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Seasonal Performance Analysis of Monocrystalline and Polycrystalline Photovoltaic Solar Panels Under Dust Deposition in Niamey, Niger

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ABSTRACT

This paper investigates the impact of dust accumulation and temperature on the performance of monocrystalline and polycrystalline photovoltaic (PV) panels under the climatic conditions of Niamey, Niger, with a focus on seasonal variations. High-resolution performance data were collected across the rainy, Harmattan, and hot seasons to evaluate power output losses. During the rainy season, natural cleaning by rainfall limited power and energy losses to 0.33% and 1.55% for monocrystalline, 5.98% and 6.67% for polycrystalline panels, respectively. In contrast, the Harmattan season showed the most severe reductions, with power and energy losses reaching, respectively, 66.46% and 65.55% for monocrystalline, 57.96% and 57.50% for polycrystalline, due to intense dust accumulation and atmospheric scattering. During the hot season, elevated temperatures and soiling combined to reduce performance by 54.6% and 52.31% for monocrystalline, 43.22% and 42.61% for polycrystalline, respectively. While monocrystalline panels perform better under clean conditions, they are more susceptible to environmental stressors than polycrystalline panels, which demonstrate greater resilience to dust and temperature effects. These findings highlight the importance of regular cleaning, antisoiling technologies, and climate-adaptive PV system design to sustain performance in dusty and high-temperature environments, such as the Sahel.

1 | Introduction

Energy plays a crucial role in the socioeconomic development of any nation. As global energy demand continues to rise, the world simultaneously confronts the challenges of fossil fuel depletion and climate change. Fossil fuels, while historically foundational to energy systems, contribute significantly to greenhouse gas emissions, exacerbating global warming. These pressing challenges underscore the urgent need for sustainable and clean energy alternatives.

Solar energy has emerged as one of the most promising renewable sources, thanks to its abundance, safety, and environmental sustainability. Photovoltaic (PV) technology, which directly converts solar irradiation into electricity using semiconductors, such as crystalline silicon, has seen widespread adoption due to declining costs and its potential to significantly reduce carbon emissions. By 2100, it is projected that PV technology could offset up to 50% of global CO_2 emissions and satisfy over 60% of energy needs [1].

The adoption of PV energy has become increasingly widespread, both in standalone and grid-connected systems, due to the significant reduction in the investment cost of PV systems in recent years [2]. The advantages of utilising PV energy are numerous, with the most significant being the reduction in carbon dioxide (CO_2) emissions. By 2100, PV technology aims to cut global CO_2 emissions by 50% and meet more than 60% of the world's energy needs [1].

However, the performance of PV systems is highly sensitive to environmental conditions, especially in regions with harsh climates. Among these factors, dust deposition on the surface of PV panels has been identified as a major contributor to power losses. Nevertheless, birds' dropping accelerates dust adhesion and reduces the transmissivity of the glass cover, limiting the amount of sunlight reaching the solar cells and thus degrading power output [3, 4]. This results in a degradation of the power production performance of the solar PV modules [5, 6]. This phenomenon is especially pronounced in arid and semiarid regions characterised by high temperatures, low rainfall, and frequent dust storms.

Numerous studies have examined the impact of dust on PV performance in diverse regions ranging from India, Algeria, and Senegal to Indonesia and Qatar. These studies underscore that the extent of performance degradation due to soiling depends on local meteorological and environmental conditions, including dust composition, humidity, wind patterns, and rainfall. For example, in India, Geetha et al. [7] revealed that dust causes a substantial reduction in current, voltage, and power after 90 days of exposure of monocrystalline and polycrystalline panels to dust. Polycrystalline modules experienced nearly double the power decline of monocrystalline modules, with 30% versus 14%, respectively [7].

Dida et al. [8] investigated the effects of dust accumulation on the performance of monocrystalline PV modules in the Saharan Environment of Ouargla, Algeria. They found that the accumulation of approximately 4.36 g/m^2 of dust on the PV module's surface after 8 weeks of exposition without cleaning caused a decrease of 8.41% in maximum power output, 6.10% in short-circuit current, and 0.51% in open-circuit voltage compared with the cleaned module. They also evaluated a 20-MW grid-connected PV power plant's performance before, during, and after a sandstorm, and they found a reduction of 32% in generated energy [8].

Research conducted at the Jordan University of Science and Technology examined the effects of shading and natural dust accumulation on PV module performance. The authors found that partial shading has the most severe impact on output, while natural gas causes a progressive decline in power, reaching about 13% after 3 months of exposure. They also stated that dust reduces the light reaching the cells by absorbing or scattering incoming photons and measurements of radiation beneath clean and dust-covered glass showed reductions comparable to the drop in electrical power. They finally suggested that this simple optical approach can serve as a low-cost method for assessing dust impacts on PV systems without requiring electrical measurements [9].

Abdessadak et al. [10] conducted a review of 30 recent studies, which highlights dust accumulation as a major barrier to PV performance in dry and semiarid regions, such as Morocco. The authors reported efficiency losses range from 10% to 40%, depending on dust density, composition, and exposure duration. While various mitigation strategies, such as autonomous cleaning systems and advanced antisoiling coatings, have been proposed, their economic and scalability limitations persist. They also noted the emerging role of AI-based predictive maintenance in optimising cleaning schedules. Overall, the authors stress the need for long-term, sustainable, and cost-effective dust mitigation solutions to improve PV productivity in dusty environments [10].

In Jeddah, Alzahrani et al. [11] examined how dust accumulation and tilt angle affect PV module performance under desert conditions over a year. Seven pairs of clean and dusty panels were tested at tilt angles ranging from 0° to 90°. Results show that dust, tilt angle, and rainfall strongly influence output power. During 183 days dry period without rain, power losses reached 80.4% at 0°, 75.6% at 15°, and 60.2% at 25°, highlighting the severe impact of dust at low tilt angles. In the rainy season, natural cleaning improved performance, with the best results for dusty modules reaching 5.9% reduction at 45° tilt. Overall, a 25° tilt produced the highest annual energy output, with annual and dry-season reductions of 20.7% and 28.7%, respectively. The study emphasises the critical role of tilt optimisation in mitigating dust impacts and improving PV system performance in desert environments.

Diop et al. [12] modelled the monocrystalline silicon cell installed in a dusty environment as a stack of thin layers (dust/glass/silicon). They found that the deposition of dust on the PV cell surface did not significantly affect the open-circuit voltage, but the short-circuit current experienced a loss of about 51% for a dust layer of 70 μm, corresponding to dust deposition of 3.3 g/m^2 [12].

Kazem et al. [13] conducted an outdoor experimental study in Sohar, Oman, comparing the dust effect on monocrystalline and polycrystalline PV modules. After exposure to external conditions for 2 weeks, they observed decreases in current, voltage, and power by 35.5%, 2.1%, and 36.76% for the monocrystalline modules, and 27.92%, 0.455%, and 28.1% for the polycrystalline modules. They concluded that monocrystalline solar panels experienced a higher power degradation (20%) compared with polycrystalline panels (12%) due to dust accumulation [13].

Chen et al. [14] studied dust composition and its impacts on the PV power outputs with real field test data in East China. They found that after 1 week, the average dust accumulation density was 0.644 g/m^2, leading to a 7.4% decrease in power compared with the clean state. After 2 weeks, power attenuation reached 13.9%. Analysis revealed that the major component of dust was SiO_2, with a small amount of Al_2O_3, CaO, and other metal oxides. A small amount of rainfall cleaned the PV modules, temporarily increasing their output power [14].

Elshazly et al. [15] investigated the effects of dust accumulation, water cooling, and coating on the performance of monocrystalline and polycrystalline panels in El-Sherouk City. They also studied how tilt angle affects dust accumulation on solar panel surfaces. Their results showed that performance degradation due to dust accumulation increased linearly, reaching a maximum of 10% after 4 weeks without cleaning. Additionally, a 10% increase in temperature resulted in approximately 7% efficiency degradation [15].

