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Research paper

Dust impact on electrical and thermal photovoltaic performance: Insights from field and laboratory experiments

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A B S T R A C T

This study investigated the impact of dust samples from Romania on small-scale silicon-based photovoltaic (PV) devices through field and laboratory experiments. Nonhomogeneous layers of natural dust were intentionally applied to the surfaces of three crystalline and amorphous silicon mini units, with dust film depth measured using an ultrasonic coating thickness gauge. Indoor testing employed a Xenon solar simulator. Key findings reveal significant deterioration in PV electrical characteristics, with maximum losses of 45.35% and 38.14% in maximum power and short-circuit current under outdoor conditions. Indoors, maximum losses were 32.02% and 33.38% for the same parameters. Temperature increases were a maximum of 2.3 °C outdoors and 0.9 °C indoors at the back surface and 3.7 °C and 1.3 °C at the front surface, respectively. The back surface proved to be a better thermal representative due to lower randomness in measured temperature values. Field experiments demonstrated greater reliability than laboratory ones despite using professional equipment. The lack of standardized indoor testing practices is believed to contribute to this discrepancy. The significance of this study lies in updating the literature with experimental studies simulating a relatively extreme condition involving dust thickness densities of 0.01936 and 0.02287 μm mm^{-2}. This scenario is not precluded from occurring in Europe with the escalating impacts of climate change.

1. Introduction

The escalating global demand for energy, driven by population growth and increasing vulnerability to climate change on a country-by-country basis, underscores the imperative to prioritize renewable energy (Younis et al., 2022). This not only positions it as a primary substitute for conventional sources but also as a superior strategy for adaptation and mitigation (Suman, 2021), even though only under certain circumstances can they provide feasible and cost-effective power (Solaun and Cerdá, 2019). Among many shapes of clean energy, solar photovoltaic (PV) appears as a potential game-changer confronting the urge to shift to modern alternatives and, at the same time, minding the restrictions like technological barriers (Raina and Sinha, 2019), global greenhouse emissions targets set by the United Nations in the Sustainable Development Goals (SDGs), and a mild prospective decline in this resource potential in specific regions and conditions, as a consequence of the policies set to meet the SDGs (Dutta et al., 2022). Therefore, improving the reliability of the PV generators is a crucial action that will encourage decision-makers and policy developers to clear more space for this technology to settle. In simpler terms, research and development in PV performance under various working conditions must thrive. Continuing in the same vein and building upon the previously mentioned importance of research, the constant threat of dust soiling on PV surfaces and other pertinent environmental elements undermines the consistency of power yield (Gupta et al., 2019), allowing various simulation-based and experimental investigations to examine its consequences (Yazdani and Yaghoubi, 2022) and create mitigation solutions (Younis and Onsa, 2022). Starting from the fundamentals, dust is defined as solid particles less than 500 μm (Paudyal and Shakya, 2016) suspended in the atmosphere with sizes ranging from smaller than 1 to 100 μm (Enaganti et al., 2022). Besides the deposition density, the morphological and chemical characteristics of the dust are vital as they also contribute to the degradation in the module performance (Chen et al., 2020). Techniques such as Scanning Electron Microscope (SEM), Energy Dispersive X-ray Fluorescence (EDS or EDX) detectors, X-ray Fluorescence (XRF) detectors, and other equipment are commonly employed to characterize dust. These methods identify particle shape and size, as well as the mineralogical and elemental characteristics, reflecting standard practices in many studies (Darwish et al., 2021; Fan et al., 2021; Huang et al., 2021; Liu et al., 2022). If a swift transition is made to the description of PV devices in terms of their electrical performance under the presence of

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Nomenclature

I	Current
V	Voltage
I - V	Current-voltage
I_{sc}	Short-circuit current
V_{oc}	Open-circuit voltage
P_{max}	Maximum power

Abbreviations

a-Si	Amorphous silicon
Mono-Si	Monocrystalline silicon
Poly-Si	Polycrystalline silicon
PV	Photovoltaic
SDG	Sustainable development goals
SEM	Scanning electron microscopy
EDS or EDX	Energy dispersive X-ray spectroscopy
XRF	X-ray Fluorescence

Units

A	Current
V	Voltage
g m^{-2}	Dust deposition density
mg m^{-2}	Dust deposition density
mg cm^{-2}	Dust deposition density
mg m^{-2} day^{-1}	Dust deposition density rate
g m^{-2} $month^{-1}$	Dust deposition density rate
°C	Temperature
K	Temperature difference
μm	Layer thickness
μm mm^{-2}	Dust thickness density
kWh/m^2	Solar irradiance
W/m^2	Solar irradiance

dust, this research line has been followed by many studies, with emphasis placed on the effect on the current-voltage (I-V) characteristics. For instance, Chanchangi et al. deployed sequentially thirteen different pollutant samples on a PV surface and obtained a 98% reduction in the short circuit current (I_{sc}) in response to the charcoal dust and only a 7% loss in the same electrical parameter associated with the salt powder, employing an indoor solar simulator setup (Chanchangi et al., 2020). Through open-air testing, Semaoui et al. observed an 8.79% reduction in I_{sc} after more than one month of exposure to natural dust (Semaoui et al., 2020). Rao et al. utilized indoor and outdoor settings to examine the dust deposition effects on the I – V characteristics of a solar panel and noticed that no changes were present considering the open circuit voltage, while a 30 – 40% reduction in the I_{sc} was documented in the laboratory and 4 – 5% decline based on the outside testbed (Rao et al., 2014). It should be highlighted that, in many experimental studies, silicon-based solar panels—such as monocrystalline (mono-Si), polycrystalline (poly-Si), and amorphous silicon (a-Si)—were the PV technologies under investigation (Adıgüzel et al., 2019; He et al., 2022; Kazem et al., 2022; Tanesab et al., 2019).

