



Nano-PV: Estimation and Mitigation of Soiling Effects on Photovoltaic Systems Using Nanomaterials

*A project submitted
in partial fulfillment of the requirements for the degree of
Bachelor in Electrical Power Engineering*

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PLEDGE

This is to declare that the project entitled **“Nano-PV: Estimation and Mitigation of Soiling Effects on Photovoltaic Systems Using Nanomaterials”** is an original work done by undersigned, in partial fulfillment of the requirements for the bachelor's degree at **Electrical Power engineering and Mechatronics department, College of Engineering, Tafila Technical University.**

All the analysis, design, and system development have been accomplished by the undersigned. Moreover, this project has not been submitted to any other college or university.

ABSTRACT

The increasing dependence on solar photovoltaic (PV) systems as a renewable energy source has highlighted several operational challenges, among which panel soiling is one of the most significant. Dust accumulation on PV panels reduces solar irradiance transmission, leading to decreased power generation efficiency, increased maintenance requirements, and economic losses, especially in arid and dusty environments such as Jordan. This project presents an integrated approach for estimating and mitigating the effects of soiling on photovoltaic systems using nanomaterial-based coatings and smart monitoring techniques at Tafila Technical University campus.

The proposed system combines environmental sensing, photovoltaic performance monitoring, and nanotechnology to improve PV system reliability and efficiency. Different nanomaterial coatings, including hydrophobic and self-cleaning materials, are evaluated for their effectiveness in reducing dust accumulation and maintaining panel transparency. In addition, a low-cost smart monitoring system is developed using environmental sensors and PV output measurements to estimate the soiling factor in real time. Machine learning techniques are also investigated to predict soiling levels and optimize cleaning schedules. The project aims to analyze the relationship between environmental conditions and PV performance degradation while comparing coated and uncoated solar panels under real operating conditions. Furthermore, a techno-economic analysis is performed to evaluate the feasibility of the proposed solution in reducing maintenance costs and improving energy yield.

The expected outcomes of this project include enhanced understanding of soiling behavior on PV systems, improved panel efficiency through nanocoating's, reduced unnecessary cleaning operations, and the development of a smart framework for sustainable PV maintenance. The findings of this study can contribute to improving the performance and operational management of solar energy systems in regions affected by high dust accumulation.

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CHAPTER 1: Introduction

1.1 Overview

Solar photovoltaic systems are considered one of the most important renewable energy technologies used to generate clean electrical energy from sunlight. The increasing demand for sustainable energy sources has encouraged the wide installation of photovoltaic systems in residential, commercial, and industrial applications. However, the performance of photovoltaic panels is highly affected by environmental conditions such as temperature, humidity, shading, and dust accumulation [1], [2].

One of the major challenges that reduces the efficiency of photovoltaic systems is soiling, which refers to the accumulation of dust, dirt, sand particles, and other contaminants on the surface of solar panels. When dust covers the glass surface of a PV module, it reduces the amount of solar irradiance reaching the solar cells. As a result, the generated current decreases, and the overall output power of the system is reduced [1], [2]. This problem becomes more serious in dry and dusty regions, where dust accumulation occurs frequently and cleaning may require large amounts of water, labor, and maintenance cost [3], [6].

Nanotechnology has recently become a promising solution for reducing soiling losses in photovoltaic systems. Nanomaterials can be used as surface coatings to improve the selfcleaning, hydrophobic, anti-dust, or anti-reflective properties of PV panels. By applying a nanomaterial coating on the surface of a solar panel, dust adhesion can be reduced, allowing the panel to maintain better optical transparency and higher power output compared with an uncoated panel [8], [9].

This project focuses on estimating and mitigating the effects of soiling on photovoltaic systems using nanomaterials. The project is mainly based on experimental work and measured data analysis. In the experimental part, two similar photovoltaic panels are tested under the same outdoor conditions. One panel is coated with a nanomaterial, while the other panel remains uncoated and is used as a reference. The voltage, current, and output power of both panels are measured and compared under different controlled soiling levels.

1.2 Project Motivation

The main motivation behind this project is the noticeable reduction in photovoltaic system performance due to dust accumulation, especially in countries with dry climates such as Jordan and other Middle Eastern regions. Solar energy is widely available in these regions, but the high level of dust and sand particles can significantly reduce the energy produced by PV panels [1], [2], [3].

Traditional cleaning methods are usually based on manual washing or water-based cleaning. Although these methods can restore part of the lost performance, they may not always be practical. They require repeated maintenance, consume water, increase operating cost, and may not be suitable for remote solar installations. Therefore, there

is a need for a more effective and passive method that can reduce dust accumulation without continuous manual cleaning [3], [6].

The proposed idea of this project is to investigate the use of nanomaterial coating as a mitigation method for soiling effects. The project is important because it combines practical measurement with experimental data analysis to evaluate whether nanomaterials can improve the performance of photovoltaic panels under dusty conditions [8], [9].

1.3 Problem Statement

Photovoltaic panels depend on the amount of solar radiation reaching their surface. When dust and dirt accumulate on the panel surface, they block part of the incident sunlight and reduce the optical transmittance of the glass cover. This leads to a reduction in the generated current and output power of the PV module. Over time, soiling can cause significant energy losses, especially when cleaning is not performed regularly [1], [2], [3].

The main problem addressed in this project is the reduction of photovoltaic performance due to soiling. In dusty environments, PV panels may lose a considerable percentage of their output power because of dust deposition. This loss affects the reliability, efficiency, and economic feasibility of solar energy systems [1], [3].

Another issue is that conventional cleaning methods are not always efficient or sustainable. Frequent cleaning requires water, labor, time, and maintenance planning. In some locations, water availability is limited, which makes regular cleaning more difficult [6]. Therefore, this project investigates the use of nanomaterial coating as a possible solution to reduce dust adhesion and improve PV panel performance.

1.4 Project Aim and Objectives

The main aim of this project is to estimate the effect of soiling on photovoltaic system performance and to investigate the ability of nanomaterials to mitigate this effect.

The project aims to achieve this goal by comparing the electrical performance of two photovoltaic panels: one coated with a nanomaterial and one uncoated reference panel. The comparison will be based on measured voltage, current, and power output under the same outdoor conditions in addition, the measured data will be organized in tables and graphs to support the experimental analysis.

The main objectives of this project are:

1. To study the effect of dust accumulation on photovoltaic panel performance.
2. To apply a nanomaterial coating on the surface of one photovoltaic panel.
3. To compare the performance of a coated PV panel with an uncoated PV panel.
4. To measure voltage, current, and output power for both panels under similar environmental conditions.
5. To calculate the power improvement achieved by using nanomaterial coating.

6. To analyze the measured data using tables and graphs.
7. To evaluate the relationship between soiling level and PV output power.
8. To evaluate the effectiveness of nanomaterials as a passive mitigation technique for PV soiling.

1.5 Project Scope

The scope of this project is limited to the study of soiling effects on small-scale photovoltaic panels and the use of nanomaterial coating as a mitigation method. The project includes experimental work, measured data analysis, and performance comparison.

The experimental work is based on two similar photovoltaic panels installed under the same environmental conditions. One panel is coated with a nanomaterial, while the second panel remains without coating and is used as a reference. The measured electrical parameters include voltage, current, and output power. These values will be used to compare the performance of the coated and uncoated panels.

This project does not include a full economic feasibility study or a long-term durability test of nanomaterial coating. Also, the project does not study all possible types of nanomaterials. The analysis is limited to the available coating material, the available PV panels, and the measurement period of the project.

1.6 Project Hardware Requirements

This project requires hardware components to perform the experimental work, data recording, data analysis, and report preparation.

1.6.1 Hardware Requirements

The main hardware components required for this project are:

1. Two similar photovoltaic panels.
2. Nanomaterial coating.
3. Batteries.
4. Charge controllers.
5. Connecting wires and terminals.
6. Measuring devices such as multimeter, voltmeter, or ammeter.
7. Supporting frame or mounting structure.

