

Investigation of the Effects of SiO₂ and TiO₂ Nanocoatings on Photovoltaic Module Performance under Iraqi Meteorological Conditions

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ABSTRACT

Solar photovoltaic (PV) systems are fundamental to the renewable energy transition, yet high ambient temperatures and dust accumulation severely impair their performance in harsh climates. While nanocoatings offer a promising mitigation strategy, comparative outdoor experimental studies under Iraqi environmental conditions remain limited. This study experimentally investigates the effects of silicon dioxide (SiO₂) and titanium dioxide (TiO₂) nanocoatings on the energy and exergy performance of photovoltaic modules under the prevailing meteorological conditions of Baghdad, Iraq. Three identical PV modules were monitored under the same conditions: two were coated, and one was left uncoated as a reference. During the testing period, the key electrical outputs, solar irradiance and temperature of the module were monitored and evaluated. The SiO₂-coated panel showed an increase in electrical efficiency of 11.41% and a 7.2% increase was observed for the TiO₂-coated panel after an exposure period of seventeen days in an outdoor environment compared to the reference PV panel. This work provides practical, realistic insights on the applicability of nanocoating technologies for large-scale PV installations in harsh climates and paves the way for the development of cheap, climate-appropriate solutions for solar energy systems in Iraq and similar environments.

Keywords: Dust accumulation, Energy efficiency, Exergy analysis, Nanocoatings, Photovoltaic modules

1. INTRODUCTION

Due to the increasing demand for electricity and the environmental problems associated with fossil fuels in the current climate, the transition to renewable energy sources is inevitable. Solar energy is one of the most important renewable energy sources among various types of available renewable energy sources. Photovoltaic cells can convert the sunlight into electricity (Luque and Hegedus, 2011; Bagher et al., 2015; Abushgair and Al-Waked, 2021). However, in field operation, solar PV modules are subjected to various

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environmental conditions like dust, high temperature, humidity, wind, rain, etc. Among these, dust and high temperature are the most important factors affecting the power and efficiency of the system. Dust reduces the amount of light available for the solar PV module to utilize and higher module temperature causes voltage decrease thereby decreasing the electrical efficiency of the system (**Khazaal et al., 2020; Hameed et al., 2024; Fatima et al., 2024**). Several studies are dedicated to the performance analysis of photovoltaic solar power systems considering the climatic conditions affecting their performance for maximizing the generation of energy while minimizing the cost implications involved. (**Elshazly et al., 2021**) confirmed that high temperatures can reduce the efficiency of solar PV panels by up to 10%, and they can lose half of their total efficiency after only a month without cleaning. Using energy and exergy analyses, (**Kareem et al., 2019**) assessed the year-round performance of a solar PV module energy system in Baghdad in a different study. The study indicated that the energy efficiency ranged from 15.71% to 15.74%, while the exergy efficiency ranged from 10.8% to 15.8%. Various techniques have been studied to improve the performance of solar photovoltaic modules, including active and passive cooling systems (**Jobair, 2017; Sharaf et al., 2022; Hussien et al., 2023**) as well as mechanical and surface-based cleaning systems (**Babu et al., 2021; Dahlioui, 2022; Dahlioui et al., 2023; Manzo et al., 2025**). While these approaches have demonstrated measurable improvements in the performance of solar PV panels, they often involve additional system complexity, increased cost, or maintenance requirements. This has led to a search for other methods that are simpler and perhaps more viable options. In this context, nanoparticle coating is one such process that has gained much importance because of its capacity to make the surface hydrophilic/hydrophobic by changing the wettability of the surface and thereby reducing dust adhesion and improving self-cleaning performance. Some studies have used various nano-coatings such as palladium, zinc oxide (ZnO) and Zirconia nanoparticles that alter the surface properties of solar panels and enhance the performance of solar panels (**Kashyout et al., 2021; Dogra et al., 2023; Elnozahy et al., 2024; Ghaffar et al., 2024**). Some previous studies have explored SiO₂- and TiO₂-based nanocoatings under controlled laboratory conditions by assessing their optical, surface and performance properties through experimental testing and demonstrated the ability of nanocoatings in improving the optical and surface properties of photovoltaic surfaces (**Zambrano et al., 2021; Lukong et al., 2022; Zhang et al., 2024; Eltohamy et al., 2025**). The field-based studies have indicated improvements in photovoltaic performance. The improvements depend on the coating material, environmental conditions, coating composition, and experimental setup (**Alamri et al., 2020; Chala et al., 2024; Duke et al., 2025**).

Furthermore, (**Samadhiya et al., 2025**) developed a superhydrophobic nanocoating of modified silicon dioxide, hexamethyldisilazane (HMDS) with a water contact angle of 156°. This coating showed a remarkable transmittance of 96.1%, which is an increase of 3.1% compared to the uncoated glass, resulting in an average power improvement of 5.8% of the coated cell compared to a manually cleaned, uncoated solar cell. In addition, (**Dabral et al., 2024**) conducted a direct comparison between a superhydrophobic SiO₂ coating and a superhydrophilic TiO₂ coating under outdoor climatic conditions in India over a 30-day experimental period. The exposure to SiO₂-coated module shows a performance improvement of 19.73% compared to the uncoated module and the TiO₂-coated module shows a performance improvement of 7.66%. SiO₂- and TiO₂-nanoparticle coatings are attractive for nano-coating applications because they are relatively low-cost and environmentally friendly (**Ai et al., 2023; Jadhav et al., 2025**).



Despite the increasing application of nanocoatings in photovoltaic systems, many previous studies have focused mainly on optical or electrical performance under controlled or short-term laboratory conditions, with relatively limited experimental evaluation under actual outdoor operating conditions. In particular, still a lack of studies that have provided a direct comparison of different nanocoating materials applied simultaneously to identical PV modules under the same outdoor climatic conditions, while considering their electrical, thermal, energy, and exergy performance.

