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Performance Degradation of Photovoltaic Panels Due to Dust Accumulation: A Case Study in Al-Bayda, Libya

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ABSTRACT

The build-up of dust on photovoltaic (PV) panels reduces sunlight reaching solar cells, which causes a decrease in the PV power output. Besides reducing solar irradiance, the dust also changes the angle at which radiation hits the surface of the panels, further diminishing the efficiency of PV energy conversion. This study investigates the impact of dust accumulation on photovoltaic (PV) panel performance through a 12-month experiment carried out on the rooftop of a residential building located near industrial activities and high vehicular traffic in Al-Bayda, Libya. Our experimental results show that, over one year, dust deposition reduced power output by nearly 7.42%. Additionally, in spring and summer, the reduction in output power reached 15.49% and 12.4%, respectively, while in winter and autumn, output power decreased to 4.86% and 3.55%, respectively. With accurate year-long experimental data, this research can support the formulation of dust-resistant solar technologies, thus serving the PV system designers, engineers, and researchers working on PV systems. The findings are particularly relevant to Libya as the country moves toward adopting solar energy to diversify its energy sources and decrease its reliance on fossil fuels.

Keywords: Photovoltaic Panels, Dust Accumulation, year-long experiment, seasonal assessment, Power output reduction.

تدهور أداء الألواح الكهروضوئية بسبب تراكم الغبار: دراسة حالة في البيضاء، ليبيا

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ملخـــــــص البحـــــــث

يؤدي تراكم الغبار علي الألواح الكهروضوئية إلي تقليل وصول ضوء الشمس إلي الخلايا الشمسية، مما يقلل من طاقة إنتاجها. بالإضافة إلي تقليل الإشعاع الشمسي، يغير الغبار أيضا من زاوية سقوط الإشعاع علي سطح الألواح، مما يضعف كفاءة تحويل الطاقة الكهروضوئية. يُقيّم هذا البحث آثار ترسب الغبار علي أداء الألواح الكهروضوئية من خلال تجربة استمرت عامًا كاملًا أُجريت على سطح مبنى سكني يقع بالقرب من أنشطة صناعية وطريق مزدحم في البيضاء، ليبيا.

تشير نتائجنا إلى أن ترسب الغبار يُقلل من إنتاج الطاقة للألواح الكهروضوئية بنسبة 7,42% تقريبًا. بالاضافة الي ذلك بلغ انخفاض القدرة الناتجة في فصلي الربيع والصيف نسبة 15.49% و12.4% علي التوالي في حين انخفضت القدرة في الشتاء والخريف الي 4.86% و3.55% علي التوالي. بفضل بيانات تجريبية دقيقة أُجريت على مدار عام، يُمكن لهذا البحث أن يدعم تطوير تقنيات شمسية مقاومة للغبار، مما يُفيد مصممي ومهندسي وباحثي أنظمة الطاقة الكهروضوئية. وتُعدّ هذه النتائج ذات أهمية خاصة لليبيا في ظل توجهها نحو اعتماد الطاقة الشمسية لتنويع مصادر الطاقة وتقليل الاعتماد على الوقود الأحفوري.

الكلمات الدالة: الألواح الكهروضوئية، تراكم الغبار، القدرة الخارجة، الاشعاع الشمسي، الوقود الأحفوري.

1. Introduction

Libya is a North African country located along the southern coast of the Mediterranean Sea. It has borders with Egypt to the east, Chad and Niger to the south, Sudan to the southeast, Algeria to the west, and Tunisia to the northwest [1]. The climate of Libya is mostly arid, with most of its area covered by desert. In Libya, the coastal regions experience a Mediterranean climate characterized by mild, wet winters and hot, dry summers, while the inland areas exhibit a desert climate, marked by extremely high temperatures during the summer and significant diurnal temperature variation [1]. Rainfall is rare and irregular, mainly concentrated in the northern regions during the winter months, and the country frequently experiences dust and sandstorms, particularly in the southern regions [2, 3].