1.7 Project Limitations

This project has several limitations that should be considered during the analysis of the results. First, the experimental measurements are affected by outdoor environmental conditions such as solar irradiance, temperature, wind speed, humidity, and dust concentration. These conditions may change during the measurement period and may affect the accuracy of the comparison.

Second, the measurement period is limited due to the available project time. A longer testing period would provide more accurate information about the long-term effectiveness and durability of the nanomaterial coating. Long-term testing is important because anti-soiling coating performance depends on coating type, environmental exposure, dust characteristics, and durability [8], [9].

Third, the project depends on the available measuring instruments. If advanced instruments such as a pyranometer or temperature sensors are not available, the analysis will mainly depend on voltage, current, and power measurements.

Fourth, the project is limited to the specific type of nanomaterial used in the experiment. Therefore, the results may not represent the performance of all nanomaterial coatings used in photovoltaic applications.

Finally, the project does not include a detailed chemical analysis of the nanomaterial or a microscopic study of dust adhesion on the panel surface.

1.8 Project Outputs

The main output of this project is an experimental comparison between the performance of a nanomaterial-coated photovoltaic panel and an uncoated photovoltaic panel under controlled soiling conditions. The comparison is based on measured voltage and current values, calculated output power, and graphical analysis.

The project provides measured electrical data for both panels at different soiling levels. These data are used to calculate the output power of each panel and evaluate the improvement achieved by the nanomaterial coating. The results are also represented using tables and graphs to show the relationship between soiling level and photovoltaic power output.

The project outputs include:

1. Experimental comparison between coated and uncoated PV panels.
2. Tables of measured voltage, current, and calculated output power.
3. Calculation of power difference between the two panels.
4. Calculation of power improvement percentage.
5. Graphical comparison of output power versus soiling level.
6. Discussion of the effectiveness of nanomaterial coating under the tested conditions.
7. Final conclusions and recommendations for future work.

1.9 Project Schedule

The project schedule is divided into several main stages. The first stage includes collecting information and reviewing previous studies related to PV soiling and nanomaterial coatings. The second stage includes preparing the experimental setup, selecting the PV panels, applying the nanomaterial coating, and connecting the system components. The third stage includes preparing the measurement procedure and organizing the data recording method. The fourth stage includes taking measurements,

collecting data, and organizing the results. The final stage includes analyzing the data, comparing the measured results, preparing graphs, writing the final report, and preparing the presentation.

1.10 Project, Product, and Schedule Risks

Several risks may affect the progress and results of this project. One of the main risks is the limited time available for measurement and data collection. Since the project depends on outdoor testing, cloudy days, unstable weather, or low solar irradiance may delay the measurement process or affect the quality of the collected data.

Another risk is related to measurement accuracy. Manual measurements may include reading errors, connection errors, or differences in measurement timing between the two panels. To reduce this risk, measurements should be taken at fixed times and under similar conditions for both panels.

There is also a technical risk related to the coating process. If the nanomaterial is not applied uniformly on the panel surface, the results may not accurately represent the actual effect of the coating. Therefore, the panel surface should be cleaned properly before coating, and the coating should be applied carefully.

In addition, the project may face hardware risks such as loose wiring, battery charging issues, or charge controller malfunction. These risks can be reduced by checking the connections before each measurement and ensuring that all components are working properly.

Finally, there is a schedule risk because the analysis and report writing depend on the completion of data collection. To manage this risk, the theoretical chapters, methodology, experimental design, and implementation sections should be written before the results are completed.

CHAPTER 2: Existing Soiling Mitigation Methods and Related Work

2.1 Introduction

Photovoltaic systems are continuously exposed to outdoor environmental conditions such as dust, sand, humidity, wind, temperature variation, and rainfall. Among these factors, soiling is considered one of the most common reasons for the reduction of PV output power. Soiling occurs when dust particles, sand, bird droppings, pollen, and other contaminants accumulate on the front glass surface of the PV module. This layer blocks part of the incoming solar radiation and reduces the amount of light reaching the solar cells [1], [2].

The effect of soiling is more significant in dry and dusty regions because dust accumulation occurs quickly, while rainfall is not frequent enough to clean the panels naturally. Several studies have reported noticeable power losses due to dust deposition. For example, a dust density of about 10 g/m² can reduce the maximum power of PV panels by approximately 34% under certain conditions [1]. Other studies reported that PV modules left unclean for more than six months may lose about 50% of their output power, while PV output in Saudi Arabia decreased by about 10.8% after only two weeks during the dry season [3].

As a result, PV systems installed in dusty environments require repeated cleaning to maintain acceptable performance. Several cleaning and mitigation methods are already used in practice, such as manual cleaning, water-based cleaning, robotic cleaning, natural cleaning by rainfall, electrostatic cleaning, and anti-soiling coatings. However, each method has limitations related to cost, water consumption, maintenance, surface damage, or longterm reliability [1], [2].

This chapter discusses the existing methods used to reduce soiling effects on PV panels. It also explains the main problems associated with these methods and presents nanomaterial coating as the proposed solution approach in this project.

2.2 Soiling Effect on Photovoltaic Panels

Soiling reduces the performance of PV panels mainly by decreasing the solar irradiance that reaches the solar cells. The front glass of a PV module is designed to allow sunlight to pass through with minimum reflection and absorption. When dust accumulates on this surface, it forms a barrier between the sun and the solar cells. This barrier scatters, absorbs, and reflects part of the incoming light [1], [2].

The reduction in received irradiance directly affects the generated current of the PV module. Since the output current of a solar panel is strongly related to the incident solar radiation, any decrease in irradiance causes a noticeable decrease in current. The voltage may also be affected, but usually the current and output power show the clearest reduction.

The output power of a PV panel can be calculated using:

$$P = V \times I$$

where P is the output power, V is the voltage, and I is the current. Therefore, when dust reduces the generated current, the total output power decreases as well.

In real PV installations, soiling may not be uniform over the entire panel surface. Some areas may contain more dust than others. This non-uniform soiling can create partial shading effects, which may lead to mismatch losses between solar cells. In severe cases, this can reduce the efficiency of the panel and increase thermal stress on some parts of the module [2].

The seriousness of soiling depends on dust type, particle size, surface tilt angle, humidity, wind speed, and cleaning frequency. For example, one reported case showed about 22% performance loss for a rooftop PV system after one month of soiling exposure [3].

Therefore, soiling is not only a cleaning issue, but also a performance and reliability issue.

2.3 Existing Cleaning and Mitigation Methods

Several methods are used to reduce or remove dust from PV panel surfaces. These methods differ in cost, effectiveness, complexity, water consumption, maintenance requirements, and suitability for different installation sizes. The most common methods include manual cleaning, water-based cleaning, robotic cleaning, natural cleaning by rainfall, electrostatic cleaning, ultrasonic or vibration-based cleaning, and anti-soiling surface coatings [1].

The selection of a suitable cleaning method depends on several factors, such as the size of the PV system, dust accumulation rate, water availability, labor cost, accessibility of the panels, and the risk of surface damage. For small rooftop systems, manual or waterbased cleaning may be practical. For large-scale PV plants, robotic or automated systems may reduce labor requirements. However, each method has practical disadvantages, and the best solution depends on the site conditions and economic constraints [1].

The need for cleaning becomes clear when considering the level of power loss caused by dust. A dust amount of about 10 g/m² has been reported to reduce the maximum power of solar panels by approximately 34% [1]. In another review, modules left unclean for more than six months showed around 50% output power reduction, and dryseason exposure for two weeks in Saudi Arabia led to about 10.8% PV output power loss [3]. These values show that soiling mitigation is essential, especially in dry and dusty regions.

2.3.1 Manual Cleaning :



Figure 2.1 Manual Cleaning

Manual cleaning is one of the simplest and most widely used methods for removing dust from PV panels. In this method, workers clean the panel surface using soft cloth, sponges, brushes, or water. It is commonly used in small PV systems, rooftop systems, and experimental setups because it does not require complex equipment or automated control systems [1].