The present study addresses this research gap through a concurrent three-panel outdoor experimental methodology, in which identical PV modules coated with titanium dioxide (TiO_2) and silicon dioxide (SiO_2) were tested simultaneously with an uncoated reference module under the same environmental and operating conditions in Baghdad, Iraq. This configuration enables a direct and consistent comparison of the coating materials while minimizing the influence of variations in solar irradiance, ambient temperature, and weather conditions between separate experiments. In addition, the study extends beyond conventional electrical and optical assessments by incorporating second-law exergy analysis and exergy decomposition to evaluate the quality of energy conversion. The combined assessment of surface properties, electrical and thermal behavior, energy efficiency, and exergy performance provides a more comprehensive evaluation of the effectiveness of SiO_2 and TiO_2 nanocoatings under real outdoor operating conditions with elevated temperature and dust deposition in Baghdad.

Accordingly, the objective of the present study is to experimentally investigate and compare the performance of an uncoated PV module and two nanocoated modules using TiO_2 and SiO_2 under real-world outdoor conditions in Baghdad, Iraq. The investigation considers the effects of solar irradiance, elevated temperature, and dust exposure on the module performance, with particular emphasis on power output, electrical efficiency, and exergy performance.

2. EXPERIMENTAL SETUP

2.1 Experimental Setup and System Configuration

The experiment was performed in an actual environment in Baghdad, Iraq (33.3N 44.4E), which is well-known for its very high summertime temperatures and solar irradiation, as well as dust storms. In this experiment, three identical monocrystalline PV panels supplied by Ollin Solar were used: the first panel was left uncoated as a reference, the second panel was coated with TiO_2 nanoparticles, and the third panel was coated with SiO_2 nanoparticles, both relatively low-cost and manufactured by SkySpring Nanomaterials, Inc., Houston, TX, USA. The panel and nanoparticle specifications are shown in **Tables 1 and 2**.

Table 1. Specification of the PV panel.

Parameter	Value
Open circuit voltage (V_{oc})	21.6 V
Short circuit current (I_{sc})	2.92 A
Maximum voltage (V_{mp})	18 V
Maximum current (I_{mp})	2.78 A
Maximum power (P_m)	50 W
Module efficiency	21.01%
Dimensions	cm 63×45×2.5

**Table 2.** General properties of the nanoparticles.

Properties	TiO ₂	SiO ₂
Chemical composition	Rutile (30-40) wt%; Anatase (60-70) wt%	(SiO ₂ -x, x = ~0.5, 99.5%), non-porous
Appearance	White nano-powder	White nano-powder
Average Particle Size (APS)	10-30 nm	20 nm
Specific Surface Area (SSA)	50-100 m ² /g	160 m ² /g

The panels were oriented southward with an inclination of 24°, optimum for capturing solar irradiance in Baghdad in April (**Muslim, 2017; Ali, 2018; Kadhim et al., 2023; Abdulridha et al., 2025**). In order to achieve self-cleaning, the second and third PV panels were coated with hydrophobic nanocoatings through a spray nozzle with a constant pressure of 0.2 MPa. In relation to the fabrication of the nanocoating solution, one gram of the nanoparticle powder (SiO₂/TiO₂) was dispersed using ultrasonication at 240 W for 50 minutes in 24 g of xylene solvent to ensure complete dispersion and break up agglomerates. Therefore, 40 grams of Methyl Phenyl Silicone Resin (MPSR) were added, and the mixture was stirred for one hour. Then, all solutions were mixed with 0.03 % (wt) of curing agent (Benzoyl Peroxide) and stirred for one hour at 1500 rpm at 60 °C to prepare the nanocoating. The thickness of the nanocoating was controlled and measured to be approximately 20 µm. The optical characteristics of the nanocoating were analyzed using a UV-visible spectrophotometer for the glass, measuring the light transmittance through the thin film over the wavelength range of 350–750 nm, for the calculation of T_{max}%. Wettability characteristics were calculated through measurement of water contact angle (WCA) using a Vano-For contact angle device.

2.2 Experimental Procedure

The experiment was carried out in April 2026 under outdoor conditions over a 17-day exposure period to examine the performance of the PV modules before and after dust accumulation. The measurements were taken on two days, April 1 and April 17, which represent the initial and final exposure conditions respectively. The electrical characteristics of the PV module including the open-circuit voltage, short-circuit current, maximum voltage, maximum current and maximum power generation were measured using the PV Analyzer (PROVA 210). The thermal measurement was done by placing thermocouples on the back side of each panel with another set used for the measurement of the ambient temperature. These sensors were integrated with a data logger for continuous temperature recording. At the same time, the solar radiation was measured by a solar power meter.

Simultaneous recordings of electrical parameters, surface temperatures and solar irradiance were taken for all modules from 9:00 AM to 3:00 PM at 30-minute intervals. This simultaneous data collection allows for an accurate comparative assessment of the performance of the three PV panels. All the measuring devices were calibrated before performing the experiment to ensure the accuracy and reliability of the measured data. The following table shows the instrumental operational ranges and their corresponding measurement recording uncertainty obtained through calibration.

Table 4 compares the measured parameters with the Standard Test Conditions (STC) specifications by the manufacturer. Though there is a difference in terms of (P_{max}) and (I_{sc}), which are about 19.6% and 13.2%, respectively, these variances are attributed to the non-ideal outdoor spectral distribution and the inherent loss factors associated with real-world



operating conditions compared to controlled laboratory environments. However, the close correspondence in terms of (V_{oc}), with a 2.73% error, testifies to the basic electrical soundness of the PV module as well as the measurement equipment used for the same.

Table 3. Calibration specifications of the measuring instruments.