Kazem and Chaichan [16] examine the impact of dust accumulation on PV panel performance and evaluate various cleaning methods to mitigate efficiency losses. The findings indicate that dust accumulation can lead to significant reductions in power output, with efficiency losses reaching up to 40% over extended periods without cleaning.

Despite these global efforts, there remains a lack of comprehensive studies that focus on the unique climatic variability and seasonal dust patterns in Niamey, Niger. Niamey experiences distinct climatic seasons, including the Harmattan, hot dry, and rainy seasons, each influencing dust deposition differently. Moreover, existing research often focuses on a single PV technology or a limited observation period, making it difficult to develop generalised conclusions. For example, one study reported a 15.29% decrease in energy output after 23 days without cleaning, emphasising the severity of dust deposition in this region [17]. Additionally, the high ambient temperatures commonly experienced in Niamey, often exceeding 33°C, exacerbate the decline in PV efficiency, as shown by Dajuma et al. [18].

In this context, Niamey presents a regionally unique testbed for PV performance studies due to the frequent dust-laden winds during the Harmattan, the high ambient temperatures throughout much of the year, the sharp seasonal transitions in humidity, rainfall, and wind speed, and the increasing deployment of PV systems with little empirical data to guide maintenance.

This study aims to address these gaps by analysing the seasonal performance of both monocrystalline and polycrystalline PV modules under real-world dust accumulation in Niamey. The study covers multiple climatic seasons to capture the dynamic effects of dust deposition.

Many previous studies on PV soiling focus either on short-term experiments or on environments that are very different from the Sahel. In contrast, the present study provides high-resolution (5-min) outdoor measurements over a full annual cycle under the specific climatic conditions of Niamey, a region where Harmattan dust events and strong seasonal contrasts are especially pronounced but remain understudied in the scientific literature.

Another contribution of this work is the direct comparison of monocrystalline and polycrystalline PV technologies operating side-by-side under identical environmental conditions. By analysing power, daily energy, and corresponding percentage reductions for both clean and dusty modules, the study offers a clearer, technology-specific quantification of soiling impacts than many existing works that rely primarily on power measurements alone.

Furthermore, by examining representative days from the rainy season, Harmattan period, and hot dry season, the study highlights how dust accumulation interacts with local climatic variability throughout the year, an aspect often missing in short-duration or single-season experiments. While the paper does not yet perform a full economic assessment, the results provide useful baseline information that can inform future discussions on cleaning frequency and PV maintenance needs in dust-prone West African environments.

2 | Materials and Methods

2.1 | Site Location

Our experiment was conducted on the rooftop of the Physics Department at Abdou Moumouni University of Niamey (longitude 13.5° N and latitude 2.09° E) with two monocrystalline and two polycrystalline modules, each with a power rating of 100 W. The panels were securely fixed in a south-facing orientation with a tilt angle of 15° to optimise solar exposure. Figure 1 shows the experimental setup: (a) the panels in the first month of exposition and (b) the fourth month of exposure to an outdoor environment. Detailed specifications of the modules are provided in Table 1 for clarity.

2.2 | Experimental Platform for PV Measurement

The experimental setup consists of the following equipment: a current sensor with a measurement error of 0.8%, a voltage sensor with an error of 1.56%, a solar pyranometer sensor from the LORA LORAWAN manufacturer with a precision of ±0.3%, which measures the global horizontal irradiation and incident radiation on the plane of the modules; an ambient temperature (T_a) and relative humidity (RH) wall-mounted sensor with an accuracy of ±0.4°C and ±2% RH, respectively; a wind speed sensor, having an accuracy of ±3%; a *K*-type thermocouple, attached to the back sheet of each panel to measure PV temperature, and the PV modules (Table 2).

2.3 | Method

To measure the PV performance, an electrical circuit was established, enabling the recording of current and voltage generated by the panels under various conditions. To specifically assess the impact of dust, nomenclatures were assigned to panels in both clean and dusty states: $PV_{1\text{-clean}}$ and $PV_{1\text{-dusty}}$ for monocrystalline panels and $PV_{2\text{-clean}}$ and $PV_{2\text{-dusty}}$ for polycrystalline panels.

At the same time, solar irradiation, ambient temperature, wind speed, RH, and electrical parameters of the panels were recorded at 5-min intervals under outdoor conditions from 6:00 a.m. to 6:00 p.m. This meticulous approach aims to elucidate the specific impact of dust on the performance characteristics of both monocrystalline and polycrystalline PV panels with a high temporal resolution.

The experiment covers a 1-year period, during which the impact of dust on the performance of the PV panels will be thoroughly assessed. The experimental setup involves alternating cleaning and dusting of one panel from each technology, while the second panel is intentionally left in a dusty state. To simulate real-world conditions, two lamps, each consuming 3 A (amps) and totalling 70 W when connected in series, are used as loads for each panel. The analysis focused on comparing power output and energy production across the clean and dusty panels, as well as the different technologies.

As previously outlined, the output current and voltage of the panels are measured continuously. Equation (1) is applied to calculate the output power of each panel, where P represents the output power, U denotes the output voltage, and I signify the output current:

$$P = U \cdot I. \tag{1}$$

The calibrated LORA LORAWAN Total solar pyranometer sensors, temperature and humidity sensor, wind speed

FIGURE 1 | Experimental setup: (a) first month of exposition and (b) fourth month of exposition.

sensor, and K-type thermocouples attached to the back sheet of the modules provide the necessary environmental data. These sensors were calibrated using reference devices, ensuring accuracy in the measurement process. The measurement error for each sensor is determined through Equation (2), where *error* (%) is the percentage error, p_{ref} is the reference measurement, and p_{m} is the measured value:

$$error\,(\%) = (p_{\text{ref}} - p_{\text{m}})/p_{\text{ref}} \cdot 100. \tag{2}$$

This methodology not only captures the dynamic performance of the PV panels under varied environmental conditions but also accounts for potential measurement errors, ensuring the reliability and accuracy of the findings. The 1-year duration of the experiment allows for a thorough examination of the long-term impact of dust on the efficiency and output of both monocrystalline and polycrystalline PV panels.

To quantify the measurement error associated with the calculated output power, Equation (3) is employed:

$$\Delta P/P = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta I}{I}\right)^2}, \tag{3}$$

where

- ΔP is the measurement error in output power.
- P is the calculated output power of the panel.
- ΔU is the measurement error in output voltage.
- U is the measured output voltage of the panel.
- ΔI is the measurement error in output current.
- I is the measured output current of the panel.

This equation provides an assessment of the uncertainty associated with the calculated output power, taking into account the individual measurement errors in both output voltage and output current. The inclusion of this error analysis enhances the robustness of the experimental methodology, ensuring that the impact of dust on the PV panels is not only measured but

TABLE 1 | Module datasheet specification.

SUNSHINE SOLAR specification (1000 W/m^2, AM1.5, 25°C) Parameter	Specification
Maximum power (P_{max})	100 W
Maximum power voltage (V_{pm})	17.5 V
Maximum power current (I_{pm})	5.72 A
Open-circuit voltage (V_{oc})	21.5 V
Short-circuit current (I_{sc})	6.0 A
Maximum system voltage	100 V
Maximum series fuse	3 A
Operating temperature	−20°C to 90°C
Application class	Class A
Years of service	> 90% after 10 years
	> 80% after 20 years

TABLE 2 | Measurement error of various parameters.

