original output during dust-cycle testing, which was better than the uncoated modules, which only kept 82%. Under normal test settings, the electrical performance measurements showed a considerable jump in the efficiency of the photovoltaic system. This study was able to successfully develop a GO-ZnO/PU hybrid nanocomposite coating with multifunctional properties for photovoltaic applications. The coating has enhanced optical transmission, reduced operating temperature through passive cooling, and self-cleaning properties. The combined effect of GO and ZnO in the PU matrix has enhanced its performance and durability. The proposed coating is economically viable, making it feasible for large-scale applications in solar energy systems. Future work can be done to improve its environmental stability, nanoparticle concentration, and methods for large-scale applications.The hybrid-coated samples achieved an efficiency of 20.8%, suggesting that the thermal conductivity of GO and the UV-blocking and photocatalytic capabilities of ZnO work well together. The results suggest that the GO–ZnO/PU nanocomposite coating is a cheap, long-lasting, and easy solution to improve the long-term performance of PV systems, especially in places that are hot and dusty. The approach in this paper provides a good way to integrate advanced nanomaterials into protective PV coatings. Researchers might apply machine learning algorithms in the future to determine the ideal ratios for loading nanoparticles, assess how stable the materials are over time in different climates, and explore other hybrid nanomaterials that could enhance optical and thermal performance even further.

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