



EXPERIMENTAL INVESTIGATION OF COTTON DUST INFLUENCE ON POWER OUTPUT OF PHOTOVOLTAIC MODULE

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This research presents the influence of cotton dust on photovoltaic (PV) systems installed in textile industries. An indigenously designed experimental setup is installed, and two different experiments have been conducted based on cotton dust concentrations from (28000 – 52431) $\mu\text{g}/\text{cm}^2$ in twelve days. The results showed that the output of the PV module decreased drastically as the cotton dust accumulation increased. The accumulated cotton dust samples are collected from the PV surface for physical examination. It is observed that cotton dust has a unique stickiness, which causes the fibre to adhere to the PV module surface. When exposed to sunlight for an extended period, its color becomes dull, and yellowness increases, which decreases the transmittance and forms large agglomerates due to an increase in humidity, which blocks irradiance. The results of this research can be utilized to devise a specific cleaning mechanism for the textile sector that will increase the PV output.

1. INTRODUCTION

Rapid industrialization and improved living standards increase energy consumption in developing economies. However, due to the cost of conventional energy and environmental influences, countries are shifting towards renewable energy [1]. Solar energy is becoming essential to cater to the increasing demand efficiently and cost-effectively [2]. The installation and operational cost of photovoltaic (PV) setups has decreased over the last decade. China is one of the leading manufacturers of PV modules. In 2022, the production of PV panels is 35%, which is planned to be enhanced to 43% by 2051. The power generation from PV power plants is estimated to be 190 GW by 2030 globally [3]. The high reliance on PV systems for fulfilling energy demands is due to the PV system's ability to generate power in adequate time and the decrease in the cost of energy. The solar cell is made of silicon and other semiconductor materials that utilize irradiance to generate electrical power. The PV cell's efficiency is crucial to its performance [4]. Various research studies are conducted to assess the efficiency of newly developed materials, including cadmium telluride and organic materials, which could be used in the future for PV cell fabrication. The organic material is used in the fabrication of thin films that provide the highest efficiency of 25.8% [5].

The PV panel installations are now expanding on a large scale worldwide, specifically in industries, to fulfil the demand for a stable electric power supply [6]. PV panel performance is a critical aspect that is a point of focus for different industries because the performance of PV panels is highly affected by different factors, including the environment, dust, and installation. PV panels installed in different industrial sectors face diverse types of problems related to the processing of materials in that industry [7,8]. Pakistani textile sector, one of the significant contributors to the economy, having a share of 58% in exports and contributing up to 8% to the country's economy, is badly affected by the high electricity cost. Therefore, many textile industries in Pakistan have installed large and medium-scale PV power plants to cater to their energy demand [9].

The PV panel output is affected by several factors, including dust types, environmental factors, irradiance levels, and installation techniques. Dust is a significant factor contributing to lowering the PV panel performance [10]. The

PV panel setup installed in the textile sector is also affected by cotton dust generated during cotton processing. Cotton is one of the natural fabrics grown on the cotton plant. The plant has a height of 1.2 m and is grown annually [11]. There are up to 52 species of cotton that are available for cultivation. The chemical properties of the cotton show that it consists of high concentrations of cellulose and minerals; due to the lower density and weight of the cotton, it easily disperses in the air. The textile sector comprises four major sections that process the cotton into fabric. These sections include ginning, spinning, weaving, and garments [12]. The cotton dust particles generally vary in size from 1 μm up to 10 μm with improper shape and irregular geometry [13]. The primary content of cotton dust consists of cellulose, wax, and other organic compounds, which help it develop a strong adhesive when deposited on any surface [14].

Several dedicated studies have been conducted to find the impact of dust on other factors on the performance of PV panels in the past two decades. In 2005, Hassan reported the results of an experimental investigation to find the dust's Influence on PV performance. It was reported that a 10% decrement was observed in the power output yield from the PV panels in 30 days installed in the outdoor experimental setup in Egypt [15]. Mastekbayeva conducted an experimental study in 2000 to explore the impact of dust particles on the solar collector surface. The study was conducted for one month, during which an adequate amount of dust developed on the surface of the collector. It was reported that a transmittance loss of 11% was observed on the collector surface [16]. In 2006, Elminir conducted an experiment to find the impact of wind on the dust deposition on the PV panel, and it was reported that a transmittance loss of 12.5% was observed in the minimum period with an average wind speed [17]. Brown conducted an experimental research study in 2012 to find the Influence of dust in high humidity on different surfaces of PV panels, including glass, polymer, and acrylic. It was reported that an increase in humidity allows the dust particles to develop a strong bond with the surface by adhesive force that ultimately decreases the power output of the PV panel with time progression [18].