As Libya begins adopting solar energy as a source of electricity, it is crucial to take into account the climatic conditions of the country, which may adversely affect the performance of solar energy systems. Addressing these environmental factors is essential to ensure the reliable and efficient generation of electrical energy from solar energy systems. One of the key challenges affecting solar energy systems in Libya is the presence of natural obstructions, particularly the accumulation of dust on the surfaces of PV panels. Dust buildup on the surfaces of PV panels reduces the amount of sunlight reaching the cells, resulting in a decrease in output power and, consequently, a reduction in overall efficiency [4-10]. Several research efforts have been devoted to investigating and analyzing the impact of dust accumulation on PV systems. The work done by [11] reported that, in the absence of rainfall, power losses due to dust accumulation on four monocrystalline silicon PV modules with three different types of glass surfaces were approximately 6% over a one-year period. In [12], the performance of one PV panel and two thermal panels was monitored over several months of outdoor exposure in the Kingdom of Saudi Arabia. For the PV panel, the average monthly decline in efficiency due to outdoor exposure was estimated at 7%. The research presented in [13] involved a real-time study conducted on the rooftop of a building in Malaysia, where solar irradiation, output power, and the corresponding dust mass accumulation were measured on hourly, daily, weekly, and monthly intervals. The results indicated that the PV performance could decrease by around 6% annually because of dust accumulation. In [14], a 32 kW PV system was installed on the rooftop of the University of Technology Bahrain (UTB) building. The system was arranged into four parallel rows, each with an equal power capacity. To assess the impact of dust accumulation, each row was cleaned at different intervals, once a week, every two weeks, every three weeks, and every four weeks. The results indicated a clear decline in PV panel performance as cleaning intervals increased. Efficiency dropped by 2.3% when panels were cleaned biweekly, by 3.5% when cleaned every three weeks, and by 7.1% when cleaned monthly. These findings highlight the significant effect of dust buildup on solar panel efficiency and the importance of regular maintenance. In reference [15], researchers examined how dust accumulation affects the performance of PV system installed at Manipal University in Jaipur, India. Important performance indicators such as open-circuit voltage, short-circuit current, and output power were measured for both clean and dust-covered PV panels and evaluated through the analysis of their characteristic curves. The study found that after 55 days without cleaning, the unclean panel exhibited a 9% reduction in output power compared to the clean panel. A study conducted at the Institute of Distributed Generation and Microgrid, Zhejiang University of Technology (East China), as cited in [16], found that dust on PV modules tends to accumulate in clusters following rainfall, resulting in a rapid drop in performance. Specifically, an average dust density of 0.644 g/m² accumulated within one week caused a 7.4% reduction in output power.

Several methods have been used to diminish dust accumulation and thus enhance the efficiency of PV panels. In [17],a robotic arm-based self-automated dust removal system employing an IR sensor-guided, PWM-controlled silicone rubber wiper was developed to effectively decline dust deposition on the surfaces of PV panels. In [18], a transparent electric curtain operated based on voltage threshold ratios was proposed as an energy-efficient solution for dust mitigation. In addition to mechanical methods, surface coatings have been explored. Specifically, a dual-layer coating combining a translucent aluminum zinc oxide film for active dust repulsion with a TiO_2-infused sol-gel layer for passive anti-soiling has been shown to significantly reduce dust accumulation [19]. A novel automatic cleaning system for solar photovoltaic panels has been developed to reduce dust accumulation and improve power output [20]. The system features a durable mechanical structure made of aluminum alloy and is equipped with a time-based control unit, enabling scheduled cleaning operations without manual intervention. An electrostatic and electrodynamic dust repelling system, employing interdigitated electrodes energized by a low-power, low-frequency AC voltage, has been developed and experimentally validated for its effectiveness in levitating and removing dust particles from the surfaces of solar panels [21].

Although numerous mechanical, electrical, and material-based strategies have been proposed and examined to mitigate dust accumulation on PV systems, as documented in the previous studies, these mitigation techniques lie beyond the scope of the present study. This study is specifically aimed at evaluating how dust accumulation affects the performance of PV panels. The primary goal is to analyze the influence of dust on critical performance metrics such as output power. Accordingly, no cleaning or dust prevention mechanisms are considered.The scope of this paper is inherently limited by not covering the measurements of dust quantity, particle size, or key environmental parameters, including temperature and humidity.