Parameter	Error
Voltage	1.56%
Current	0.80%
Power	1.70%
Irradiation	0.30%
Temp	0.5°C
Humidity	3%

also characterised with a well-defined level of precision. The percentage reduction in PV power is given by the following equation:

$$R_P = [(p_{clean} - p_{dusty})/p_{clean}]\cdot 100, \tag{4}$$

where

- R_P is the percentage reduction in power.
- P_{clean} is the power of the clean module.
- P_{dusty} is the power of the dusty module.

The efficiency coefficient of the modules is calculated using the following equation:

$$\eta = (p_{max}/S\cdot E)\cdot 100, \tag{5}$$

where

- η is the efficiency coefficient, expressed as a percentage.

- P_{max} is the maximum output power of the PV module (W).

- S is the area of the panel (m^2).

- E is the incident solar irradiation on the PV surface (W/m^2).

This efficiency coefficient provides a comprehensive measure of the module's performance relative to its size and the available solar irradiation. A higher efficiency coefficient indicates a more effective conversion of incident solar energy into electrical power. By calculating this coefficient under both clean and dusty conditions, the impact of dust on the overall performance of the PV modules can be quantified.

Furthermore, accounting for uncertainties in the efficiency coefficient, the measurement error $\Delta\eta$ can be determined using a similar approach as Equation (6):

$$\Delta\eta/\eta = \sqrt{\left(\frac{\Delta P_{max}}{P_{max}}\right)^2 + \left(\frac{\Delta S}{S}\right)^2 + \left(\frac{\Delta E}{E}\right)^2}. \tag{6}$$

This consideration of measurement error ensures a detailed evaluation of the impact of dust on the efficiency of the PV modules, taking into account uncertainties in the measurements of maximum output power, panel area, and incident solar irradiation.

The percentage reduction in PV efficiency is calculated by Equation (7):

$$\eta_{(\%\ reduction)} = \frac{\eta_{clean} - \eta_{dusty}}{\eta_{clean}}\cdot 100, \tag{7}$$

where

- $\eta_{(\%reduction)}$ is the percentage reduction in efficiency.
- η_{clean} is the efficiency of the clean module.
- η_{dusty} is the efficiency of the dusty module.

The daily energy yield is calculated using the following equation:

$$E_{daily} = \sum_{i=1}^{N} P_i \times \Delta t_i, \tag{8}$$

where

- E_{daily} = daily energy yield (Wh),
- P_i = power output at hour I (W),
- Δt_i = time interval (h),
- N = number of recorded hourly values in a day.

The loss in energy yield is given by

$$E_{loss} = E_{clean} - E_{dusty}. \tag{9}$$

3 | Results

From August 2023 to July 2024, the performance of PV modules was continuously monitored in Niamey, Niger, a region characterised by high solar insolation and significant seasonal dust variation. This long-term, high-resolution data set offers valuable insights into how seasonal climatic shifts influence PV performance under real-world Sahelian conditions.

Key parameters, including output power, power reduction percentage, temperature, and dust density, were analysed to

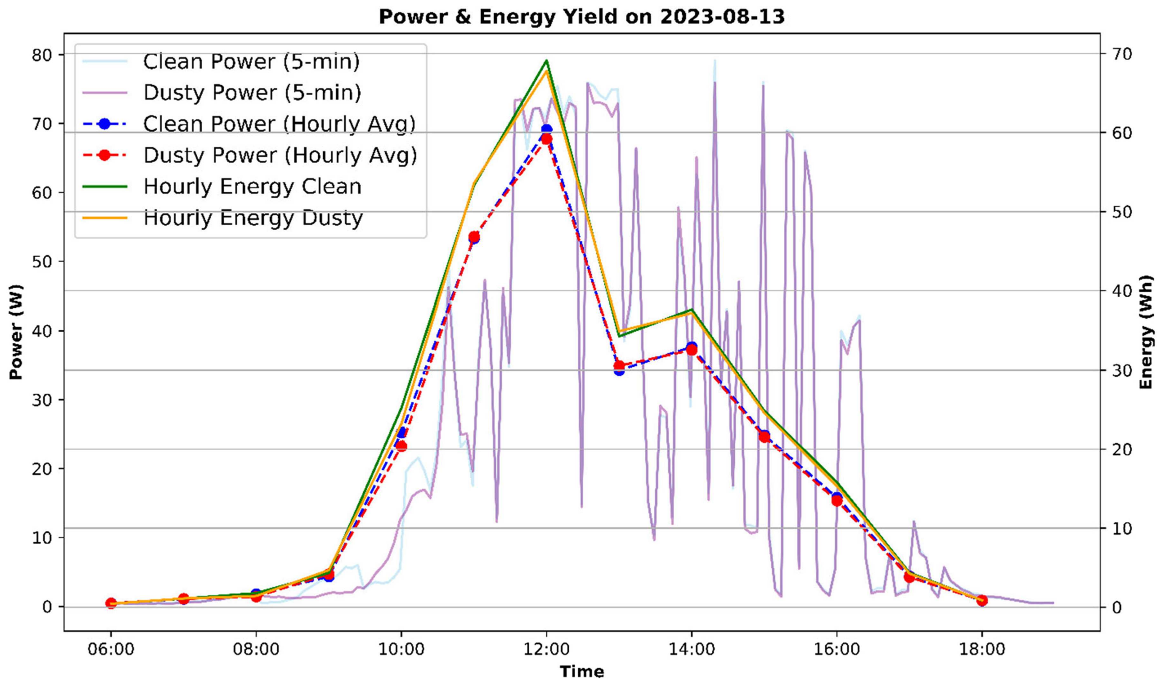

FIGURE 2 | Typical daily variation of power and energy during the rainy season for the monocrystalline panels.

assess the impact of dust deposition throughout the year. Results indicate a noticeable influence of dust accumulation on the output power of both module technologies.

3.1 | Monocrystalline Panel Performance During the Rainy Season

Figure 2 illustrates the power and energy performance of the monocrystalline PV panels for a typical day during the rainy season. The figure presents three data sets: 5-min interval power measurements, hourly averaged power, and hourly cumulative energy. According to the 5-min data, the clean panel reaches a maximum power output of 79.16 W, while the dusty panel achieves 75.93 W. For the hourly averaged data, the maximum power values are 69.12 W for the clean and 67.78 W for the dusty module, corresponding to a mean percentage power reduction of 1.36% attributable to the deposition of dust on the panel surface. In terms of energy output, the clean panel produces a total of 273 Wh, while the dusty panel delivers 269.3 Wh, reflecting an energy reduction of 1.4%.

3.2 | Polycrystalline Panel Performance During the Rainy Season

Figure 3 presents the same parameters for the polycrystalline technology. The 5-min interval data show a maximum power output of 70.12 W for the clean panel and 78.06 W for the dusty panel. This reversal is likely due to short-term weather fluctuations or momentary irradiance spikes. However, the hourly averaged power data show more consistent results, with maximum power outputs of 59.27 W for the clean panel and 57.78 W for the dusty one. This corresponds to a mean percentage power reduction of −0.34%, indicating a slight increase in the dusty panel output, likely caused by natural cleaning from rainfall, local irradiance variability, or passing clouds, rather than any actual performance improvement due to dust.

Regarding energy output, the polycrystalline clean panel generates 204.7 Wh, while the dusty panel delivers 205.4 Wh, resulting in a percentage energy difference of −0.3%. This small negative loss suggests negligible or slightly favourable conditions for the dusty panel during the test period, again likely influenced by external weather factors and not necessarily a performance gain.

3.3 | Monocrystalline Panel Performance During the Harmattan

The Harmattan season in Niger is characterised by dry, dust-laden winds from the Sahara Desert, significantly reducing solar irradiation due to increased aerosol loading in the atmosphere. Figure 4 illustrates a typical daily profile of power and energy output for monocrystalline PV panels during this period, highlighting a sharp decline in performance attributable to severe soiling and atmospheric attenuation.

