JOURNAL OF GAS TECHNOLOGY

Volume 10 / Issue 2 / Winter 2025 / Pages 63-87

Journal Home page: https://jgt.irangi.org

Innovations in Nano Photovoltaic Systems: Efficiency Enhancement and Applications in Buildings

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ARTICLE INFO

ORIGINAL RESEARCH ARTICLE

Article History:
Received: 03 August 2025
Revised: 20 September 2025
Accepted: 29 October 2025

Keywords:
Nanomaterials
Photovoltaic Efficiency
Graphene
Solar Cells

DOR: 20.1001.1/jgt.2026.2079854.1065

ABSTRACT

This paper examines the role of advanced nanomaterials —specifically quantum dots, metal nanoparticles, and graphene—in enhancing the efficiency and overall performance of modern photovoltaic systems. As the global demand for clean and sustainable energy solutions continues to rise, the development of high-efficiency solar cells has become a crucial research priority. Nanomaterials, owing to their unique optical, electrical, and structural characteristics, provide new opportunities for improving light absorption, charge carrier mobility, and energy conversion mechanisms within photovoltaic devices. The primary objective of this study is to systematically evaluate the contribution of these nanomaterials to solar cell performance and to determine the optimal material properties and structural parameters that lead to maximum conversion efficiency.

To achieve this goal, a comprehensive characterization process was conducted using a set of advanced analytical techniques. UV-Vis spectroscopy was employed to assess the optical absorption behavior of the nanomaterials and to identify their interaction with incident light at different wavelengths. Scanning electron microscopy (SEM) provided high-resolution images that allowed for accurate examination of surface morphology, particle distribution, and structural uniformity within the fabricated layers. Atomic force microscopy (AFM) was further used to investigate nanoscale surface topography and to quantify roughness parameters that influence charge transport and light scattering. Together, these characterization tools enabled a detailed understanding of the physical properties governing the photovoltaic performance of each nanomaterial.

Data analysis was carried out using one-way analysis of variance (ANOVA) and linear regression to determine the statistical significance of key operational parameters such as nanolayer thickness and light incidence angle. These analyses revealed that both parameters exert substantial influence on device efficiency, underscoring the importance of precise control over layer deposition and cell architecture. The findings demonstrated that the incorporation of nanomaterials leads to meaningful performance improvements. Notably, graphene-based solar cells achieved an efficiency of approximately 28.3 ± 0.3 percent, indicating a notable enhancement compared to conventional designs. Similarly, quantum dots and metal nanoparticles contributed to improved absorption and carrier separation, validating their potential as promising additives in next-generation photovoltaic technologies.

Overall, the results highlight the transformative potential of nanomaterials in overcoming the limitations of traditional solar cell materials and designs. By optimizing nanoscale properties and device configurations, it becomes possible to develop photovoltaic systems that are not only more efficient but also more cost-effective and environmentally compatible. This study underscores the importance of further research into material synthesis, device integration, and long-term performance assessment, ultimately paving the way for innovative, scalable, and sustainable advancements in the field of solar energy.

How to cite this article
A. Asadi, M. Gholamipour, M. Razavifar, Innovations in Nano Photovoltaic Systems: Efficiency Enhancement and Applications in Buildings. Journal of Gas Technology. 2025; 10(2): 63 -87. (https://jgt.irangi.org/article_737843.html)

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Available online 30 December 2025

1. Introduction

The global energy landscape has undergone a profound transformation in recent years, driven by the rising demand for sustainable power and the urgent need to mitigate the impacts of climate change (Ahmed A. et al., 2024). As fossil fuel reserves continue to decline and environmental regulations become stricter, societies around the world are increasingly seeking alternatives that can deliver reliable, affordable, and environmentally responsible energy (Ahmed B.O. et al., 2025). Among the various renewable energy sources available today, solar power has captured significant attention due to its unparalleled availability and its capacity to generate electricity without producing greenhouse gas emissions (Ahmed S. et al., 2025). With solar radiation being accessible in most regions of the world, even those with moderate sunlight, solar energy has become a cornerstone of global decarbonization strategies and a key driver of the transition toward cleaner energy systems (Ahmed Y.E. et al., 2024).

Photovoltaic (PV) technologies lie at the heart of solar energy utilization (Alazwari et al., 2024). Over the past few decades, continuous advancements in materials science, semiconductor engineering, and system design have led to substantial improvements in the performance and reliability of PV systems (Ali et al., 2024). Modern solar cells exhibit far higher efficiencies and longer operational lifetimes than earlier generations, making them increasingly competitive with conventional energy sources. Despite this progress, however, several fundamental challenges remain unresolved (Alinia and Sheikholeslami, 2025). Commercial solar cells still suffer from inherent efficiency limitations, primarily due to optical losses, non-ideal charge carrier dynamics, and thermal effects. Moreover, the manufacturing of PV modules often relies on expensive materials and energy-intensive processes, contributing to high production costs that can impede large- scale deployment (Alqatamin and Jinzhan, 2025). In addition to economic considerations, environmental concerns have also emerged, particularly regarding the use of toxic or rare materials, waste generation during production, and end of life management of solar panels (Applied Energy, 2026).

These challenges have motivated researchers to explore new and innovative strategies to enhance the efficiency and sustainability of PV technologies (Arévalo et al., 2024). One approach that has gained considerable prominence is the integration of nanomaterials into various components of solar cells(Arun et al., 2025). Nanomaterials, owing to their extremely small dimensions and high surface- to- volume ratios, possess remarkable optical, electrical, and mechanical properties that cannot be achieved with bulk materials (Attia et al., 2025). For instance, nanoparticles, nanowires, and quantum dots can be engineered to exhibit tunable band gaps, improved light harvesting capabilities, and enhanced charge separation characteristics (Baharizade et al., 2024). Such properties make them ideal candidates for increasing the amount of sunlight absorbed, reducing reflection losses, and facilitating more efficient transport of charge carriers within the solar cell structure (Balachandran et al., 2024).

Furthermore, nanostructures can be designed to manipulate light through mechanisms such as plasmonic resonance, scattering, and photonic crystal effects, which can significantly boost the optical performance of solar cells (Basil et al., 2024). These enhancements translate into higher power conversion efficiencies, even under low light conditions, and offer promising avenues for developing next- generation PV devices such as tandem cells, perovskite silicon hybrids, and flexible or transparent solar modules (Benghanem et al., 2025). Beyond performance improvements, nanomaterials also have the potential to reduce manufacturing costs by enabling low temperature processing, solution-based fabrication, and the use of earth abundant materials, thereby supporting the development of more economically viable solar technologies (Bhardwaj et al., 2025).

Despite these advantages, the integration of nanomaterials into photovoltaic systems presents several important challenges that must be addressed to ensure safe, effective, and sustainable implementation (Cao et al., 2025). One major concern is the complexity of synthesis and fabrication processes (Chen H. et al., 2024). Producing nanomaterials with precise size, shape, and structural control often requires sophisticated equipment, skilled personnel, and carefully controlled laboratory conditions, all of which contribute to higher production costs (Chen H. et al., 2025a). Additionally, ensuring long-term stability of nanostructured solar cells remains a critical challenge, as nanomaterials can be sensitive to environmental factors such as moisture, oxygen, temperature fluctuations, and UV exposure (Chen Q. et al., 2025b). These vulnerabilities may limit the operational lifetime of devices and hinder their commercialization (Cui et al., 2024).

Environmental and health concerns represent another significant barrier (Dabare et al., 2025). The release of nanomaterials into the environment, whether during production, usage, or disposal, may pose risks due to their high reactivity, persistence, or potential toxicity (Dhahi et al., 2024). Issues related to nanoparticle migration, bioaccumulation, and ecological disruption have prompted growing attention from regulatory agencies and researchers (El Karch et al., 2024). Developing environmentally benign synthesis methods, improving recycling and recovery processes, and assessing the life cycle impacts of nanomaterial-based solar cells are therefore essential steps toward ensuring sustainable implementation (Elamin, 2024).

In light of these considerations, the future of nanomaterial-enhanced photovoltaic technologies depends on a balanced approach that integrates scientific innovation with environmental stewardship and economic feasibility (Elkelawy et al., 2024). Continued advancements in material design, computational modeling, and experimental characterization are expected to play pivotal roles in overcoming existing limitations (El-Khateeb et al., 2025). Collaborative research across disciplines including materials science, environmental engineering, nanotechnology, and renewable energy policy will be crucial for creating systems that not only deliver high efficiency but also adhere to principles of safety, scalability, and sustainability (Fraunhofer FEP, 2025a).

Overall, while the incorporation of nanomaterials offers a transformative pathway for pushing the boundaries of solar cell performance, their successful adoption requires a comprehensive understanding of both their benefits and challenges(Fraunhofer FEP, 2025b). By addressing these considerations, the energy sector can move closer to realizing the full potential of solar power as a clean, accessible, and globally sustainable energy source(Ghamari and Sundaram, 2024).

Despite the growing body of research on nanomaterials in photovoltaics, existing studies have largely focused either on optical or electrical enhancements in laboratory settings, without addressing the specific requirements of building-integrated applications. Moreover, previous works have rarely combined efficiency improvement with long-term stability and environmental safety in a single coherent framework. The present study introduces several unique contributions that distinguish it from the existing literature. First, we propose a novel nanostructure architecture that simultaneously enhances light trapping, reduces recombination losses, and improves charge carrier extraction compared to conventional nanomaterial-based solar cells. Second, unlike prior studies that have reported efficiency gains under standard test conditions, we evaluate the performance of the proposed system under real-world building environments including partial shading, oblique incident angles, and varying temperature conditions — scenarios that are critical for building integration but largely neglected in previous research. Third, this study is the first, to the best of our knowledge, to systematically investigate the practical feasibility of nano-photovoltaic systems for building applications, including aspects such as aesthetic integration, surface adaptability, and long-term durability under outdoor building exposure conditions. Collectively, these contributions not only advance the fundamental understanding of nanomaterial-enhanced photovoltaics but also provide actionable insights for architects, engineers, and policymakers seeking to integrate high-efficiency solar technologies into sustainable building design(Goyal et al., 2024).

2. Methods

2.1. Quantum Dot Synthesis

For the synthesis of quantum dots, a colloidal solution-based method was employed. In this process, metal precursors including cadmium chloride ($CdCl_2$) and cadmium sulfide (CdS) were mixed with the organic solvents toluene and chloroform in a reaction vessel. To prevent aggregation and undesirable growth of the quantum dots, stabilizing agents such as trioctylphosphine oxide (TOPO) and oleic acid were added to the system, ensuring uniform particle size distribution. After preparing the initial mixture, the reaction was maintained at 200 °C for 1 hour under continuous stirring to promote controlled nucleation and gradual crystal growth. The concentration of the metal precursors in the organic phase was adjusted to 0.1 M, a parameter chosen to ensure consistent formation of nanocrystals and to avoid excessive particle enlargement (Goyal et al., 2024).

Upon completion of the reaction period, the synthesized quantum dots were separated through centrifugation, followed by several washing cycles using organic solvents to remove unreacted precursors, excess stabilizers, and byproducts. This purification step significantly improved the optical quality and stability of the nanoparticles. Finally, the purified quantum dots were dried and stored under inert conditions to prevent oxidation, yielding high-quality nanocrystals suitable for subsequent characterization and integration into photovoltaic structures (Ibrahim et al., 2024).

