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Research article

Analysis of dust accumulation effects on the long-term performance of solar PV panels

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Abstract: Solar cells are the most common and important applications of solar energy. However, dust accumulation can have a very serious impact on the performance of Photovoltaic (PV) systems. Here, we investigated the dust and its influence on solar modules, both polycrystalline and monocrystalline. The specified site had four horizontally oriented 80 W PV modules. To mitigate the environmental effect, one of the two PV modules was intentionally kept dusty while the other was consistently cleaned. Over 90 days, measurements of PV performance and ambient factors were taken every 30 minutes. Time-based and normalized measurements were used to discuss how dust affects current, voltage, and power. Research revealed that the accumulation of dust led to a higher rate of power decline (30.48%) in polycrystalline PV modules compared to monocrystalline PV modules (14.1%). The current and power losses for monocrystalline PV modules ranged from 0.21 to 2.16 A and 13 to 56 W, respectively. When subjected to external conditions for an equivalent duration, polycrystalline PV modules had degradation rates ranging from 0.1 to 2.37 A in terms of current, and power losses ranging from 10 to 60.5 W, respectively. The results confirmed that polycrystalline surface characteristics significantly increase the amount of dust accumulation, which must be considered when designing all such solar arrays and testing for deployment. This finding provides a lesson for high PV maintenance strategy optimization, specifically in high dust operating environments, for continued PV energy.

Keywords: PV modules; polycrystalline; monocrystalline; ambient factors; Dust accumulation; dust deposition

1. Introduction

Over the last ten years, there have been notable breakthroughs in solar energy technology. The improved performance and cost-efficiency of PV and solar thermal systems have facilitated the wider use of solar technology by organizations and governments as a sustainable and efficient energy alternative. While solar thermal collectors use the sun's heat to heat water or air for various purposes, PV systems convert solar light energy into direct current (DC) electricity [1]. Combining these two technologies leds to the creation of photovoltaic/thermal (PV/T) systems, which produce electricity and heat. However, meteorological factors like sun radiation, wind speed, ambient temperature, and dust deposition affect solar technologies. Dust accumulation on the outside of PV modules blocks sunlight and lowers power-generating efficiency [2]. Researchers have used computer models, experimental techniques, or a mix of them to examine how dust affects PV system performance. The researchers are largely focused on quantifying and assessing the magnitude of the losses and their influence on the performance measures. Furthermore, the presentation comprised the simulation of dust and the examination of strategies for reducing and removing it, considering both technological and financial aspects. We conducted empirical research to examine how dust affects PV system performance, with a focus on temperature increases. According to the scientists, adding heating to dust exacerbates the losses brought on by the rise in surface temperature and decrease in irradiance. On the other hand, the effect will be greatly diminished as wind speed increases. Additionally, the findings imply that the temperature of the PV glass's top layer is 1.106 times greater than that of the bottom surface [3].

The research used Computational Fluid Dynamics (CFD) to measure the influence of dust deposition on the shaded region of panels, especially concerning the tilt angle. The authors found that both direct and indirect shadowing led to a 2.49% reduction in the anticipated energy production [4]. The tilt angles that minimized the shading impact were found to be between 15.84 and 17.69 degrees. The authors developed a quadratic model to explain how dust affects the alignment and gradient angle of an object. Thus, they examined the impact of indoor dust particles under constant and changing loads. The effects suggest that carbon particles have a substantial negative influence on efficacy and fill factor, unlike Fe_2O_3, MnO_2, CaO, and natural dust, which have different impacts. Moreover, an increase in the bulk density of dust is indicated by an increase in both the shunt and series resistances [5]. An analysis was conducted on the dust collected in the UAE to examine the meteorological parameters over a period of 15 weeks. A comprehensive study was performed on the gathered dust to ascertain its deposition rate and composition, and to select the most efficient cleaning method. Applying CFD to analyze the effects of dust on rooftop PV modules, including factors such as wind velocity and dust buildup, is studied [6]. Multiple writers have asserted that the characteristics of dust are significantly impacted by the size of the particles. The researchers analyzed the effects of dust accumulation during an 8-week period (1stcase) and later a dust tempest (2nd case) on a 30-MW PV power plant. The outcome demonstrates a reduction in power production of 8.41% and 32.00% for the 1st case and 2nd case, respectively. The research quantitatively investigated the effects of dust accumulation on PV systems with dual-axis tracking [7].

Tension and momentum assessments were employed to estimate the PV system impact in fine detail. The proposed model intends to address the tilt angle that can maximize the immersion efficiency, once dust elements are distanced from the surface of the PV system. The composition of atmospheric dust matter (ADM), its potency, and the chemical composition of dust vary according to seasonal fluctuations [8]. The authors demanded that ADM with decreased dust effectiveness demonstrates a noteworthy increase in particle size. To assess the effect of dust on the presentation of PV systems, experimental research has been carried out. Eight different angle monocrystalline PV modules were utilized and included in the investigation. Pairs of PV modules were presented; one PV module in each pair was pristine, but the other module was soiled. The quantities were gathered every two weeks and then equated to evaluate their influence on the operation of the PV system. The authors state that an elevation in the tilt angle leads to a fall in both dust accretion and power losses. Research was done to experimentally examine the effects of dust deposition and dusting on PV modules. Periodic tests were performed on many PV modules and compared to the pristine PV module. The results suggested a significant decline in the reliability of PV modules that were subjected to dust exposure [9]. In addition, a thorough examination was carried out on a grid-connected PV system with a capacity of 1.4 kilowatts for the PV panels and 1.7 kilowatts for the inverter. The assessment occurred in arid conditions and lasted for one year. The academics evaluated the system's presentation, output, and efficiency with varying standard conditions. The investigation indicated that the system's energy generation had an efficiency of 10.80%, the inverter had an efficiency of 94.00%, and the overall performance of the system was 73.00%. The authors determined that the efficiency of the examined system in the Sultanate of Oman aligns with the anticipated rate. Researchers largely recognize periodic cleaning as the most efficient approach for reducing agricultural production losses in PV systems [10]. This dusting procedure will decrease these damages to the smallest. An empirical investigation was undertaken to examine the chemical makeup of dust collected from a dust collector over 2 months at six specific positions in the Al Batinah area of Oman. The objective was to determine the origins and proportions of the dust constituents. The researchers performed a laboratory investigation to analyze the effects of dust buildup on two PV modules, one using monocrystalline technology and the other utilizing polycrystalline technology [11]. They also investigated to determine how each component of the dust deposition affected the two panels' performance. The goal was to identify the elements that most affected the ensuing losses. If ash, calcium carbonate, limestone, cement, sulfur, sawdust, and brown dirt stuck to a monocrystalline panel, the amount of electricity generated went down by 12%, 6%, and 6% for that panel. The 5%, 4%, 4%, 1%, 2%, and 2% represented the degradation rates for the polycrystalline panel. To determine the most effective cleaning technique, taking into account the unique dust conditions at each location, the researchers conducted studies on several hand-cleaning techniques for solar panels [12]. The researchers concluded that the best way to clean PV is by using a saline fluid along with towels and brushes. Numerous cleaning procedures, including both human and robotic technology-based methods, have been documented in the literature. Based on geographic location and meteorological conditions, various approaches were distributed. The restricted supply of water in arid climates makes it impractical to use it for cleaning solar modules [13].

The researchers utilized several cleaning methods in arid environments, such as the use of fabric wipes and vacuum cleaners. They analyzed the ideal frequency of cleaning sessions that successfully minimize production losses. The performance of the assessed PV systems in the study region declined when a monthly regular cleaning interval was introduced, irrespective of the dusting technique used [14]. Nevertheless, the implementation of a fixed cleaning routine yielded the most efficient retrieval of lost power and the most cost-effective results. The researchers devised a complex cleaning method that utilizes electric curtains to produce an electric wave. A fundamental limitation of using this cleaning method is its substantial expense and the existence of safety issues during adverse weather conditions. Another modern method includes the application of dust-resistant nanoparticles onto the surfaces of PV modules [15]. According to the research, one of the most efficient ways to reduce dust that accumulates is to incorporate a TiO_2 layer into the coating. Unfortunately, because this particular type of paint needs water to work, it cannot be used in dry environments [16].

In addition to the extensive research conducted, other revisions were undertaken to reassess the impacts of dust. The published research in Table 1 includes noteworthy findings that are worth emphasizing. Over the last two years, there has been a significant emphasis and curiosity in the field of dust modeling, cleaning, and mitigation [17]. Accumulation of dust on PV modules diminishes their power output, energy generation, and overall efficiency. However, other meteorological factors, such as a rise in surrounding temperature and the velocity of wind, might either amplify or diminish the losses. The published research could not reach a consensus on a certain duration for cleaning or the best techniques for cleaning. Nevertheless, it emphasized that the meteorological data of the areas plays a crucial role in choosing the appropriate cleanup methods. Ultimately, sandstorms lead to a rise in PV losses due to their significant negative impact on output. In this article, we describe a study that looked at the impact of dust on two types of PV modules: Panels made with monocrystalline and polycrystalline. This was done outdoors. The study was conducted in the northern Omani city of Sohar. Each technology was then tested over 35 days between September 1, 2020, and October 5, 2020, to assess the performance of dusty and clean PV modules. Performance comparisons were made using electrical parameters. It was carefully compared to other work in the literature. Two more monocrystalline dusty modules were put on the last day of the experiment for the three cleaning method experiments. In this empirical review, an emphasis on differences in PV technology and climatic conditions, the effect of dust deposition on PV panel performance [18].