Instrument	Range	Uncertainty ($\pm$)
Data Logger +Thermocouple	20–80 °C	± 0.08 °C
PV Analyzer (PROVA 210)	10–20 V	$\pm 0.002 - 0.006$ V
Solar Power Meter (TES-1333R)	0–2000 W/m ²	± 10 W/m ²

Table 4. Validation of the solar PV module Electrical Parameters.

Parameters	STC	$G_t = 996 \text{ W/m}^2, T_{amb}=19^\circ\text{C}, T_{cell}=25^\circ\text{C}$	Error %
V_{oc}	21.6 V	22.19V	2.73
I_{sc}	2.92 A	2.533A	13.2
V_{max}	18 V	16.37V	9
I_{max}	2.78 A	2.455A	11.7
P_{max}	50 W	40.18W	19.6

3. ENERGY AND EXERGY ANALYSIS

Electrical efficiency is commonly referred to as the performance of solar PV modules in converting sunlight into electricity. It can be expressed as the maximum power output of the PV module per incident solar radiation reaching the surface **(Kareem et al., 2019)**.

$$\eta = \frac{P_{max}}{G_t \times A_{pv}} \quad (1)$$

Where G_t and A_{pv} are solar radiation and the PV panel area, respectively. The maximum output power can be calculated as:

$$P_{max} = V_{max} \times I_{max} \quad (2)$$

The exergy represents the maximum useful work that can be extracted from the PV system as it comes to equilibrium with a reference condition. Exergy analysis is one of the main applications of the second law of thermodynamics and is an important tool for system design and development. The exergy balance of the solar PV panel can be derived from **(Alomar et al., 2023)**:

$$Ex_{in} = Ex_{out} + Ex_{loss} + Ir \quad (3)$$

Where Ex_{in} and Ex_{out} denote the input and output exergy (W), respectively, while Ex_{loss} represents exergy destruction, and Ir signifies the module irreversibility. The solar exergy input (Ex_{in}) is estimated using Patela's model, formulated as follows **(Khudhur and Jobair, 2026)**:

$$Ex_{in} = A_{pv} \times G_t \times \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun}} \right) + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}} \right)^4 \right] \quad (4)$$

Where T_{amb} and T_{sun} are the ambient and sun temperatures which is assumed to be 5777 K **(Kumar et al., 2020)**. The output exergy represents the electrical exergy generated by the



PV panel, excluding the thermal losses dissipated to the surroundings:

$$Ex_{out} = Ex_{el} - Ex_{th} \quad (5)$$

Where Ex_{el} , and Ex_{th} are the electrical exergy, and dissipated thermal exergy, respectively. The electrical exergy can be calculated from:

$$Ex_{el} = V_{max} \times I_{max} \quad (6)$$

Thermal exergy denotes the fraction of energy dissipated from the PV panel to the ambient environment, representing a loss in the overall work potential of the system (**Kumar et al., 2020**):

$$Ex_{th} = (h_{con} + h_{rad}) \times A_{pv} \times (T_{amb} - T_{pv}) \times \left(1 - \frac{T_{amb}}{T_{pv}}\right) \quad (7)$$

Where T_{pv} is the PV panel temperature. h_{con} and h_{rad} are convective and radiative heat transfer coefficient between the PV panel and the surrounding environment, respectively, which are given by:

$$h_{con} = 2.8 \times 3V_w \quad (8)$$

$$h_{rad} = \varepsilon \sigma (T_{sky} + T_{pv}) (T_{sky}^2 + T_{pv}^2) \quad (9)$$

$$T_{sky} = T_{amb} - 6 \quad (10)$$

Where V_w are the local wind speed parallel to the PV panel surface, ε represents the emissivity of PV panel, σ are the Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$), and T_{sky} indicates the effective temperature of the sky. Finally, the exergy efficiency is defined as the output exergy to input exergy ratio (**Prakash et al., 2023**):

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \quad (11)$$

4. RESULTS AND DISCUSSION

This section presents the characterization results of the prepared SiO_2 and TiO_2 nanocoatings, followed by the performance results of the reference and nanocoated photovoltaic modules under real-world conditions. The characterization focuses on the surface wettability and optical transmittance of the nanocoatings, while the performance analysis compares the electrical, thermal, energy, and exergy performance of the coated and uncoated PV modules over the seventeen-day experimental period.

4.1 Surface and Optical Properties of Nanocoatings

The measurement of the water contact angle confirmed the alteration of the surface properties of the glass after its coating with a nanocoating, as illustrated in **Fig. 1**. The contact angle increased from 29.79° for an uncoated surface to 139.01° for a surface coated with TiO_2 and 152.07° for a surface coated with SiO_2 . This rise in the contact angle can be explained by the reduction in the surface energy due to the use of the MPSR matrix and the nanoparticles. The incorporation of the silicone resin improves significantly the hydrophobic properties, which has been evidenced by a previous study where a superhydrophobic coating with a contact angle around 165° was obtained from SiO_2 and MPSR nanoparticles. (**Song et al., 2023**) Other studies dealing with Polydimethylsiloxane

(PDMS), another silicone-based material, which was combined with SiO₂ nanoparticles, have already achieved superhydrophobic surfaces with a contact angle higher than 150° (Gong and He, 2020; Ayyanar and Sabariraj, 2026). Therefore, the high contact angles contribute to reducing water and dust adhesion and support the self-cleaning potential of the coated surfaces.