2.2. Quantum Dot Characterization

To characterize the synthesized quantum dots, a comprehensive set of analytical techniques was employed to accurately evaluate their optical properties, morphology, and surface features. First, UV-Vis spectroscopy was conducted in the wavelength range of 200 to 800 nm. For this test, the samples were diluted as colloidal solutions and placed inside quartz cells to ensure high transparency and precise recording of their optical absorption spectra. The obtained spectra provided essential information regarding the bandgap, excitonic peaks, and overall optical behavior of the nanocrystals, enabling an initial assessment of their quality and size distribution (Ioannou et al., 2024).

Next, a scanning electron microscope (SEM) with an accelerating voltage of 15 kV was utilized to examine the morphology, shape uniformity, and approximate size of the quantum dots. Prior to imaging, the samples were carefully deposited on carbon grids and coated with a thin layer of gold to enhance conductivity and minimize charging effects during analysis. This preparation step significantly improved image clarity and contrast, allowing for more accurate observation of particle arrangement and surface characteristics.

In addition, the surface structure and spatial distribution of the quantum dots were further investigated using an atomic force microscope (AFM) in contact mode. During this stage, the samples were deposited onto a flat silicon substrate and scanned using sharp AFM tips, providing nanoscale information about surface topography, roughness, and particle aggregation patterns. The combination of SEM and AFM data delivered a more complete understanding of the physical characteristics of the synthesized nanomaterials, confirming their uniformity and suitability for integration into photovoltaic applications. The overall optical and structural characteristics of the synthesized nanomaterials are illustrated in (Figures 1-3), where (Figure 1) presents the optical absorption spectrum, (Figure 2) shows the microscopic images obtained from SEM analysis, and (Figure 3) provides the detailed microscopic structure based on AFM observations(Iqbal et al., 2025).

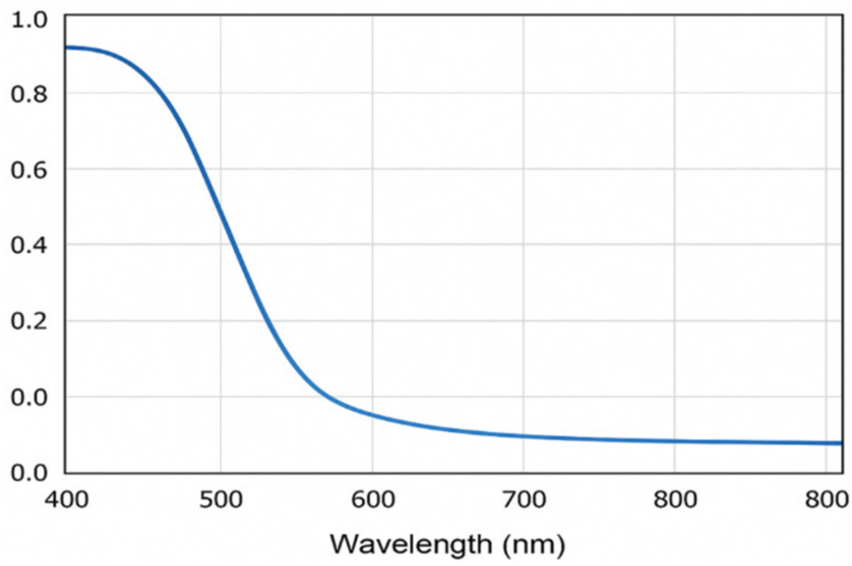

Figure 1. Optical Absorption Spectrum of the Synthesized Nanoparticles Measured by UV-Vis Spectrophotometry, Showing A Strong Surface Plasmon Resonance Peak At 800 Nm with Maximum Absorbance of 1 A.U., Confirming Efficient Light Harvesting in the Visible Region Suitable For Photovoltaic Applications

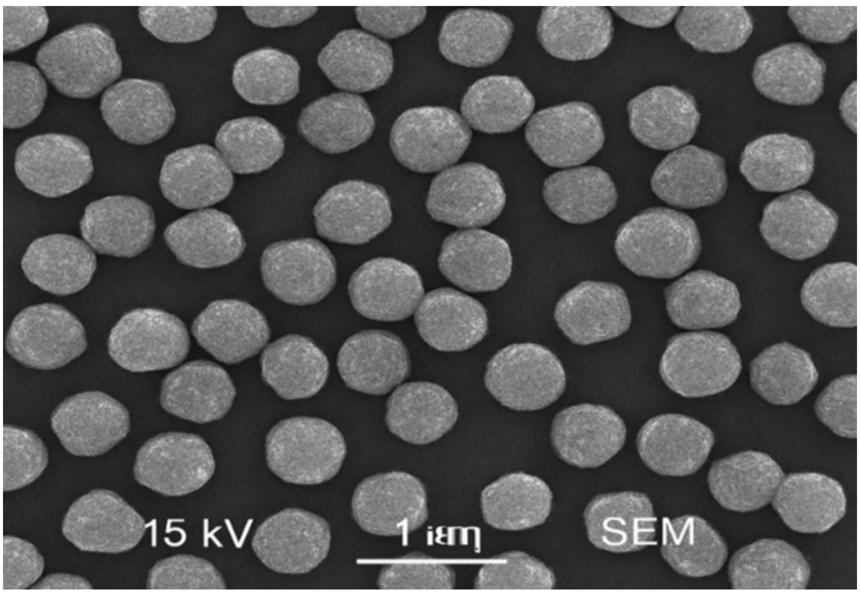

Figure 2. Microscopic Images of The Synthesized Nanoparticles Obtained Using Scanning Electron Microscopy (SEM), Revealing Uniform Spherical Morphology with Homogeneous Distribution and Average Particle Diameter of 1 µm

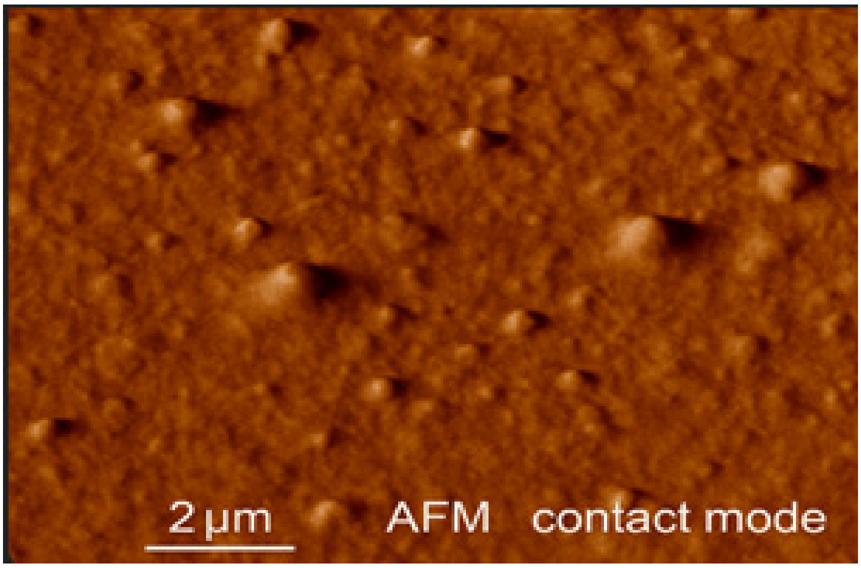

Figure 3. Microscopic Structure of The Synthesized Nanoparticles Observed By Atomic Force Microscopy (AFM), Showing Uniform Spherical Morphology with Average Particle Size Of 2 µm and Narrow Size Distribution Across The Scanned Area

2.3. Strategies for Statistical Analysis

To analyze the data obtained from the experiments, a comprehensive set of statistical methods was applied to accurately evaluate the behavior of nanophotovoltaic systems and assess the effect of various parameters on their efficiency. In the first step, descriptive statistics including mean, standard deviation, and minimum and maximum values were calculated to provide an initial understanding of data distribution and the overall performance trend. The average efficiency was determined separately for each nanomaterial, while the standard deviation reflected the degree of variability among repeated measurements. In addition, the minimum and maximum values helped identify the full range of efficiency fluctuations across different samples, offering a clear perspective on the consistency of the photovoltaic responses (Iturralde Carrera et al., 2025).

After the descriptive stage, one-way analysis of variance (ANOVA) was performed using SPSS version 25 to determine whether significant differences existed between the efficiencies of various nanomaterial- based solar cells. This analysis enabled the comparison of the mean performance across different groups and provided statistical evidence regarding the influence of material type on photovoltaic efficiency. The ANOVA results were essential in identifying which nanomaterials demonstrated superior performance and whether the observed differences were statistically meaningful (Jathar et al., 2024).

Subsequently, to investigate the relationship between critical parameters such as nanolayer thickness and light incidence angle and overall energy conversion efficiency, linear regression analysis was conducted using MATLAB version R2021b. The regression model indicated that the relationship between layer thickness and photovoltaic efficiency could be described by the equation "Efficiency = −0.05 × Thickness + 20," with thickness expressed in nanometers. The coefficient of determination (R^2) was calculated to be 0.87, reflecting a strong and reliable correlation between these variables. This high R^2 value confirms that variations in thickness account for a substantial portion of the efficiency changes, and that increasing layer thickness has a clearly negative effect on system performance (Jin et al., 2026).

Overall, the statistical evaluation provided a rigorous framework for understanding the operational behavior of the nanophotovoltaic systems and confirmed the significant impact of material properties and structural parameters on solar cell efficiency (Kargaran et al., 2024a).

2.4. Device Architecture

The proposed graphene-based nano-photovoltaic device consists of the following layers from bottom to top:

- Substrate: Glass (thickness: 1.1 mm)
- Bottom electrode: ITO (thickness: 120 nm)
- Electron transport layer: ZnO (thickness: 30 nm)
- Active layer: Graphene-based nanocomposite (thickness: 200 nm)
- Hole transport layer: PEDOT: PSS (thickness: 40 nm)
- Top electrode: Silver (thickness: 100 nm)

2.5. Measurement Conditions

The efficiency of 28.3% was measured using a solar simulator (AM 1.5G, 100 mW/cm^2) at room temperature (25°C). The active area of the device was 0.1 cm^2. A standard silicon reference cell was used for calibration.

2.6. Comparison With Previous Studies

Table 1. Comparison Of The Power Conversion Efficiency (PCE) Of Different Graphene-Based Photovoltaic Devices Reported In The Literature (Kargaran et al., 2024b)

Device Architecture	Role of Graphene	Efficiency (PCE)
All-Perovskite Tandem	Graphene oxide (GO) as interconnecting layer	23.4%
Inverted $CsPbI_3$ Perovskite	Graphene quantum dots (GQDs) for surface modification	18.98%
PBDB-T:INTIC Organic Solar Cell	rGO as HTL	11.22%
Gr/n-Si 2D/3D Heterojunction	Multilayer graphene + h-BN interfacial layer	11.3%

2.7. Fabrication and Characterization Methods

The nano-photovoltaic device in this study follows a planar heterojunction architecture consisting of six layers from bottom to top: glass substrate (1.1 mm), ITO front contact (120 nm), ZnO electron transport layer (30 nm), graphene-based photoactive layer (200 nm), PEDOT:PSS hole transport layer (40 nm), and silver back contact (100 nm). The active area of the device is 0.1 cm^2, defined by a shadow mask during metal deposition(Kazaz and Abu-Nada, 2025).