The main advantage of manual cleaning is its simplicity and low initial cost. It can be performed using basic tools, and workers can visually inspect the panels during the cleaning process. This makes it useful for removing heavy dirt, bird droppings, mud spots, or localized dust accumulation.

However, manual cleaning has several disadvantages. First, it must be repeated regularly because dust can accumulate again after a short time, especially in dusty regions. This increases labor requirements and maintenance cost. Second, if the cleaning process is not performed carefully, it can damage the PV surface. For example, dry wiping, hard brushes, scraping tools, or abrasive materials may create scratches on the front glass.

Another important issue is the possible damage to the anti-reflective coating on the PV glass. This coating helps reduce light reflection and allows more solar radiation to reach the solar cells. Some cleaning guidelines warn that rubbing or scraping dirt can create micro-scratches and may damage the anti-reflective coating on module glass [4]. First Solar also indicates that some wet contact cleaning methods are restricted for antireflective coated modules, which shows that cleaning method selection is important for protecting the surface [5].

Therefore, manual cleaning may remove dust in the short term, but repeated improper cleaning may reduce long-term optical performance. This makes manual cleaning less attractive when cleaning must be performed frequently.

2.3.2 Robotic Cleaning:



Figure 2.2 Robotic Cleaning

Robotic cleaning systems are used mainly in medium and large PV installations. These systems use automated or semi-automated robots to clean the surface of PV panels. The robots may use brushes, microfiber rollers, air flow, or waterless cleaning mechanisms. Some robots move along panel rows and clean the modules according to a programmed schedule [1].

The main advantage of robotic cleaning is that it reduces the need for manual labor. It is useful in large solar farms where cleaning thousands of panels manually would require significant time and effort. Robots can also improve safety because workers do not need to climb rooftops or walk between large PV arrays frequently.

However, robotic cleaning also has several disadvantages. The first disadvantage is the high initial cost. Robotic systems require purchasing the robot, installing supporting systems, and sometimes modifying the PV layout to allow robot movement. This makes the method less suitable for small PV systems or low-budget projects.

The second disadvantage is maintenance. Cleaning robots contain mechanical and electrical parts such as motors, wheels, brushes, sensors, batteries, and control circuits. These components may fail or require periodic inspection and replacement. If the robot stops working, the cleaning process is delayed until maintenance is completed.

Some studies show that scheduled robotic cleaning can improve PV performance. For example, a robotic dry-cleaning study reported a performance improvement of about 15.54% for a weekly cleaned PV string compared with uncleaned conditions during the

test month. The same study reported high accumulated losses for the never-cleaned string during the test period [7]. However, even when robotic systems improve performance, they still require capital cost, maintenance, and technical support.

Another issue is the possibility of surface damage. If the robot applies excessive pressure, uses unsuitable brushes, or moves incorrectly on the panel surface, it may scratch the glass or affect the anti-reflective coating. Therefore, robotic cleaning must be carefully designed and controlled to avoid damaging the panels.

2.3.3 Natural Cleaning by Rainfall:



Figure 2.3 Natural Cleaning by Rainfall

Rainfall can act as a natural cleaning method for PV panels. When rain falls on the panel surface, it can wash away loose dust particles and reduce the amount of accumulated dirt. This method does not require labor, electricity, equipment, or additional water supply, which makes it attractive from a cost point of view.

However, relying on rainfall is not a dependable cleaning strategy in dry regions. Rainfall is seasonal and cannot be controlled. In some periods, dust may accumulate for a long time before rain occurs. During this period, the PV system continues to operate at reduced performance.

Also, light rain may not clean the panel surface completely. In some cases, it can mix with dust and form mud spots after drying. These spots may create non-uniform soiling patterns, which can reduce the panel output and cause partial shading effects. Because soiling can reduce PV performance by values such as 10.8% within two dry weeks or around 22% within one month in some reported cases, waiting for rainfall may not be sufficient in dusty locations [3].

Therefore, rainfall can help reduce soiling under certain conditions, but it cannot be considered a complete or reliable mitigation method, especially in dusty and lowrainfall environments.

2.3.4 Electrostatic and Advanced Cleaning Methods:

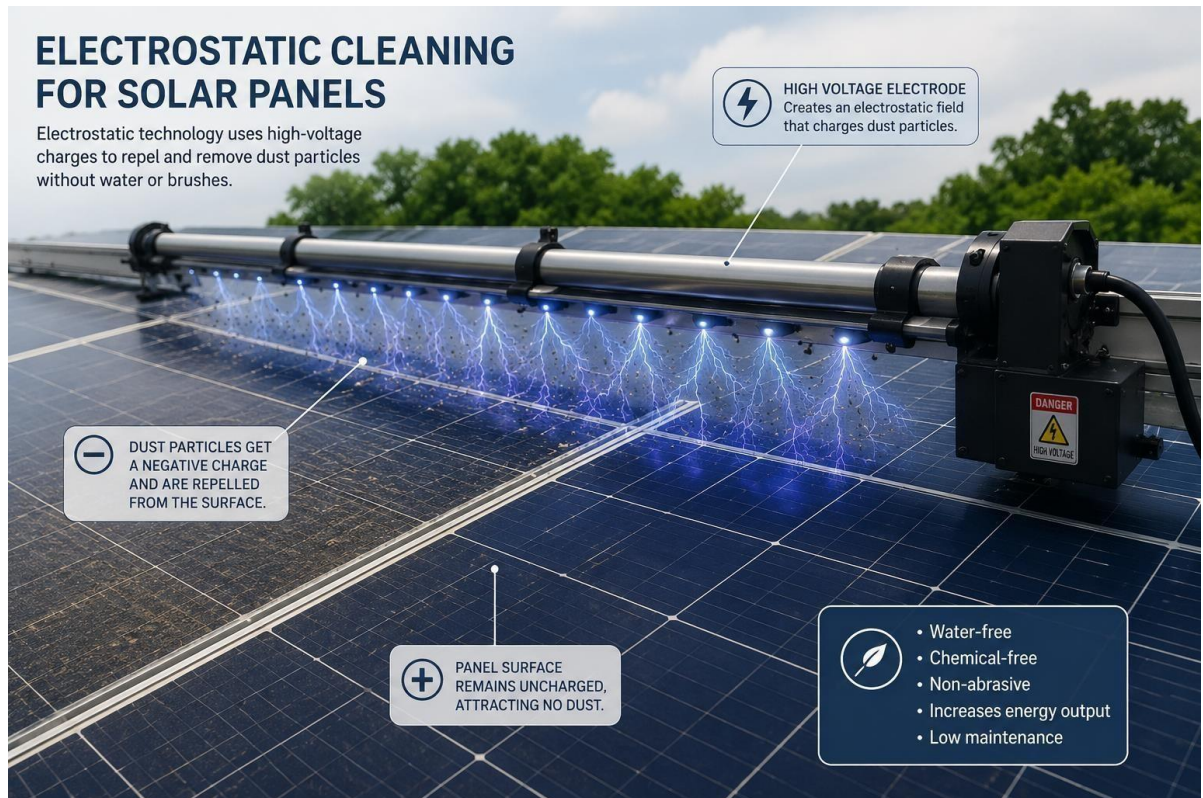


Figure 2.4 Electrostatic Cleaning

Advanced cleaning methods include electrostatic cleaning, ultrasonic cleaning, vibrationbased cleaning, and air-blowing systems. These methods aim to remove dust without using large amounts of water or manual labor [1], [2].

Electrostatic cleaning uses electric fields to move dust particles away from the panel surface. This method is attractive because it can reduce water consumption and may be suitable for dry regions. Ultrasonic and vibration-based methods depend on mechanical waves or vibration to loosen dust particles from the glass surface. Air-blowing systems use compressed air to remove dust.