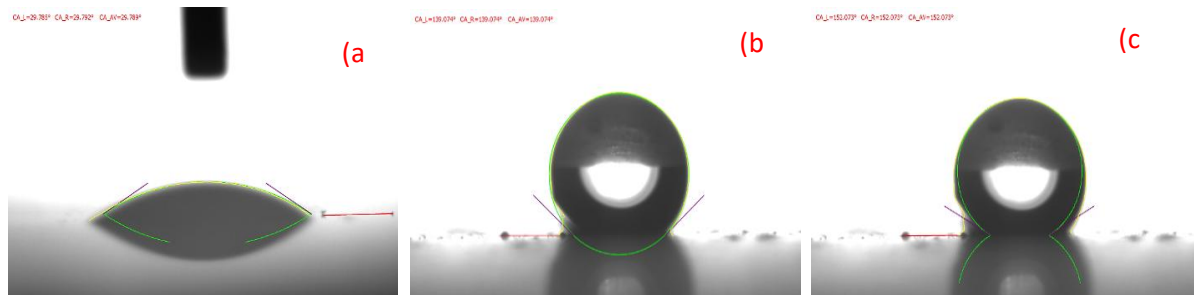


Figure 1. Water contact angle analysis of (a) reference, (b) TiO₂ coating, and (c) SiO₂

From the transmittance analysis, it was found that the uncoated glass had the lowest transmittance value, which was around 91.51%. Conversely, the glass coated with TiO₂ had a higher maximum transmittance of 92.60%, while that of the glass coated with SiO₂ had a maximum transmittance of 93.48%, as shown in **Fig. 2**. From the transmittance graph, it can be seen that the nanocoatings have high values of optical transmittance at the wavelengths tested in the present experiment. Of the two nanocoatings, the SiO₂ nanocoating possessed the highest transmittance value. This relatively high optical transmittance is desirable because it allows a greater fraction of incident solar radiation to pass through the coating and reach the photovoltaic cell, thereby minimizing optical losses.

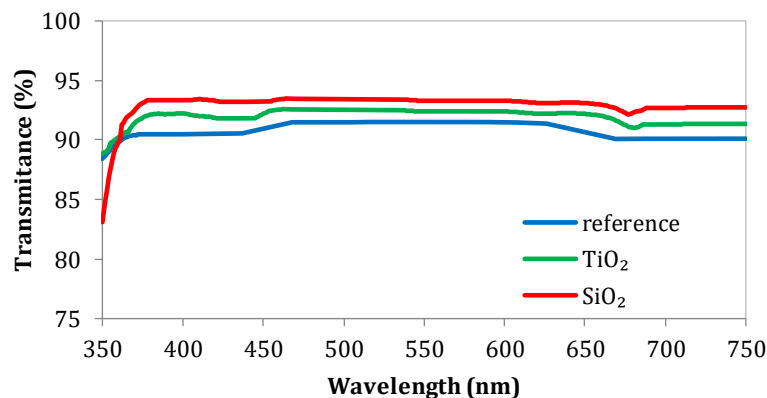


Figure 2. Transmittance investigation for the three nanocoatings of -SiO₂, TiO₂, and the reference

4.2 Environmental and Operating Conditions

During the experimental work, climate conditions such as solar radiation and ambient temperatures were measured on April 1 and April 17, between 9:00 AM and 3:00 PM. These changes are illustrated in **Fig. 3** for both solar radiation and ambient temperatures within that time frame. Solar radiation readings for both days showed a clear indication of convergence with a high of 1009 W/m² on April 1 and 997 W/m² on April 17. However, contrary to this convergence in solar radiation, ambient temperatures recorded on April 17

were higher than those on April 1. This could be seen in the range of ambient temperatures, about 16.2° to 27.6°C on April 1 and 28.1° to 31.8°C on April 17. Wind speeds ranging from around 2.22 to 2.78 m/s during the testing period were also observed, which could affect dust deposition on PV module surfaces and convective heat transfer.

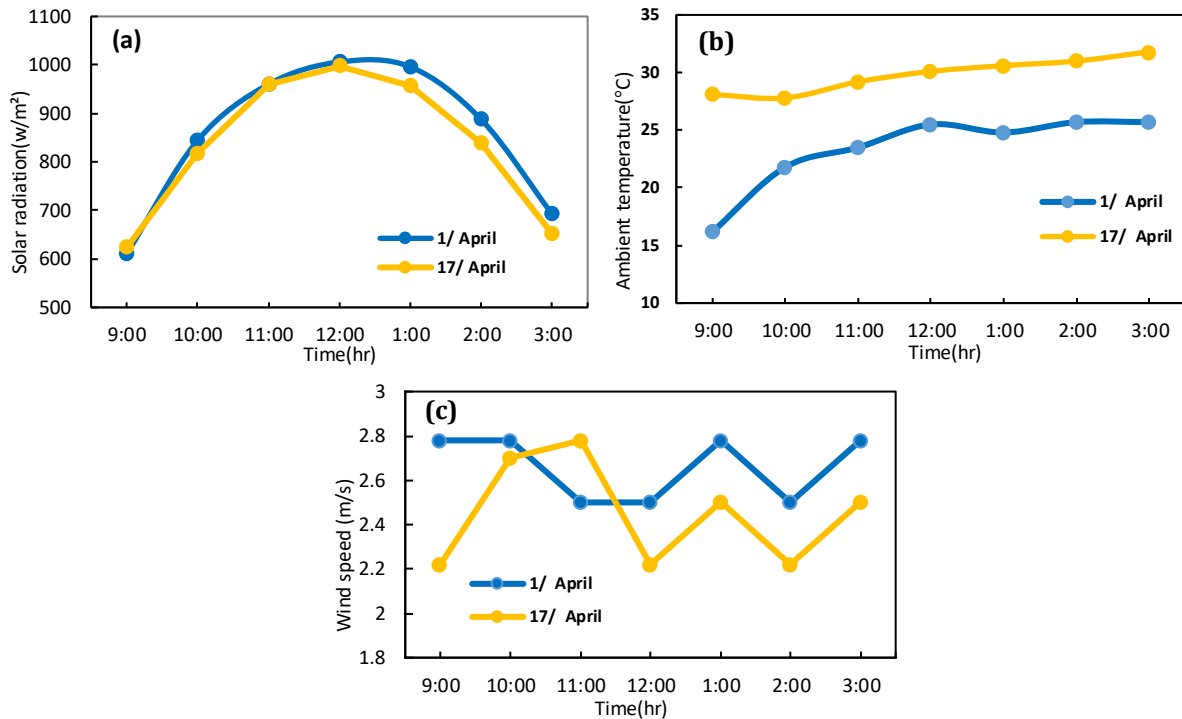


Figure 3. Variation of (a) solar radiation, (b) ambient temperature, and (c) wind speed over time on April 1 and April 17