Another outdoor experimental research study by Adinoyi was conducted on the desert side in 2013. Different dust samples were examined that show a high calcium, phosphorus, and sulfur content. Two different modules were utilized in the research investigation, including monocrystalline and

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polycrystalline. It was observed that an output decrement of 50% was observed in six months of the experimental period [19]. In 2014, Sulaiman conducted an indoor experimental study to find the influence of different types of physical properties. A 50 W PV panel was utilized to explore the effects of different dust materials, including sand, talcum powder, and moss, on the output performance. It was observed that the power decrement was 31% for the PV panel. Moreover, the moss dust reduced irradiance more than other dust materials [20].

In 2017, Abderrezak investigated the impact of different dust types to determine the influence of dust on the performance of PV panels equipped with surface glazing. A comparison has been drawn between glazed and non-glazed PV panels. Due to non-uniform dust deposition on the surface, hot spots develop, irregular heating is observed, and issues are found in voltage regulation. Compared to glazed and non-glazed panels, the power output of the non-glazed PV panel was reduced by up to 16% [21]. Gholami conducted a study to find the impact of different minerals present in the environment. The experiment was conducted for two months. The sample collected from the outdoor environment contains abundant silicon and calcium oxide. The concentration of dust reaches up to 6.09 g/m², reducing the PV module's output power by up to 21% [22].

In 2019, Tanesab conducted a research study to find the influence of different dust particles with distinct physical and chemical properties. The dust samples were collected from Australia and Indonesia. This experiment used two different PV panels: monocrystalline and polycrystalline. The primary content of the dust contains significant traces of potassium, calcium, and carbon. It was observed that the dust samples collected from Indonesia had better transmittance than those from Australia due to different morphological properties. The dust collected from the PV panel surface is about 0.3 mg/cm². Additionally, linear power decrements were reported in both PV panels due to dust accumulation on the surfaces [23]. Darwesh conducted another indoor experimental study in 2021 to gauge the performance of PV modules under dusty environments and varying loads. The PV panels were exposed to different types of dust that contained iron, carbon, potassium, and silicon traces. It was observed that the module's power output was significantly reduced under carbon dust compared to other types of dust. Additionally, the transmittance of PV panels is affected by carbon due to the irregular shape of the dust particles [24]. In 2020, a study was conducted that showed a hybrid ANN-ACO MPPT controller combined with a shunt APF was shown to enhance MPP tracking speed in a 12.2 kW PV system for arc welding applications [25]. A 2021 study reported a TCAD (Silvaco) numerical study of CdS/CIGS thin-film solar cells with a maximum efficiency of 20.10% [26].

Recent studies have also been conducted to determine the effect of dust deposition on PV panels. In 2022, Kazem conducted an indoor experimental study to gauge the optimum performance of PV panels installed in dusty locations. The dust samples are collected from five different areas with distinct characteristics. The study found that different types of dust have distinct effects based on their morphological and chemical characteristics. The highest decrement in PV panel output is caused by ash dust, which reduces 12% of power output in fifteen days. Based on these results, a cleaning pattern was suggested to maintain the PV panel's performance [27]. Another outdoor experimental

study was conducted on a large PV power plant to estimate the power loss incurred due to the dust accumulation on the PV panels installed in the power plant by Gungour in 2023. The topographical study reveals that the area contains a significant share of calcium carbonate and silica deposited on the PV panel by wind blow. The physical evaluation of the accumulated particles shows that most of the dust particles have sharp edges and irregular geometry that harm the surface of the PV panel. After experimentation, it was reported that the PV panel suffered a cumulative loss of 27% due to the accumulation of dust particles [28]. Another experimental study by Deepak was conducted in 2023. For this experiment, five strings from the PV power plant were selected on which irradiance obstructing material was deposited, including powder, sand, dry leaves, cement, and silica. It was observed that a maximum power reduction of 81% was achieved by cement dust deposition and talcum powder, which reduces only 9% of the power output. It was also reported that cement dust requires a specialized cleaning setup for dust removal [29]. In 2023, an outdoor study was conducted by Kazem in the dry climate of Oman to perform a comparison analysis between monocrystalline and polycrystalline PV modules. Both PV panels are 100 W and are exposed to dry climates for one year. Different dust particles are present in the environment where calcium oxide and silicon dioxide are abundant. On analysis, it was reported that polycrystalline panels reduce power output by 10.76%, while in monocrystalline panels, 9.7% [30].