According to the 5-min interval data, the clean monocrystalline panel achieves a peak power output of 66.48 W, while the dusty panel's output drops to 28.48 W. This trend is confirmed by the hourly averaged data, which shows a reduction from 64.11 W for the clean panel to 26.35 W for the dusty one, resulting in a mean percentage power reduction of 67.2%. This corresponds to the panels operating at only 36% of their optimal output. In terms of cumulative daily energy yield, the clean panel produces 380 Wh, while the dusty panel generates only 124.4 Wh, reflecting an energy loss of 67.3%. These results reflect a significant drop in performance under Harmattan conditions.

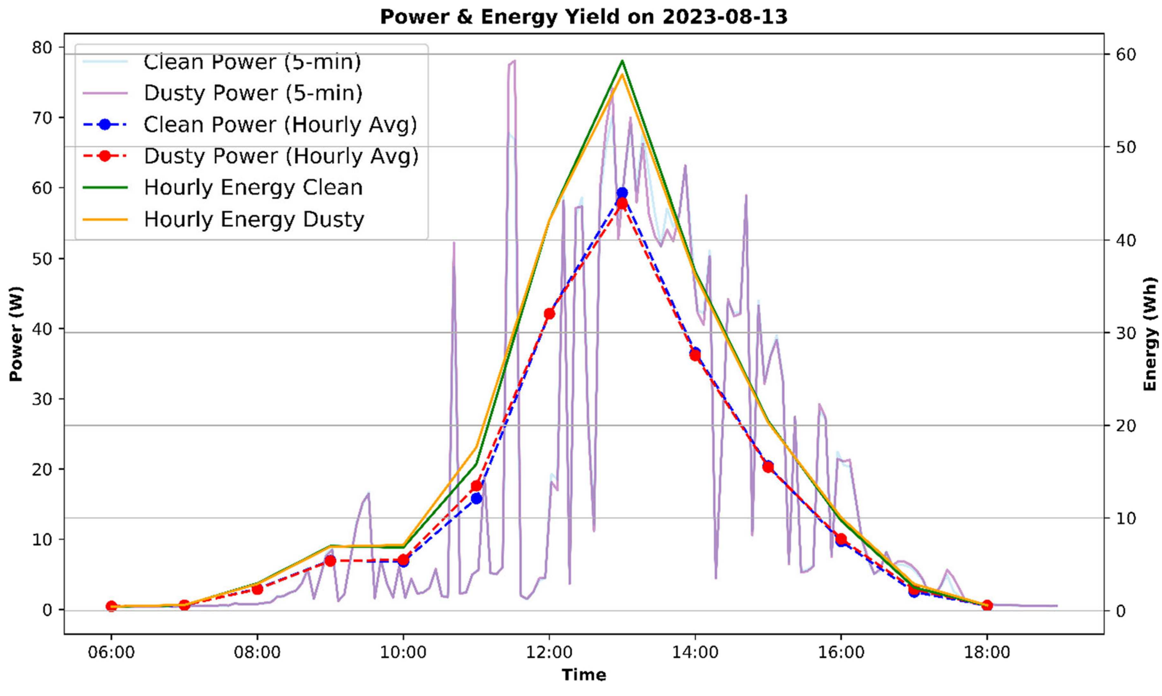

FIGURE 3 | Typical daily variation of power and energy during the rainy season for the polycrystalline panels.

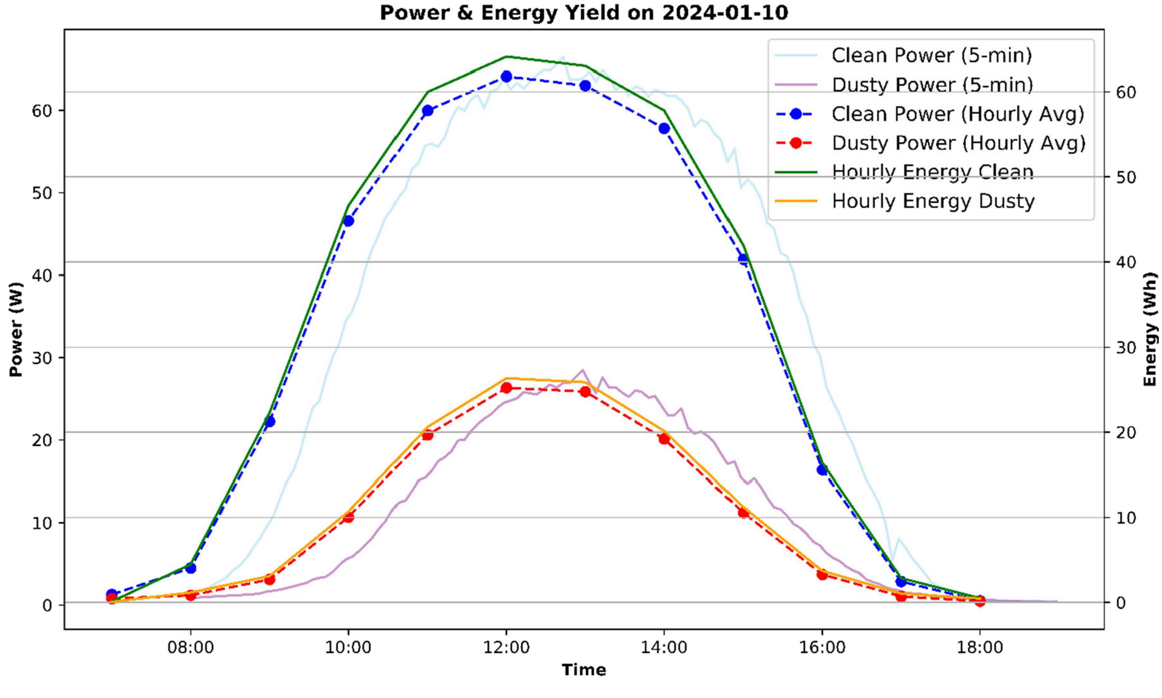

FIGURE 4 | Typical daily variation of power and energy during the Harmattan season for the monocrystalline panels.

3.4 | Polycrystalline Panel Performance During the Harmattan

Figure 5 shows the performance of polycrystalline PV panels under Harmattan conditions. The clean panel reaches a maximum power output of 49.22 W based on 5-min data, while the dusty panel peaked at 23.57 W. Hourly averaged power output values are 47.14 W for the clean panel and 22.47 W for the dusty panel, resulting in a mean percentage power reduction of 58.2%, with the dusty panel delivering approximately 48% of its clean output. The corresponding daily energy yields are 255.6 Wh for the clean panel and 106.5 Wh for the dusty panel, also reflecting an energy loss of 58.2%.

3.5 | Monocrystalline Panel Performance During the Hot Season

Figure 6 illustrates a typical daily variation in power and energy output for monocrystalline PV panels during the hot season. The data reflect notable performance degradation due to the elevated temperatures combined with dust accumulation.