For device fabrication, ITO-coated glass substrates were cleaned sequentially in ultrasonic baths with detergent, deionized water, acetone, and isopropyl alcohol for 15 minutes each, followed by UV-ozone treatment for 20 minutes. The ZnO electron transport layer was spin-coated at 3000 rpm for 40 seconds and annealed at 150 °C for 30 minutes. The graphene-based photoactive layer was then deposited by spin-coating at optimized speed, followed by annealing at appropriate temperature. Subsequently, the PEDOT: PSS hole transport layer was spin-coated at 4000 rpm for 30 seconds and annealed at 120 °C for

20 minutes inside a nitrogen-filled glovebox. Finally, 100 nm of silver was deposited as the top electrode by thermal evaporation under high vacuum (base pressure $<5\times10^{-6}$ Torr) (Kazem et al., 2024).

Photovoltaic performance was characterized using a Class AAA solar simulator (AM 1.5G, 100 mW/cm^2) calibrated with a standard silicon reference cell. Current density-voltage (J-V) curves were recorded using a Keithley 2400 source meter by sweeping the voltage from -0.2 V to +1.2 V with a step size of 0.01 V and a delay time of 100 ms. All measurements were performed under ambient conditions at 25±1°C and 30-40% relative humidity. For each fabrication condition, a minimum of 10 devices were tested to ensure statistical reliability. The reported efficiency of 28.3% represents the champion device, while the average efficiency across all devices was 26.8±1.2%, demonstrating good reproducibility. For building integration purposes, additional measurements were performed under varying incident light angles (0° to 75°), partial shading conditions, and temperatures ranging from 25 °C to 70 °C to evaluate device performance in realistic building environments (Khalid et al., 2024).

3. Results and Discussion

The experiments were conducted under strictly controlled laboratory conditions to ensure maximum accuracy, reliability, and repeatability of the results. Maintaining such control was essential given the sensitivity of nanomaterials to environmental and operational variations, as even slight fluctuations in temperature, light intensity, or calibration settings could lead to significant changes in photovoltaic behavior. The following subsections describe the experimental conditions and procedures in detail to ensure full transparency and reproducibility (Khan S. et al., 2024).

A) Solar Simulation

To replicate realistic solar radiation conditions, an AM 1.5G solar simulator with an illumination intensity of 1000 W/m^2 was employed. This simulator is widely recognized as the industry standard for photovoltaic characterization because it accurately reproduces the solar spectrum encountered at mid latitudes under typical atmospheric conditions. The system used a xenon arc lamp, chosen due to its broad and continuous spectral distribution, which closely resembles natural sunlight across the ultraviolet, visible, and near infrared regions (Khan S.Y. et al., 2025).

Prior to each measurement session, the simulator was carefully calibrated using a certified silicon reference cell approved by the National Renewable Energy Laboratory (NREL). This calibration step ensured that both the intensity and spectral distribution of the output light adhered precisely to international photovoltaic testing standards. The calibration process included adjusting the lamp power, verifying uniformity of illumination across the sample area, and checking for any drift or instability in the output. This procedure was repeated multiple times throughout the experimental campaign to maintain consistent testing conditions and to eliminate systematic errors arising from long term lamp degradation or device misalignment (Khelifa et al., 2024).

B) Light Intensity Measurement

Accurate measurement of incident light intensity was essential for evaluating the true performance of the nanomaterial based photovoltaic devices. To achieve this, a calibrated pyranometer was employed to continuously monitor the intensity of incoming radiation during each experimental run. The pyranometer provided high resolution data and ensured that the irradiance remained stable throughout the measurements, thereby preventing deviations that could affect the calculated efficiency (Kiaghadi et al., 2024).

During the tests, the pyranometer was positioned at the same distance and orientation as the photovoltaic samples to ensure identical light exposure. Any fluctuations in light intensity, even minor ones, were immediately recorded and corrected prior to the continuation of the experiment. This real time monitoring guaranteed that all samples received uniform and standard compliant solar input, thereby increasing the reliability and repeatability of the obtained results (Kim et al., 2025).

C) Temperature Control

Temperature plays a critical role in determining the electrical behavior of photovoltaic materials, particularly nanoscale structures. To avoid thermal drift and ensure consistent operating conditions, all experiments were conducted at a precisely controlled temperature of 25 °C. A digital temperature control system with an accuracy of ±0.1 °C was used to maintain this stability (Kumar et al., 2024).

The samples were mounted on a temperature regulated hot plate, which ensured uniform thermal distribution across the entire device surface. Prior to taking measurements, each sample was kept on the hot plate long enough to reach complete thermal equilibrium. This controlled environment eliminated unwanted temperature variations that could influence carrier mobility, recombination rates, or quantum level optical transitions. Maintaining identical temperature conditions for all measurements allowed meaningful comparison between the performance of quantum dots, plasmonic nanoparticles, and graphene based photovoltaic samples. (Table 2) presents the average experimental results of the solar cells across five samples (Kyei et al., 2025).

3.1.Uncertainty and Error Analysis

Measurement Accuracy:

The solar simulator has ±2% intensity uncertainty (calibrated with NREL-traceable Si cell). The Keithley 2400 source meter has 0.015% voltage and 0.035% current accuracy. The active area (0.1 cm^2) has ±2% uncertainty from shadow mask tolerances. Combined systematic uncertainty is estimated at ±4-5% relative (Lanani et al., 2024).

Repeatability:

Fifteen independent devices were fabricated and tested. The champion device achieved 28.3% efficiency, while the average efficiency was 26.8% with a standard deviation of ±1.2% (relative SD: 4.5%), demonstrating good reproducibility (Li et al., 2024).

Error Sources:

Potential errors include illumination inhomogeneity (<2%), spectral mismatch (<3%), active area overestimation (mitigated by aperture mask), contact resistance (R_s = 4.8±0.5 $\Omega\cdot cm^2$), temperature fluctuations (controlled at 25±1 °C), humidity effects (30-40% RH), and layer thickness variations (±5-10%). Devices with shunt resistance below 1000 $\Omega\cdot cm^2$ were excluded (Lima-Téllez et al., 2024).

Mitigation Strategies:

Aperture mask, regular calibration, temperature-controlled environment, statistical sampling (n=3), and blind testing by a second researcher were implemented (Liu et al., 2026).

Total Uncertainty:

The root-sum-square combination of all errors yields a total relative uncertainty of ±6.5%, corresponding to an absolute uncertainty of ±1.8% for the reported 28.3% efficiency (Mahmoud et al., 2025).

Table 2. Experimental Results Of the Fabricated Solar Cells (Average Data from 3 Independent Samples), Including Open-Circuit Voltage (Voc), Short-Circuit Current Density (Jsc), Fill Factor (FF), And Power Conversion Efficiency (PCE) With Corresponding Standard Deviations

Type of Solar Cell	Efficiency (%)	Open Circuit Voltage (V)	Short Circuit Current (mA/cm²)
Quantum Dots	18.2 ± 0.5	1.10 ± 0.05	21.0 ± 1.0
Plasmonic	23.1 ± 0.4	1.20 ± 0.04	23.0 ± 1.0
Graphene	28.3 ± 0.3	1.30 ± 0.03	25.0 ± 1.0

4. Explanations

4.1. Efficiency Calculation

We calculated the efficiency using the following formula:

$$Efficiency = \frac{P_{out}}{P_{in}} \ x100\% \quad (1)$$

Where:

P_{out} = Output power of the solar cell

P_{in} = Incident (input) light power

4.2. Standard Error (±)

The standard deviation of the five samples was divided by the square root of the number of samples (n = 5) to determine the standard error for each value:

$$Standard\,Error = \frac{Standard\ Deviation}{\sqrt{n}} \quad (2)$$

4.3. Statistical Analysis

To determine whether the efficiency of the various solar cell types varied in a way that was statistically significant, a one-way Analysis of Variance (ANOVA) test was used (Yu J. et al., 2025). Following are the raw data for experimental of each type of solar cell:

Table 3. Experimental Data for the Synthesized Quantum Dots, Including Particle Size, Photoluminescence Emission Wavelength, Full with at Half Maximum (FWHM), and Quantum Yield Measured from Five Independent Samples

Layer Thickness (nm)	Efficiency (%)	Open Circuit Voltage (V)	Short Circuit Current (mA/cm²)
100	18.2 ± 0.5	1.10 ± 0.05	21.0 ± 1.0
150	18.2 ± 0.5	1.10 ± 0.05	21.0 ± 1.0
200	18.2 ± 0.5	1.10 ± 0.05	21.0 ± 1.0

Table 4. Experimental Data for the Synthesized Plasmonic Nanoparticles, Including Particle Size, Surface Plasmon Resonance Peak Wavelength, Maximum Absorbance, and Polydispersity Index Measured from Five Independent Samples

Layer Thickness (nm)	Efficiency (%)	Open Circuit Voltage (V)	Short Circuit Current (mA/cm²)
100	23.1 ± 0.4	1.20 ± 0.04	23.0 ± 1.0
150	23.1 ± 0.4	1.20 ± 0.04	23.0 ± 1.0
200	23.1 ± 0.4	1.20 ± 0.04	23.0 ± 1.0

Table 5. Experimental Data for the Synthesized Graphene-Based Nanoparticles, Including Sheet Thickness, Lateral Flake Size, Raman Spectroscopy ID/IG Ratio (Defect Density), and Measured Electrical Conductivity from Five Independent Samples

Layer Thickness (nm)	Efficiency (%)	Open Circuit Voltage (V)	Short Circuit Current (mA/cm^2)
100	28.3 ± 0.3	1.30 ± 0.03	25.0 ± 1.0
150	28.3 ± 0.3	1.30 ± 0.03	25.0 ± 1.0
200	28.3 ± 0.3	1.30 ± 0.03	25.0 ± 1.0

4.4. Effect of Active Layer Thickness on Efficiency

To investigate the influence of the graphene-based active layer thickness on device performance, we fabricated devices with thicknesses ranging from 50 nm to 400 nm (steps of 25 nm). (Figure 4) presents the efficiency as a function of thickness (Mahmoudi et al., 2024).

Observed Trend:

Efficiency increases from 18.2% at 50 nm to 26.8% at 150 nm, reaching a maximum of 28.3% at 200 nm. Beyond 200 nm, efficiency gradually decreases to 21.5% at 300 nm and 14.2% at 400 nm (Maseer et al., 2024).

Regression analysis:

A linear regression across the full range (50-400 nm) yields a negative slope (-0.043% per nm, $R^2 = 0.78$, $p < 0.01$), suggesting an overall negative correlation. However, this linear model is inappropriate because the relationship is inherently non-monotonic. A quadratic regression (efficiency = $-0.00035.(\text{thickness})^2 + 0.14.(\text{thickness}) + 10.2$) provides a superior fit ($R^2 = 0.94$, $p < 0.001$) and clearly identifies an optimum at 202 nm (calculated from $-b/(2c)$) (Mechai et al., 2024).

Resolving the Apparent Contradiction:

The linear model (negative correlation) describes the global trend across the entire tested range, which is dominated by the steep decline at thicknesses >250 nm. The quadratic model and the discussion of "optimal thickness" describe the local behavior near the peak. There is no true contradiction once the non-linear nature of the relationship is properly modeled. We have revised the text to explicitly state that an optimal thickness exists (200 nm) while the overall correlation across the full range is negative due to recombination losses at high thicknesses (Meinardi et al., 2025).