In 2024, another research study was conducted by Aziz to explore the influence of various dust densities on the power output. Two PV panels were used in this study. One was kept clean, and the other panel was used for dust deployment. It was reported that four different samples with different dust densities reduced the power output as the dust density increased because greater dust densities reflect the greater particle size [31]. To assess the cleaning patterns for PV panels in dusty environments, an experimental study was conducted by Kulsoom in 2024. The dust deposited has various sizes and shapes, including different geometrical shapes. In two weeks of the experimental procedure, 187 ug/m³ dust mass was available. A power reduction of 7% was observed in two weeks, ultimately showing that a cleaning is required after two weeks to maintain optimum performance of the PV panel in a dusty environment [32]. Muhammed conducted an experimental study in the 2024 desert region of Saudi Arabia to find the Influence of different tilt angles with fixed PV modules. The experiment concluded that the PV panel reduced soil by up to 85% by adopting the tracking mechanism and anti-soiling coating [33]. Similarly, in textile units, carding and spinning units produce cotton dust in significant amounts that ultimately disperse in an environment that may deposit on the PV panels [34]. Different environmental factors also affect the dispersion and accumulation rate of cotton dust [35]. Some other studies also conclude that cotton dust spread in the textile unit's environment disturbs the PV plant's health and impacts PV panel performance [36,37].

This study focuses on cotton dust as a distinct particulate and observes how its structure and deposition behavior differ from other dust types. The study is structured into four major sections. Section 1 encompasses a comprehensive review of relevant literature and a fundamental introduction related to the topic. Section 2 delivers an overview of the methodology

employed in this research. The research outcomes are discussed in Section 3, while Section 4 presents a summary of the conclusions.

2. METHODOLOGY

Cotton dust dispersion in the textile unit influences the PV module's performance. This section discusses the experimental methodology designed to determine the Influence of various concentrations of cotton dust particles on the PV panel. Figure 1 provides the comprehensive method adopted to determine the Influence of cotton dust concentration on the PV module.

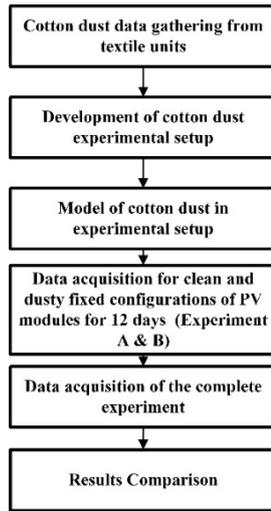


Fig. 1 – Methodological framework to determine the Influence of varying cotton dust concentration levels.

To determine the influence of varying cotton dust concentration levels on PV panels, initial data is being acquired from the two textile units using the ultra-low power specified dust sensor that works on the principle of laser scattering [38,39]. Based on the acquired data from the textile units, the same is modelled in the specifically designed experimental setup that mimics the process of cotton dust dispersion and accumulation on the PV panel. The experimental setup is equipped with sensors for data acquisition of the different physical parameters involved in the dust deposition and dispersion process. The PV panel is installed in the experiment setup, and a uniform load resistance is added parallel to it. Table 1 describes the PV panel parameters installed in the experimental setup for investigation.

Table 1
PV panel description.

Specifications	Parameters
Output Peak Power	5 W
Short circuit current	0.30 A
Max power voltage	17.9 V
Max power current	0.28 A
Number of Cells	36
Maximum System Voltage	1000 VDC

Two experiments are conducted based on the two textile units' distinct concentration data of cotton dust. The data acquired from the experimental setup is based on a 12-day experiment for each concentration level. The physical parameters of a clean PV module are also acquired, in which no accumulation of dust is involved. The output power of the PV module is exposed to two different cotton dust

concentration levels that are used to compare PV panel performance.

3. EXPERIMENTAL APPROACH

The experiment is conducted based on the cotton dust dispersion data collected from the textile units. Table 2 depicts the data related to cotton dust concentration acquired from the textile units.

Table 2
Concentration data of cotton dust acquired from textile units.