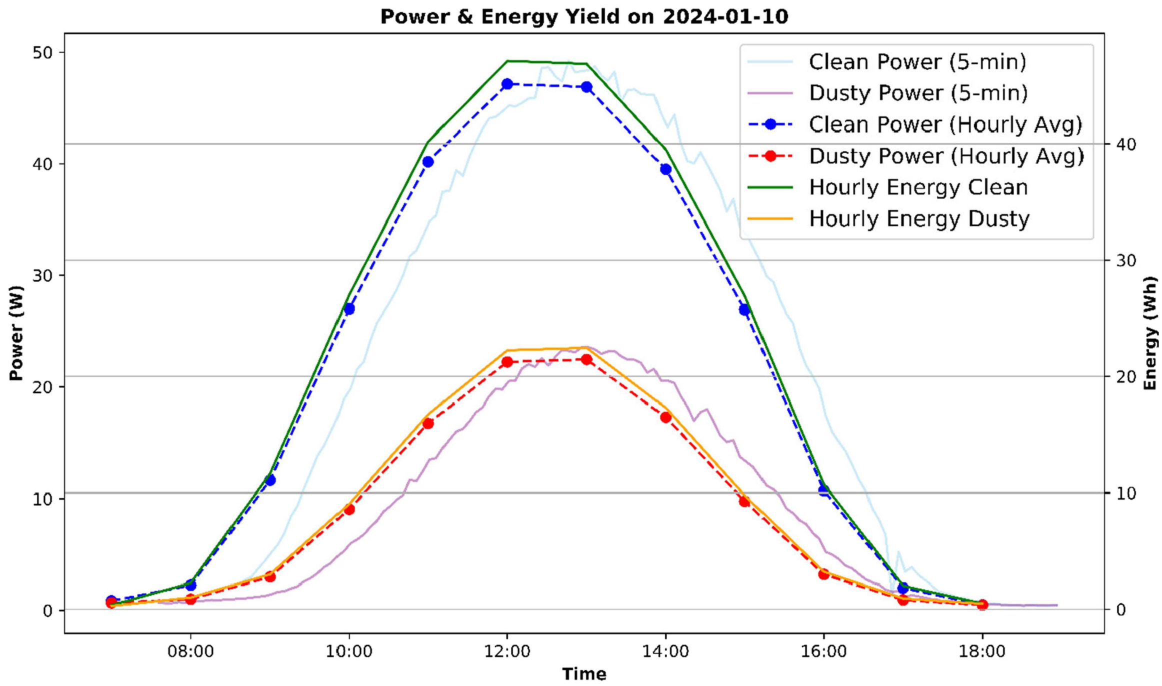

FIGURE 5 | Typical daily variation of power and energy during the Harmattan season for the polycrystalline panels.

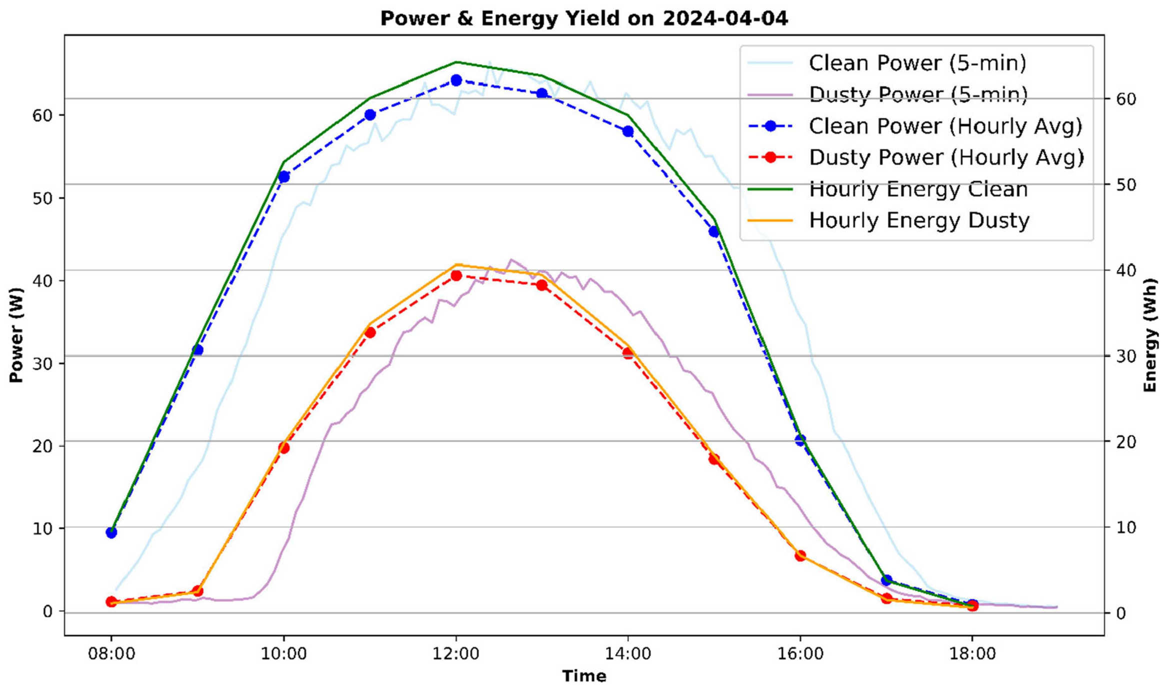

FIGURE 6 | Typical daily variation of power and energy during the hot season for the monocrystalline panels.

The 5-min interval data show a maximum power output of 66.39 W for the clean panel and 42.44 W for the dusty panel. On the basis of hourly averages, peak power values are 64.21 W for the clean panel and 40.62 W for the dusty one, resulting in a mean percentage power reduction of 52.28%. Regarding energy production, the clean panel generates 409.6 Wh, while the dusty panel yields 195.5 Wh, corresponding to a 52.3% reduction in energy output.

3.6 | Polycrystalline Panel Performance During the Hot Season

For the polycrystalline panels, Figure 7 shows that the clean module achieves a maximum power output of 53.04 W based on the 5-min interval data, whereas the dusty panel peaks at 37.73 W. The corresponding hourly averaged maximum power values are 50.38 W for the clean module and 36.25 W for the dusty one, indicating a mean percentage power reduction of 38.95%. In terms of energy

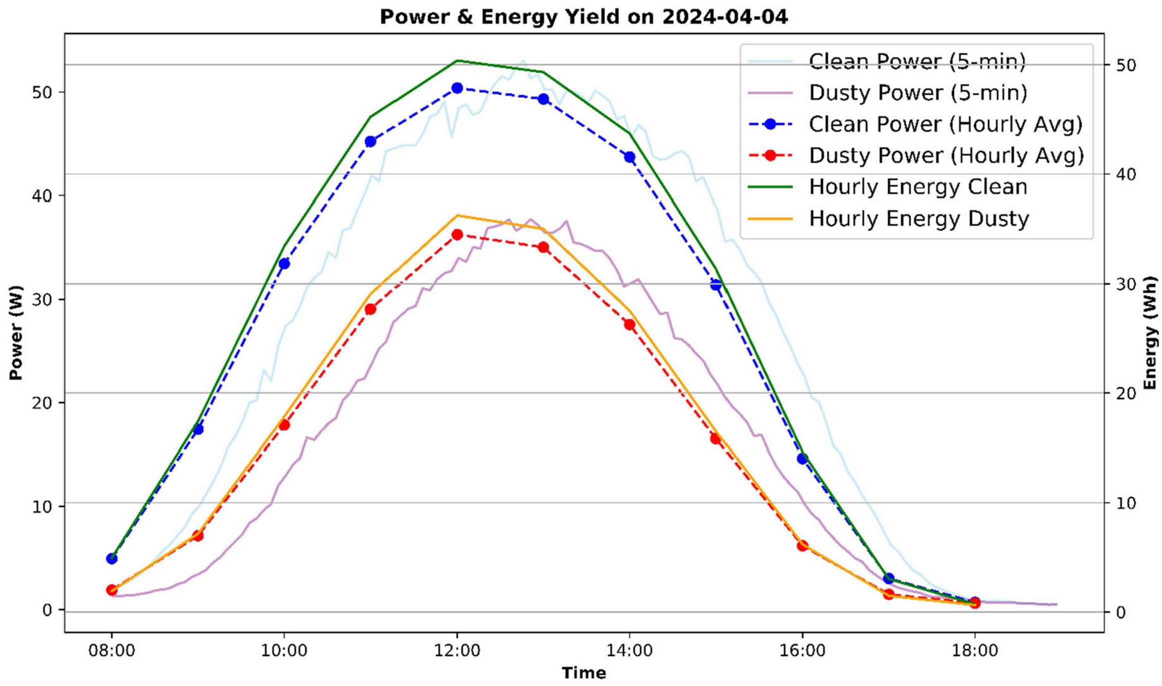

FIGURE 7 | Typical daily variation of power and energy during the hot season for the polycrystalline panels.