Previous investigations have reported that dust accumulation can lead to a decline in PV system performance based on methodologies such as long- term monitoring, outdoor exposure assessments, dust mass quantification, and analysis of cleaning intervals. However, many of these studies have been conducted in controlled or relatively clean environments, offering limited insight into the effects of dust in more complex, real-world conditions. This underscores the necessity for further investigation in regions where dust accumulation occurs more frequently and exhibits greater compositional diversity, largely driven by the proximity of industrial activities, construction operations, and vehicular emissions. To address this gap, the present study was conducted in an environment characterized by close proximity to industrial facilities and heavy vehicular traffic.

The motivation for conducting this research stems from the lack of prior studies on the effect of the buildup of dust on PV panels in Al-Bayda city and the surrounding regions. Another key motivation is Libya's strong potential for solar energy development, as its climate and high solar irradiance make it an ideal candidate for future solar energy investments.

Our research provides multiple significant contributions:

- First, this study presents year-long experimental data on the effect of the buildup of dust on PV system performance in environment characterized by industrial activity and frequent vehicular traffic that remain underrepresented in existing literature.
- Second, although the general impact of dust on PV performance is well established, the originality of this work lies in quantifying this effect within the specific industrial and high traffic environment, thereby filling a critical geographical research gap.
- Third, the experimental data collected in Al-Bayda city serve as a valuable reference for similar locations across the country, thereby supporting informed decisions regarding the deployment and performance optimization of PV systems.

- Fourth, this study provides a seasonal breakdown, presenting detailed power loss data for each season. This analysis enhances the understanding of temporal variations in PV performance and adds practical value for planning and optimizing PV systems throughout the year.

2. Methodology

Our case study site is Al-Bayda city, Libya, that located in the northeast part of the country, in the Jabal Al-Akhdar in the Cyrenaica area. Two PV modules of the same type were mounted next to each other on a non-tracking mounting system with the same tilt and azimuth angle in order to have the same solar irradiance on the two modules. The site of the experiment was the rooftop of a residential building in Al-Bayda (32.7627°N, 21.7551°E), which is 632 meters above sea level. The residential building is located adjacent to a high density of traffic and an industrial area that encompasses construction material sales such as gravel, sand, and cement, marble manufacturing, and automotive repair workshops, as well as numerous local factories.

The performance of two PV panels was assessed by comparing the power output of a dust-accumulated panel with a routinely cleaned panel. To achieve an accurate comparison, one panel was kept clean by weekly planned cleaning in order to guarantee a controlled comparison, while the other panel was left uncleaned to permit dust buildup naturally. Once per week, the electrical measurements were taken from both panels, only just before the cleaning of the maintained panel. Thus, four readings per month of data were collected from each panel.

i) Experimental setup

To complete the electrical circuit of two panels, a fixed resistive load was connected to each panel. Current and voltage were measured using a digital voltmeter and a digital ammeter. The output power of each panel was calculated as the product of the measured current and voltage. To minimize the effects of irradiance variability, and ensure consistency, all measurements were taken at regular intervals during peak sunlight hours. This experiment was performed without interruption over a period of 12 months. The percentage degradation in output power due to dust was calculated by the following relation:

$$D(\%) = \frac{P_{clean} - P_{dust}}{P_{clean}} \%$$

The average degradation was computed by the following relation:

$$D_{av} = \frac{1}{N}\sum_{i=1}^{N} D_i$$

Where D is the degradation in output power due to dust, D_{av} is the average degradation in output power due to dust, N is the number of measurements, P_{clean} is the output power of the routinely cleaned panel and P_{dust} is the output power of the dust-accumulated panel, The manufacturer's datasheet specification of the PV panels applied in the study is given in Table 1.

Table 1. Monocrystalline solar module

Parameters	Value
P_{max}	200W
I_{mp}	8.43A
V_{mp}	17.8V
V_{oc}	21.8V
I_{sc}	9.08A
FF	0.85

Figure 1 shows the setup of the experiment.

Figure 1. The experimental setup of two identical PV panels

ii) Assumptions, Limitations, and uncertainties.

a) Assumptions.

In conducting this study, it was assumed that both PV panels received equal solar irradiance throughout the experimental period due to their identical orientation, tilt angle, and placement on the same rooftop. The resistive load was assumed to remain constant throughout the experiment, unaffected by temperature and adequately matched to the PV modules' operating point to ensure that variations in power output were mainly due to dust accumulation.

b) Limitations.