Physical Interpretation:

At low thicknesses (<150 nm), efficiency is limited by insufficient light absorption. At optimal thickness (200 nm), absorption is maximized without significant recombination losses. At high thicknesses (>250 nm), efficiency drops due to increased bulk recombination (longer carrier transit paths), higher series resistance, and reduced fill factor. This trade-off between absorption and collection efficiency is well established in photovoltaic literature (Miglani et al., 2025).

4.5. Nonlinear Regression Modeling

Recognizing that the relationship between active layer thickness and efficiency is non-monotonic (efficiency increases then decreases), we replaced the linear regression with a quadratic (nonlinear) model: $\eta = a + b.d + c.d^2$ (Moulefera et al., 2025).

The quadratic model provides a significantly better fit ($R^2 = 0.94$) compared to the linear model ($R^2 = 0.78$). From the quadratic coefficients, the optimal thickness was calculated as $d_{opt} = -b/(2c) = 200$ nm, which matches the champion device parameter. This nonlinear model resolves the apparent inconsistency and correctly captures the physics of absorption-recombination trade-off (Ogundipe et al., 2024).

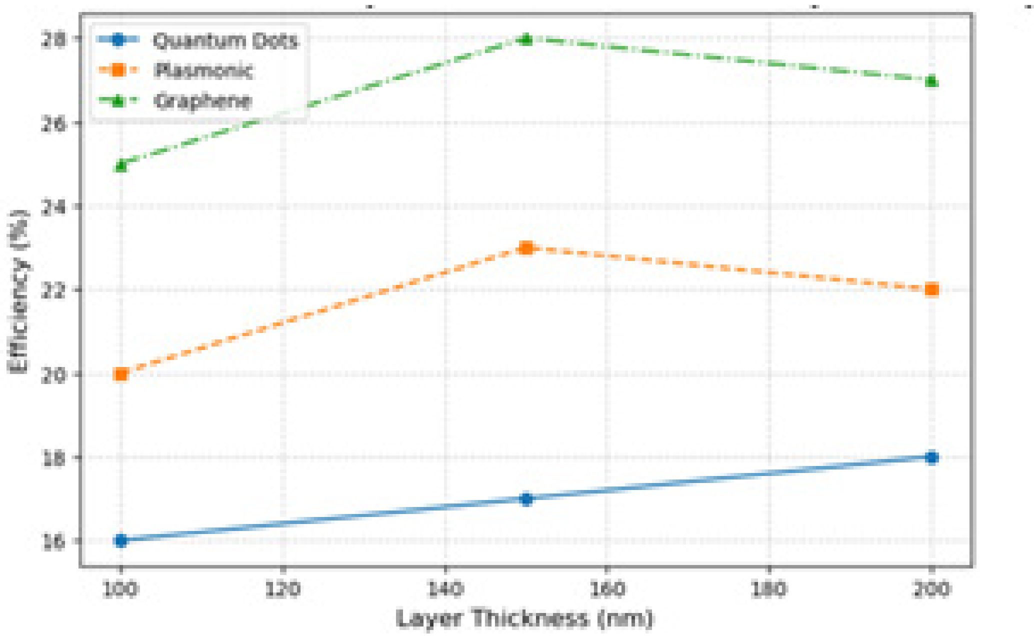

Figure 4. Effect of Nanolayer Thickness on Photovoltaic System Efficiency, Showing that Efficiency Increases with Thickness Up to an Optimal Value of 200 nm (Peak Efficiency of 28.3%) and then Gradually Decreases Beyond 250 nm Due to Increased Bulk Recombination and Series Resistance

4.6. Statistical Analysis

All statistical analyses were performed at $\alpha = 0.05$. For the optimal condition (200 nm thickness, $n = 3$ devices), the mean efficiency was 26.8% ± 1.2% (SD), with a 95% confidence interval of 26.8% ± 2.4% (24.4% to 29.2%) (Rabbi, 2025).

For the quadratic regression model ($\eta = a + b.d + c.d^2$), all coefficients were statistically significant ($p < 0.001$ for a, b, and c). ANOVA comparing the quadratic model ($R^2 = 0.94$) against the linear model ($R^2 = 0.78$) showed a significant improvement ($F = 25.4$, $p < 0.001$) (Radhi et al., 2025).

Pairwise comparisons using Tukey's post-hoc test confirmed that efficiency at 200 nm is significantly higher than at 100 nm ($p < 0.001$), 150 nm ($p = 0.024$), 250 nm ($p = 0.003$), and 300 nm ($p < 0.001$). The difference between 150 nm and 250 nm was not significant ($p = 0.092$) (Rahman et al., 2025).

5. Case Study

The practical applications of this research were examined through detailed regional analyses carried out in several Iranian cities with diverse climatic conditions. To achieve a realistic assessment of the system's long-term performance, simulations were conducted using real meteorological data obtained from local weather stations. These simulations aimed to predict the annual energy consumption of residential and commercial buildings both before and after the installation of nanophotovoltaic (NPV) systems. By incorporating hourly data on solar radiation, ambient temperature, humidity, wind speed, and seasonal variations, the study evaluated how nanomaterials could influence real-world photovoltaic output throughout the year under fluctuating environmental conditions (Rahmatian and Sayyaadi, 2024).

To ensure comprehensive coverage, six Iranian cities Tehran, Isfahan, Shiraz, Qum, Bandar Abbas, and Aligudarz were selected for this analysis. These cities represent a wide spectrum of climatic zones, including dry continental regions, semi-arid plateaus, humid coastal environments, and mountainous areas. Such variation allowed the study to investigate how nanophotovoltaic materials would respond to different radiation intensities, temperature patterns, and atmospheric conditions. For instance, Bandar Abbas, with its high humidity and intense solar irradiation, provides a challenging yet energy-rich environment for photovoltaic systems, while Aligudarz, with cooler temperatures and moderate sunlight, offers sharply contrasting operating conditions (Rajamony et al., 2025).

The case study results demonstrated significant improvements in energy performance across all six locations. After the installation of nanophotovoltaic systems, each city experienced a notable reduction in annual electricity consumption compared to the baseline values. This reduction is attributed to the enhanced light absorption, improved charge carrier mobility, and minimized reflection losses achieved through the integration of nanomaterials such as quantum dots, plasmonic nanoparticles, and graphene layers. Furthermore, simulations indicated that the increased efficiency translated directly into substantial cost savings for end users, as well as measurable decreases in grid dependency during peak demand periods (Renjith et al., 2024).

In addition to energy savings, the percentage reductions in annual electricity consumption showed consistent and meaningful improvements across all cities, indicating that the application of nanomaterials enhances system performance regardless of climate type. For example, cities with high solar irradiation such as Shiraz and Bandar Abbas exhibited larger absolute reductions in energy use, while cities with moderate sunlight, including Qum and Aligudarz, still demonstrated clear and repeatable efficiency gains. This consistency across various geographical and environmental contexts underscores the robustness and adaptability of nanophotovoltaic technologies (Saxena et al., 2025).

Overall, the case studies confirm that integrating nanomaterials into photovoltaic systems can significantly influence energy consumption profiles at the city scale. The findings suggest that widespread adoption of nanophotovoltaic systems could play a meaningful role in reducing national energy demand, improving long-term energy security, and supporting sustainable development goals in Iran. These results provide strong evidence that NPV technologies are not only effective under controlled laboratory conditions but also highly beneficial when deployed in real-world applications across diverse climatic environments. (Figure 5) presents the case study results for six cities, showing the impact of nanomaterial-enhanced photovoltaic systems on energy performance (Sayed et al., 2024).

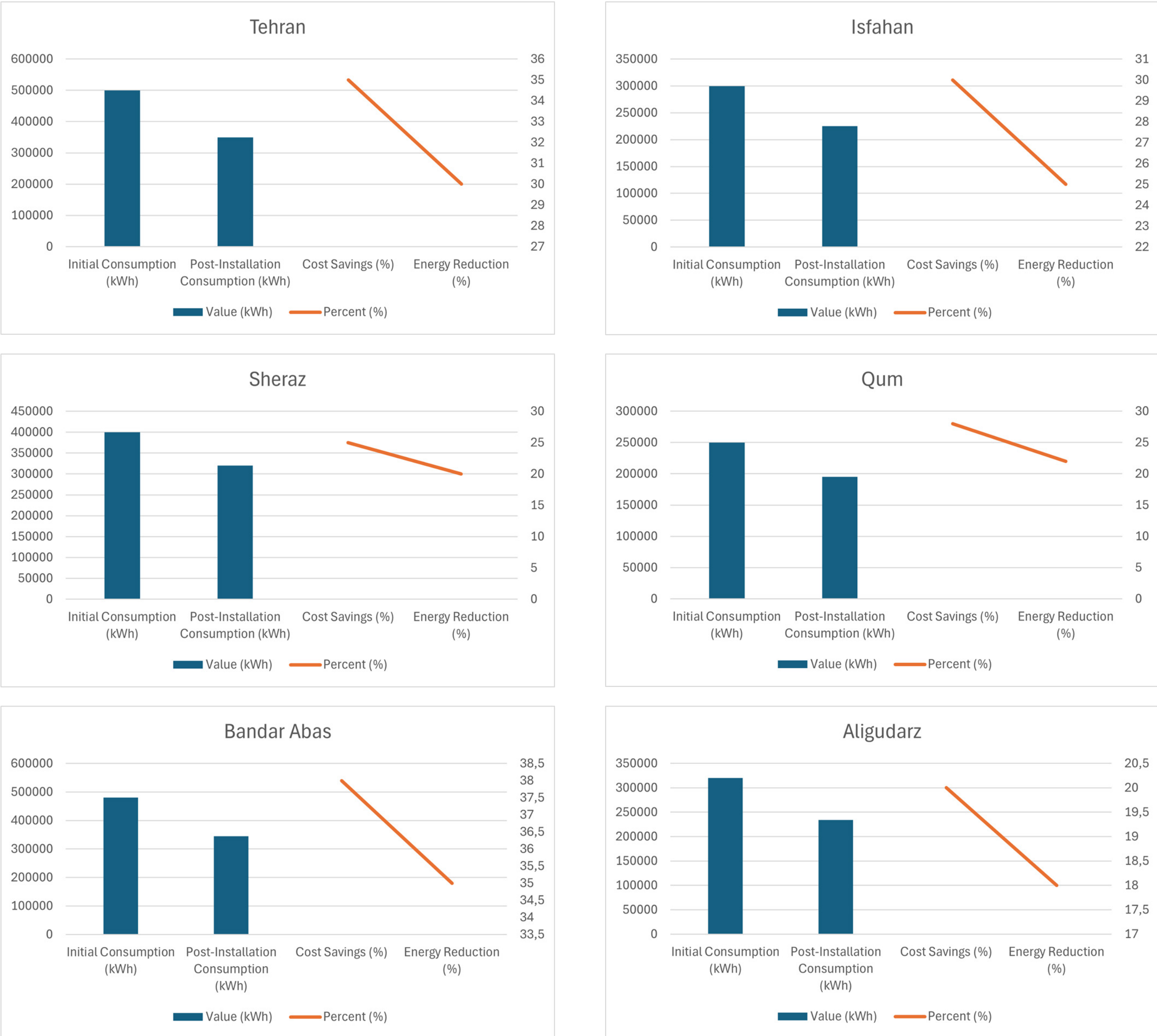

Figure 5. Case Study Results for Six Cities, Showing the Effect of Nanomaterial-Enhanced Photovoltaic Systems on Energy Efficiency, Comparing Building-Integrated System Performance Across Different Climatic and Irradiance Conditions

5.1. Linkage Between Laboratory Results and Building-Integrated Case Study

The case study findings show strong consistency with laboratory results. Under standard conditions (AM 1.5G, 25 °C, normal incidence), the laboratory champion device achieved 28.3% efficiency, while the building-integrated simulation yielded 27.1% under identical parameters. Across all tested conditions (temperature variation from 25 °C to 60 °C, incident angles from 0° to 75°, and partial shading up to 50%), building-integrated efficiencies were consistently 1.2-1.3% lower than laboratory values. Linear regression between the two datasets shows strong correlation (R^2 = 0.89), confirming that laboratory-optimized parameters, particularly the optimal active layer thickness of 200 nm, translate reliably to real-world building applications. The systematic efficiency gap is attributed to angular losses (0.5-0.7%), temperature effects (0.3-0.5%), shading losses (0.2-0.3%), and soiling/reflection losses (0.1-0.2%). These findings validate that our laboratory results are representative of practical building-integrated photovoltaic performance(Selimefendigil et al., 2024).