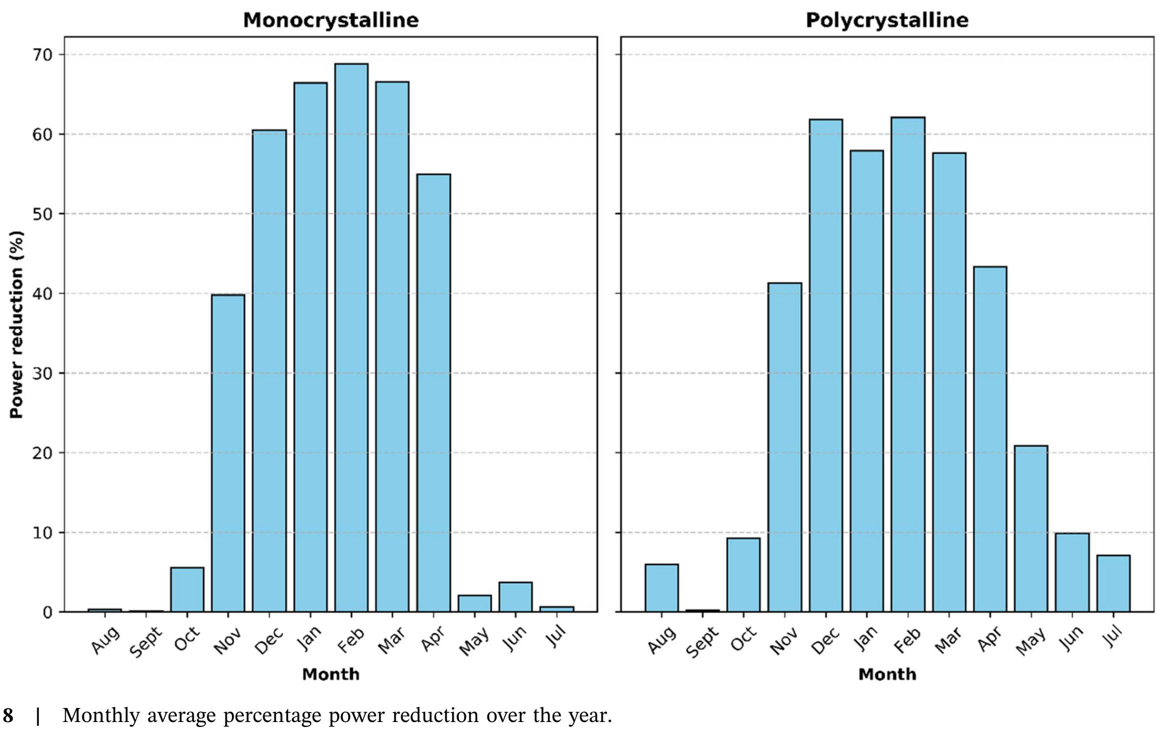

FIGURE 8 | Monthly average percentage power reduction over the year.

production, the clean module generates 294.2 Wh, while the dusty panel delivers 179.6 Wh, resulting in a 38.9% reduction in daily energy yield.

3.7 | Monthly Average Power Reduction

Figure 8 presents the monthly average percentage power reduction for monocrystalline and polycrystalline PV panels from August 2023 to July 2024. The data highlight clear seasonal variations in performance.

During August, the power reductions are 0.33% for monocrystalline and 5.98% for polycrystalline panels. In September, the reductions drop further to 0.12% and 0.26%, respectively. June and July follow similar patterns, with reductions of 3.62% and 9.54% in June, and 0.72% and 6.98% in July, for monocrystalline and polycrystalline panels, respectively.

In October, power reduction increases to 5.57% for monocrystalline and 9.26% for polycrystalline. This trend continues into November, with more pronounced reductions of 39.83% and 41.34%, respectively.

The most substantial declines occur between December and March. The power reductions reach 60.48% and 61.84% in December, 66.46% and 57.96% in January, 68.84% and 62.21% in February, and 66.68% and 57.91% in March, for the monocrystalline and polycrystalline panels, respectively.

A notable improvement begins in April, with power reductions dropping to 54.6% for the monocrystalline and 43.22% for the polycrystalline.

3.8 | Seasonal Energy Performance Under Dust Influence

Figure 9 shows the monthly cumulative energy output and the corresponding percentage energy loss for monocrystalline and polycrystalline PV panels during the three representative seasons of Niamey's climatic seasons.

In August (rainy season), energy losses are minimal for both technologies, with reductions of 1.55% for monocrystalline and 6.67% for polycrystalline panels.

In January (Harmattan), energy losses increase significantly to 65.55% for monocrystalline and 57.50% for polycrystalline panels.

In April (hot season), energy reductions are 52.31% for monocrystalline and 42.61% for polycrystalline panels.

For all three seasons, the clean monocrystalline panels generated higher total energy than the clean polycrystalline panels.

3.9 | Seasonal Variation in PV Cell Temperature

Figure 10 presents the average cell temperatures recorded across the three main seasons in Niamey for both monocrystalline and polycrystalline panels under clean and dusty conditions.

The highest average cell temperatures are observed during the hot season, with monocrystalline panels reaching 40.49°C for the clean and 42.76°C for the dusty, and polycrystalline panels reaching 40.03°C for the clean and 41.72°C for the dusty panel.

The lowest average cell temperatures occur during the Harmattan season, with monocrystalline panels recording 28.65°C