To help guide cleaning techniques, we examined dust particles that were collected from PV panels in the United Arab Emirates. This offers insights into the composition and morphology of these particles [19]. These researchers examined the effects of various dust kinds, such as sand, cement, and gypsum, on the efficiency of PV panels, especially in desert settings. According to this study, dust buildup can drastically lower PV module power production and efficiency, with decreases of up to 50% over a month without cleaning [20,21]. To evaluate the combined effects of dust accumulation and wind speed on performance, a particle-based model is suggested for estimating dust coverage on PV panels. These researchers provide a way to measure dust accumulation levels by quantifying dust accumulation on solar panels by figuring out the density of dust particles [22,23]. This study presents a deep learning method for dust detection on PV surfaces to enhance maintenance plans by spotting accumulation trends. With an emphasis on certain climatic circumstances, the study examines how the buildup of limestone dust affects the performance of PV panels [24,25]. These researchers look at how the conductivity of collected dust might raise leakage current in PV modules, increasing their vulnerability to damage caused by potential [26]. The following are the key conclusions drawn from the literary analyses: The fields of dust modeling, cleaning, and mitigation have seen a great deal of attention and interest in recent years. Power output, energy production, and overall efficiency are all decreased when dust builds up on PV modules. Nevertheless, further meteorological information, such as rising temperatures and wind speeds, could either raise or decrease the magnitude of the losses. The presented research was not clear in terms of the suggested frequency and the most effective cleaning methods. Nevertheless, it underscored the need for meteorological data in determining the most suitable clean-up method for the locations. In the end, sandstorms result in a rise in PV losses since it has a substantial adverse effect on the electricity generated [27]. Research has expanded the knowledge about dust accumulation impacts on PV modules by analyzing their performance across different environmental elements. The researchers in [28] delved into dust particle dimensions together with chemical makeup to evaluate heat transfer efficiencies and discover new surface treatments providing antifouling defense. The research team investigated hybrid dust cleaning technology, which included heating elements and mechanical tools for better removal methods in dry climates [29]. A comprehensive examination of dust deposition rates in relation to weather parameters such as wind speed and relative humidity was detailed by [30], who also established predictive modeling methods for module accuracy. The integration of knowledge from other studies enhances both the fundamental context and the experimental results' connection to contemporary industry standards of this investigation.

Extensive research has been carried out to study the impact of dust accrue on the output of solar PV systems. Scientific evidence shows how dust can reduce the electrical production of PV installations, and dust attributes, panel placement, and local climate influence the level of power loss. Scientists have researched many cleaning methods, including simple water washing, sophisticated chemical substances, and equipment for automatic cleaning. Researchers mostly summarize dust accumulation and cleaning practices rarely provide empirical comparisons of cleaning methods for real-world situations, their real cost, and prompt ability to scale up for higher PV projects. In addition, conditions that limit the applicability of cleaning methods in different regions due to water scarcity have not been given much attention.

The gaps are directly addressed in the investigation with an evaluation of cleaning using water, alcohol, and sodium solution under standardized field circumstances. Further, the research assesses the accompanying costs, operational efficiencies, and scalability of these strategies, pinpoints their relevance to various climates with critics, especially highlighting their applicability in water-scarce regions. The comparative analysis between the methods in parallel provided by this study offers a practical understanding that is missing in prior sources.

The study illustrates that both polycrystalline and monocrystalline solar modules' performance decreases due to dust accumulation. Field testing enables researchers to examine the way dust accumulation influences voltage, current, and power. The study was conducted in Chennai, situated in the southern region of India. Every PV module, regardless of its technological specifications, underwent a rigorous 90-day testing and comparison phase spanning from April to June 2023. The major findings of this study consist of the following:

- We performed an extended field analysis of dust effects on both polycrystalline and monocrystalline PV panels, which exceeds most previous research timeframes.
- The dissimilar characteristics between monocrystalline and polycrystalline surfaces lead to a higher efficiency decline in polycrystalline panels since they show a total drop of 30.48% compared to monocrystalline panels, which is reduced by 14.1%.
- The research provides fundamental findings regarding power reduction patterns and establishes that regularly cleaning devices for six to twelve weeks helps prevent efficiency degradation in high-dust environments.
- The research enhances knowledge about external factors that influence dust accumulation by demonstrating how wind velocity, together with moisture content and surface composition, influence PV performance decline over extensive periods.

- The research recommends selecting monocrystalline panels for dusty areas, as these panels demonstrate reduced power reduction from dust accumulation effects, although they need cleaning procedures more often.

2. Experimental setup and its analysis

We used four 80 W PV modules. Table 1 also shows the properties of two monocrystalline and two polycrystalline modules. Depending on whether they are dusty or clean, monocrystalline PV modules are referred to as panels 1 and 2, respectively. The block diagram of the system under test for the polycrystalline PV module panels 3 and 4, assumed to be in dust-free and dusty scenarios, is presented in Figure 1. A sunshine sensor with an accuracy of ± 5 W/m^2 and a measuring range of 0–1250 W/m^2 was used to measure the solar irradiance. All four PV modules have been measured for a short circuit current, and all four PV modules have been measured for maximum power, short circuit current, and open circuit voltage.

Figure 1. Schematic layout of the proposed system.

2.1. Study area

Selection of the experimental site was carefully conducted to enable maximum dust accumulation potential, where the realistic performance of PV under natural dust accumulation conditions can be evaluated. It is near urban roads, industrial zones, and still under-construction zones next to the site, causing frequent dust deposition processes. The chosen research site has a latitude of 12.49° and a longitude of 80.02°, determined based on hypothetical considerations. The site is SRMIST, situated in

India with postal code 603203. Furthermore, because of changes in temperature, humidity, and wind speed throughout the year, the location proves suitable for studying the long-term effect of dust deposition in different ambient conditions. The panels were mounted in an open area with no obstructions to ensure that the panels were not shadowed.

The test facility occupies a tropical region with savanna-like seasonal patterns, which belongs to the Koppen climate classification. Studies of dust effects on PV modules benefit strongly from the test site's climatic conditions, which feature high solar irradiation together with hot temperatures and humid conditions between April and June. During the entire research period, the onsite weather station continually measured and stored environmental data about ambient temperature and relative humidity, and wind speed. The study period's typical daily mean temperature spanned between 30 and 38 °C, while relative humidity levels fluctuated between 60% and 85%, and wind speeds stayed between 2 and 6 m/s. Continuous monitoring of environmental factors confirmed that performance decline stemmed mainly from dust accumulation than exceptional weather conditions. Figure 2 depicts an important and prominent site near the sea, surrounded by buildings and highways, resulting in the generation of construction and transportation dust.

Figure 2. Site location.

The average global horizontal irradiance is 5.35 kWh/m^2/day, and the average horizontal diffuse irradiation is 2.52 kWh/m^2/day, for the year 2022. Along with this, it was noted that May has the highest temperature ever observed at 31.7 °C, and there is 3.6 m/s of wind speed in June. The hourly variations in the selected city's solar radiation intensity are shown in Figure 3.

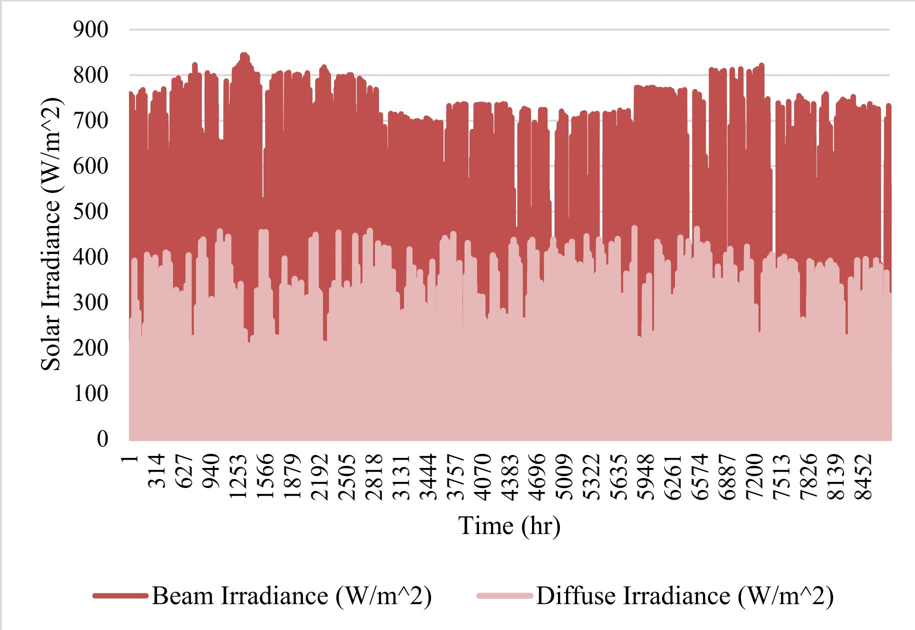

Figure 3. Status of solar intensity in the selected area.