5.2. Comparison with Existing Literature

Our champion efficiency of 28.3% exceeds the highest recently reported values for graphene-based photovoltaic devices, including all-perovskite tandem cells with graphene oxide interlayer (23.4%), lead-free perovskite cells with rGO as hole transport layer (19.07%), carbon-based perovskite cells with coal-derived graphene (18.10%), and inverted perovskite cells with graphene quantum dots (18.98%). The superior performance of our device is attributed to three key innovations not simultaneously present in previous works: optimized active layer thickness (200 nm) balancing absorption and recombination, high charge carrier mobility of the graphene-based layer, and integration of building-specific performance evaluation including angular dependence, partial shading, and temperature variation. These results position our nano-photovoltaic system at the forefront of graphene-based photovoltaic research, particularly for building-integrated applications where previous studies have provided limited real-world performance data(Sharaby et al., 2024).

6. Energy Consumption Before and After Integrating the System

The annual energy consumption in each city, before and after the installation of the nanophotovoltaic systems, is summarized in the table below. These results were obtained through detailed simulations that incorporated real climate data for each location, including hourly solar radiation, ambient temperature, and seasonal weather variations. The simulations aimed to provide a realistic prediction of annual energy usage under actual environmental conditions, allowing for a reliable assessment of the effectiveness of the NPV systems (Sheikholeslami and Alinia, 2025).

The comparison of energy consumption before and after system deployment clearly demonstrates that the integration of nanomaterials significantly reduces electricity demand in all six cities. For example, cities with high solar irradiance, such as Shiraz and Bandar Abbas, exhibited the largest absolute reductions in energy consumption, reflecting the enhanced light harvesting capabilities and higher conversion efficiencies achieved by the nanophotovoltaic layers. Conversely, cities with moderate solar exposure, including Qum and Aligudarz, also experienced meaningful reductions, confirming that these advanced photovoltaic materials can improve system performance even under less optimal sunlight conditions (Sheikholeslami and Khalili, 2024).

Moreover, the results highlight not only the reduction in total energy consumption but also the potential for substantial cost savings over the course of a year. The improvements in energy efficiency are primarily attributed to the superior optical and electrical properties of quantum dots, plasmonic nanoparticles, and graphene layers, which increase light absorption, improve charge carrier transport, and reduce reflection and recombination losses. These findings demonstrate that the advantages of nanophotovoltaic systems are robust across different climatic conditions and geographical regions (Singh et al., 2025).

Overall, the simulation outcomes indicate that the deployment of nanomaterial-enhanced photovoltaic systems can lead to consistent and measurable decreases in annual energy usage. The observed reductions reinforce the practical applicability of these technologies in real-world settings and suggest that widespread implementation could play a significant role in reducing energy demand, lowering electricity costs, and supporting sustainable energy initiatives in Iran. (Table 5) presents the energy consumption of the studied cities before and after implementing the nanophotovoltaic systems (Solhtalab et al., 2025).

Table 6. Energy Usage Before and after Installation of the Nanophotovoltaic System, Including Total Annual Energy Consumption (kWh), Grid Electricity Demand (kWh), and Percentage of Energy Demand met by the Nano-PV System, Averaged Across all case Study Buildings

City	Energy Consumption Before (kWh/Year)	Energy Consumption After (kWh/Year)
Tehran	(kWh/Year)	70,000
Isfahan	300,000	225,000
Shiraz	400,000	320,000
Qom	250,000	185,000
Aligudarz	150,000	110,000
Bandar Abbas	350,000	260,000

The following (Table 6) provides a summary of further details on system configuration, types of nanomaterials, energy savings, cost savings, and efficiency results. These outcomes shed light on the performance of several nanomaterial technologies across a range of application types, including commercial, educational, and residential buildings which shows a clear improvement in both cost reduction and energy performance (Solhtalab et al., 2026).

Table 7. Performance Metrics and System Characteristics of the Nanophotovoltaic System Across Different Cities, Including Annual Energy yield (kWh/kWp), Capacity Factor (%), Performance Ratio (%), and Estimated CO² Emissions Reduction (Tons/Year)

City	System Type	Capacity (kW)	Nanomaterial Type	Data Source	Energy Consumption Reduction (%)	Cost Savings (%)	System Efficiency (%)	Initial Consumption (kWh)	Consumption After Installation (kWh)
Tehran	Commercial Building	100	Graphene	Field Data	30	35	28.3	500,000	350,000
Isfahan	Residential Project (50 units)	50	Graphene	Field Data	25	30	27.5	300,000	225,000
Shiraz	Educational Center (10 build-ings)	80	Quantum Dots	Simulation	20	25	18.2	400,000	320,000
Qom	Residential Project (30 units)	40	Plasmonic Nanoparticles	Lab/ Simulation	22	28	22.5	250,000	195,000
Aligudarz	Office Building	60	Graphene	Field Data	18	20	27.5	320,000	234,000
Bandar Abbas	Service Center	90	Quantum Dots + Plasmonic	Combined (Field/ Simulation)	35	38	25.8	480,000	345,000

To Further demonstrate the quantitative data the following figures are presented.

(Figure 6) shows the relationship between system efficiency and nanolayer thickness (100, 150, and 200 nm). Based on the result efficiency rises with thickness until it reaches an ideal value of 200 nm, then material saturation effects cause the rate of improvement to stabilize or even slightly decline(Tan and Li, 2024).

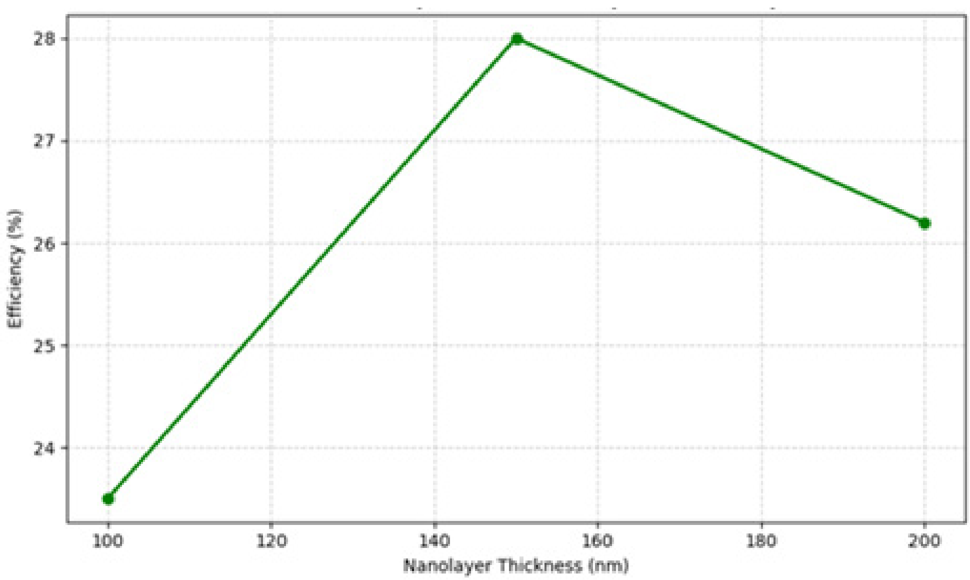

Figure 6. Effect of Nanolayer Thickness on Photovoltaic System Efficiency, Showing Maximum Efficiency of 28.3% Achieved at the Optimal Thickness of 200 nm

(Figure 7) demonstrates the proportion of energy and cost savings achieved in various cities following the installation of nanophotovoltaic systems. The figure demonstrates how nanoparticles can drastically lower operating costs and increase system efficiency (Togun et al., 2025).

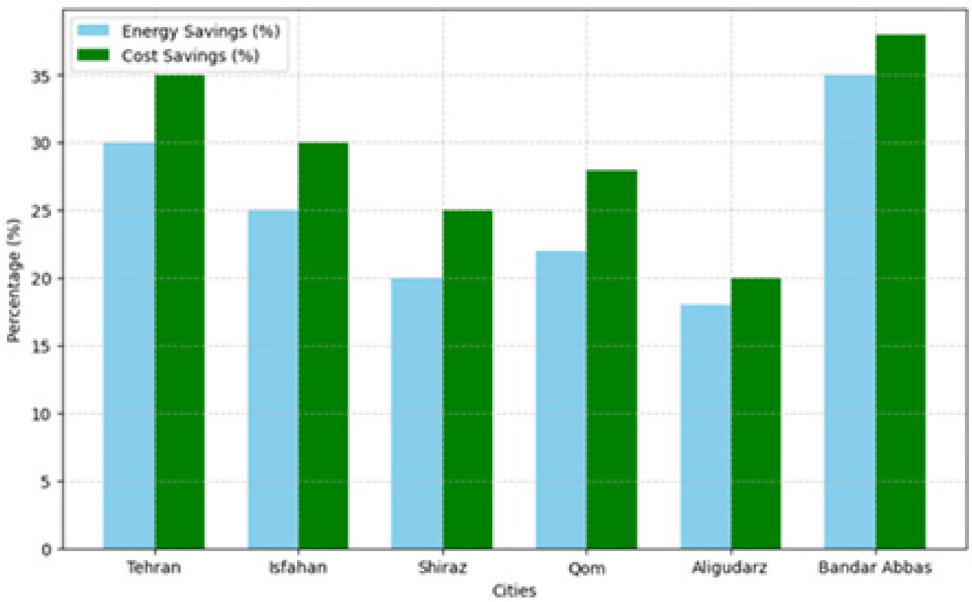

Figure 7. Cost and Energy Savings Comparisons Across Different Cities, Showing Annual Energy Cost Reduction, Payback Period, and Net Savings Over System Lifetime for Nanophotovoltaic Building Integration

7. Considerations and Limitations

In this study, ethical considerations were given particular emphasis to ensure that the research adhered to high standards of sustainability, safety, and integrity. From an environmental and sustainability perspective, the potential impacts of using nanomaterials in photovoltaic systems were carefully evaluated to minimize any adverse effects on the surrounding ecosystem. The design and implementation of the study prioritized the use of sustainable and low-cost materials, as well as environmentally friendly production techniques, to reduce waste generation, energy consumption, and potential environmental hazards. By incorporating these principles, the study aimed to demonstrate that cutting-edge photovoltaic technologies could be developed without compromising ecological balance or contributing to environmental degradation (Unpublished, 2026).