The experiment setup was limited to two PV modules, which may not fully capture variability across larger PV arrays or under different installation conditions. The study was carried out at a single residential location, which may limit the applicability of the results to other regions with varying environmental factors and types of dust. Additionally, due to budget constraints, the experiment was conducted using only two PV panels, which may limit the statistical robustness and generalizability of the findings.

c) Uncertainties.

Fluctuations in irradiance and ambient temperature, even during peak sunlight hours, may have introduced minor deviations in the recorded data. Instrumental uncertainties in current and voltage measurements could also affect the computed power output. Furthermore, natural differences in dust particle size, composition, and deposition rate across seasons may introduce uncertainties when generalizing the results.

3. Results and Discussion

From our experimental study, we observed that the accumulation of dust on the surface of the PV panel causes a significant reduction in the power output of the PV panel. This highlights the significant influence of external conditions, particularly dust, on the performance and power generation of solar PV systems over a longer time span. Figure 2 displays the power output of both the regularly cleaned panel and the dust-accumulated panel over the entire 12-month monitoring period. It is clear from the figure that the solar panel that was left exposed to natural dust accumulation invariably had a lower output power than the cleaned panel. Both panels show an increase in output power during the summer months from May to August, which corresponds to the times of high solar irradiance. Even in the high insolation months, however, the dust-covered panel did not perform well compared to the cleaned panel. This confirms that dust accumulation can greatly hamper energy harvest even when plentiful sunshine is available.

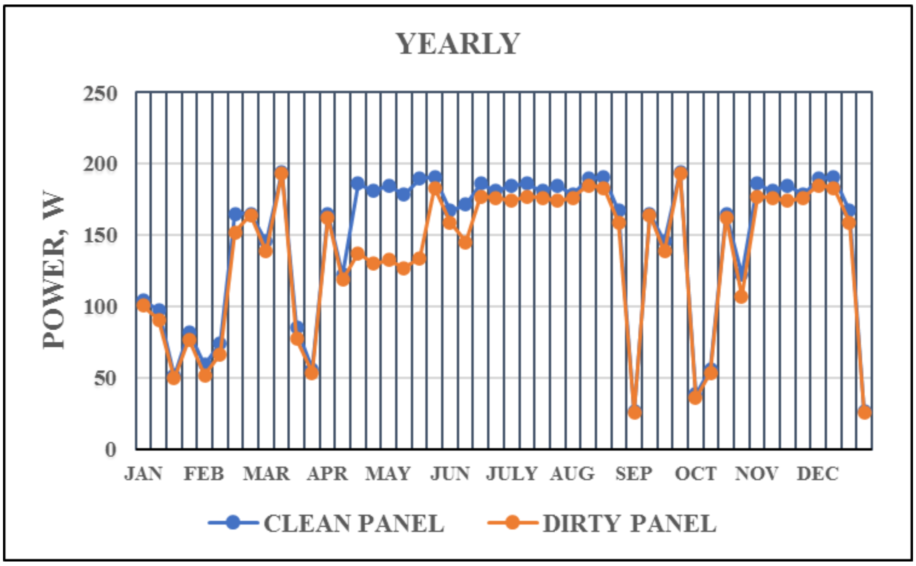

Figure 2. The power output of the clean panel and the dirty panel over the whole year

Based on our experimental results, the reduction in output power during the summer and spring seasons reached peak values of 12.486% and 15.486%, respectively. Analysis of the collected data indicates that these elevated loss rates are closely associated with extended periods of dry weather in both seasons, characterized by minimal or no rainfall. The absence of precipitation is identified as a significant contributing factor to the observed increase in output power reduction, as it diminishes the natural cleaning effect of rainfall on solar panel surfaces, thereby allowing dust and other particulates to accumulate. As demonstrated in Figures 3 and 4, the output power of the dusty panel was consistently lower than that of the clean panel across the measurement period. These findings confirm that dust accumulation under dry conditions has a substantial negative impact on PV system performance.