2.2. Cleaning materials

There are several methods for removing accumulated dust from PV modules. These strategies were thoroughly examined in many papers. However, in large stations with high amounts of PV modules, the use of automatic cleaning equipment is far more advantageous, requiring conventional dusting solutions and manual labor. Therefore, three distinct dusting causes were selected: Water, alcohol, and sodium solution. In areas where water availability and its purity are secured, water is more desirable. Alcohol provides superior cleaning efficacy compared to water, but at a greater expense. When dealing with dust that contains particles of carbon, cement, and calcium, alcohol is the best material to use. Numerous studies have shown that the sodium solution, which is made up of water and a sodium compound, is more effective than water and alcohol for treating dust that contains a lot of carbon.

Table 1. Specifications of the modules under study.

Factors	Mono crystalline	Poly crystalline
Wattage	80 W	80 W
Isc	4.8 A	4.82 A
Voc	22 V	20.7 V
Weight	6.5 Kg	5 Kg
Vmpp	18 V	17.6 V
Impp	4.4 A	4.55 A

An extremely frequent error is enabling the water to evaporate as a result of air currents and exposure to sunlight. This process results in the water evaporating and leaving behind stiffness and contaminants in the panel. Regardless of the tiny particles, these substances adhere strongly to surface cleaning, a challenging and costly task. In this study, cloth and brushes were utilized to prevent residues and contaminants from being left on the PV modules' surface during the drying process. To provide a fair comparison, we used an identical brush for both the alcohol and salt solution situations.

2.3. Experimental procedure

Control variables were carefully managed throughout the study to be able to ensure the reliability of the experimental observations. To provide constant exposure to sunlight, all PV modules were installed at a fixed tilt angle of 13 degrees. The panels were installed in an outdoor environment with no shading on the panels, and care was taken to have the same amount of wind across the panels as well as the same amount of ambient dust. Voltage and current were measured with a high-precision digital multimeter, whereas an accuracy of ± 5 W/m² pyranometer was used to measure irradiance. The measurement instruments were calibrated before the deployment of survey programs to reduce systematic errors.

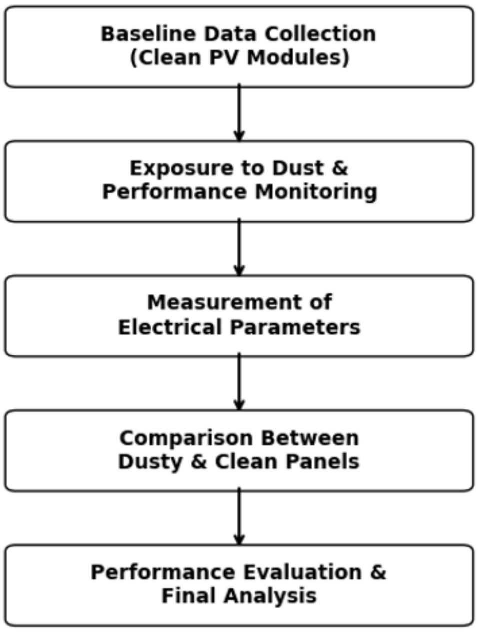

Figure 4. Flowchart of the experimental procedure.

To study the dust accumulation effect, one set of PV panels was cleaned regularly, while the other set accumulated dust. A detailed experiment procedure flow is given in Figure 4. The trials were done continuously for a period of 90 days, spanning from April to June 2023. Nevertheless, a subset of days was chosen as a representative sample due to their unobstructed sky conditions. The experiment started on April 1st when the PV panel elements were in an untouched condition. After a period of 6 weeks, the quantities were conducted again for both a pristine PV module and a module that had accumulated dust. After another 6 weeks, the measurements were repeated, resulting in a total accumulation of dust over a period of 12 weeks. Power output loss, voltage dropout, and current distortion were the performance degradations measured. To isolate the effect of dust deposition from other environmental factors such as temperature and humidity, the results were compared under identical environmental conditions. For precise data acquisition, the irradiance data were taken from the NREL using the chosen location's latitude and longitude. To ensure all panels received equal solar radiation and environmental condition exposure, the experimental site was very carefully selected to minimize the number of external obstructions.

3. Results and discussion

Based on Standard Test conditions (STC), manufacturers give the rated power and other features. However, according to the surrounding environmental circumstances, the PV module's real performance may vary. For users, dust deposition presents a major detection and identification challenge. Researching how dust affects different types of PV modules in various places offers important information on the best options for PV investments. Current, voltage, and power generation all decreased as a result of the airborne dust build-up on the PV module, which impeded the passage of solar radiation. Depending on the particular characteristic and the selected technologies (polycrystalline and monocrystalline), dust has a different effect on electrical performance. The empirical results of these technologies will be examined in this section from several angles. Many cleaning techniques have been tested to assess their effectiveness and efficiency. Field studies are a challenge experimentally, and various measures were taken to avoid possible errors in data deposition. By calibrating the irradiance sensor and temperature sensors as well as the instruments of measurement before and after the experiment, instrumental errors were minimized. Measurements were taken at fixed 30-minute intervals to ensure data consistency and eliminate data inconsistency caused by the change in sunlight conditions. Standardization was also applied to sensor placement to ensure uniform exposure, as well as the elimination of any misalignment errors. Furthermore, the measurements were repeated among different PV panels to find anomalies and minimize the effects of random errors. Any sudden change in cloud cover or wind speed was accounted for by averaging multiple readings and by continuous data logging. This improved the reliability of the results and made sure that observed results did not degrade due to measurement fluctuations, but due to the accumulation of dust.

The study period data reliability was ensured by measuring data points at regular 30-minute intervals. To minimize the impact of environmental changes, the system reevaluated readings at regular intervals with an average computation over 5-minute periods. The protocol included several measurements within each 5-minute window so researchers could calculate the average data point that helped remove temporary fluctuations and validate stable performance conditions. By employing this methodology, researchers eliminated brief disturbances and obtained better module performance data under predominantly clear-sky conditions.

The educational institutional laboratory's measurement instruments were used, which included pyranometers, digital multimeters, and data loggers, before they underwent regular calibration processes meeting manufacturer requirements. Periodic tests at certified calibration centers help both validate measurement accuracy and confirm compliance with international standards for all instruments. A strict calibration schedule was maintained throughout the 90-day measurement period to maintain both accuracy and reliability of recorded data.

The temperature variation from 08:00 to 16:00 hrs is exhibited in Figure 5. In the morning (at 08:00 hrs), the temperature was approximately around 29 °C, and then it increased until it reached the highest value of about 36–37 °C around 12:30–13.30 hrs during the solar irradiance peak period. After this peak, there was a slight fall in temperature toward the later part of the afternoon. The variation of temperature is important to know the influence of the environmental conditions on the PV module performance because higher temperature causes a higher thermal loss and lower efficiency.

Figures 6 and 7 depict the presence of dust impact on the appearance of current and voltage on monocrystalline PV modules with and without dust. The tendency was observed to decrease the current, voltage, and power of an uncleaned PV module. However, the decrease had a different dependency on different parameters. The voltage decreased more than the current. Moreover, dust deposition caused the surface permeability to fall, causing the amount of solar radiation that can pass through to be reduced.

Figure 6 shows how the short circuit current (Isc) of a PV panel varies due to dust accumulation in a day graphically. All panels were exposed while the experiment was conducted under real environmental conditions, receiving the same irradiance levels. However, the Isc decrease for dusty panels was proof of decrements in the current generation due to dirtiness, with a negative influence on dusty panels' performance for panels with high dust accumulation, necessitating frequent cleaning to achieve optimal performance of solar panels. The empirical data shown indicate that the rates of decrease in the 6th and 12th week of exposure to outside conditions were 1.34% and 8.06%, respectively. The voltage decrease rates for the same scenarios were 1.91% and 2.09%, respectively. Nevertheless, the impact became more evident on the power curves. After being exposed to external environments for 6 and 12 weeks, the power decrease rates were 1.51% and 14.17%, respectively. We also found that the rate of decrease after the 12th week is significantly greater than before the 12th week, with 6.72% for current, 12.6% for power, and 0.18% for voltage. The power reduction reached its maximum amount during the peak hour from 11:00 p.m. to 2:00 p.m. The decrease amounted to 27.91% and 25.29% after 6 and 12 weeks of contact with outside environments, respectively. Furthermore, the I-V appearances shown in Figure 8 substantiate the observation that monocrystalline PV modules are more susceptible to the negative impact of dust deposition compared with polycrystalline PV modules. Moreover, the impact on the current is evident since it is directly linked to the decrease in solar irradiation caused by the deposition of dust.