4.3 Maximum Power Output Analysis

In the course of measurement, **Figs. 4 and 5** show the time-based variations of power produced by the three photovoltaic modules: the reference module, the TiO_2 -coated module, and the SiO_2 -coated module. The power follows a similar everyday pattern, gradually increasing from the morning hours to a peak around lunchtime before falling in the afternoon. This behavior can be explained by changes in solar irradiance, wherein the increase in current is associated with the number of photons hitting the surface of the solar module, hence generating more electrons. The SiO_2 -coated panel produced the highest power of 41.15 W under the peak solar irradiance of 1006 W/m^2 on April 1, which was higher than the other panels due to the higher transmittance of the nano-coating and lower reflectivity, leading to the improvement of the generated current. The maximum power output by the TiO_2 -coated panel was comparable with that of the reference panel at 38.99 W, whereas the power output from the reference panel was 38.91 W under the same amount of solar irradiance, indicating that its optical effect was less pronounced in this case.

On April 17, the maximum power values decreased despite similar levels of solar radiation. This is due to the increase in the temperature of the surroundings which reduces the voltage and hence there is a reduction in the overall power. The panel coated with silicon dioxide (SiO_2) produced the highest power output of about 38.77 W which was better than the other panels. In contrast, the TiO_2 -coated panel reached a maximum power of approximately 36.96



W, while the reference panel recorded approximately 34.95 W, at a maximum solar irradiance of 997 W/m^2 .

In general, the outcomes show that output power is the result of a relationship between two factors: increased current with increased solar irradiance and decreased voltage with increased temperature, whereas the optical properties of the coatings play an important role in improving absorption and reducing losses, resulting in improved overall output power of photovoltaic panels.

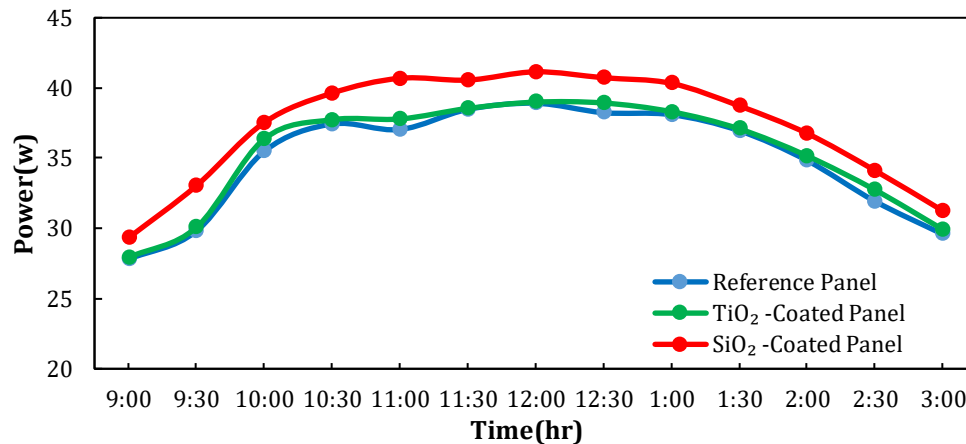


Figure 4. Diurnal variation of output power for coated and uncoated PV modules on April 1

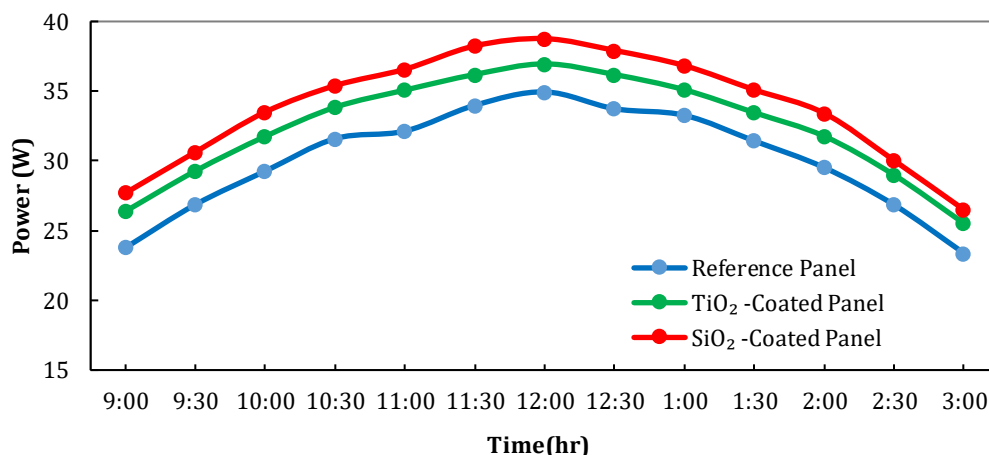


Figure 5. Diurnal variation of output power for coated and uncoated PV modules on April 17

4.4 Energy Efficiency Analysis

The efficiency of the solar PV panel does not remain constant over time. Still, it decreases due to rising operating temperatures, as shown in **Figs. 6 and 7**, where the electrical efficiency on the two measurement days (April 1 and April 17) exhibits similar behavior. It starts with high values in the morning, then decreases as the panel temperature rises, before rising again in the afternoon. This behavior is attributed to the combined effect of solar irradiance and temperature. Higher irradiance causes higher electrical current, but the majority of the energy absorbed gets converted to heat, causing an increase in the temperature of the PV module. This causes a voltage drop, which adversely affects efficiency. On April 1st, the efficiency of the SiO₂-coated panel was highest at an average value of 15.18% compared to the reference panel, whose average value was 14.26%, making it more

efficient than the latter by 6%. The TiO_2 -coated panel exhibited an average efficiency of 14.42% as illustrated in **Tables 5 and 6** below.