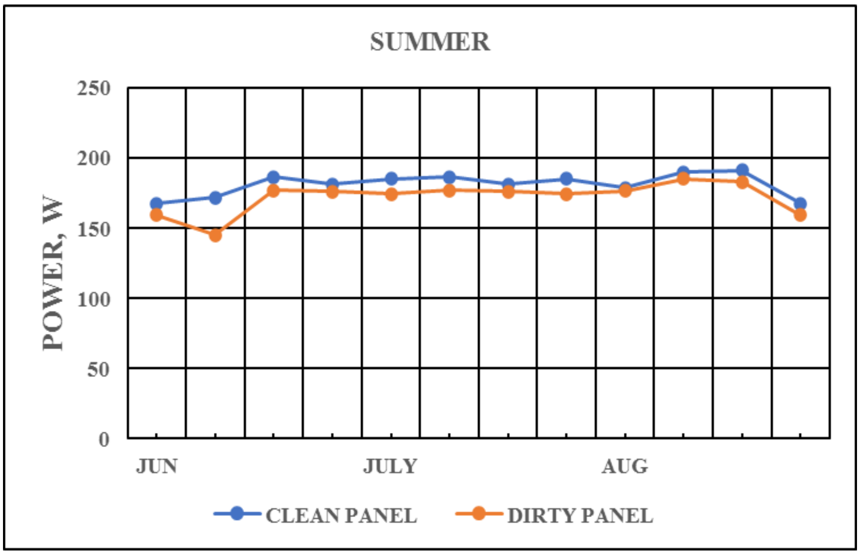

Figure 3. The power output of both clean and dirty panels through the summer season

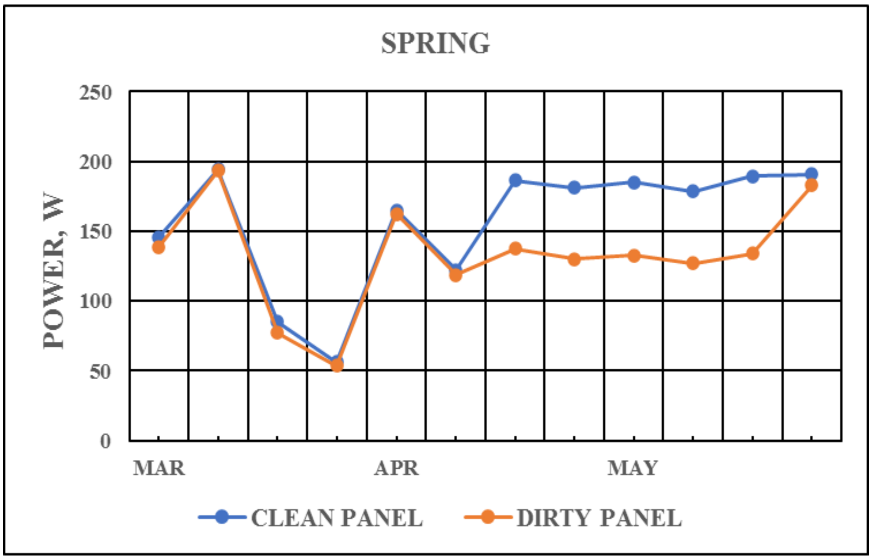

Figure 4. The power output of clean and dirty panels through the spring season

During the autumn and winter seasons, which are characterized by increased rainfall, power losses were observed to be at their lowest levels, measuring 3.551% and 4.862%, respectively. This reduction in power loss is attributed to the natural cleaning effect of rainwater, which removes accumulated dust and debris from the surface of the cells, thereby enhancing their performance. This improvement is clearly illustrated in Figures 5 and 6, where the difference in output power between clean and dusty panels is significantly smaller compared to the drier seasons.