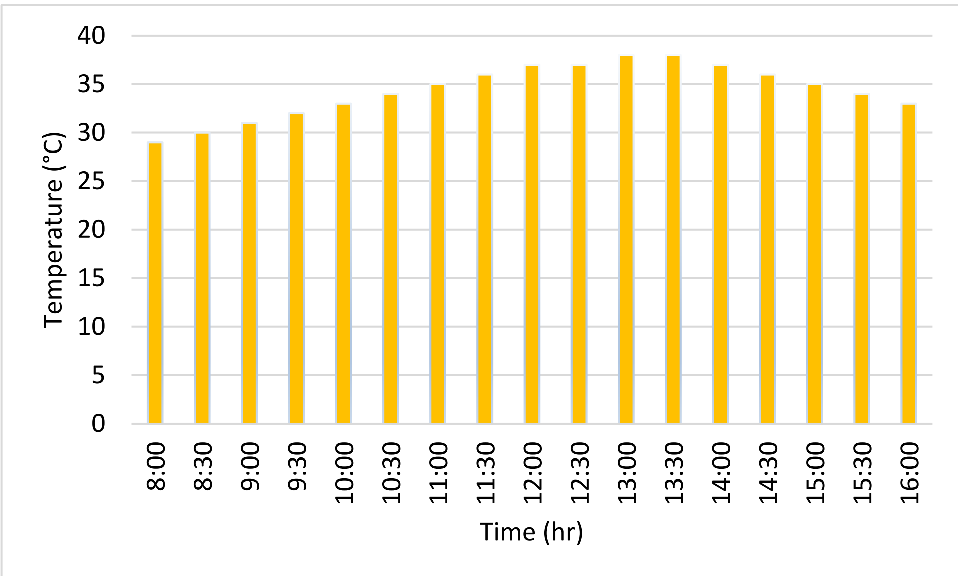

Figure 5. Variation of temperature in the selected location.

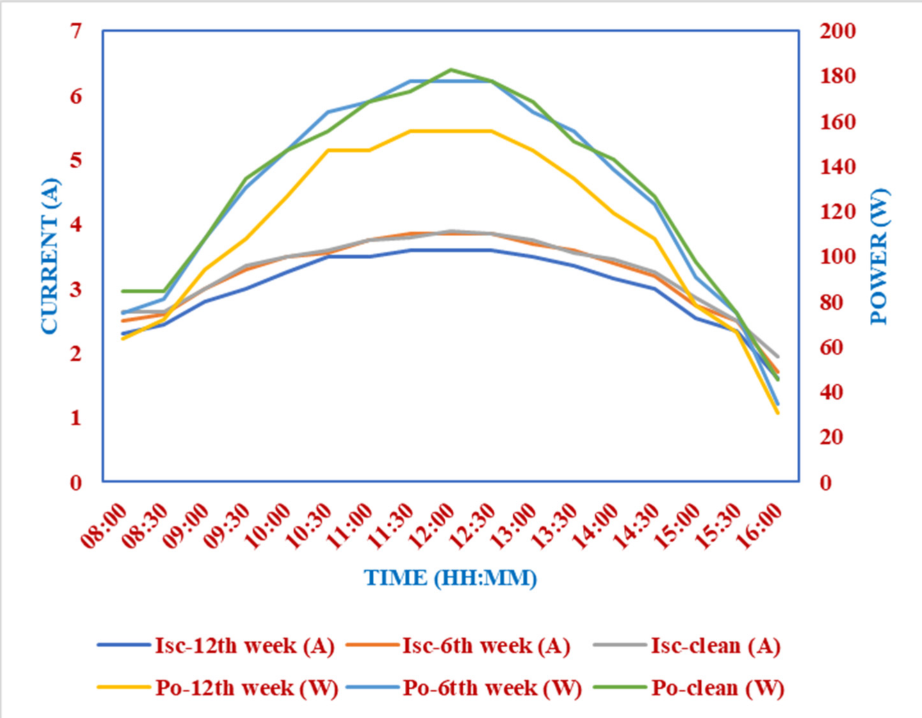

Figure 6. Effect of dust on short circuit current (Mono-crystalline).

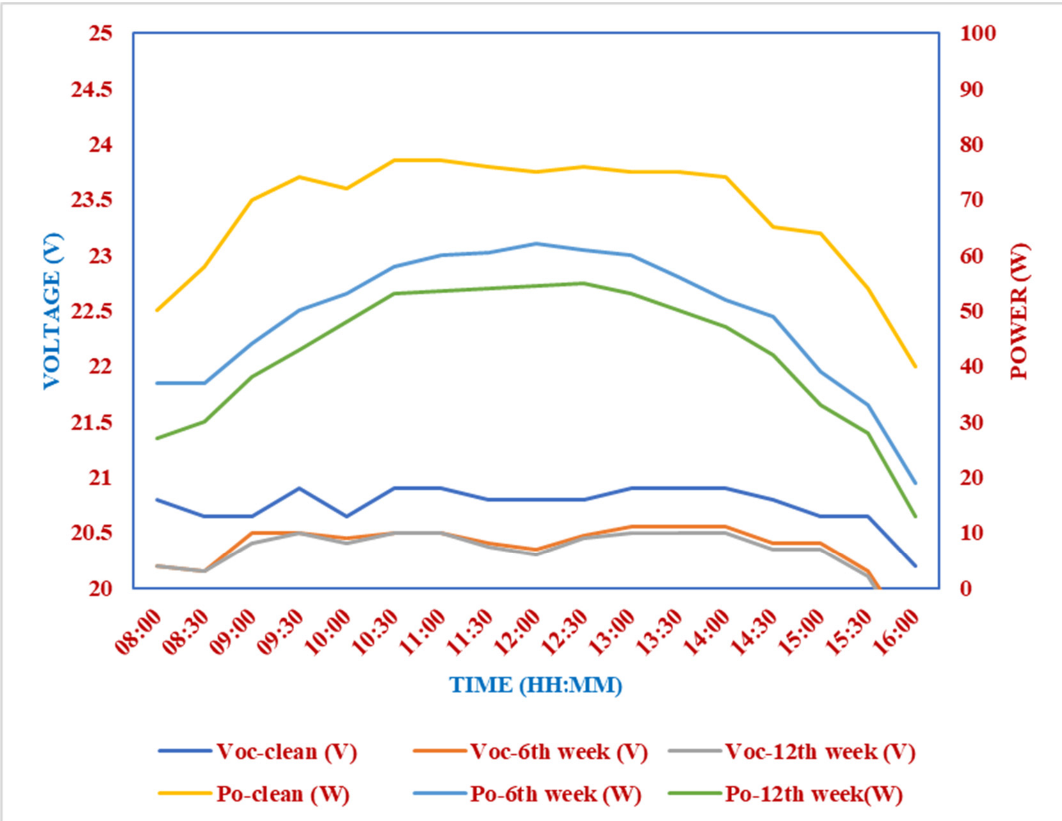

Figure 7. Effect of dust on open circuit voltage (Mono-crystalline).

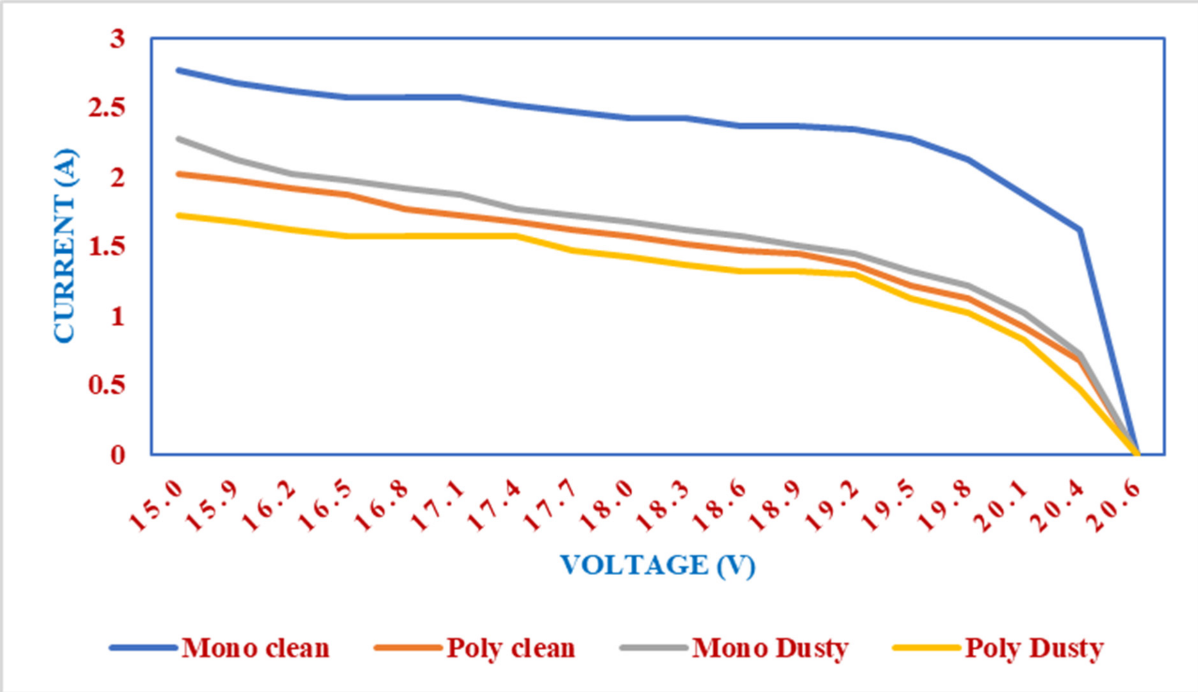

Figure 8. V-I characteristics of the monocrystalline panel with dust deposition.