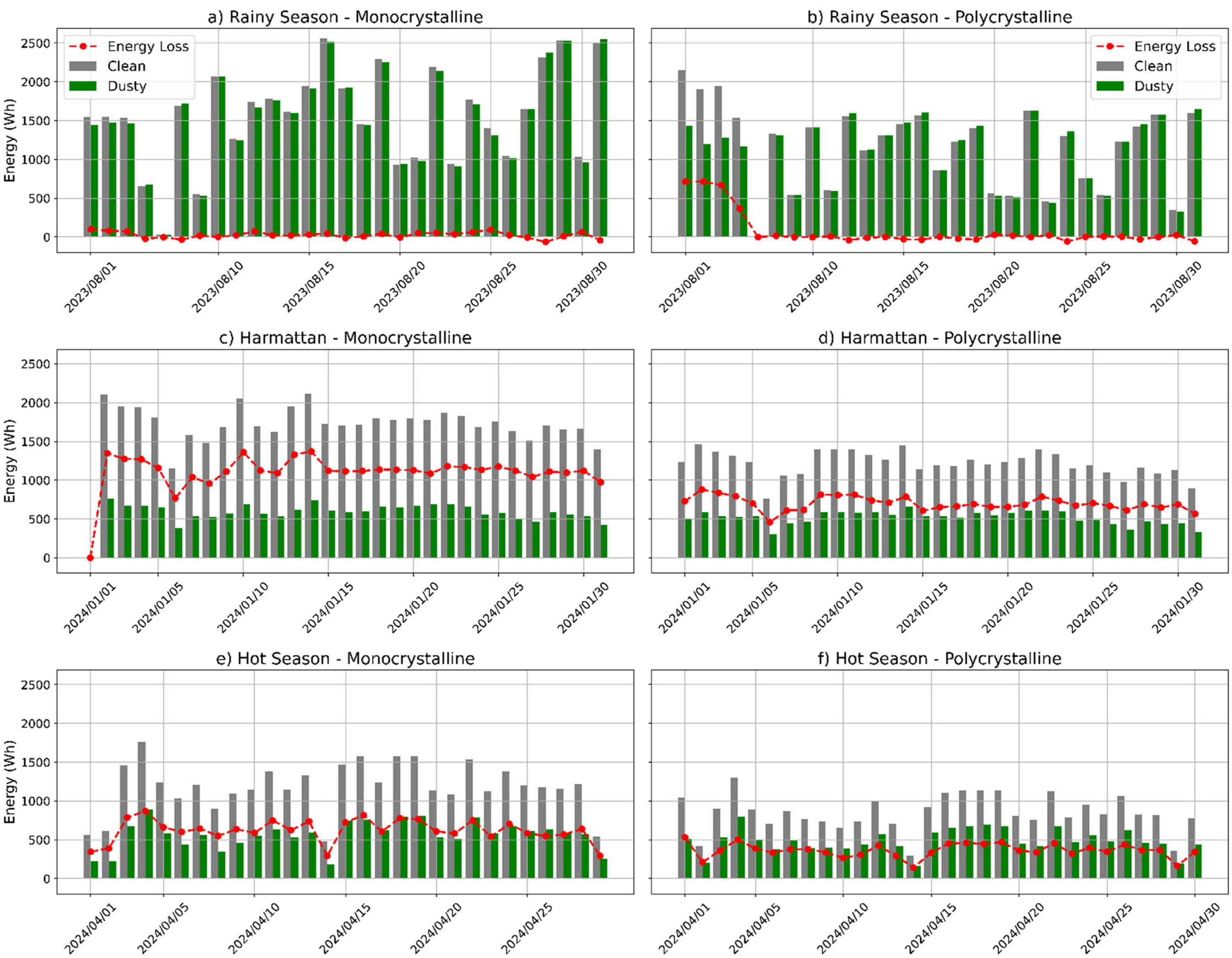

FIGURE 9 | Variation of the cumulative energy based on the season. (a) Rainy season—monocrystalline, (b) rainy season—polycrystalline, (c) Harmattan—monocrystalline, (d) Harmattan—polycrystalline, (e) hot season—monocrystalline, and (f) hot season—polycrystalline.

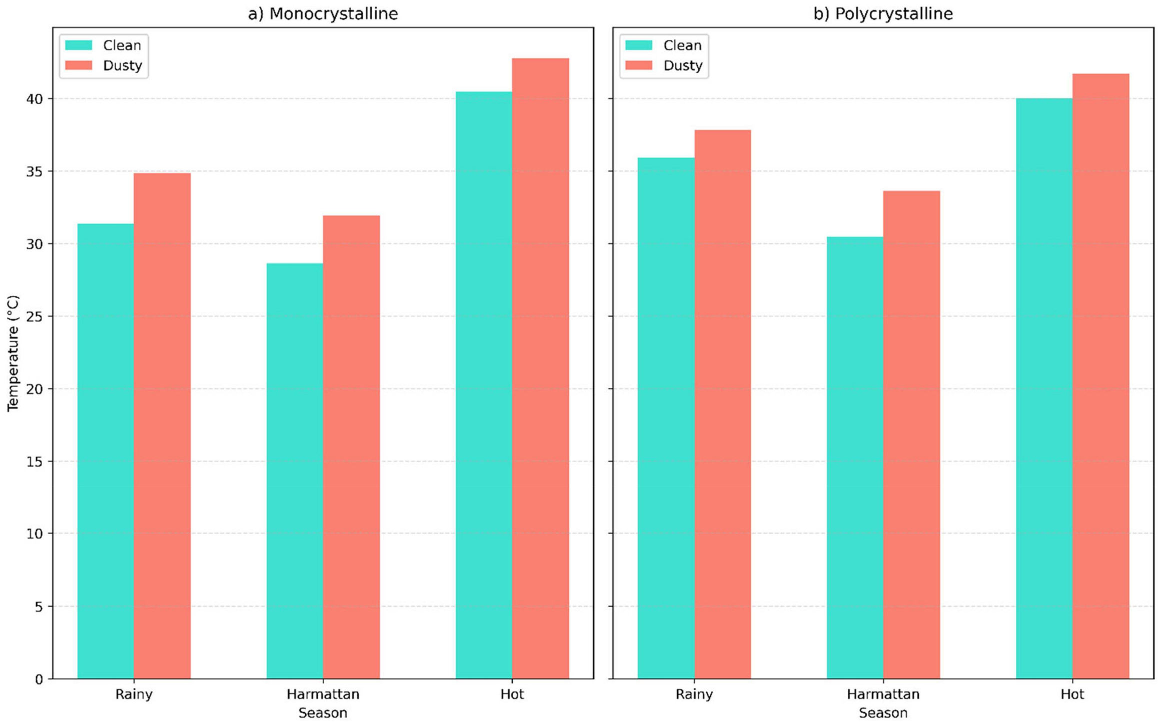

FIGURE 10 | Average cell temperature variation by season. (a) Monocrystalline and (b) polycrystalline.

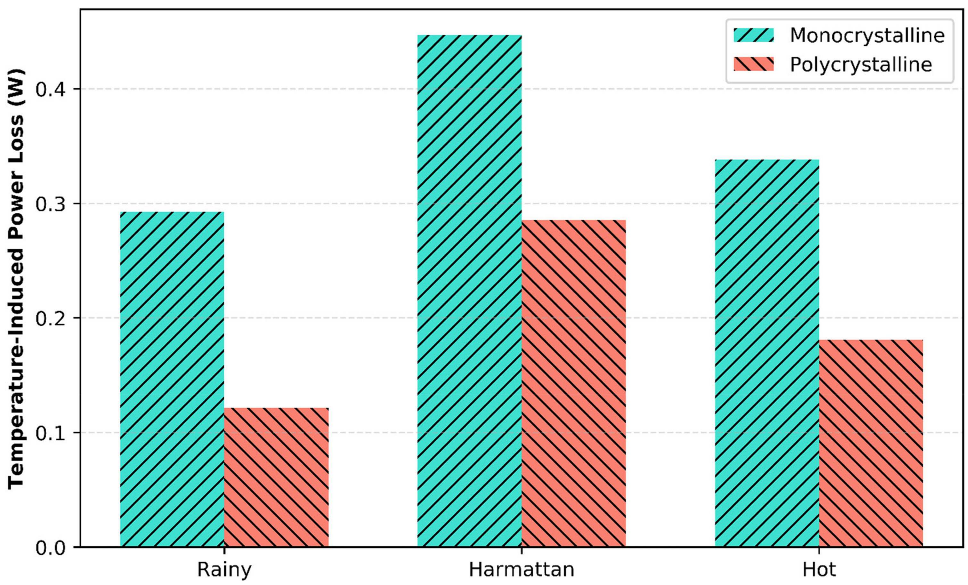

FIGURE 11 | Seasonal power loss due to dust-induced temperature rise.

for the clean and 31.91°C for the dusty, while polycrystalline panels show 30.46°C for the clean and 33.65°C for the dusty panel.

Across all seasons, dusty panels consistently exhibit higher cell temperatures than their clean counterparts.

During the rainy season, monocrystalline panels show average temperatures of 31.39°C for the clean panel and 34.87°C for the dusty, while polycrystalline panels record 30.18°C for the clean panel and 33.51°C for the dusty.

Figure 11 illustrates the seasonal power loss resulting from dust-induced temperature rises for both monocrystalline and polycrystalline PV panels. Across all seasons, monocrystalline modules experience higher temperature-induced power losses compared with polycrystalline panels. The highest losses occur during the Harmattan season, reaching approximately 0.45 W for monocrystalline modules and 0.29 W for polycrystalline modules. This corresponds to the period with the largest temperature increase between clean and dusty modules. During the rainy season, losses remain the lowest for both technologies, with values around 0.29 and 0.12 W, respectively. In the hot season, intermediate losses are observed, with monocrystalline modules losing about 0.34 W and polycrystalline modules about 0.18 W. Overall, the figure shows that dust-related heating effects contribute measurable but modest reductions in PV output, with seasonal variability driven by differences in module temperature rise.