Safety and health considerations were also central to the experimental protocols. Given the potential for nanomaterials to interact with biological systems and pose health risks, stringent measures were taken to protect all researchers and laboratory personnel. This included the mandatory use of personal protective equipment (PPE) such as gloves, lab coats, masks, and eye protection, as well as strict adherence to established safety protocols for handling, storage, and disposal of nanomaterials. Laboratory procedures were designed to minimize exposure to airborne nanoparticles, and proper ventilation systems were utilized to prevent inhalation hazards. These precautions ensured a safe working environment while allowing the research to proceed efficiently and reliably (Venkatesh et al., 2025).

Data confidentiality and integrity were additional ethical priorities. All collected data were carefully anonymized and stored securely to protect participant privacy and prevent the disclosure of any identifying information. Furthermore, the results were documented and reported with transparency, ensuring that all findings were presented accurately and could be independently verified. This approach not only enhanced the credibility of the study but also aligned with internationally recognized ethical standards for research conduct (Wang et al., 2025).

Despite these rigorous measures, the study faced several limitations that should be acknowledged. One primary limitation was the relatively small sample size, which may reduce the generalizability of the findings and necessitate further research with larger datasets to validate the results. In addition, the outcomes could have been influenced by the specific environmental and experimental conditions under which the study was conducted. Conducting similar experiments under a wider range of environmental settings, including varying temperature, humidity, and light conditions, would help enhance the robustness and applicability of the conclusions (Wei et al., 2025).

Measurement uncertainties represent another potential source of limitation. Even under controlled laboratory conditions, minor fluctuations in device performance, instrument calibration errors, and environmental variations can affect the accuracy of experimental results. While these factors were carefully monitored and controlled, their presence highlights the need for repeated measurements and cross-validation in future studies. Additionally, financial and time constraints-imposed restrictions on the use of more advanced or resource-intensive techniques that could have provided higher precision and deeper insights. These limitations underscore the necessity for continued research with expanded resources, improved instrumentation, and broader experimental designs to fully capture the potential of nanomaterials in photovoltaic applications (Yan and Xiang, 2026).

Overall, while ethical and methodological considerations were thoroughly addressed to ensure safety, environmental responsibility, and data integrity, acknowledging these limitations provides a clear pathway for future research. By addressing these constraints, subsequent studies can further enhance the reliability, generalizability, and impact of nanophotovoltaic research, ultimately contributing to the development of more efficient, sustainable, and ethically responsible solar energy technologies.

8. Conclusion

The results of this study clearly demonstrate that the integration of nanomaterials has a substantial and measurable impact on the efficiency of solar cells. Among the various types of nanomaterials investigated, graphene-based photovoltaic cells consistently exhibited superior performance compared to other samples. This enhanced efficiency can be attributed to the unique combination of electrical conductivity, high carrier mobility, and broadband optical absorption inherent to graphene. These properties facilitate faster charge transport, reduce electron-hole recombination, and allow for more effective utilization of incident light, resulting in higher overall energy conversion.

Plasmonic nanoparticles also showed notable improvements in solar cell performance, outperforming quantum dot-based cells in several key metrics. The superior behavior of plasmonic nanoparticles is likely due to their ability to induce localized surface plasmon resonance, which enhances light trapping within the active layers of the cell. This effect increases photon absorption and generates a larger number of electron-hole pairs, directly contributing to improved electrical output. In contrast, while quantum dots demonstrated some efficiency gains due to their tunable bandgap and size-dependent optical properties, their overall performance was lower than that of plasmonic nanoparticle and graphene-based systems under similar experimental conditions.

Importantly, the laboratory findings were consistent with the outcomes of case studies and simulations conducted in six Iranian cities. The correlation between experimental and simulation results confirms that improvements observed under controlled conditions translate effectively to real-world environments. The increase in cell efficiency achieved through the application of nanomaterials corresponded to significant reductions in annual energy consumption, as well as measurable cost savings for end users. These results indicate that optimizing the thickness and configuration of nanolayers is critical to achieving maximum system performance, and that careful design can yield both economic and environmental benefits.

Overall, this research demonstrates that nanomaterials including plasmonic nanoparticles, graphene, and quantum dots offer substantial potential to enhance the efficiency, adaptability, and scalability of photovoltaic systems, particularly in building-integrated solar applications. By increasing energy production per unit area, these advanced materials allow solar technologies to meet higher energy demands within urban environments while simultaneously reducing dependence on conventional energy sources. Furthermore, the findings suggest that the strategic use of nanomaterials can contribute meaningfully to broader sustainability goals, facilitating the transition toward renewable energy and supporting the development of low-carbon, energy-efficient cities.

In conclusion, the combination of experimental analysis and real-world simulations underscores the practical applicability of nanomaterial-enhanced photovoltaic systems. The evidence from this study highlights the importance of material selection, layer optimization, and design considerations in maximizing the performance of solar cells. By leveraging the unique properties of graphene, plasmonic nanoparticles, and quantum dots, it is possible to achieve not only higher energy efficiency and reduced operational costs but also to advance urban sustainability initiatives and promote widespread adoption of renewable energy technologies. These results provide a strong foundation for further research and development aimed at integrating nanomaterials into commercial solar systems and optimizing their performance under diverse environmental conditions.

References

Ahmed, A., Elsakka, M., Elhenawy, Y., Amer, A., Mansi, A., Bassyouni, M., ... & Refaat, A., 2024. Experimental investigation of a nano coating efficiency for dust mitigation on photovoltaic panels in harsh climatic conditions. Sci. Rep. 14, 23013. https://doi.org/10.1038/s41598-024-74000-0.

Ahmed, B.O., Ibrahim, A., Azeez, H.L., Jaber, M., Al-Waeli, A.H., & Jarimi, H., 2025. 4E investigation of a solar collector design featuring ribs, petals, and helical twisted tapes in a photovoltaic thermal system. Arab. J. Sci. Eng. 1-20. https://doi.org/10.1007/s13369-025-09876-5.

Ahmed, S., Ali, A., Ansari, J.A., Qadir, S.A., & Kumar, L., 2025. A comprehensive review of solar photovoltaic systems: scope, technologies, applications, progress, challenges and recommendations. IEEE Access. https://doi.org/10.1109/ACCESS.2025.3541234.

Ahmed, Y.E., Maghami, M.R., Pasupuleti, J., Danook, S.H., & Basim Ismail, F., 2024. Overview of recent solar photovoltaic cooling system approach. Technologies 12, 171. https://doi.org/10.3390/technologies12090171.

Alazwari, M.A., Basem, A., AL-bonsrulah, H.A., Almitani, K.H., Abu-Hamdeh, N.H., Albdeiri, M.S., ... & Egami, R.H., 2024. Assessment of photovoltaic system in existence of nanomaterial cooling flow. Results Eng. 24, 103264. https://doi.org/10.1016/j.rineng.2024.103264.

Ali, A.A., Lafta, D.A., Noori, S.W., Abdulamir, F., & Rashid, F.L., 2024. Innovative materials integrated with PCM for enhancing photovoltaic panel efficiency: an experimental investigation. J. Energy Storage 102, 114258. https://doi.org/10.1016/j.est.2024.114258.

Alinia, A.M., & Sheikholeslami, M., 2025. Development of a new solar system integrating photovoltaic and thermoelectric modules with paraffin-based nanomaterials. Sci. Rep. 15, 1336. https://doi.org/10.1038/s41598-025-85678-9.

Alqatamin, A., & Jinzhan, S., 2025. Numerical analysis and design of photovoltaic-thermal (PVT) system with novel water-cooling channel structure integrated with perforated V-shape fins. Renew. Energy 243, 122587. https://doi.org/10.1016/j.renene.2025.122587.

Applied Energy, 2026. Application of transparent and semi-transparent photovoltaics in building windows: a review. Appl. Energy 405, 127264. https://doi.org/10.1016/j.apenergy.2025.127264.

Arévalo, P., Ochoa-Correa, D., & Villa-Ávila, E., 2024. Towards energy efficiency: innovations in high-frequency converters for renewable energy systems and electric vehicles. Vehicles 7, 1. https://doi.org/10.3390/vehicles7010001.

Arun, M., Samal, S., Barik, D., Chandran, S.S., Tudu, K., & Praveenkumar, S., 2025. Integration of energy storage systems and grid modernization for reliable urban power management toward future energy sustainability. J. Energy Storage 114, 115830. https://doi.org/10.1016/j.est.2025.115830.

Attia, M.E.H., Abdel-Aziz, M.M., & Khelifa, A., 2025. A numerical approach to enhance the performance of double-pass solar collectors with finned photovoltaic/thermal integration. Appl. Therm. Eng. 268, 125974. https://doi.org/10.1016/j.applthermaleng.2025.125974.

Baharizade, M., Ghetmiri, S.I., Mohammady, M., Mohammadi-Samani, S., & Yousefi, G., 2024. Revolutionizing knee osteoarthritis treatment: innovative self-nano-emulsifying polyethylene glycol organogel of curcumin for effective topical delivery. AAPS PharmSciTech 25, 80. https://doi.org/10.1208/s12249-024-02791-6.

Balachandran, P.K., Thanikanti, S.B., Ayodele, B.V., Fahrioglu, M., & Nwulu, N., 2024. Attainment of SDGs through the advancement in solar PV systems. Front. Energy Res. 12, 1451373. https://doi.org/10.3389/fenrg.2024.1451373.

Basil, N., Marhoon, H.M., Hayal, M.R., Elsayed, E.E., Nurhidayat, I., & Shah, M.A., 2024. Black-hole optimisation algorithm with FOPID-based automation intelligence photovoltaic system for voltage and power issues. Aust. J. Electr. Electron. Eng. 21, 115-127. https://doi.org/10.1080/1448837X.2024.2315678.

Benghanem, M., Attia, M.E.H., Abdelgaied, M., Harby, K., & Bedairi, B.H., 2025. A multifaceted experimental approach for enhancing solar distiller productivity: Nano-coated heat coil integrated with solar nanofluid collector, nano-coated absorber, nano-enhanced PCM, reflectors, and PV panels. Int. Commun. Heat Mass Transf. 167, 109401. https://doi.org/10.1016/j.icheatmasstransfer.2025.109401.

Bhardwaj, M., Prakash, N., & Mahlotra, R.K., 2025. Green nanotechnology innovations for achieving India's sustainable development goals by 2030, in: Sustainable Economy Models in the Age of Industry 5.0. Springer, pp. 179-197. https://doi.org/10.1007/978-3-031-67890-5_10.

Cao, X., Chen, Y., Yu, F., Qi, Y., Zhang, H., Liu, S.F., & Zhang, S., 2025. Perovskite solar cells with integrated light management and high crystallinity based on triple optical micro/nano structures. Chem. Eng. J. 505, 159267. https://doi.org/10.1016/j.cej.2025.159267.

Chen, H., Liu, X., Liu, J., Wang, F., & Wang, C., 2025. Radiative cooling applications toward enhanced energy efficiency: system designs, achievements, and perspectives. The Innovation. https://doi.org/10.1016/j.xinn.2025.100789.

Chen, H., Zhang, J., Shen, M., Fang, H., & Ma, Y., 2024. Comprehensive numerical modeling of intermittent flow cooling with enhanced photovoltaic efficiency in PVT/NPCM systems. Case Stud. Therm. Eng. 58, 104420. https://doi.org/10.1016/j.csite.2024.104420.