The presence of airborne dust creates a shadow effect that obstructs sunlight from the attainment of the PV module. Additionally, the accumulation of dust further exacerbates this issue, leading to a decline in the above metrics. Installing PV with an angle of zero raises the quantity of dust that collects on them. It is continuously better to place solar panels at an angle to minimize the pace at which dust accumulates. Our purpose of this research is to achieve the maximum rate of accumulation by mounting the panels horizontally, which leads to the greatest decrease in power, as shown by the findings. Another contributing factor to higher dust deposition on the PV was humidity. As humidity created condensing water in the space between the dust particles and the PV module surface, adhesion forces are augmented. We found that this water capillary bridge enhances the adherence of dust particles to the surface. Figure 9 illustrates that the power decrease in post post-12-week period is in relation to the performance of clean and dusty PV modules compared to each other. There is a strong resemblance between the solar irradiance curve and the power curve. After being exposed to outside conditions for 12 weeks, the rate of decline was 19.74%. Furthermore, the decrease was most significant in the midday hours, with a peak drop of 27.63%.

The crystal cover limits the diffusion of light that reaches the solar cells due to dust particles. Only a portion of the light can pass through the dust, regardless of whether the intensity of solar radiation rises or not. Figure 10 denotes that PV module current exhibited a similar decrease trend, with average reductions of 30.86% and 11.64% for monocrystalline and polycrystalline modules, respectively.

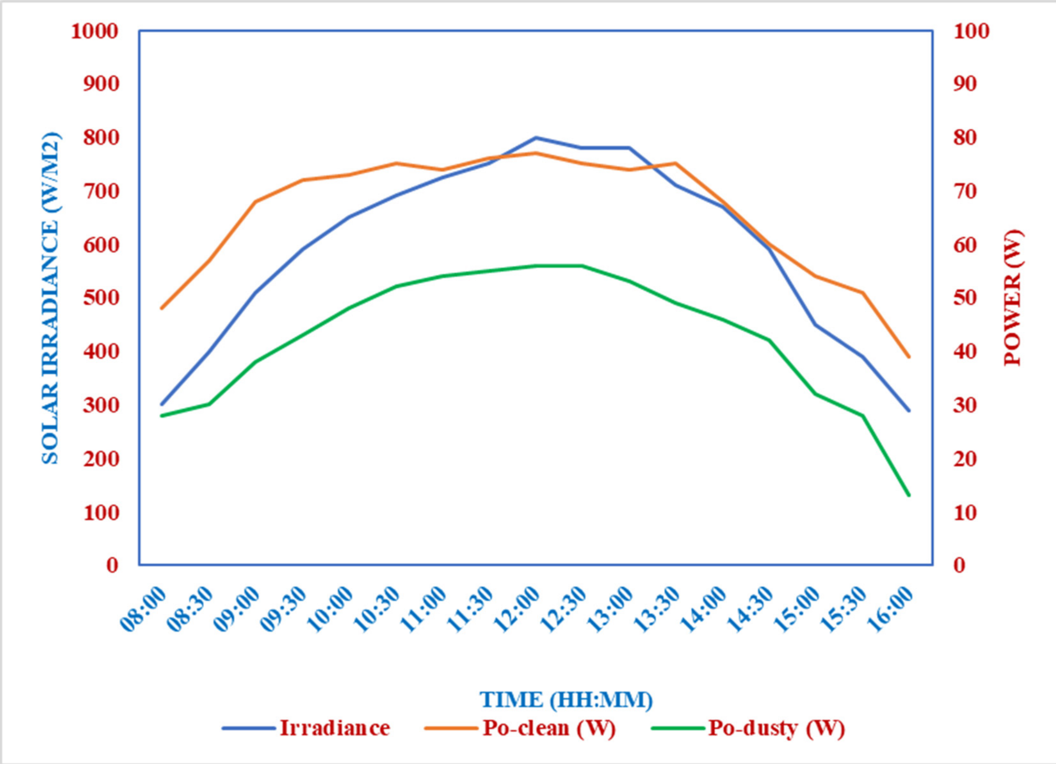

Figure 9. Impact of dust on power output after 12th week (Mono-crystalline).

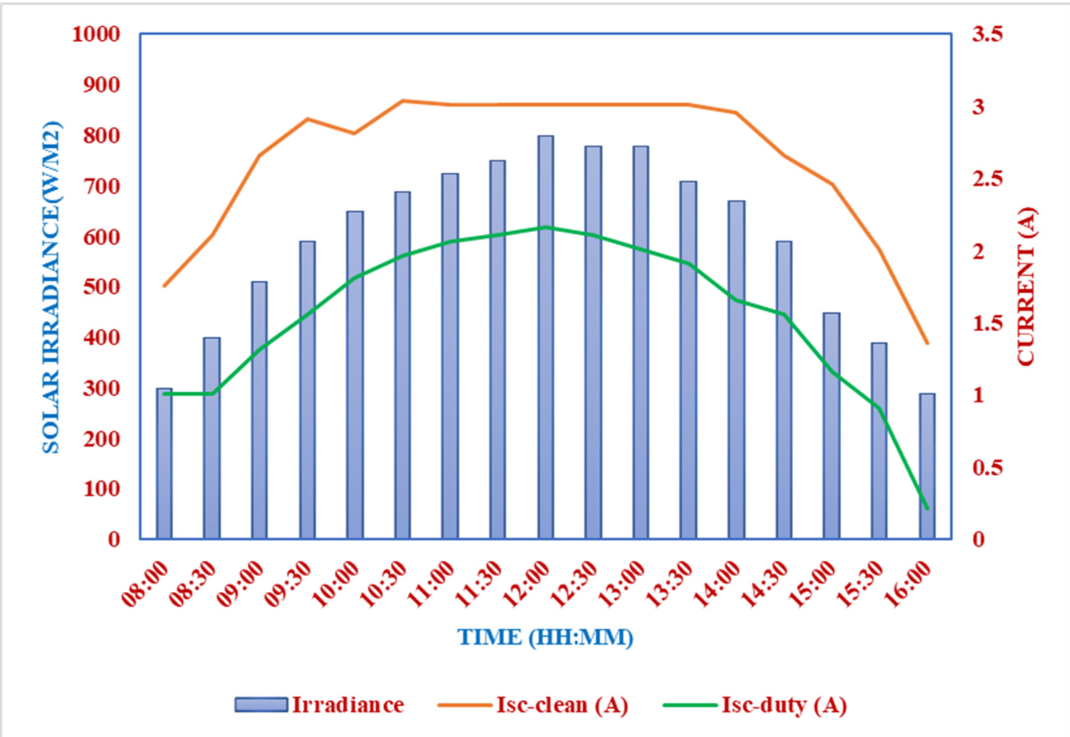

Figure 10. Impact of dust on a short circuit current after the 12th week (Mono-crystalline).

3.1. Polycrystalline

In this section, the effect of dust on polycrystalline PV modules, both clean and dusty modules, is examined. According to Figure 11, the current decrease rates were 18.98% and 31.35% after 6 and 12 weeks of being exposed to external environments, respectively. Figure 12 displays the voltage decrease rates for the same examples, which were 0.19% and 0.46%, respectively. After being exposed to external environments for 6 and 12 weeks, the power loss rates were 18.52% and 30.48%, respectively. The average power decrease caused by dust deposition was lower than that seen in the monocrystalline scenario. The biggest power decrease during midday was mostly caused by the combination of the maximum solar irradiation and the influence of dust.