4 | Discussion

This study highlights the clear seasonal influence of dust deposition on the performance of PV panels in Niamey's Sahelian climate. While power and energy losses were minimal during the rainy season, the Harmattan and the hot seasons demonstrated substantial degradation due to persistent dust accumulation and adverse atmospheric conditions.

During the rainy season, frequent rainfall acted as a natural cleaning mechanism, limiting dust accumulation. The total amount of rainfall recorded in Niamey this year was 404.7 mm, with 73.1 mm for the representative month [19, 20]. As a result, monocrystalline and polycrystalline modules exhibited only slight performance degradation: 1.55% and 6.67% energy losses, respectively. These modest reductions confirm that even under regular cleaning from rainfall, dust particles, and overcast conditions can still impair performance slightly.

The Harmattan season presented the most severe impact, with energy reductions reaching 65.55% for monocrystalline and 57.50% for polycrystalline panels. This is due to both surface-level soiling and atmospheric attenuation caused by dense Saharan dust. These conditions reduce the transmissivity of the panel glass and scatter (absorb) incoming solar radiation, compounding the energy deficit. The higher losses in monocrystalline panels can be attributed to their dependence on direct sunlight, which is significantly blocked during this season.

The magnitude of performance reduction aligns with findings in Senegal and Algeria, where similar climatic conditions yielded comparable energy losses [8, 21]. The dual impact, soiling and atmospheric dust, confirms the Harmattan as a critical threat to PV performance in semiarid environments.

During the hot season, energy losses were also considerable, with 52.3% for monocrystalline and 42.61% for polycrystalline panels. Elevated ambient and cell temperatures, combined with dust buildup, negatively impacted performance. Notably, monocrystalline modules, which generally operate with higher efficiencies, became more susceptible to thermal and dust soiling stress. These results corroborate findings in Oman, where heat and dust synergistically diminished PV performance [16].

Monocrystalline panels consistently outperformed polycrystalline ones under clean conditions, but suffered higher relative losses due to dust. Their lower tolerance to diffuse radiation and greater thermal sensitivity explain this pattern. Conversely, polycrystalline modules, which possess a higher cell packing density and perform better under scattered light, demonstrated greater stability under dusty and humid conditions [22, 23].

Despite these advantages, polycrystalline panels recorded slightly higher absolute power losses in certain cases. This paradox reflects their lower baseline performance, making them more susceptible to even modest drops in irradiance [24].

Diurnal analysis further reveals that dust-induced power losses are most pronounced during peak solar hours (11 a.m.–2 p.m.), when irradiance is highest. In contrast, during early morning and late afternoon, losses were less significant, suggesting that dust impact is less critical under low-irradiance or diffuse conditions. This trend aligns with findings by Mostefaoui et al. [25], who demonstrated that shading from dust has a disproportionate effect under high irradiance. In fact, under low irradiance conditions, the shading caused by dust has a relatively smaller impact due to the already reduced light intensity. Conversely, under high irradiance conditions, even a small shaded area leads to a disproportionately larger drop in power, particularly in monocrystalline panels that depend on direct sunlight.

Monthly trends (Figure 8) further corroborate seasonal dynamics. From August to September, and again in June–July, reductions were negligible due to consistent rainfall. Studies have shown that rainfall can significantly mitigate the effects of dust accumulation, maintaining PV efficiency close to optimal levels. For instance, Nezamisavojbolaghi et al. [26] indicate that natural cleaning by rain can reduce dust-related power losses, enhancing overall performance during wet periods. However, starting in October, reductions gradually increased, marking the transition to dry conditions. Peak reductions occurred in January and February, coinciding with peak Harmattan intensity. In April, partial recovery was observed, likely due to the end of the Harmattan and occasional cleansing by wind.

Temperature data (Figure 10) showed that dusty panels were consistently hotter than clean ones across all seasons, with maximum values observed during the hot season. Dust acts as a thermal insulator, trapping heat and reducing convection-based cooling. Even during the Harmattan, cooler ambient conditions combined with strong winds helped maintain lower panel temperatures. Nonetheless, dust still raised cell temperatures by several degrees. This thermal burden compounds electrical losses, especially in crystalline silicon modules, which exhibit negative temperature coefficients. These findings are consistent with [27], who identified dust as a factor elevating module temperatures and reducing conversion efficiency.

The seasonal power loss due to dust-induced temperature rise (Figure 11) indicates that dust-induced temperature rise contributes only a minor share of the total dust-related power loss, with seasonal losses remaining below 0.5 W for both technologies. Monocrystalline modules consistently exhibit higher temperature-related losses than polycrystalline ones, mainly due to their higher seasonal operating temperatures. The Harmattan season shows the largest effect, consistent with its higher dust load and reduced convective cooling. These findings agree with previous studies reporting that while dust increases module temperature, its impact on power is relatively small compared with the optical effect. Earlier works by Shen et al. similarly show that dust-driven heating typically accounts for only a marginal fraction of dust losses, confirming that soiling's dominant mechanism remains optical attenuation rather than thermal effects [28].

5 | Conclusion

This paper assessed the effect of dust accumulation on monocrystalline and polycrystalline PV panels across the three main seasons in Niger: rainy season, Harmattan, and hot season, using high-resolution data. The main conclusions are as follows:

- Dust accumulation significantly reduces PV performance, with reductions peaking during the Harmattan season when dense, dust-laden winds result in power losses of up to 68.84% for the monocrystalline and 62.21% for the polycrystalline. The insulating and shading effects of dust contribute to increased cell temperatures and reduced light absorption, exacerbating power losses.
- The highest power is observed during the rainy season due to frequent rainfall, which naturally cleans the panels. However, localised heating and occasional soiling still slightly affect performance, with maximum power reductions of 3.62% and 9.54% depending on the technology.
- Despite higher solar radiation levels, the Harmattan season exhibits the lowest cell temperatures due to frequent wind events and cooler ambient temperatures. However, the combined effect of atmospheric scattering and dust deposition leads to significant power losses.
- The hot season results in the highest temperatures (40.49°C–42.76°C for monocrystalline and 40.03°C–42.72°C for polycrystalline), intensifying performance losses due to the synergistic effects of heat and dust accumulation.
- Monocrystalline panels exhibit a higher percentage of power reductions compared with polycrystalline panels during heavily soiled conditions like the Harmattan. This is likely due to their stronger dependence on direct beam irradiance, which is heavily attenuated by airborne dust and aerosols. Monocrystalline panels are more susceptible to performance degradation from uneven soiling, which is typical during dust-laden wind events, due to their cell structure and electrical characteristics.
- The interaction of dust with bird droppings further exacerbates soiling effects, increasing localised heating and power losses. This highlights the importance of addressing both dust and biological soiling for reliable PV operation.

Recommendations:

- *Implement regular cleaning schedules:* To minimise power losses caused by dust and bird droppings, particularly during the Harmattan and hot seasons when losses are most severe. Maintenance frequency should be aligned with seasonal soiling rates to ensure optimal performance.
- *Adopt advanced cleaning technologies:* Automated and self-cleaning systems, though initially more costly, offer long-term benefits by reducing labour requirements and ensuring consistent maintenance in regions like Niger.
- *Use protective surface technologies:* PV modules equipped with antidust coatings or constructed from materials with higher thermal conductivity can mitigate both dust and heat accumulation, improving energy output and extending module lifespan in dusty, high-temperature climates.

Author Contributions

Falmata Abdoulaye Moussa: conceptualisation, investigation, methodology, writing – original draft, writing – review and editing. **Ibrahim Halidou:** supervision, validation, writing – review and editing. **Stefanie Meilinger:** supervision, writing – review and editing. **Bruno Korgo:** supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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