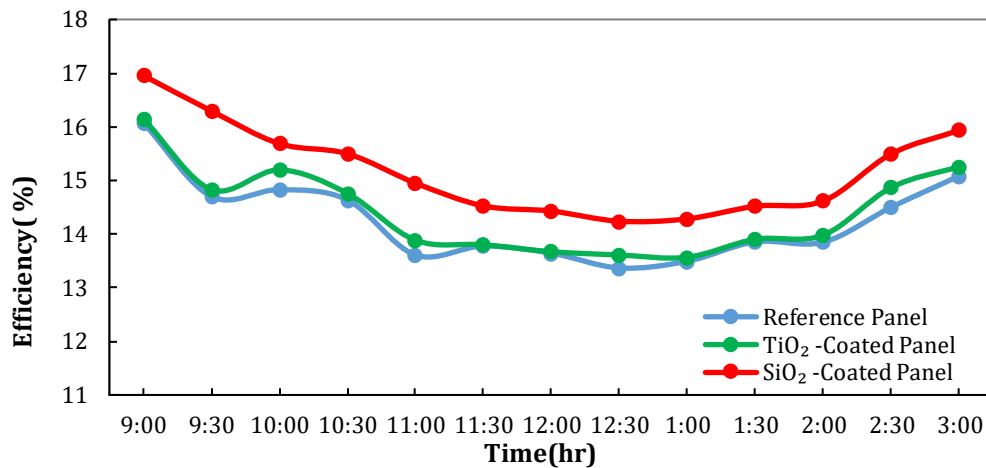


Figure 6. Diurnal variation of efficiency for coated and uncoated PV modules on April 1

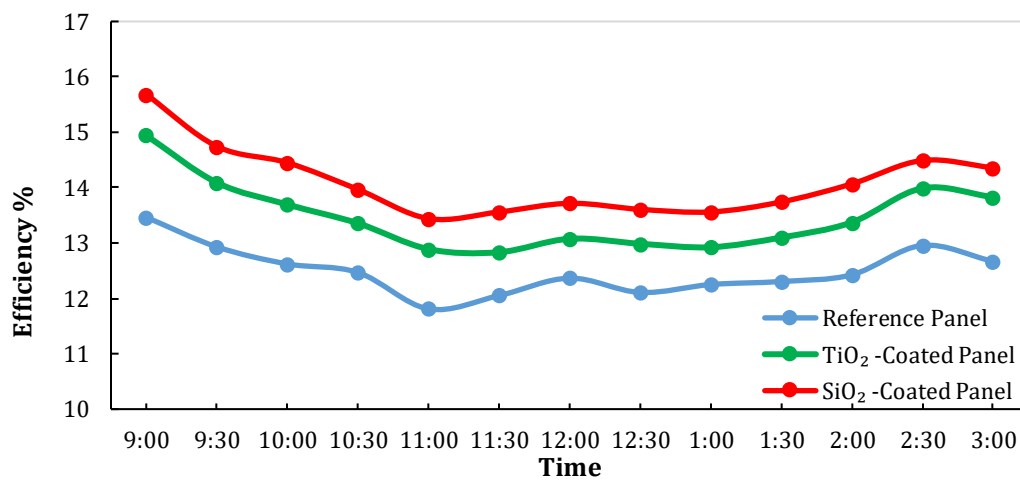


Figure 7. Diurnal variation of efficiency for coated and uncoated PV modules on April 17.

Table 5. The Average electrical efficiency

Type of PV panel	Efficiency (%)	
	April 1	17 April
Reference	14.26	12.49
TiO_2 coated	14.42	13.46
SiO_2 coated	15.18	14.10

Table 6. Improvement electrical efficiency compared to reference panel.

Type of PV panel	1 April	17 April
TiO_2 coated	1.1%	7.2%
SiO_2 coated	6%	11.41%

Efficiency values on April 17 were relatively lower compared to those in April. This is because of the high ambient temperature, which caused a rise in operating temperature. Nevertheless, the drop in efficiency was less noticeable in coated panels due to the influence of nanocoatings in minimizing the impact of environmental and thermal factors. Under such



circumstances, the SiO_2 -coated panel had the highest efficiency value of about 14.10%, which was 11.41% better than the efficiency of the reference panel. Although the TiO_2 -coated panel had an efficiency value of 13.46%, it was 7.2% better than the efficiency of the reference panel with 12.49%. These results are in good agreement with (Dabral et al., 2024), who reported efficiency improvements of 8.20% and 4.92% for SiO_2 and TiO_2 , respectively, on the first day, increasing to 14.90% and 9.11%, respectively, after 20 days of outdoor exposure.

4.5 Exergy Efficiency Analysis

Exergy-based evaluation is more inclusive when analyzing the performance of solar modules than the energy efficiency approach since it takes into consideration not only the amount of energy generated but also the quality of the energy and how convertible the energy is into useful work, incorporating the effects of non-reflection and heat losses within the system. Therefore, exergy analysis is a more accurate tool for characterizing actual performance, particularly under less-than-ideal operating conditions. **Figs. 8 and 9** illustrate the time-dependent changes in the exergy efficiency of the three solar PV panels on April 1 and April 17. The results show the same trend as the electrical efficiency, but the values are much lower. This is because part of the absorbed solar energy is converted into unusable heat. On April 1, the silicon dioxide (SiO_2)-coated panel presented the highest average exergy efficiency (14.32%), followed by the titanium dioxide (TiO_2)-coated panel (13.76%), while the reference panel had the lowest value (13.69%).