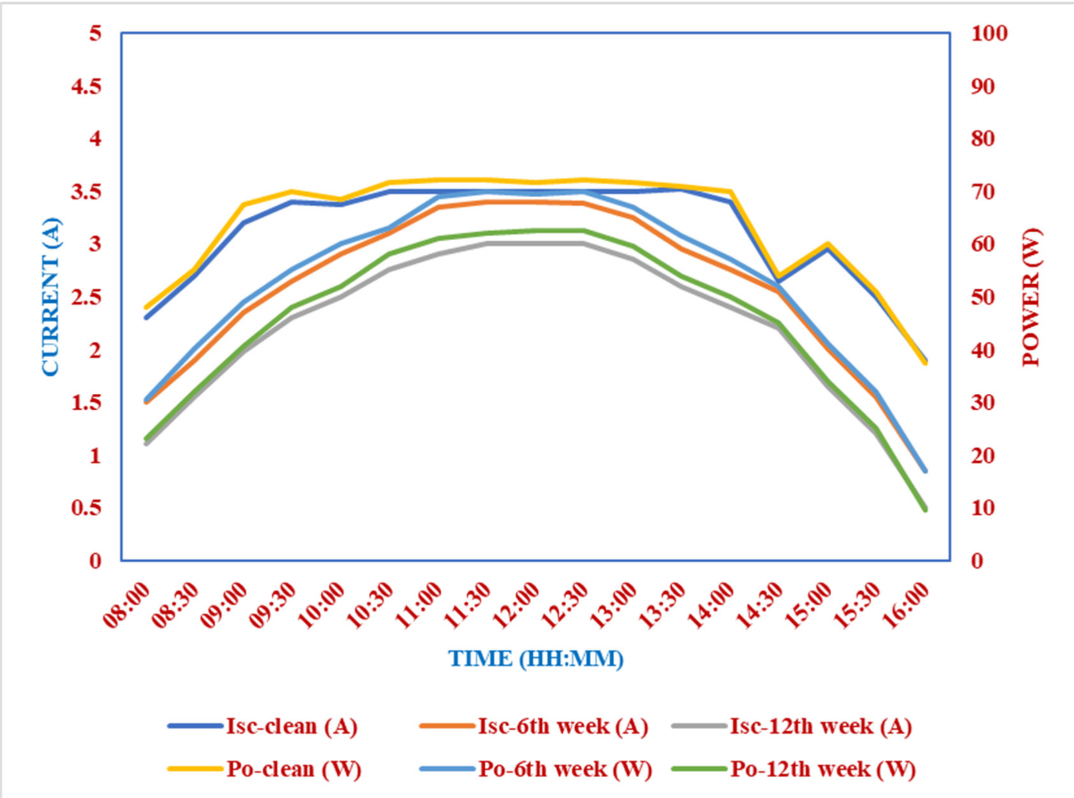

Figure 11. Effect of dust on short circuit current (Poly-crystalline).

During peak hours shown in Figure 13, PV modules produce about the same amount of power, regardless of whether they are clean or dusty. During this period, a drop rate of 20.37% was achieved for the day's operations. The high intensity of solar radiation is one important factor that influences the PV module's productivity since it raises the module's temperature and hence reduces its output.

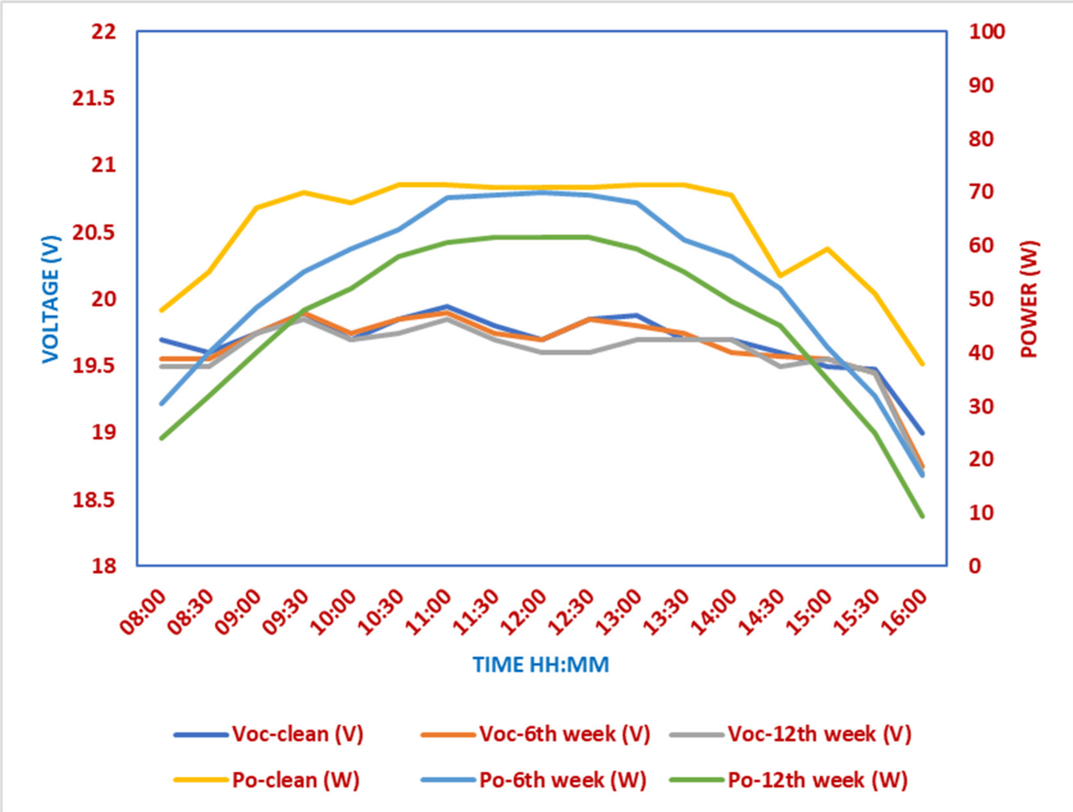

Figure 12. Effect of dust on open circuit voltage (Poly-crystalline).

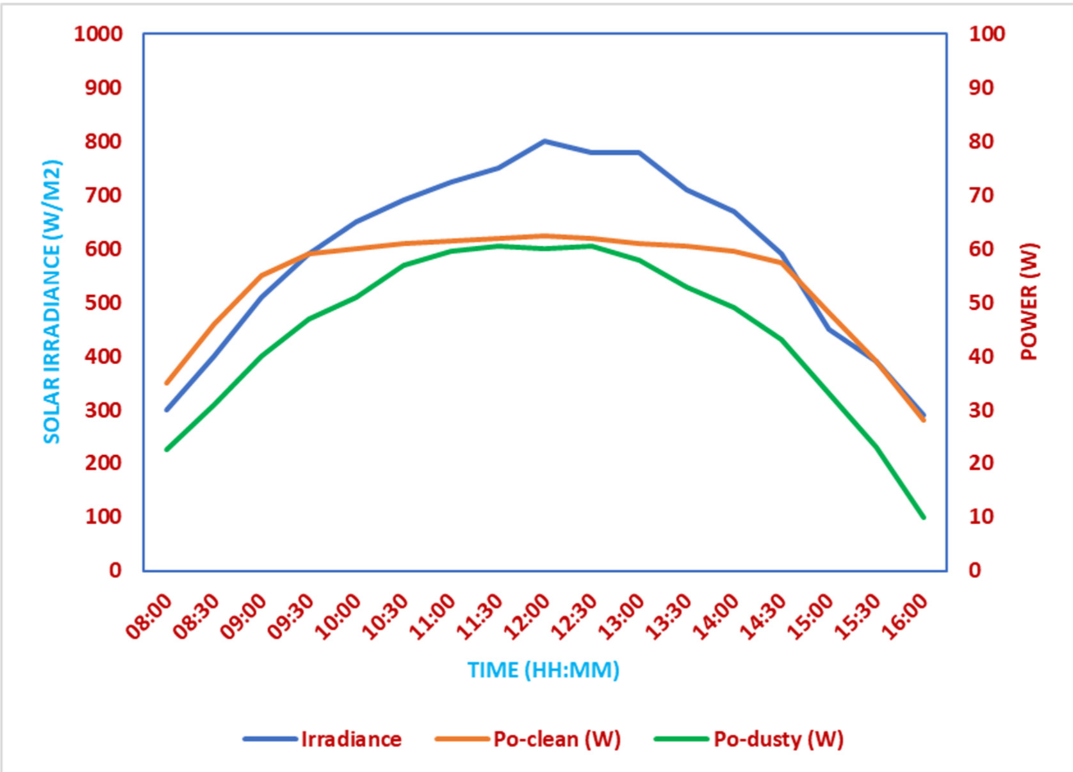

Figure 13. Effect of dust on power output after 12th week (Poly-crystalline).

The impact of the intense radiation on the voltage is also noticeable, though the build-up of dust leads to a decline in the ampere. The amalgamation of these two factors resulted in the convergence of values during the pinnacle era. In Figure 14, the effect of dust accumulation on a polycrystalline element after three weeks in the outside environment is shown.