Although these methods are promising, they are usually more complex than traditional cleaning methods. They may require additional power supply, control circuits, sensors, special surface design, or high installation cost. Some of these technologies are still under development or are not widely used in small-scale PV systems.

For this reason, advanced cleaning methods may be effective in certain applications, but their cost and complexity can limit their practical use. In small experimental systems, these methods are usually less suitable because they add extra electrical and mechanical requirements.

2.3.5 Nanomaterial and Anti-Soiling Coatings

Nanomaterial and anti-soiling coatings are considered passive methods for reducing soiling effects on PV panels. Instead of removing dust after it accumulates, these coatings aim to modify the surface properties of the PV glass to reduce dust adhesion and make the surface easier to clean [8], [9].

Anti-soiling coatings may provide hydrophobic, hydrophilic, self-cleaning, anti-dust, or antireflective properties. Hydrophobic coatings reduce surface wettability and allow water droplets to roll over the surface, carrying dust particles away. Hydrophilic coatings allow water to spread over the surface, which can help remove dust more uniformly. Self-cleaning coatings can also improve surface behavior and reduce the amount of dust remaining on the glass [8], [9].

Some experimental studies on nano-hydrophobic coatings showed improved water droplet contact angle and beneficial effects on light transmittance and open-circuit voltage of PV modules [9]. However, coating performance depends on coating material, surface preparation, application quality, environmental conditions, and exposure time.

The main advantage of nanomaterial coating is that it does not require moving parts, motors, controllers, or continuous water supply. Once applied correctly, it can work passively on the panel surface. This makes it suitable for small PV systems, rooftop installations, and experimental studies. However, its long-term durability should be evaluated before largescale application [8].

In this project, nanomaterial coating was selected because it directly addresses several limitations of conventional cleaning methods. It reduces dependence on repeated manual cleaning, lowers the need for water, and avoids the mechanical complexity of robotic or electrostatic systems.

2.4 Overall Problems of Existing Systems

Although the existing methods can reduce soiling losses, none of them is perfect. Each method has specific limitations that may affect its suitability depending on the system size, location, climate, and available budget.

Manual cleaning is simple and low-cost at the beginning, but it requires repeated labor. It can also cause scratches if incorrect cleaning tools are used. Repeated cleaning with rough brushes, scraping tools, or dry cloth may damage the glass surface or the antireflective coating, which can reduce the long-term optical performance of the PV panel [4], [5].

Water-based cleaning is effective, but it consumes water. This is a serious problem in arid regions where solar energy is abundant but water resources are limited. For large PV plants in the Middle East, water use for panel cleaning may reach around 0.5 L/m², which becomes significant for large-scale installations [6]. Poor water quality can also leave mineral deposits on the panel surface and create additional optical losses.

Robotic cleaning reduces labor and is suitable for large PV plants, but it has a high initial cost. In addition, robots require maintenance because they include moving mechanical parts and electrical control components. Although robotic cleaning can improve performance, one study reported about 15.54% performance improvement for weekly cleaned PV strings, the system still required a robotic mechanism and scheduled operation [7].

Rainfall is a free natural cleaning method, but it is unreliable. It depends completely on weather conditions and may not occur when cleaning is needed. Light rain can sometimes make the soiling condition worse by forming mud spots or non-uniform dirt patterns. This is important because studies have reported power losses such as 10.8% after two dry weeks and 22% after one month in certain soiling conditions [3].

Advanced cleaning methods such as electrostatic or ultrasonic cleaning can reduce water use, but they are more complex and may require additional cost, power electronics, and control systems [1], [2]. Based on these problems, there is a need for a simple, passive, and low-maintenance solution that can reduce dust adhesion and decrease the frequency of cleaning. This supports the selection of nanomaterial coating as the proposed solution in this project.

2.5 Nanomaterial Coating as the Proposed Solution

Nanomaterial coating is proposed in this project as a passive method to mitigate soiling effects on photovoltaic panels. Instead of removing dust after it accumulates, the coating aims to reduce the adhesion of dust particles to the panel surface. This can make the surface easier to clean and may reduce the amount of dust that remains on the glass [8], [9].

Nanomaterial coatings can change the surface properties of PV glass. Depending on the material used, the coating may provide hydrophobic, hydrophilic, self-cleaning, antidust, or anti-reflective properties. A hydrophobic coating reduces the ability of water and dust to stick to the surface. A hydrophilic coating can help water spread over the surface and carry dust particles away. Some nanomaterials may also improve surface smoothness or reduce light reflection [8], [9].

The main advantage of nanomaterial coating is that it does not require moving parts, motors, controllers, or continuous water supply. Once applied correctly, it can work passively on the panel surface. This makes it suitable for small PV systems, rooftop installations, and experimental studies.

In this project, the effectiveness of nanomaterial coating is evaluated by using two similar

PV panels. One panel is coated with nanomaterial, while the other remains uncoated as a reference panel. Both panels are installed under the same environmental conditions. The voltage, current, and output power of both panels are measured and compared. This comparison helps determine whether the coated panel can maintain better performance under soiling conditions.

2.6 Summary and Research Gap

Existing PV cleaning methods are useful, but they still have important limitations. Manual cleaning is simple but labor-intensive and may scratch the surface. Water-based cleaning is effective but consumes water and may leave mineral deposits. Robotic cleaning reduces labor but has high initial cost and maintenance requirements. Rainfall is free but unreliable. Advanced cleaning methods are promising but may be complex and costly [1]–[7].

These limitations show the need for a passive mitigation method that can reduce dust accumulation and decrease the need for frequent cleaning. Nanomaterial coating is selected in this project because it can modify the surface properties of PV glass and reduce dust adhesion without requiring continuous operation or mechanical movement [8], [9].

The research gap addressed by this project is the practical evaluation of nanomaterial coating under real outdoor conditions using a simple experimental setup and measured electrical data analysis. The project compares the performance of a coated PV panel with an uncoated PV panel to estimate the improvement in voltage, current, and output power.

Table 2-1: Comparison of Existing Soiling Mitigation Methods

Method	Main Idea	Advantages	Limitations	References
Manual cleaning	Cleaning panels by workers using cloth, sponge, brush, or water	Simple, low initial cost, suitable for small systems	Requires repeated labor; may cause scratches or damage anti-reflective coating if done incorrectly	[1], [4], [5]
Water-based cleaning	Removing dust using water and soft cleaning tools	Effective for heavy dust and mud	Consumes water; about 0.5 L/m ² may be used in large PV plants in the Middle East; water quality may leave deposits	[1], [6]
Robotic cleaning	Automated or semi-automated robots clean panel surfaces	Reduces labor and improves safety in large PV plants	High initial cost, requires maintenance, possible surface damage; may be unsuitable for small systems	[1], [7]
Rainfall cleaning	Natural rain washes loose dust from panels	No equipment or labor required	Unreliable in dry regions; light rain may create mud spots and non-uniform soiling	[2], [3]
Electrostatic cleaning	Electric fields remove dust particles	Reduces water usage, promising for dry regions	Complex, costly, requires additional electrical systems and control circuits	[1], [2]
Ultrasonic/vibration cleaning	Vibrations loosen dust from the panel surface	Can reduce manual cleaning and water use	Requires extra equipment, power, and control system	[1], [2]
Nanomaterial coating	Surface coating reduces dust adhesion	Passive, low maintenance, may reduce cleaning frequency	Needs durability testing; effectiveness depends on coating type and environment	[8], [9]

Therefore, the use of nanomaterial coating is considered a suitable approach for this project because it directly addresses the limitations of conventional cleaning methods. It provides a passive surface-based solution that may reduce dust adhesion, lower cleaning frequency, and improve the electrical performance of photovoltaic panels under outdoor soiling conditions.

CHAPTER 3: Methodology

The proposed system in this project is designed to estimate and compare the effect of soiling on photovoltaic panel performance with and without nanomaterial coating. The system consists of two similar photovoltaic panels installed under the same outdoor environmental conditions. One panel is coated with a nanomaterial layer, while the second panel remains uncoated and is used as a reference panel.