S.no	Industry	Cotton dust accumulated ($\mu\text{g}/\text{cm}^2$)	Duration (minutes)
1	Textile A	6759	60
2	Textile B	12960	60

Two different experiments are conducted based on the concentration level of cotton dust. Each experiment is conducted on an artificially designed experimental setup specifically designed to imitate the process of dust dispersion in the textile units. The experimental setup follows a modular approach consisting of primary and secondary chambers. The primary chamber is the main chamber where the PV panel is installed for cotton deposition and measurement of physical parameters. In contrast, the secondary chamber is the blower chamber, where high-speed blowers are installed to transport the cotton dust from the secondary chamber to the primary chamber using the installed ducts. The setup comprises thick sheets of high-density unplasticized polyvinyl chloride with dimensions of 0.56 m^3 for the primary chamber and 0.26 m^3 for the secondary chamber. Figure 2 depicts the fundamental structure design of the experimental setup utilized for experimental purposes.

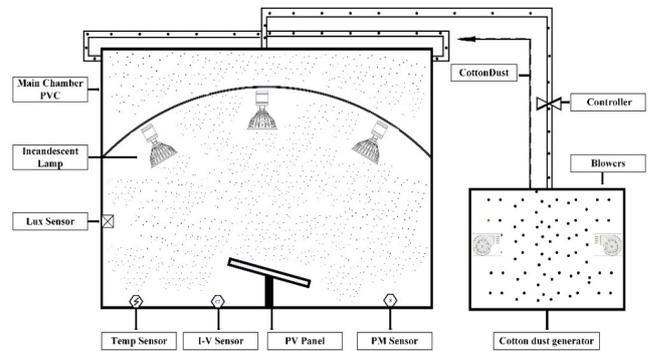


Fig. 2 – Experimental setup design.

The experiment is conducted in two different configurations, including fixed and clean. It is conducted for each concentration for 12 days, with an 8-hour daily interval. In experiment A, the cotton dust concentration of textile mill "a" is applied, while in experiment B, the cotton dust concentration of textile mill "b" is applied. Different physical parameters are recorded, including dust concentration, voltage, temperature, and humidity. A factory-calibrated HM3301 dust sensor was used to keep track of the dust concentration, and calibrated sensors were used to detect the temperature and relative humidity. Two high-speed fans were installed in the dust chamber to ensure uniform airflow and even dust distribution during the tests. Figure 3 depicts the internal view of the primary and secondary parts of the experimental setup.

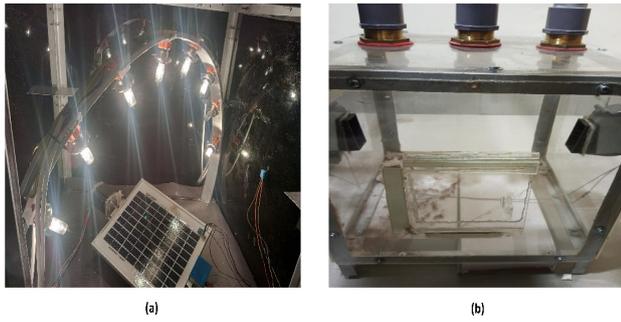


Fig. 3 – Internal view. (a) Primary experimental chamber; (b) Secondary experimental chamber.

4. RESULTS AND DISCUSSION

The experimental investigation is conducted in two configurations: clean and dusty. The PV panel is installed in the experimental setup at a fixed angle of 30°. The first experiment is conducted based on the concentration data of dust generated from the textile unit a. Table 3 depicts the experimental results acquired from the chamber.

Table 3

Average power output from the PV panel acquired from the textile unit, a cotton dust concentration.

Days	Total Dust accumulated/day (µg/cm²)	Average Temp (C°)	Average Humidity (%)	Average Power (W)
1	2297	34.50	40.50	1.545
2	3966	35.00	42.38	1.521
3	7019	34.50	41.38	1.486
4	9402	34.50	39.25	1.462
5	11927	35.00	40.63	1.458
6	14228	34.00	42.75	1.431
7	16329	35.00	41.88	1.384
8	18720	35.00	44.63	1.335
9	21085	35.00	40.38	1.274
10	23325	34.50	43.50	1.234
11	25696	35.00	41.33	1.121
12	28000	35.00	41.75	1.095

The second experiment lasted 12 days. The cotton dust concentration data were applied to the experimental setup acquired from textile unit b. Table 4 shows the experimental result of the cotton dust concentration applied from the textile unit b.

Table 4

Average power output from the PV panel acquired from the textile unit, b, cotton dust concentration.