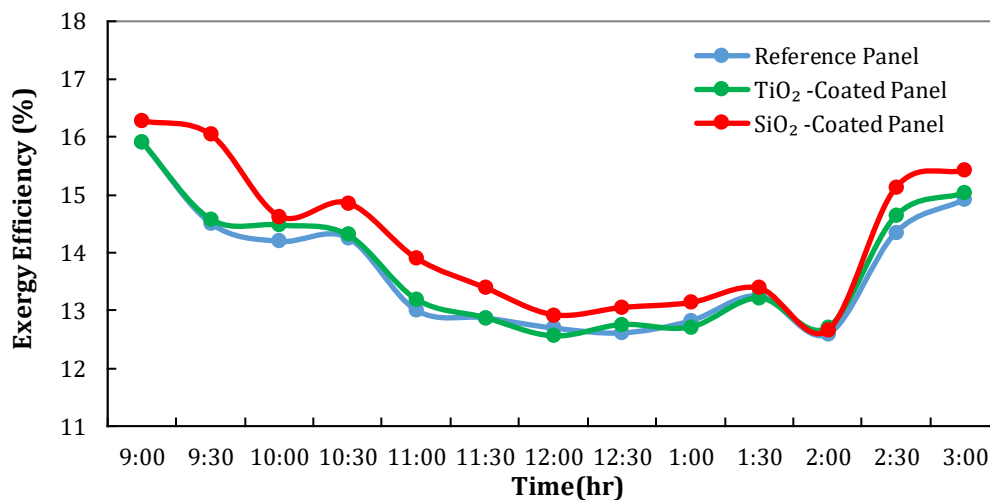


Figure 8. Diurnal variation of exergy efficiency for coated and uncoated PV modules on April 1

The average exergy efficiency of all panels was lower on April 17 than on April 1, which is attributed to a considerable rise in ambient temperature. Increase in temperature leads to an increase in heat losses in the PV module, which causes higher exergy losses and a reduction in the usable power derived from solar radiation. Nevertheless, the coated panels continued to show superior performance, with the silicon dioxide SiO_2 coated panel showing the highest average exergy efficiency followed by the TiO_2 coated panel. The reference panel remained the lowest performing, as shown in **Tables 7 and 8**.

Unlike simple energy efficiency comparisons, the second-law exergy decomposition applied here, separating convective and radiative thermal exergy losses from the useful electrical exergy output as in Eq. (5), reveals that the SiO_2 -coated module not only generates more

power but also converts a higher fraction of the available solar exergy into useful work, even as ambient and module temperatures rise under Baghdad's hot, dusty climate. This decomposition provides a more rigorous, thermodynamically grounded basis for evaluating nanocoating performance than energy efficiency alone.

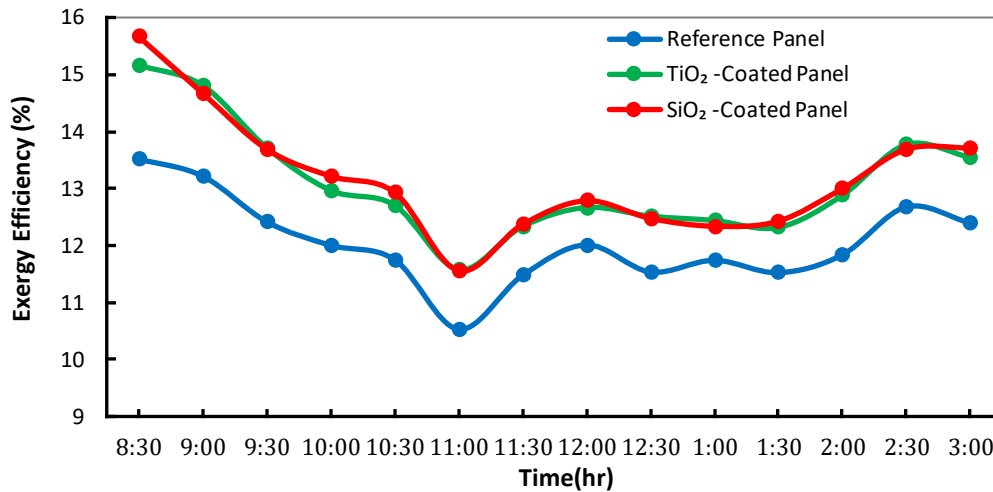


Figure 9. Diurnal variation of exergy efficiency for coated and uncoated PV modules on April 17

Table 7. Average exergy efficiency

Type of Panel	Exergy efficiency (%)	
	April 1	17 April
Reference	13.69	11.93
TiO ₂ coated	13.76	12.85
SiO ₂ coated	14.32	12.98

4.6 Effect of Nanoparticle Coatings and Dust Accumulation

Dust particles degrade the performance of solar PV panels by preventing some of the solar radiation from reaching the cells, thus reducing power output. **Figs. 4 and 5** show that the coated panels outperformed the control panel in terms of electrical power, with the silicon dioxide (SiO₂)-coated panel consistently outperforming the reference panel. This advantage on the first measurement day is owing to improved optical transmittance, but the difference becomes more obvious later due to increased dust deposition on the reference panel. The overall comparison, as shown in **Tables 5 and 7**, demonstrates the coated panels' outperformance in both energy and exergy efficiency. The silicon dioxide (SiO₂)-coated panel achieved the highest average efficiency on both days, while the TiO₂ panel showed a slight improvement, particularly on April 17 under the prevailing outdoor conditions. Quantitatively, the efficiency reduction rate for the reference panel was found to be about 12.4%, as against 7.1% and 6.7% for the SiO₂- and TiO₂- coated panels, respectively. The above observations have clearly proved the effectiveness of coating technology in minimizing the effects of dust deposition. Such a result is due to the hydrophobic property of the nanocoatings, allowing the adhesion of dust particles to be minimized while they are easily removed through wind action.