The purpose of using two panels is to create a direct comparison between the coated and uncoated PV surfaces. Since both panels are exposed to almost the same solar irradiance, temperature, wind, and dust conditions, the difference in electrical output can be used to evaluate the effectiveness of the nanomaterial coating.

In this experiment, different soiling levels were applied gradually to the PV panels. The soiling levels used in the test were 10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80%. For each soiling level, the voltage and current of both coated and uncoated panels were measured, and the output power was calculated.

3.1 Experimental Setup

Two identical photovoltaic panels were used to evaluate the effectiveness of nano coating in reducing soiling effects. One panel was coated with the selected nano-coating material, while the second panel remained uncoated and served as a reference panel. Both panels were operated under the same environmental conditions to ensure a fair comparison.



Figure 3.1 Two Identical PV Panels

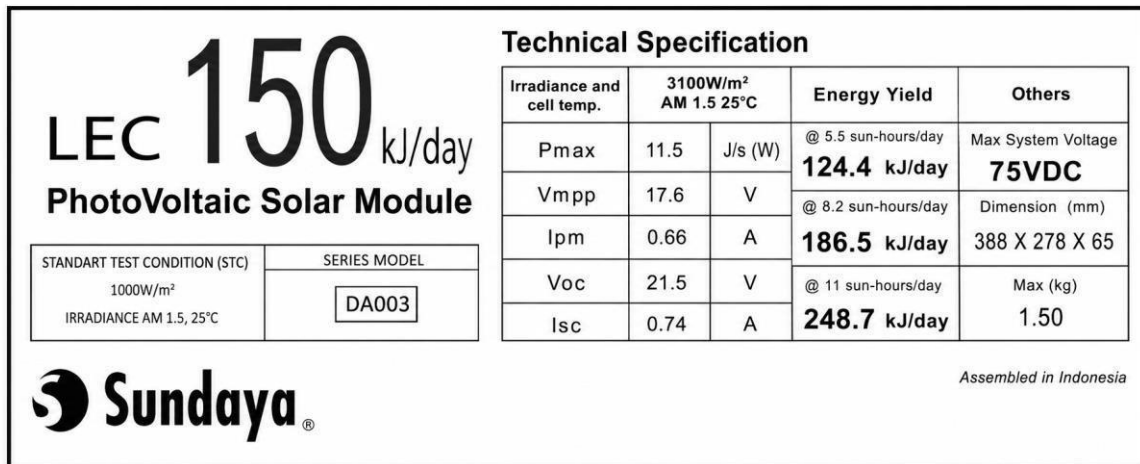


Figure 3.2 Nameplate

Both panels were connected to the required electrical components, including charge controllers and batteries. The charge controller regulates the charging process and protects the battery from overcharging. The voltage and current of each panel were measured during the experiment.



Figure 3.3 12-Volt Battery



Figure 3.4 PMW Charge controller



Figure 3.5 Final Setup

The experimental setup was designed to ensure that both photovoltaic panels operate under identical environmental and electrical conditions. This configuration allowed the effect of the nanocoating to be isolated and evaluated by comparing the performance of the coated panel with that of the uncoated reference panel.

3.2 Nano-Coating Application Procedure

Before applying the nano-coating, both photovoltaic panels were cleaned to remove dust and surface contaminants. One panel was selected for coating, while the other remained untreated and served as the reference panel.

Chemical Decontamination (The "Pre-Cleaner") was applied, and used to remove residual dust, grease, and contaminants from the glass surface and to improve the adhesion of the nano-coating layer. This cleaner breaks down oils and, crucially, exposes the free **hydroxyl (-OH) groups** on the surface of the solar glass. These (-OH) groups are the exact sites where the nano-coating will chemically cross-link to form a covalent bond.

After surface preparation, the nano-coating material was applied to the selected photovoltaic panel. The coating was distributed uniformly across the glass surface using a microfiber cloth and circular wiping motions to ensure complete coverage.

A microfiber cloth was used during both the surface preparation and coating application processes due to its non-abrasive nature and low lint generation. This minimizes the risk of scratching the photovoltaic glass surface and helps achieve a clean and uniform coating layer.

The coating was applied using circular motions to improve surface coverage and ensure the formation of a consistent coating layer over the entire panel surface.

The coating process is important because non-uniform coating may affect the accuracy of the comparison. Therefore, the nanomaterial layer was applied as uniformly as possible to reduce testing errors. PV module cleaning and surface preparation should avoid abrasive tools and harsh mechanical contact to reduce the risk of glass scratches or anti-reflective coating damage [4], [5].

The experiment was performed one day using a controlled dust application. The dust level was increased gradually, and readings were taken at each soiling level. After applying each soiling condition, voltage and current readings were recorded for both panels, then the output power was calculated.



=



Figure 3.6 pre-cleaner

Figure 3.7 Solar Coat GC

3.3 Measurement Parameters

The main measured parameters in this project are voltage and current. The output power was calculated from these two values.

The basic power equation is:

$$P = V \times I$$

where:

P = output power in watts

V = voltage in volts

I = current in amperes

During the experiment, the voltage of the uncoated panel remained approximately constant at 20.5 V, while the voltage of the coated panel remained approximately constant at 20.7 V. The current changed clearly as the soiling level increased. This shows that soiling mainly affected the generated current, which directly affected the output power.

The measured parameters are summarized in Table 3-1.

Table 3-1: Measured Parameters

Parameter	Symbol	Unit	Description
Soiling level	S	%	Controlled relative dust level applied during the experiment
Voltage	V	Volt	Output voltage of each PV panel
Current	I	Ampere	Output current of each PV panel
Power	P	Watt	Calculated using $P = V \times I$
Panel condition	—	—	Coated or uncoated

3.4 Data Collection Method

The data collection was carried out during one experimental day. The panels were exposed to controlled soiling levels starting from 10% and increasing gradually up to 80%. At each soiling level, the voltage and current of both panels were measured.

The procedure used for data collection was as follows:

1. Both PV panels were prepared and exposed to the same outdoor conditions.
2. The uncoated panel was used as the reference panel.

3. The coated panel was used as the tested panel.
4. A controlled dust level was applied.
5. The voltage and current of the uncoated panel were recorded.
6. The voltage and current of the coated panel were recorded.
7. The output power of both panels was calculated.
8. The soiling level was increased gradually.
9. The same measurement procedure was repeated for all soiling levels. The purpose of this method was to observe the change in PV output power as the soiling level increased and to compare the performance difference between the coated and uncoated panels.

3.5 Performance Analysis Method

The measured voltage and current values are used to calculate the output power of each PV panel. The output power is calculated using:

$$P = V \times I$$

where P is the output power in watts, V is the voltage in volts, and I is the current in amperes.

The power difference between the coated and uncoated panels is calculated using:

$$\Delta P = P_{coated} - P_{uncoated}$$

The percentage improvement achieved by the coated panel is calculated using

$$Power\ Improvement(\%) = \frac{P_{coated} - P_{uncoated}}{P_{uncoated}} \times 100$$

These equations are used later in Chapter 5 to analyze the experimental results.

3.6 System Constraints

First, the soiling levels were applied as controlled relative dust levels. They were not measured using precise dust mass per unit area such as g/m^2 . Therefore, the results are suitable for comparison between coated and uncoated panels under the same test conditions, but they should not be considered exact laboratory dust-density measurements.

Second, the experiment was affected by outdoor conditions such as sunlight variation, temperature, wind, and possible changes in dust distribution. These factors may affect the measured current and output power.

CHAPTER 4: Results and Discussion

This chapter presents the results obtained from the experimental investigation and discusses the performance of the nano-coated photovoltaic panel in comparison with the uncoated reference panel. The chapter includes the analysis of hydrophobic behavior, anti-soiling performance, outdoor exposure observations, and electrical performance measurements. The results are used to evaluate the effectiveness of nanocoating in reducing soiling effects and maintaining photovoltaic panel performance under different operating conditions.