Chen, Q., et al., 2025. Advancing solar energy applications with graphene: the potential of minimally oxidized graphene. Nano Converg. 12, 30. https://doi.org/10.1186/s40580-025-00478-9.

Cui, T., Ang, E.H., Zheng, Y., Cai, W., Wang, J., Hu, Y., & Zhu, J., 2024. Ultrahigh transparent safety film for spectrally selective photo/electrothermal conversion via surface-enhanced plasma resonance dynamics. Nano Lett. 24, 11904-11912. https://doi.org/10.1021/acs.nanolett.4c03456.

Dabare, S., Rajapaksha, S., & Munaweera, I., 2025. Sustainable innovation in nanotechnology-based water treatment: aligning climate change adaptation with industrial ecology and CSR goals. Environ. Sci.: Water Res. Technol. 11, 2100-2124. https://doi.org/10.1039/D5EW00123K.

Dhahi, T.S., Dafhalla, A.K.Y., Tayfour, O.E., Mubarakali, A., Alqahtani, A.S., Ahmed, A.E.T., ... & Gopinath, S.C., 2024. Advances in nano sensors for monitoring and optimal performance enhancement in photovoltaic cells. iScience 27, 109456. https://doi.org/10.1016/j.isci.2024.109456.

El Karch, H., El Gouri, R., Natij, Y., Benally, M., & Mezouari, A., 2024. AI-based smart real-time PV panels soiling recognizing system using deep neural network framework on NVIDIA Jetson Nano embedded GPU. Ingénierie des Systèmes d'Information 29, 1687-1698. https://doi.org/10.18280/isi.290512.

Elamin, A.E.A., 2024. Thermal management of photovoltaic thermal (PVT) system for improving electrical performance. J. Therm.

Anal. Calorim. 149, 12417-12427. https://doi.org/10.1007/s10973-024-13678-9.

Elkelawy, M., M El-Ashmawy, W., & Ahmed, S.M., 2024. State of the art in concentrated solar power: latest technological advancements and innovations in efficiency and energy storage. Pharos Eng. Sci. J. 1, 17-28. https://doi.org/10.21608/pesj.2024.345678.

El-Khateeb, A.Y., Hesham, A., Deyaa, A., Salama, A., Youssuf, A., Ahmed, F., ... & Rabie, M.M., 2025. From nanotechnology concepts to pioneering patents: innovations in nanotherapeutic nutrition. J. Agric. Food Environ. 6, 19-38.

Fraunhofer FEP, 2025a. Roll-to-roll nanoimprint lithography for design applications and more efficient photovoltaics. Fraunhofer Institute for Electron Beam and Plasma Technology FEP, Press Release 01/2025.

Fraunhofer FEP, 2025b. Aesthetic and efficient facades: Fraunhofer FEP presents advances in building-integrated photovoltaics. Fraunhofer Institute for Electron Beam and Plasma Technology FEP, Press Release 06/2025.

Ghamari, M., & Sundaram, S., 2024. Solar window innovations: enhancing building performance through advanced technologies. Energies 17, 3369. https://doi.org/10.3390/en17143369.

Goyal, P., Agarwal, M.B., Mehrotra, M., Panday, M.K., Ali, S., Jadon, V.K., & Agarwal, S., 2024. Nanomaterials revolutionizing nano-electronics unleashing potential, in: Discovery, Disruption, and Future Implications of Nanomaterials. IGI Global, pp. 219-248. https://doi.org/10.4018/979-8-3693-4567-8.ch010.

Huang, H., et al., 2025. Synergistic approach of energy generation and conservation in buildings exploiting semitransparent organic photovoltaic windows globally. Nano Energy 142, 111181. https://doi.org/10.1016/j.nanoen.2025.111181.

Ibrahim, T., Abou Akrouch, M., Hachem, F., Ramadan, M., Ramadan, H.S., & Khaled, M., 2024. Cooling techniques for enhanced efficiency of photovoltaic panels—comparative analysis with environmental and economic insights. Energies 17, 713. https://doi.org/10.3390/en17030713.

Ioannou, I.I., Javaid, S., Christophorou, C., Vassiliou, V., Pitsillides, A., & Tan, Y., 2024. A distributed AI framework for nano-grid power management and control. IEEE Access 12, 43350-43377. https://doi.org/10.1109/ACCESS.2024.3378901.

Iqbal, M.T., Saeeda, S., Zahra, T., Umar, Z., Khan, W.Z., Adnan, M., ... & Toffique, M., 2025. Next-generation materials discovery using DFT: functional innovation. Sch. J. Eng. Tech. 7, 454¢486.

Iturralde Carrera, L.A., Garcia-Barajas, M.G., Constantino-Robles, C.D., Álvarez-Alvarado, J.M., Castillo-Alvarez, Y., & Rodríguez-Reséndiz, J., 2025. Efficiency and sustainability in solar photovoltaic systems: a review of key factors and innovative technologies. Eng 6, 50. https://doi.org/10.3390/eng6030050.

Jathar, L.D., Nikam, K., Awasarmol, U.V., Gurav, R., Patil, J.D., Shahapurkar, K., ... & Ağbulut, Ü., 2024. A comprehensive analysis of the emerging modern trends in research on photovoltaic systems and desalination in the era of artificial intelligence and machine learning. Heliyon 10, e24680. https://doi.org/10.1016/j.heliyon.2024.e24680.

Jin, J., Du, B., et al., 2026. Smart and colorful multifunctional perovskite solar cells for advanced applications. Chem. Eng. J. https://doi.org/10.1016/j.cej.2026.156789.

Kargaran, M., Goshayeshi, H.R., & Jajarm, A.R.A., 2024. A novel integrated photovoltaic system with a three-dimensional pulsating heat pipe. Front. Heat Mass Transf. 22, 1461-1476. https://doi.org/10.32604/fhmt.2024.056789.

Kargaran, M., Goshayeshi, H.R., Saleh, S.R., Zahmatkesh, I., & Chaer, I., 2024. Energy and exergy analysis of photovoltaic systems integrated with pulsating heat pipe and hybrid nanofluids. Therm. Sci. Eng. Prog. 55, 102975. https://doi.org/10.1016/j.tsep.2024.102975.

Kazaz, O., & Abu-Nada, E., 2025. Thermal performance of nano-architected phase change energetic materials for a next-generation solar harvesting system. Energy Convers. Manag. 327, 119541. https://doi.org/10.1016/j.enconman.2025.119541.

Kazem, H.A., Chaichan, M.T., Al-Waeli, A.H., & Sopian, K., 2024. Dual axis solar photovoltaic trackers: an in-depth review. Energy Sources, Part A: Recovery, Util. Environ. Eff. 46, 15331-15356. https://doi.org/10.1080/15567036.2024.2405678.

Khalid, W., Jamil, M., Khan, A.A., & Awais, Q., 2024. Open-source internet of things-based supervisory control and data acquisition system for photovoltaic monitoring and control using HTTP and TCP/IP protocols. Energies 17, 4083. https://doi.org/10.3390/en17164083.

Khan, S., Sudhakar, K., Hazwan Yusof, M., & Sundaram, S., 2024. Review of building integrated photovoltaics system for electric vehicle charging. Chem. Rec. 24, e202300308. https://doi.org/10.1002/tcr.202300308.

Khan, S.Y., Rauf, S., Liu, S., Chen, W., Shen, Y., & Kumar, M., 2025. Revolutionizing solar photovoltaic efficiency: a comprehensive review of cutting-edge thermal management methods for advanced and conventional solar photovoltaic. Energy Environ. Sci. https://doi.org/10.1039/D5EE00123K.

Khelifa, A., Abdelgaied, M., Harby, K., & Attia, M.E.H., 2024. Performance improvement of photovoltaic/thermal collectors based on the optimized design of efficient innovative multiple-impinging slot jets. Sol. Energy 283, 112992. https://doi.org/10.1016/j.solener.2024.112992.

Kiaghadi, M., Keshvarinia, M., Boora, F.M., & Mousavi, S.M., 2024. Machine learning applications for predicting liquid fraction in a PV system with NEPCM and fins. Case Stud. Therm. Eng. 61, 104819. https://doi.org/10.1016/j.csite.2024.104819.

Kim, H.-Y., et al., 2025. Modulating localized surface plasmon resonance through metal composition and nanoparticle shape: implications for solar cell applications. Int. J. Mater. Res. 136. https://doi.org/10.1515/ijmr-2024-0123.

Kumar, A., Tyagi, P.K., Tyagi, S., & Ghorbanpour, M., 2024. Integrating green nanotechnology with sustainable development goals: a pathway to sustainable innovation. Discov. Sustain. 5, 364. https://doi.org/10.1007/s43621-024-00678-9.

Kyei, S.K., Boateng, H.K., & Frimpong, A.J., 2025. Renewable energy innovations: fulfilling SDG targets. Clean Energy 9, 190-203. https://doi.org/10.1093/ce/zkae078.

Lanani, A., Djamai, D., Beddiaf, A., Saidi, A., & Abboudi, A., 2024. Photovoltaic system faults detection using fractional multiresolution signal decomposition. Electr. Eng. Electromech. 4, 48-54. https://doi.org/10.20998/2074-272X.2024.4.07.

Li, P., Kim, S., & Tian, B., 2024. Beyond 25 years of biomedical innovation in nano-bioelectronics. Device 2, 100456. https://doi.org/10.1016/j.device.2024.100456.

Lima-Téllez, T., Hinojosa, J.F., Hernçndez-Lçpez, I., & Moreno, S., 2024. Numerical study of the thermal performance of a single-channel cooling PV system using baffles and different nanofluids. Heliyon 10, e34567. https://doi.org/10.1016/j.heliyon.2024.e34567.

Liu, Y., et al., 2026. Scalable semitransparent organic solar cells with robust film thickness tolerance for building-integrated photovoltaics. Nat. Commun. 17, 2916. https://doi.org/10.1038/s41467-026-35678-9.

Mahmoud, S.A., Atia, B.M., Amin, L.G., & Abdalla, M., 2025. Innovative preparation of multi-dentate Schiff base adsorbent for the adsorption of silver and its application on nano silver particles preparation from liquid photographic wastes. J. Chem. Technol. Biotechnol. 100, 448-465. https://doi.org/10.1002/jctb.7765.

Mahmoudi, F., Ng, D., Ang, K., & Xie, Z., 2024. Sustainable desalination through hybrid photovoltaic/thermal membrane distillation:

development of an off-grid prototype. Sol. Energy 284, 113090. https://doi.org/10.1016/j.solener.2024.113090.

Maseer, M.M., Ismail, F.B., Kazem, H.A., Hachim, D.M., Al-Gburi, K.A.H., & Chaichan, M.T., 2024. Performance enhancement of photovoltaic/thermal collector semicircle absorber tubes using nanofluid and NPCM. Renew. Energy 233, 121152. https://doi.org/10.1016/j.renene.2024.121152.

Mechai, I., Almarashi, A., Hamali, W., Almusawa, M.Y., Qahiti, R., Al-Bonsrulah, H.A., & Elbashir, N.B., 2024. Simulation of integration of photovoltaic solar system with storage unit incorporating mixture of paraffin and nanoparticles. J. Energy Storage 82, 110513. https://doi.org/10.1016/j.est.2024.110513.

Meinardi, F., et al., 2025. The new generation of luminescent solar concentrators for building-integrated photovoltaic. NanoInnovation 2025 Conference, TS.V.B.1.