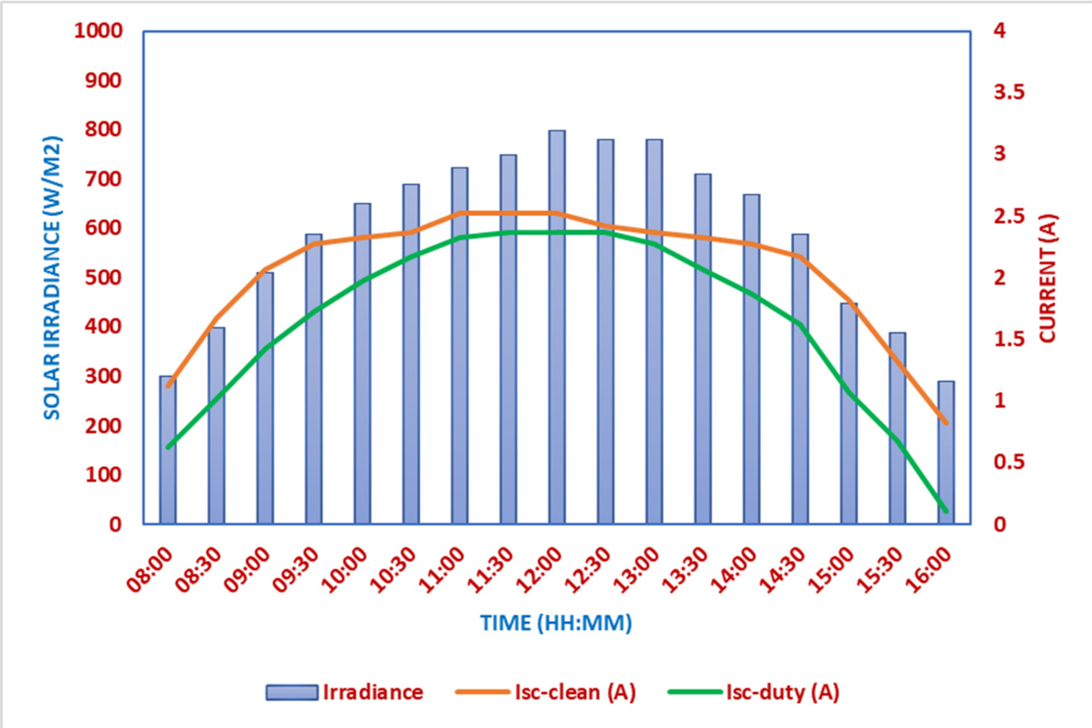

Figure 14. Effect of dust on the short circuit current after 12th week (Mono-crystalline).

This reveals the influence of dust accumulation on the electric current reduction, with an average drop of up to 24.75% in one day of operation. Moreover, we found that the clean PV current drops as its value approaches that of the dusty module current during peak time. During this time, it was noticed with a 14% difference was noticed between clean and dirty modules. This phenomenon could be from the increased solar radiation intensity, an average of 764 W/m^2 that was noticed in this period. The impact of this aspect on the clean module was more significant compared to the dusty one due to the latter's ability to absorb a substantial portion of the irradiance to generate heat, thereby creating a shadow effect on the module.

The influence of each parameter was examined to demonstrate the significance, magnitude, and interrelationships. Outdoor settings often do not provide the standard test conditions used in the denominator, which indicate the highest values that the 3 parameters may achieve. The equations below were applied:

$$V_{OC}^{red} = \left(\frac{(V_{pv}^{clean} + V_{pv}^{dust})}{V_{pv}^{std}}\right) \times 100\% \quad (1)$$

$$I_{sc}^{red} = \left(\frac{(I_{pv}^{clean} + I_{pv}^{dust})}{I_{pv}^{std}}\right) \times 100\% \quad (2)$$

$$P_{pv}^{red} = \left(\frac{(P_{pv}^{clean} + P_{pv}^{dust})}{P_{pv}^{std}}\right) \times 100\% \quad (3)$$

The parameter values under standard circumstances (std) for the polycrystalline module were Isc = 4.82 A, Voc = 20.7 V, and Prated = 80 W. The values for the monocrystalline module were 4.8 A, 22 V, and 80 W, as illustrated in Table 1. Figure 15 below shows that, whereas the voltage did not change significantly due to the presence of dust, the current, and thus power, dropped to almost half. Each of the devices had a range of values for the current, voltage, and power losses on the order of 10.5–24.0%, 1.5–2.55%, and 13.5–30.5%, respectively. Nevertheless, it was seen that the power curve exhibits a consistent pattern for current, indicating a robust link between the two. Conversely, the voltage trend has a nearly straight-line correlation with a negligible impact.

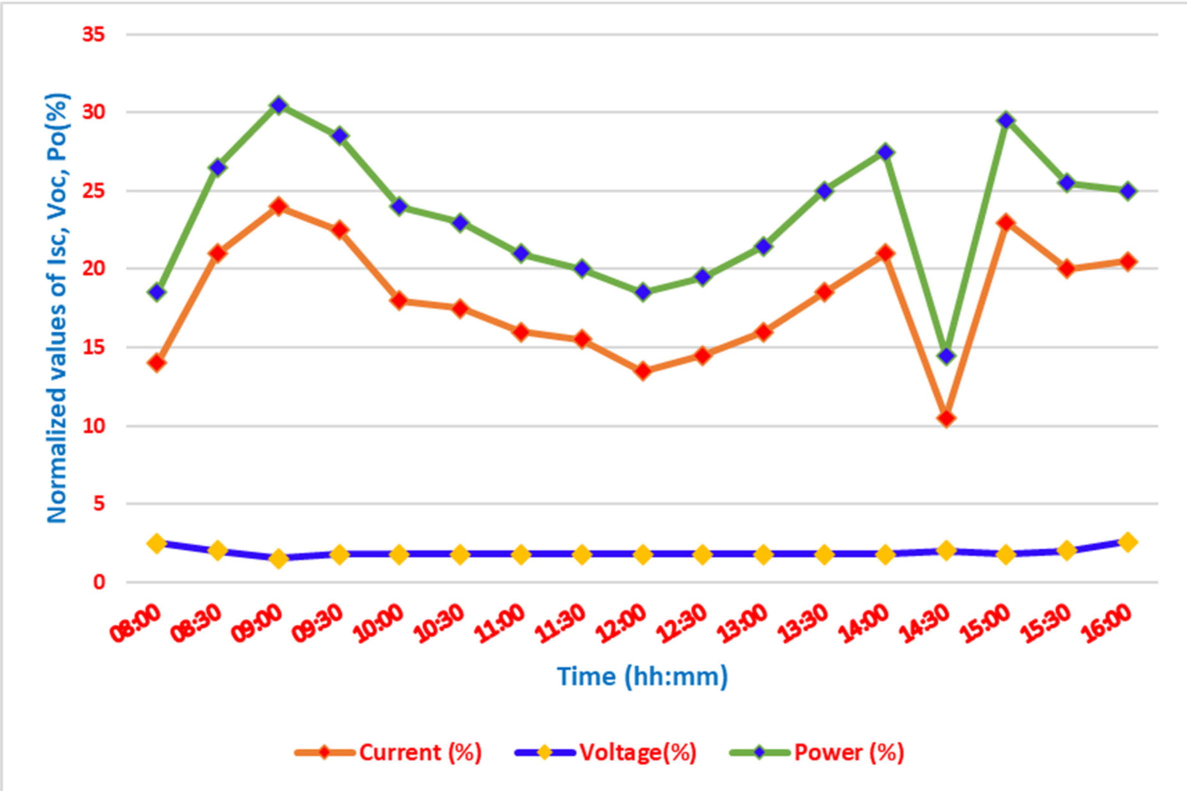

Figure 15. Comparison of electrical factors for the monocrystalline panel.

The study site was near an ongoing construction project and a national highway. The location subjects PV modules to a broad array of airborne particulate debris that includes construction dust particles and cement residue and silica particles alongside fine vehicle-generated carbonaceous particles. Different dust compositions that affect PV module performance through their diverse optical characteristics, as well as thermal properties and adhesive behavior, are well documented. Weighty silica, together with cement particles, creates irregular glass surfaces and tiny shadows; yet, carbon-based particles construct a blocking film to reduce glass transmittance. The high humidity throughout the April–June 2023 study period most likely strengthened dust attachment, which resulted in increased performance reduction. Experimental power loss data between monocrystalline and polycrystalline modules suggests that their susceptibility to dust deposition varies because of environmental conditions, particularly affecting polycrystalline panels in mixed dust environments.