**Table 8.** Improvement exergy efficiency compared to reference panel.

Type of Panel	April 1	17 April
TiO ₂ coated	0.5%	7.1%
SiO ₂ coated	4.39%	8.1%

On the other hand, increased transmittance may lead to higher panel temperature, negatively impacting voltage. However, the increase in the current due to the improved absorption dominates this effect, leading to an increase in power and overall efficiency, which is most evident in the exergy analysis, where the coated panel exhibited higher values than the reference panel. Exergy also has a higher temperature dependence, making it a more reliable indicator for performance evaluation under real conditions. The coated panel showed an improvement in exergy efficiency of 8.1% and 7.1% for SiO₂ and TiO₂, respectively. These results confirm that the use of nanocoatings, especially SiO₂, enhances the PV panel performance. The improvement is due to the coatings improving the optical properties of the panel surface by increasing the transmittance of solar radiation and reducing reflective losses, as well as mitigating the effects of dust accumulation, making them a promising option for use in hot and dusty environments.

5. CONCLUSIONS

An experimental study has been carried out to examine the effect of SiO₂ and TiO₂ nanocoatings on the performance of PV modules under the climatic conditions of Baghdad, Iraq. The results have revealed that the performance of PV modules was enhanced with the application of the nanocoatings compared to the uncoated modules. The silicon dioxide coated module achieved the highest water contact angle (152.07°) and highest light transmittance (93.48%), compared to 139.01° and 92.60% for the titanium dioxide coated module, confirming its superior properties in dust resistance and light transmission. After seventeen days of exposure to outdoor environmental conditions, the electrical efficiency of the reference module considerably decreased, while the coated modules maintained higher performance. In particular, among the studied nanocoatings, the SiO₂-coated module had the best overall performance, which reached an 11.41% enhancement in electrical efficiency compared to the reference module. In contrast, the TiO₂-coated module showed slightly enhanced electrical efficiency compared to the reference module. The exergy analysis revealed that nanocoated PV modules retained a higher percentage of accessible solar exergy and performed better in terms of useful energy conversion in dusty conditions. To summarize, this study shows that nanocoatings, especially SiO₂ coating, can be a feasible and effective solution to enhance the performance of solar PV systems under dusty and desert climates.

NOMENCLATURE

Symbol	Description	Symbol	Description
A_{pv}	Solar module surface area (m ²)	T_{amb}	Ambient temperature (°C)
Ex_{el}	Electrical exergy (kJ)	T_{pv}	PV cell temperature (°C)
Ex_{in}	Input exergy (kJ)	T_{sun}	Sun temperature (°C)
Ex_{out}	Output exergy (kJ)	T_{sky}	Sky temperature (°C)
Ex_{th}	Thermal exergy (kJ)	V_{max}	Maximum power output point voltage (V)
G_t	Solar irradiance(W/m ²)	V_{oc}	Open-circuit voltage (V)



h_{con}	Convective heat transfer coefficient (W/m ² . K)	V_w	Wind speed m/s
h_{rad}	Radiative heat transfer coefficient (W/m ² . K)	σ	Stefan Boltzmann Constant (W/m ² .K ⁴)
I_{max}	Maximum power output point current (Amp)	η	Energy efficiency (%)
I_{sc}	Short-circuit current (Amp)	η_{ex}	Exergy efficiency (%)
P_{max}	Maximum power output (W)	ε	Thermal emissivity
STC	Standard test condition		

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Credit Authorship Contribution Statement

Ahmed Abdulsalam Khudhur: Experimental work, Writing, Validation, Methodology, review & editing. Hussein K. Jobair: Methodology, Investigation, Supervision, Technical guidance, Validation, Writing –review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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التحقيق التجريبي لتأثير الطلاءات النانوية على أداء الألواح الكهروضوئية تحت الظروف المناخية العراقية

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الخلاصة

برزت أنظمة الطاقة الشمسية الكهروضوئية (PV) بوصفها ركيزة أساسية في التحول نحو الطاقة المتجددة، إلا أن ارتفاع درجات الحرارة وتراكم الغبار يؤثران سلباً في أدائها، خاصة في المناخات القاسية. وعلى الرغم من أهمية الطلاءات النانوية في الحد من هذه التأثيرات، لا تزال الدراسات التجريبية المقارنة في الظروف البيئية العراقية محدودة. تبحث هذه الدراسة تجريبياً في تأثيرات طلاءات ثاني أكسيد السيليكون (SiO_2) وثاني أكسيد التيتانيوم (TiO_2) النانوية على أداء الطاقة والإكسيري للوحات الكهروضوئية في ظل الظروف الجوية السائدة في بغداد، العراق. جرت مراقبة ثلاث لوحات كهروضوئية متطابقة في ظل نفس الظروف: اثنتان مطليتان وواحدة تركت غير مطلية كمرجع. تمت مراقبة المخرجات الكهربائية الرئيسية وشدة الإشعاع الشمسي ودرجات حرارة اللوحات وتقييمها طوال فترة الاختبار. أظهرت اللوحة المطلية بـ SiO_2 تحسناً في الكفاءة الكهربائية بنسبة 11.41%، ولوحظ تحسن بنسبة 7.2% للوحة المطلية بـ TiO_2 بعد فترة تعرض خارجي مدتها سبعة عشر يوماً مقارنةً باللوحة الكهروضوئية المرجعية. يُعد هذا العمل مفيداً بوصفه توجيهات عملية وقابلة للتطبيق حول مدى ملائمة تقنيات الطلاء النانوي للمنشآت الكهروضوئية واسعة النطاق في المناخات القاسية، مما يُرسي الأساس لتطوير حلول اقتصادية ملائمة للمناخ لأنظمة الطاقة الشمسية في العراق والمناطق ذات الظروف البيئية المماثلة.

الكلمات المفتاحية: التحليل الإكسيري، تراكم الغبار، الكفاءة الطاقية، الألواح الكهروضوئية، الطلاءات النانوية