4.1 Nano-Coating Performance Evaluation

4.1.1 Hydrophobic Test

To evaluate the hydrophobic properties of the nano-coating, water was sprayed onto both the coated and uncoated photovoltaic panels under similar conditions. The behavior of water droplets on each surface was then visually observed and compared. The test was performed to assess the ability of the coating to repel water and promote self-cleaning characteristics.



Figure 4.1 Coated Panel



Figure 4.2 Uncoated panel

Figures 4.1 and 4.2 show the difference in water behavior between the uncoated and nanocoated photovoltaic panels. On the uncoated surface, water tended to spread over larger areas of the glass, resulting in the formation of irregular wet regions. In contrast, the coated panel exhibited noticeable water beading, where the droplets remained more concentrated and retained a more spherical shape.

This behavior indicates that the nano-coating increased the hydrophobicity of the panel surface by reducing the interaction between water and glass. As a result, water is less likely to remain attached to the coated surface and can more easily roll off the panel. This characteristic is beneficial for photovoltaic applications because it may support the selfcleaning process by carrying dust particles away from the surface during rainfall or cleaning events.

The visual observations obtained during the hydrophobic test demonstrate that the selected nano-coating successfully modified the surface wettability of the photovoltaic panel and provided enhanced water-repellent properties compared with the untreated panel.

4.1.2 Anti-Soiling Test

To evaluate the anti-soiling performance of the nano-coating, dust particles were applied to both the coated and uncoated photovoltaic panels under similar conditions. The distribution and adhesion behavior of the dust were then visually observed and compared. The objective of this test was to investigate whether the nano-coating could reduce dust attachment to the panel surface



Figure 4.3 Coated panel



Figure 4.4 Uncoated panel

Figures 4.3 and 4.4 illustrate the behavior of dust particles on the coated and uncoated photovoltaic panels. It was observed that the dust on the nano-coated panel tended to accumulate in separated clusters rather than forming a uniformly distributed layer. In contrast, the uncoated panel exhibited a more continuous and evenly distributed dust coverage across the surface.

The difference in dust distribution suggests that the nano-coating modified the surface characteristics of the photovoltaic panel and reduced the adhesion of some dust particles. As a result, dust was less likely to spread uniformly over the coated surface. Although the coating did not completely prevent dust accumulation, the observed particle distribution indicates a potential reduction in dust attachment compared with the untreated panel. This behavior is beneficial because lower dust adhesion may facilitate natural cleaning processes such as wind or rainfall.

The results of the anti-soiling test indicate that the selected nano-coating contributes to improving the resistance of the photovoltaic panel surface to dust accumulation.

4.1.3 24-hour Exposure Test

To evaluate the performance of the nano-coating under real environmental conditions, both photovoltaic panels were placed outdoors and exposed to the surrounding environment for approximately 24 hours. The panels were subjected to natural conditions including sunlight, wind, and airborne dust. Photographs were taken before and after the exposure period to compare dust accumulation patterns on the coated and uncoated surfaces.



Figure 4.5 Coated panel before



Figure 4.6 Uncoated panel before



Figure 4.7 Coated panel after 24-hours



Figure 4.8 Uncoated panel after 24-hours

The 24-hour exposure test was conducted to assess the behavior of the nano-coated panel under practical operating conditions. After the exposure period, dust accumulation was observed on both photovoltaic panels. However, differences in the distribution pattern of the dust were visible between the coated and uncoated surfaces.

The coated panel exhibited less uniform dust attachment in certain areas, while the uncoated panel showed a more continuous dust layer. These observations are consistent

with the results obtained from the anti-soiling test and suggest that the nano-coating influences the interaction between dust particles and the panel surface.

Environmental factors such as wind direction, particle size, and airborne dust concentration may have affected the results. Therefore, while the coating did not completely prevent dust accumulation, the observations indicate a potential reduction in dust adhesion under outdoor conditions.

4.1.4 Dry Cleaning Test



Figure 4.9 coated panel



Figure 4.10 Uncoated panel

Following the dry cleaning process, both panels showed a reduction in visible dust accumulation. However, residual dust traces and cleaning marks remained on the surfaces of the uncoated panel. Visual inspection indicated differences in the dust removal patterns between the coated and uncoated panels, suggesting that the nanocoating influenced the interaction between dust particles and the panel surface.

4.2 Electrical Performance Analysis

The testing process was carried out in one experimental day using a controlled dust application. The dust level was increased gradually, and readings were recorded at each soiling level. The controlled soiling levels used in the experiment were:

10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80%.

The purpose of the implementation was to evaluate the effect of dust accumulation on the electrical performance of both panels and to determine whether the nanomaterial coating could reduce the negative impact of soiling.

At each soiling level, the voltage and current of both the coated and uncoated panels were measured. Then, the output power was calculated using:

$$P = V \times I$$

It is important to mention that the soiling percentages represent controlled relative dust levels applied gradually during the experiment. They were used for comparison purposes and do not represent exact laboratory-measured dust density.

4.2.1 Experimental Results

The measured voltage and current values were used to calculate the output power for both panels. Table 5-1 shows the experimental measurements for the coated and uncoated PV panels under different soiling levels.

Table 4-1: Experimental Measurements for Coated and Uncoated PV Panels

Soiling Level	Uncoated Current (A)	Coated Current (A)	Uncoated Voltage (V)	Coated Voltage (V)	Uncoated Power (W)	Coated Power (W)
10%	0.51	0.59	20.5	20.7	10.455	12.213
20%	0.50	0.57	20.5	20.7	10.250	11.799
30%	0.48	0.55	20.5	20.7	9.840	11.385
40%	0.42	0.53	20.5	20.7	8.610	10.971
50%	0.38	0.45	20.5	20.7	7.790	9.315
60%	0.32	0.38	20.5	20.7	6.560	7.866
70%	0.27	0.29	20.5	20.7	5.535	6.003
80%	0.23	0.25	20.5	20.7	4.715	5.175

The results show that the coated panel produced higher current and higher output power than the uncoated panel at all soiling levels. The voltage remained almost constant during the test, while the current decreased clearly as the soiling level increased.

4.2.2 Power Improvement Calculation

The output power improvement achieved by the coated panel was calculated by comparing the coated panel power with the uncoated panel power at each soiling level.

The power difference was calculated using:

$$\Delta P = P_{coated} - P_{uncoated}$$

The percentage improvement was calculated using:

$$Power\ Improvement(\%) = \frac{P_{coated} - P_{uncoated}}{P_{uncoated}} \times 100$$

The calculated power difference and improvement percentage are shown in Table 5-2.

Table 4-2: Power Improvement of Coated Panel Compared with Uncoated Panel

Soiling Level	Uncoated Power (W)	Coated Power (W)	Power Difference (W)	Power Improvement (%)
10%	10.455	12.213	1.758	16.81
20%	10.250	11.799	1.549	15.11
30%	9.840	11.385	1.545	15.70
40%	8.610	10.971	2.361	27.42
50%	7.790	9.315	1.525	19.58
60%	6.560	7.866	1.306	19.91
70%	5.535	6.003	0.468	8.46
80%	4.715	5.175	0.460	9.76

The average power improvement achieved by the coated panel was approximately:

$$Average\ Improvement = 16.59\%$$

This result indicates that, under the tested experimental conditions, the nanomaterialcoated panel showed better output power compared with the uncoated panel.

4.2.3 Graphical Results

The experimental results were represented using graphs to make the comparison between the coated and uncoated panels clearer. The most important graph is the relationship between output power and soiling level.