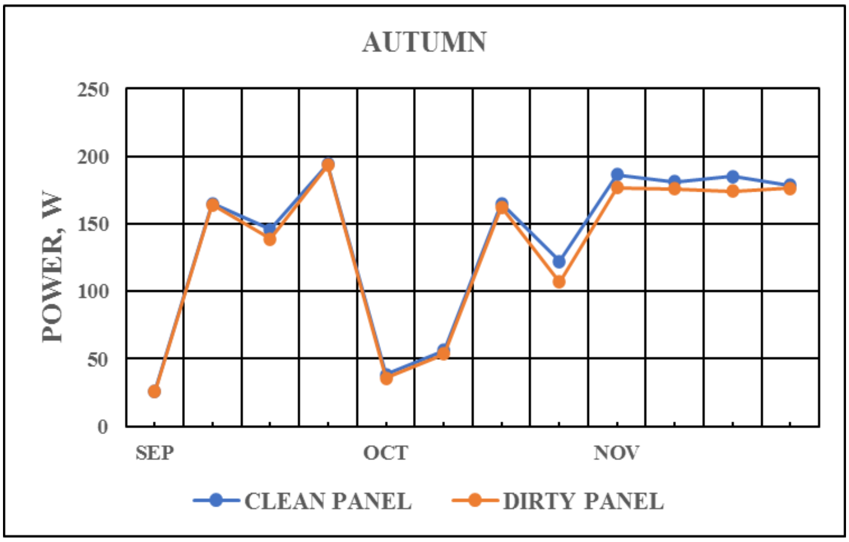

Figure 5. The power output of the clean panel and the dirty panel through the autumn season

Our experimental study shows a significant reduction in PV panel output due to dust accumulation, consistent with previous studies [11–15], which reported losses of 6–9% without cleaning. In our study, reductions peaked at 12.486% in summer and 15.486% in spring, higher than prior reports, highlighting the strong impact of an industrial and high-traffic environment combined with dry weather. These results confirm that local environmental factors, such as industrial emissions and vehicular activity, strongly affect PV performance, particularly during dry periods.

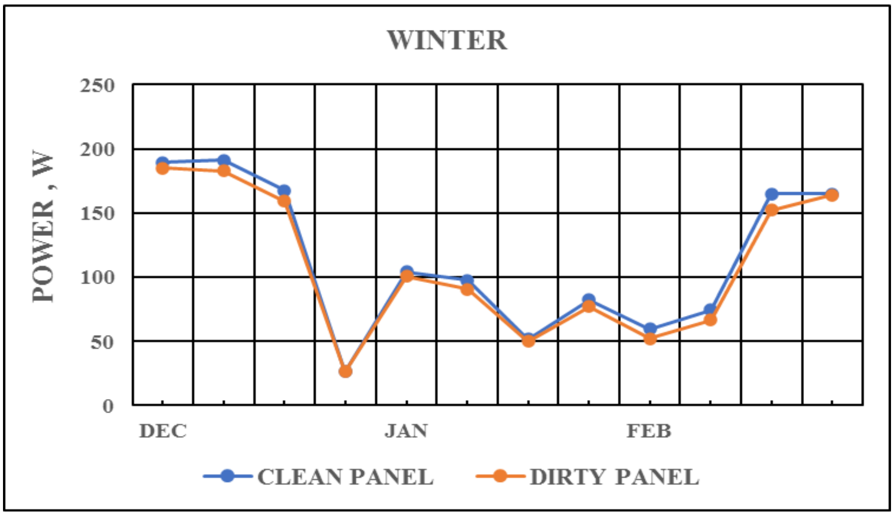

Figure 6. The power output of the clean panel and the dirty panel through the winter season

4. Conclusion and future work

This study has demonstrated the significant impact of accumulated dust on the performance of photovoltaic panels installed on a residential building in Al-Bayda, Libya. The experimental findings confirm that dust deposition significantly limits the solar irradiance incident on photovoltaic panels, resulting in a notable decline in their power output. Over the course of one year, an average output power reduction of 7.417% was recorded due to dust accumulation. Seasonal variations played a critical role in the extent of PV performance degradation. The highest reduction occurred during the dry seasons, summer and spring, reaching up to 12.486% and 15.486%, respectively, primarily due to the prolonged absence of rainfall, which otherwise serves as a natural cleaning agent. In contrast, during the wetter seasons of autumn and winter, the reduction in output power was significantly lower, at 3.551% and 4.862%, respectively. These findings underscore the necessity of considering local environmental conditions when designing and maintaining PV systems. Future research should aim to broaden the geographical scope by conducting similar investigations across multiple regions characterized by diverse climatic and environmental conditions. Additionally, examining the chemical and physical properties of dust in various locations could contribute to the development of more effective and region-specific cleaning and maintenance strategies for PV systems.

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