Days	Total Dust accumulated/day (µg/cm²)	Average Temp (C°)	Average Humidity (%)	Average Power (W)
1	4462	35.00	39.25	1.529
2	9056	35.00	42.38	1.492
3	13378	34.50	50.25	1.465
4	17801	34.45	45.63	1.402
5	22195	35.00	43.75	1.334
6	26503	34.00	42.63	1.291
7	30813	34.50	45.63	1.121
8	35139	35.00	45.25	1.125
9	39903	34.00	43.25	1.061
10	44133	35.00	44.13	0.935
11	48485	35.00	44.44	0.845
12	52431	35.00	43.75	0.774

Figure 4 depicts the influence of different cotton dust concentrations on the PV panel. The graph shows that the PV's output power decreased drastically with increased cotton dust concentration.

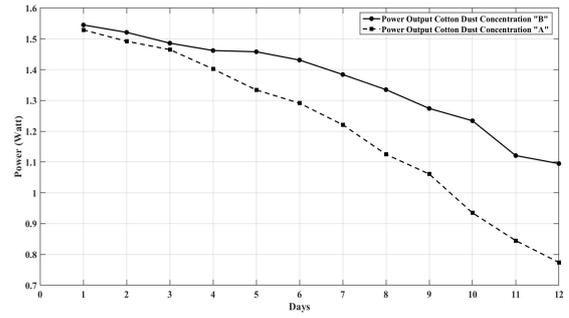


Fig. 4 – Comparison of PV panel output power following two different cotton dust concentrations.

The experiment was also conducted in a clean configuration, with no cotton dust deposition on the experimental setup. It was conducted for 12 days with a fixed tilt angle of 30°. Table 5 shows the details of the experiment conducted on a clean PV panel.

Table 5

Average power output from the PV panel in a clean configuration.

Days	Average Temp (C°)	Average Humidity (%)	Average Power (W)
1	35.00	38.25	1.580
2	35.00	41.38	1.579
3	35.00	41.38	1.579
4	34.50	39.25	1.579
5	34.50	47.25	1.579
6	34.00	47.25	1.579
7	35.00	42.00	1.581
8	34.00	45.38	1.581
9	34.50	45.00	1.579
10	34.50	54.88	1.579
11	34.00	47.78	1.579
12	35.00	45.38	1.579

Table 6 compares the power output of the PV module exposed to two different cotton dust concentrations with that of the clean PV module not exposed to cotton dust. Figure 5 shows a clean and a dusty PV module.

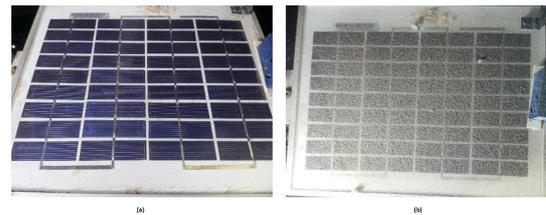


Fig. 5 – (a) Clean PV module (b) PV module with cotton dust accumulation.

Table 6

Comparison between PV panel power output exposed to cotton dust and clean conditions.

Day	Average Power (watt)	Average Power (watt) Exp 1	Average Power (W) Exp 2
	Clean	Dusty	Dusty
1	1.580	1.545	1.529
2	1.579	1.521	1.492
3	1.579	1.486	1.465
4	1.579	1.462	1.402
5	1.579	1.458	1.334
6	1.579	1.431	1.291
7	1.581	1.384	1.121
8	1.581	1.335	1.125
9	1.579	1.274	1.061
10	1.579	1.234	0.935
11	1.579	1.121	0.845
12	1.579	1.095	0.774

The comparison in Table 6 shows that the PV module power decreases with the increase in cotton dust concentration. In Table 6, based on the cotton dust concentration used for experiment 1, the PV panel power output decreases with time increment. Similarly, it shows the power degradation of PV panels having a greater cotton dust concentration in experiment 2. It shows that the increase in cotton dust deposition on the PV panel is inversely proportional to the power output of the PV panel. Figure 6 shows a comparison between the output power of clean and dusty PV modules.