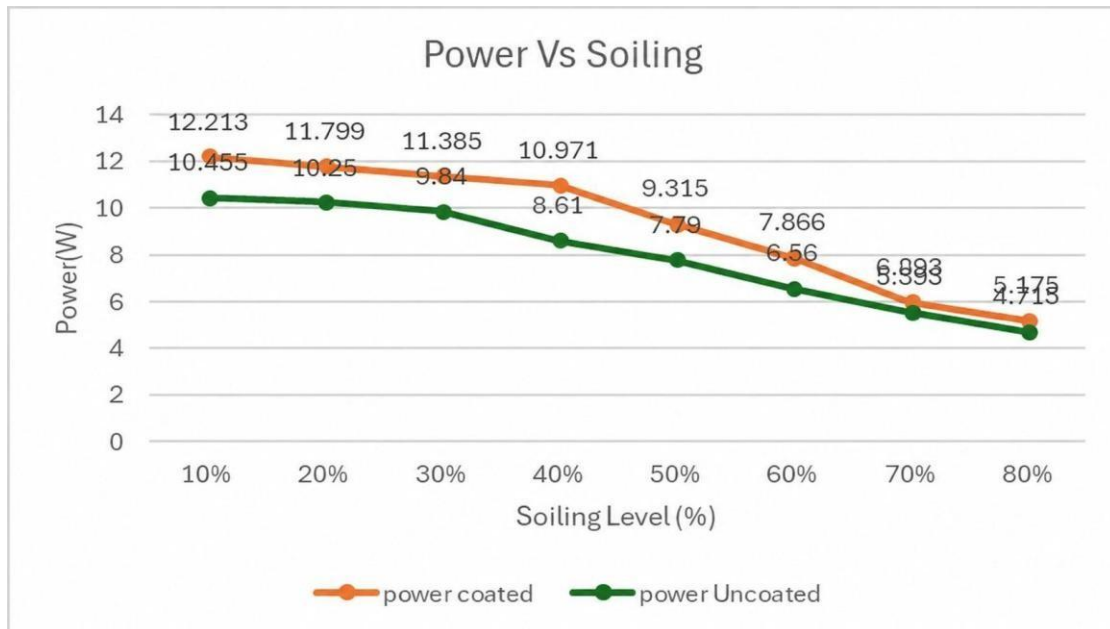


Figure 4.11 Output Power vs. Soiling Level

This graph compares the output power of the coated and uncoated panels at different soiling levels.

The graph shows that the output power decreases as the soiling level increases for both panels. This is expected because dust accumulation reduces the amount of sunlight reaching the solar cells.

However, the coated panel produced higher output power than the uncoated panel at every soiling level. For example, at 10% soiling, the coated panel produced 12.213 W, while the uncoated panel produced 10.455 W. At 80% soiling, the coated panel produced 5.175 W, while the uncoated panel produced 4.715 W.

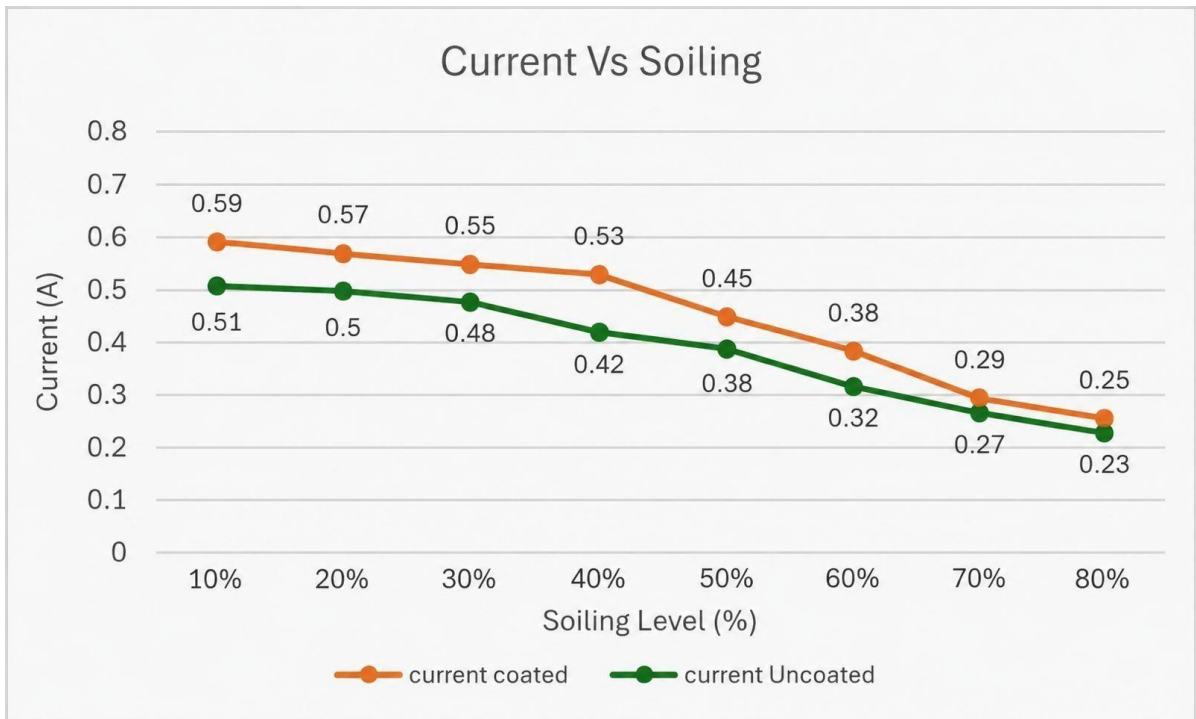


Figure 4.12 Current vs different soiling levels

A current comparison graph can also be used to show the effect of soiling on the generated current.

This graph is important because the experimental results showed that the voltage remained almost constant, while the current decreased significantly as soiling increased. Therefore, the reduction in output power was mainly caused by the reduction in generated current.

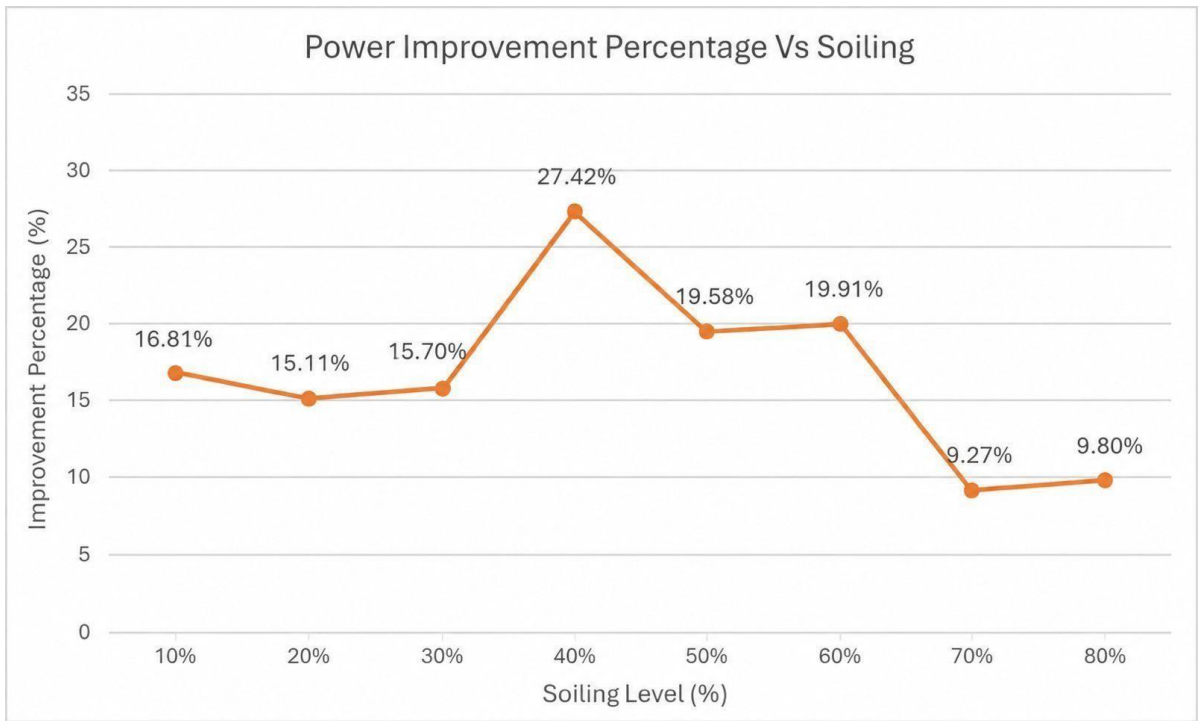


Figure 4.13 Power Improvement Percentage vs Soiling

This graph shows how the coating performance changed at different soiling levels. The highest improvement was observed at 40% soiling, where the coated panel achieved an improvement of approximately 27.42% compared with the uncoated panel.