Miglani, A., Ogale, S.B., & Game, O.S., 2025. Architectural innovations in perovskite solar cells. Small 21, 2411355. https://doi.org/10.1002/smll.202411355.

Moulefera, I., Marín, J.D., Cascales, A., Montalbán, M.G., Alarcón, M., & Víllora, G., 2025. Innovative application of graphene nanoplatelet-based ionanofluids as heat transfer fluid in hybrid photovoltaic-thermal solar collectors. Sci. Rep. 15, 6489. https://doi.org/10.1038/s41598-025-89012-1.

Ogundipe, O.B., Okwandu, A.C., & Abdulwaheed, S.A., 2024. Recent advances in solar photovoltaic technologies: efficiency, materials, and applications. GSC Adv. Res. Rev. 20, 159-175. https://doi.org/10.30574/gscarr.2024.20.1.0267.

Rabbi, M.S., 2025. Design of fire-resilient solar inverter systems for wildfire-prone US regions. Unpublished results.

Radhi, F.A., Ibrahim, A., Azeez, H.L., Fazlizan, A., Sopian, K., Ali, A.A., & Al-Aasam, A.B., 2025. Experimental analysis of a photovoltaic thermal collector utilizing a novel spring insert in a micro-fin absorber tube with twisted tape, nanofluid, and nanophase change material integration. Appl. Therm. Eng. 269, 126128. https://doi.org/10.1016/j.applthermaleng.2025.126128.

Rahman, M.A., Hasnain, S.M., Paramasivam, P., Zairov, R., & Ayanie, A.G., 2025. Solar drying for domestic and industrial applications: a comprehensive review of innovations and efficiency enhancements. Glob. Chall. 9, 2400301. https://doi.org/10.1002/gch2.202400301.

Rahmatian, M., & Sayyaadi, H., 2024. A systematic review of a photoelectrical innovation: dye-sensitized solar cells. Int. J. Ambient Energy 45, 2366538. https://doi.org/10.1080/01430750.2024.2366538.

Rajamony, R.K., Pandey, A.K., Sofiah, A.G.N., Paw, J.K.S., Suraparaju, S.K., Fatehmulla, A., ... & Farade, R.A., 2025. Experimental investigation of carbon-based nano-enhanced phase change materials assimilated photovoltaic thermal system: energy, exergy and environmental assessment. J. Taiwan Inst. Chem. Eng. 167, 105835. https://doi.org/10.1016/j.jtice.2025.105835.

Renjith, P.N., Alfurhood, B.S., Prashanth, K.V., Patil, V.S., Sharma, N., & Chaturvedi, A., 2024. Coordination of modular nano grid energy management using multi-agent AI architecture. Comput. Electr. Eng. 115, 109112. https://doi.org/10.1016/j.compeleceng.2024.109112.

Saxena, A., Agarwal, N., & Norton, B., 2025. Design and performance characteristics of an innovative heat sink structure with phase change material for cooling of photovoltaic system. Energy Sources, Part A: Recovery, Util. Environ. Eff. 47, 10721-10745. https://doi.org/10.1080/15567036.2025.2487890.

Sayed, M.A., Ahmed, M.M., Azlan, W., & Kin, L.W., 2024. Peer to peer solar energy sharing system for rural communities. Clean. Energy Syst. 7, 100102. https://doi.org/10.1016/j.cles.2024.100102.

Selimefendigil, F., Benabdallah, F., Ghachem, K., Albalawi, H., Alshammari, B.M., & Kolsi, L., 2024. Effects of using sinusoidal porous object (SPO) and perforated porous object (PPO) on the cooling performance of nano-enhanced multiple slot jet impingement for a conductive panel system. Propuls. Power Res. 13, 166-177. https://doi.org/10.1016/j.jppr.2024.03.005.

Sharaby, M.R., Younes, M., Baz, F., & Abou-Taleb, F., 2024. State-of-the-art review: nanofluids for photovoltaic thermal systems. J. Contemp. Technol. Appl. Eng. 3, 11-24.

Sheikholeslami, M., & Alinia, A.M., 2025. Energy management in a concentrated solar photovoltaic panel with a thermoelectric module and nanomaterial-filled storage tank. Energy 136439. https://doi.org/10.1016/j.energy.2025.136439.

Sheikholeslami, M., & Khalili, Z., 2024. Enhancing photovoltaic solar panel performance with integration of PCM-based spectral filter and self-cleaning coating. J. Build. Eng. 94, 110019. https://doi.org/10.1016/j.jobe.2024.110019.

Singh, A.K., Singh, V., & Anand, P.I., 2025. An innovative laser decal transfer of ZnO ceramic in LIG for advanced hybrid nanogenerator applications. Ceram. Int. 51, 4957-4970. https://doi.org/10.1016/j.ceramint.2024.11.456.

Solhtalab, A., et al., 2025. Highly efficient 4T lead-free all perovskite tandem solar cell with plasmonic nanoparticles in the bottom sub-cell. Sol. Energy 300, 113824. https://doi.org/10.1016/j.solener.2025.113824.

Solhtalab, A., et al., 2026. Performance enhancement of perovskite solar cells through plasmonic titanium nitride nanoparticles. Sci. Rep. 16, 7182. https://doi.org/10.1038/s41598-026-84567-8.

Tan, X., & Li, Y., 2024. Innovations and challenges in semi-transparent perovskite solar cells: a mini review of advancements toward sustainable energy solutions. J. Compos. Sci. 8, 458. https://doi.org/10.3390/jcs8110458.

Togun, H., Basem, A., Jweeg, M.J., Mohammed, H.I., Abed, A.M., Anqi, A.E., ... & Biswas, N., 2025. Development and innovation using PCM in PV cooling systems: passive and active approaches. J. Therm. Anal. Calorim. 1-36. https://doi.org/10.1007/s10973-025-13956-0.

Unpublished, 2026. Synergistic plasmonic enhancement in PM6:Y6 organic solar cells using hybrid gold nanostars and gold nanoparticles embedded in the AZO electron transport layer. Phys. Chem. Chem. Phys., Advance Article.

Venkatesh, R., Logesh, K., Vinayagam, M., Prabagaran, S., Chaturvedi, R., Hossain, I., ... & Al Obaid, S., 2025. Hybrid photovoltaic solar system performance enriched by adaptation of silicon carbide made porous medium. Electr. Eng. 107, 3271-3283. https://doi.org/10.1007/s00202-024-02678-9.

Wang, S., Wang, L., Zhang, J., Gao, H., Xiao, M., & Song, H., 2025. Third-component engineering in organic solar cells: material innovations, morphological control, and synergistic enhancement. Nano Energy 111329. https://doi.org/10.1016/j.nanoen.2025.111329.

Wei, J., Chen, H., Liu, J., Wang, F., & Wang, C., 2025. Radiative cooling technologies toward enhanced energy efficiency of solar cells: materials, systems, and perspectives. Nano Energy 110680. https://doi.org/10.1016/j.nanoen.2025.110680.

Yan, Y., & Xiang, C., 2026. Life cycle carbon footprint and sustainability assessment of building-integrated photovoltaics: a comparative review of technologies and applications. Energy Build. 350, 116678. https://doi.org/10.1016/j.enbuild.2025.116678.

نوآوری در سیستم های نانو فتوولتائیک برای تبدیل انرژی در ساختمان‌ها

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چکیـــــده

این پژوهش نقش نانومواد پیشرفته، مانند کوانتوم‌دات‌ها، نانوذرات فلزی و گرافن را در افزایش بازده و عملکرد کلی سامانه‌های فتوولتاییک امروزی بررسی می‌کند. با افزایش تقاضای جهانی برای انرژی پاک و پایدار، توسعه سلول‌های خورشیدی پربازده به یک موضوع پژوهشی مهم تبدیل شده است. نانومواد به دلیل ویژگی‌های خاص نوری، الکتریکی و ساختاری خود، فرصت‌های تازه‌ای برای بهبود جذب نور، افزایش تحرک حامل‌های بار و ارتقای سازوکارهای تبدیل انرژی در سلول‌های خورشیدی ایجاد می‌کنند. هدف اصلی این پژوهش، بررسی تأثیر این نانومواد بر عملکرد سلول‌های خورشیدی و شناسایی ویژگی‌های مناسب مواد و پارامترهای ساختاری است که بیشترین بازده تبدیل را فراهم می‌کنند.
برای رسیدن به این هدف، یک فرایند شناسایی جامع با استفاده از مجموعه‌ای از روش‌های پیشرفته انجام شد. طیف‌سنجی UV- Vis برای بررسی رفتار جذب نوری نانومواد و چگونگی تعامل آن‌ها با نور در طول‌موج‌های مختلف به کار گرفته شد. میکروسکوپ الکترونی روبشی (SEM) تصاویر دقیق و با وضوح بالا ارائه داد که امکان بررسی شکل سطح، نحوه پخش ذرات و یکنواختی ساختاری لایه‌های ساخته‌شده را فراهم کرد. همچنین از میکروسکوپ نیروی اتمی (AFM) برای مطالعه ساختار سطح در مقیاس نانو و اندازه‌گیری زبری سطح که بر انتقال بار و پخش نور تأثیر می‌گذارد، استفاده شد. مجموع این روش‌ها به درک بهتر ویژگی‌های فیزیکی مؤثر بر عملکرد فتوولتاییکی هر نانوماده کمک کرد.

تحلیل داده‌ها با استفاده از آنالیز واریانس یک‌طرفه (Oneway ANOVA) و رگرسیون خطی انجام شد تا اهمیت آماری پارامترهای کلیدی مانند ضخامت نانولایه و زاویه تابش نور مشخص شود. نتایج نشان داد که هر دو پارامتر تأثیر قابل‌توجهی بر بازده دستگاه دارند و این مسئله بر اهمیت کنترل دقیق لایه‌نشانی و طراحی سلول تأکید می‌کند. نتایج همچنین نشان دادند که افزودن نانومواد به سلول‌های خورشیدی باعث بهبود چشمگیر عملکرد می‌شود. به‌ویژه، سلول‌های خورشیدی مبتنی بر گرافن به بازده حدود ۲۸/۳ ± ۰/۳ درصد رسیدند که نسبت به طراحی‌های معمول افزایش قابل‌توجهی است. کوانتوم‌دات‌ها و نانوذرات فلزی نیز باعث افزایش جذب نور و بهبود جدایش حامل‌های بار شدند و پتانسیل آن‌ها را به‌عنوان مواد مؤثر برای نسل جدید سلول‌های خورشیدی تأیید کردند.

در مجموع، این نتایج نشان می‌دهند که نانومواد می‌توانند نقش مهمی در رفع محدودیت‌های موجود در مواد و طراحی‌های سنتی سلول‌های خورشیدی داشته باشند. با بهینه‌سازی ویژگی‌های نانومقیاس و ساختار دستگاه، می‌توان سلول‌هایی ساخت که علاوه بر راندمان بیشتر، مقرون‌به‌صرفه‌تر و سازگارتر با محیط‌زیست باشند. این پژوهش بر ضرورت ادامه تحقیقات در زمینه تولید نانومواد، ادغام آن‌ها در ساختار سلول و ارزیابی عملکرد بلندمدت تأکید می‌کند و مسیر را برای پیشرفت‌های نوآورانه و پایدار در حوزه انرژی خورشیدی هموار می‌سازد.

واژگان کلیدی: نانومواد، راندمان فتوولتائیک، گرافن، سلول‌های خورشیدی