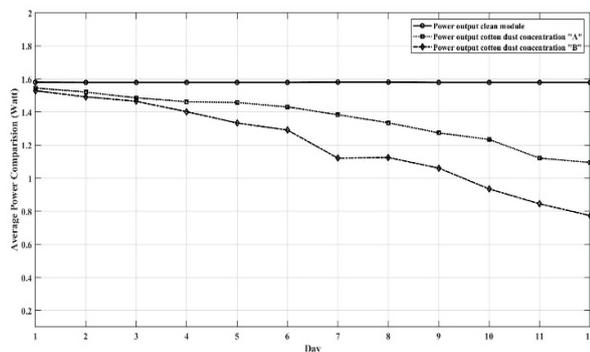


Fig. 6 – Comparison of PV module output power clean vs cotton dust accumulation.

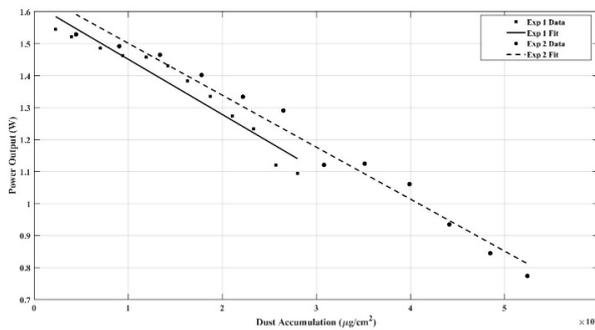


Fig. 7 – Linear regression of PV power output versus cotton dust accumulation for two experiments.

In both experiments, linear regression demonstrates a significant negative association between dust deposition and PV power output. Both experiments show a consistent decline in power with increasing dust deposition, with regression slopes indicating a 0.014 - 0.016 W reduction per 1000 $\mu\text{g}/\text{cm}^2$ of dust. The correlation between accumulation of dust and power ($r = 0.98$) indicates that dust deposition is the primary factor impacting PV performance.

The physical examination also shows some distinct characteristics of deposited cotton dust on the PV panel. Figure 8 shows the microscopic examination of the cotton dust sample collected from the surface of the PV module. There are fibers, particulate matter, and small clumps in the cotton dust sample. The long fibers can be seen and can twist with other particles because of the humidity and moisture. Small dots, which look like cotton fragments with different shapes, show that there are particles present. Also, when magnified, the cotton dust samples that were taken from the surface of the PV module are clumped together, and threads are tied together. This shows that cotton dust has an irregular pattern, distinguishing it from other dust types deposited on the PV module.

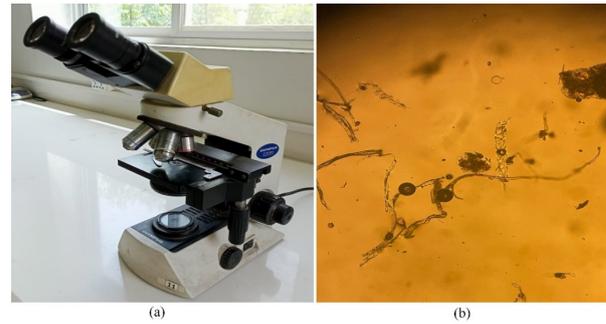


Fig. 8 – (a) Microscopic examination of the cotton dust sample. (b) Microscopic view of cotton dust sample 10x.

6. CONCLUSION

This research study is based on the influence of cotton dust on the PV module surface. It shows that cotton dust influences the performance of the PV module output. Based on data collected from textile units A and B, which was later applied to the testing experimental setup. It shows that power reduction is greater when cotton dust deposition is higher. Similarly, it shows a 29% power decrement in the PV module based on textile unit A, cotton dust accumulation. A 49% power decrement is also observed in the PV module, which is based on the textile unit B cotton dust deposition. Cotton dust reduces PV power consistently, with a strong correlation ($r = 0.98$) and 0.014 - 0.016 W loss per 1000 $\mu\text{g}/\text{cm}^2$.

The decreasing power output trend of the PV module shows that cotton dust accumulation on the PV module not only significantly influences the power output reduction but also deteriorates its physical health. During the physical examination, it was observed that the cotton dust's distinct physical nature makes it stick to the PV module's surface, making it difficult to remove by natural wind speed. Along with that, high-humidity areas make it difficult to remove swelling. Regular cleaning schedules and protective coatings should be implemented in the future to maintain optimal PV performance. This study will help the textile units devise a cleaning mechanism for their large-scale PV power plants based on the cotton dust accumulation on the surface of PV panels.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Basit Ali: conceptualization, methodology, writing original draft.
Muhammad Faisal Khan: data curation, software, validation.
Kashif Ishaque: formal analysis, supervision, and editing.

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