A detailed comparative analysis is provided in Table 2. Light absorption characteristics together with material properties, determine the performance difference between monocrystalline and polycrystalline modules that face equivalent dust accumulation. Silicon-based monocrystalline modules achieve better efficiency while absorbing more sunlight because they have high-purity silicon content, yet their smooth appearance makes them reflect light more strongly under conditions of dust accumulation. Due to their multiple-crystal structure, polycrystalline modules develop increased surface roughness that lets dust particles stay on them more strongly. Performance levels decrease to a greater extent in monocrystalline modules compared to monocrystalline modules.

Table 2. Comparative analysis of PV performance.

Reference	Type of panel	Period under study and location	Methods and remarks
[31]	Mono and Poly	30 Days (Middle East)	CFD and Empirical (20–25) % decrease in power. Lack of long-term performance analysis
[32]	Mono	Simulation	CFD and Numerical (Modelling via airflow dynamics). Lack of a real-world experiment
[7]	Poly	45 Days (Jordan)	Empirical (28% reduction in power). Lack of comparison between both PV Panels
[8]	Poly and Mono	56 Days (Qatar)	Empirical (15–30)% reduction in power. Limited Daily Performance Tracking
Proposed work	Poly and Mono	90 Days (India)	Empirical Field Study. (30.48%) Poly and (14.1%) Mono. Real-world environmental exposure

Degradation patterns from this study demonstrated 30.48% for polycrystalline and 14.1% for monocrystalline because Potheri near Chennai (12.8216° N, 80.0451° E) has high environmental conditions composed of elevated temperatures and humidity, together with heavy dust levels near infrastructure. The research conditions replicate conditions found across urban, industrial, and semi-arid environments because excessive dust occurs together with human-generated particulates. Results from using a 15° tilt angle in this research display broad applicability across South India, along with tropical areas such as Southeast Asia and portions of the Middle East, and with northern Africa and Latin America, because these regions share high temperatures and mixed urban-dust environments. The research demonstrates that monocrystalline panels experience diminished power losses during dusty conditions, which supports global findings about the transferability of these results to similar environmental risk areas. This research provides degradation rate patterns that extend to numerous urbanized and industrial regions throughout the world because local dust types and rainfall distributions affect specific degradation rates.

In Table 3, the effectiveness of three cleansing approaches to solar PV modules is compared with each other: Spraying water, wiping with alcohol, and treatment with a sodium solution for cleaning solar PV modules. The table shows each method in terms of factors such as workforce requirements, prices, appropriateness (geography), efficiency (output power recovery), advantages, and shortcomings. The method for water cleaning is the cheapest solution, but it demands a large amount of water. It is not effective in sticky or oily dust accumulations and is not suitable for areas with water deficiency. Despite the outstanding 98% power recovery possibility that it proposes, alcohol wiping is a costly option because the prices of alcohol are high, not to mention the need to have trained personnel to undertake the process safely. It is very effective in removing adhesive and greasy contaminants. Sodium solution presents a compromise between the two-cost and efficiency (97%). This solution is suitable for removing cementitious or inorganic dust; however, it should be used with care because of disposal and corrosion issues. By comparing the various methods, stakeholders can determine which cleaning method is most suitable for their PV installation context, resources required, and maintenance costs.

Table 3. Comparative analysis of cleaning methods for pv modules.

Parameters	Cleaning with water	Wiping with alcohol	Cleaning with sodium solution
Labor	Manual (Unskilled Person)	Manual (Skilled Person)	Manual (Skilled Person)
Cost	Low	High	Moderate
Region with resources	Areas with plenty of water	Areas with scarce water	Areas with scarce water
Efficiency (%) (Output power recovery)	95	98	97
Advantages	Low cost, easy to apply, widely available	Easy removal of sticky or oily particles, fast drying	Easy removal of cement or inorganic dust, minimized particle adhesion
Limitations	Difficult for sticky or oil dust, ineffective in regions with water scarcity	Material cost is high, and needs a trained person for the process	Post-cleaning process is required, High disposal issues and corrosion effects

4. Solar panel performance analysis results

It is shown via ANOVA that effects like dust accumulation, module type, and exposure length always and independently influence the electrical efficiency of photovoltaic modules. From the best F-values among the studied variables, it is obvious that dust accumulation has a vast impact on power output. This demonstrates that dust deposition is a major, rather than minor and passing concern, affecting PV system efficiency, especially if dust accumulation is severe. The clear differences between the polycrystalline and monocrystalline modules suggest that the material and surface construction of the modules play a major role in determining their response to environmental pollutants. The heightened sensitivity to dust accumulation for polycrystalline modules suggests that the choice of modules should be informed by the prevailing environmental factors on each site. The longer the dust lies over the modules, the greater the reduction of the overall efficiency. The longer dust stays on modules without any interference, the worse the declines in current and power output are. Combined, this is how insufficient maintenance or cleaning can lead to continuous and great losses in energy generation.

It is essential to know that there is a non-linear, multiple-asset relationship between dust, module characteristics, and exposure duration. However, the rate and extent of lapse in performance is not constant for all conditions. As such, some module types suffer a more rapid performance decay upon being exposed to long-term dusting. These remarks imply that maintenance and cleaning methodologies must consider the nature of the local environment and the selected PV system. Taken altogether, these outcomes underline the importance of having regular and preventive maintenance of PV establishments, especially in the case of high levels of dust. These insights govern module choice and suggest that standard cleaning and protective measures are of special importance for polycrystalline modules to provide the best possible output. These insights, supported by their statistical power, serve as a reminder of the need to consider environmental conditions and operation procedures in the design or maintenance PV system.

Table 4. Anova table.

Performance parameter	Statistical result	Significance level	Research findings
Short circuit current (A)	F = 15.4	p < 0.001	Complex interrelationship observed
Open circuit voltage (V)	F = 4.9	p < 0.05	Minor interrelationship detected
Power output (W)	F = 19.2	p < 0.001	Substantial interrelated influences

To reinforce the findings, we compared the results with relevant literature, and the results match the trends from the literature that losses occur with dusty conditions. With regard to recommendations, the frequency of cleaning PV modules depends on the environmental conditions, such as the dust concentration in the atmosphere, wind speed, and humidity. The observations suggest cleaning periodically every 6–12 weeks to mitigate efficiency loss. Based on performance data gathered during this study, monocrystalline PV devices better resist degradation from dust accumulation as opposed to polycrystalline modules. The technical and economic balance created by monocrystalline panels' slightly higher maintenance frequency needs outweigh their superior baseline output.

Initial costs for monocrystalline modules exceed those of polycrystalline modules by approximately 15–20%, but this module type delivers 3–5% additional energy output yearly from installation until end-of-life, especially in areas with heavy dust exposure, when regular cleaning of polycrystalline panels is essential to avoid efficiency loss. Higher monocrystalline module efficiency decreases installed system dimensions, which leads to lower structural and land expenses that standard cost assessments typically ignore. The USD 5–15 per kW yearly cleaning costs correspond to 1–2% of annual monocrystalline energy output, thus maintaining affordable operational maintenance expenses. The cost of monocrystalline systems paying off energetically and financially throughout their lifespan provides better power output in regions like the study area with dusty conditions and similar arid and semi-arid regions.

5. Conclusions

We provide a unique and comprehensive analysis of the impact of dust on solar PV panels, with a focus on comparing polycrystalline and monocrystalline panels over an extended duration of 90 days. Examining three distinct cleaning methods under identical conditions, this study provides practical insights into their efficiency, cost-effectiveness, and scalability. The findings are especially valuable for optimizing PV maintenance strategies in high-dust regions, guiding stakeholders in selecting suitable panel types and cleaning techniques based on local conditions. The results reveal that polycrystalline panels experienced a higher power loss of 30.48% compared to 14.1% for monocrystalline panels, demonstrating the superior performance of monocrystalline technology in high-dust environments. Among the three cleaning methods tested, alcohol wiping showed the highest efficiency (~98%), followed by sodium solution (~97%) and water rinsing (~95%). However, the cost, scalability, and regional suitability of these methods must be considered when selecting a cleaning strategy. This study provides practical guidance for PV deployment in dusty regions, highlighting the importance of selecting suitable panel types and optimizing cleaning methods. Future work can build on this study in the following ways: (1) Investigating the impact of dust accumulation and cleaning methods on other PV technologies such as thin-film or bifacial panels; (2) developing predictive models to optimize cleaning schedules based on regional climatic conditions and dust characteristics; (3) conducting a detailed economic analysis to balance the initial cost of panels and long-term maintenance expenses, providing stakeholders with clear cost-benefit insights; (4) and the PV degradation trends can be predicted by machine learning algorithms based on environmental conditions, and the best cleaning schedules and performance estimate correction factors could also be optimized.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Surender Reddy Salkuti is an editorial board member for AIMS Energy and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

Author contributions

A.Geetha: Conceptualization, Resources, Data curation, Writing original draft; **S.Usha:** Software, Validation, Methodology, Writing review, editing; **J. Santhakumar:** Investigation, Visualization, Data curation, Software; **Surender Reddy Salkuti:** Methodology, Formal analysis, Project administration, Supervision, Writing—review and editing.

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