4.3 Discussion of Results

The experimental results show a clear relationship between soiling level and PV output power. As the soiling level increased, the output power decreased for both coated and uncoated panels. This confirms that dust accumulation has a negative effect on photovoltaic performance [1], [2], [3].

For the uncoated panel, the output power decreased from 10.455 W at 10% soiling to 4.715 W at 80% soiling. For the coated panel, the output power decreased from 12.213 W at 10% soiling to 5.175 W at 80% soiling. Although both panels were affected by increasing dust level, the coated panel maintained higher output power at all tested soiling levels.

The results also show that the voltage remained nearly constant during the experiment. The uncoated panel voltage was approximately 20.5 V, while the coated panel voltage was approximately 20.7 V. The current, however, decreased clearly as the soiling level increased. This means that the main effect of soiling appeared in the reduction of generated current, which directly reduced the output power.

The highest power difference was observed at 40% soiling, where the coated panel produced 10.971 W, while the uncoated panel produced 8.610 W. The power difference at this level was 2.361 W, corresponding to an improvement of approximately 27.42%.

At high soiling levels, such as 70% and 80%, the improvement percentage became lower. This may indicate that when the dust layer becomes too heavy, the coating becomes less effective because a large portion of the sunlight is blocked before reaching the solar cells.

Overall, the experimental results suggest that the nanomaterial coating improved the electrical performance of the PV panel under the tested conditions. However, since the experiment was performed in one day, longer testing periods are recommended to study the long-term durability and effectiveness of the coating [8], [9].

Chapter 5 Conclusions and Recommendations

This chapter presents the conclusions drawn from the experimental results and evaluates the practical feasibility of applying nano-coating technology to photovoltaic panels. The technical performance of the coating is summarized based on the hydrophobic, antisoiling, and electrical performance tests conducted in this study. In addition, an economic evaluation is performed by comparing the cost of nano-coating with conventional manual cleaning methods. Finally, recommendations for future work and practical implementation are provided.

5.1 Technical Conclusions

Based on the experimental results obtained in this study, the application of nano-coating demonstrated a positive effect on the performance of photovoltaic panels under dusty conditions.

The hydrophobic test confirmed that the coated panel exhibited improved water repellency compared to the uncoated panel. This characteristic can enhance the selfcleaning capability of the panel surface and reduce the adhesion of contaminants. The dry-cleaning and anti-soiling tests showed that dust accumulation was less severe on the coated panel, indicating that the nano-coating can help mitigate soiling effects. The electrical performance analysis revealed that the coated panel consistently maintained higher current and power output than the uncoated panel across all tested soiling levels. The measured power improvement ranged from approximately 9% to 27%, with an average improvement of about 16.7% under the experimental conditions. Overall, the results demonstrate that nano-coating can reduce the negative impact of dust accumulation and improve the operational performance of photovoltaic panels.

5.2 Economic Evaluation

5.2.1 Description of the Case Study System

For the economic evaluation, the photovoltaic installation located on the rooftop of the Faculty of Engineering in Tafila technical university was selected as a case study. The system consists of 160 photovoltaic modules rated at 260 W each, resulting in a total installed capacity of 41.6 kW. This installation was used as a reference system to estimate the costs associated with conventional cleaning and nano-coating implementation.

For the purpose of the economic analysis, the area of each photovoltaic panel was assumed to be 1.6 m², which is representative of a typical 260 W module. Therefore, the total surface area of the photovoltaic array was estimated as:

$$\text{Total Area} = 160 \times 1.6 = 256 \text{ m}^2$$

5.2.2 Manual Cleaning Cost Analysis

To estimate the cost of conventional photovoltaic panel cleaning, quotations were obtained from three local solar panel cleaning service providers. The quotations were based on the Faculty of Engineering rooftop installation consisting of 160 photovoltaic modules with a total capacity of 41.6 kW.

The collected quotations ranged from 125 JOD to 160 JOD per cleaning cycle. The average cleaning cost was calculated to be approximately 145 JOD per cleaning operation and was used as the reference value in the economic evaluation.

Since photovoltaic cleaning frequency varies according to environmental conditions, three cleaning scenarios were considered. The annual cleaning cost was calculated using the average cleaning cost of 145 JOD per cleaning cycle.

Table 5.1 Estimated Annual Manual Cleaning Costs

Scenario	Cleaning Frequency	Cleanings/Year	Cost
Conservative (Neglected)	Every 3 months	4	580 JOD/year
Typical Operation	Every 2 months	6	870 JOD/year
Intensive Maintenance	Every month	12	1740 JOD/year

The results indicate that the annual cleaning cost can vary significantly depending on the selected maintenance strategy. For the Faculty of Engineering photovoltaic installation, the annual cost ranges from 580 JOD for low-frequency cleaning to 1740 JOD for intensive monthly cleaning.

5.2.2 Nano-Coating Cost Analysis

The economic evaluation of the nano-coating was based on information obtained through direct communication with a technical engineer from Nasiol Eng. Abdullah AlShboul. The estimated application cost of the selected nano-coating was reported to be approximately 5.5 JOD/m², with an expected service life of approximately three years.

Table 5.2 Estimated Nano-Coating Cost for the Faculty of Engineering PV System

Parameter	Value
Number of panels	160
Assumed panel area	1.6 m ²
Total panel area	256 m ²
Coating cost	5.5 JOD/m ²
Total coating cost	1408 JOD
Expected lifespan	3 years
Annualized cost	469.3 JOD/year

5.2.3 Economic Comparison

Table 5.3 Economic Comparison Between Manual Cleaning and Nano-Coating

Maintenance Strategy	Annual Cost (JOD/year)
Nano-Coating	469
Low-Frequency Cleaning	580
Typical Operation	870
Intensive Maintenance	1740

The results indicate that the annualized nano-coating cost is lower than the annual cost of all considered manual cleaning scenarios. The greatest economic advantage is

observed when compared with intensive monthly cleaning, where the annual cleaning cost exceeds the annualized coating cost by more than three times.

5.2.4 Energy Benefit

In addition to reducing maintenance costs, the nano-coating demonstrated improved electrical performance under all tested soiling conditions. Based on the experimental results, the coated panel achieved an average power improvement of approximately 16.59% compared with the uncoated panel.

Although the experimental results were obtained using a small-scale test system under controlled soiling conditions, the observed improvement indicates the potential for higher energy production and reduced soiling losses in practical photovoltaic installations.

5.3 Overall Recommendation

Based on the technical and economic analyses conducted in this study, the application of nano-coating on photovoltaic panels is considered a promising solution for reducing the impact of dust accumulation. The coating demonstrated improved hydrophobic behavior, reduced dust adhesion, and higher electrical performance compared with the uncoated panel.

The economic evaluation showed that the annualized coating cost was lower than the estimated annual cost of conventional manual cleaning for the considered case study. In addition, the observed improvement in electrical performance suggests the potential for increased energy production and improved system efficiency.

Therefore, the use of nano-coating is recommended for photovoltaic installations operating in dusty environments, particularly where frequent cleaning is required. However, long-term field studies are recommended to evaluate coating durability, environmental effects, and actual energy gains under real operating conditions.

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