Dust accumulation also changes the thermal characteristics of the PV device, resulting in higher temperatures, which is an outcome of blocked heat dissipation (Lakshmi and Ramadas, 2022). It is essential to note that the efficiency of the PV module is strongly associated with its operating temperature (Menemmeche et al., 2022). Moreover, in PV generators, it is intuitive that the entire structure heats up when dust deposits partially cover the PV surface, leading to hotspots in these blocked regions (Gupta et al., 2019). Fig. 1 illustrates a thermal image captured by a thermo-vision camera of a PV module contaminated with bird droppings, resulting in an additional 10 °C temperature increase at the dirty spot (Dorobantu et al., 2011). Xu et al. examined the effect of dust soiling on the glass plate of a PV module, utilizing an indoor setup to disclose that temperatures of upper and lower surfaces of dusty glass plate are much higher than a clean one, with more impact on the lower side (Xu et al., 2020). Abderrezek and Fathi monitored the thermal response of the PV glazing when the dust was there, especially under the nonhomogeneous dispersion condition. The shadow that occurred due to the nonuniform dust agglomeration led to the formation of hotspots that overheated the entire module. Interestingly, the researchers noticed that under salt powder, the module temperature decreased (Abderrezek and Fathi, 2017).

Continuing the narrative regarding the effect of dust on the performance of PV modules, many researchers explored this phenomenon with a focus on geographical location, like Majeed et al., who conducted outdoor experiments in Pakistan on mono-Si and poly-Si PV modules. The team observed a 16.16% and 11.54% decrease in power after one month of dust accumulation, with a corresponding deposition density of 4.6 g m^{-2} (Majeed et al., 2020). In Iran, Khodakaram-Tafti and Yaghoubi studied the combined effect of tilt angle and dust deposition density on PV performance through field experiments. They found that the average daily reduction in power on the horizontal surface was 8.6%, while on the tilted surface, it was 0.8%. Following a dust storm, the researchers recorded a 58.2% deterioration at the horizontal position and a 21.7% reduction at 30° compared to the performance on the latitude inclination (Khodakaram-Tafti and Yaghoubi, 2020). In Algeria, within a Saharan environment, Dida et al. utilized crystalline silicon modules and identified a 32% reduction in the generated energy of a 30 MWp PV power plant following a sandstorm incident (Dida et al., 2020). Song et al. published a thorough assessment of the influence of dust soiling on the techno-economic performance of solar PV systems in various countries and the global PV market (Song et al., 2021).

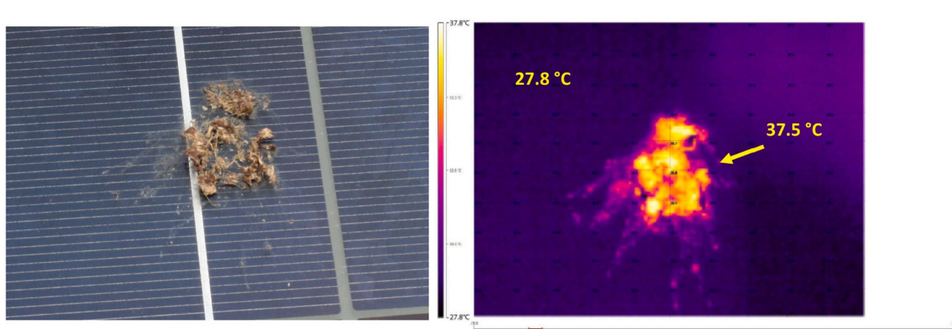

Fig. 1. Effect of bird dropping on the front surface temperature of the solar panel: left) contaminated module, right) thermal image of the module displaying the difference in temperature (Dorobantu et al., 2011).

Shifting the focus to Europe as the location for conducting the current study, Styszko et al. quantified the dust deposition density in Kraków, Poland, one of the most contaminated cities in Europe, characterized by low wind speeds. They revealed that the daily density rate can reach 40 mg m-^{2} day^{-1} in the absence of rain, which is considered very low but accumulates significantly on a weekly basis (up to 277 mg m^{-2}). However, this amount decreased with time, as natural cleaning was responsible for removing 90% of the dust (Styszko et al., 2019). In Bucharest, Romania, Danu et al. quantified the dust deposition density rate to be 11.7 g m^{-2} month^{-1} based on data collected in 2015 and experiments following the local "Determination of settable particulates" standard. They reported that these amounts have an insignificant effect on PV performance. However, the researchers mentioned that more than 14 g m^{-2} causes a poly-Si module to lose more than 30% of its efficiency (Danu et al., 2018). In Brighton, England, Ghazi and Ip obtained a minimal effect of dust deposition on experimental PV modules placed to quantify the effects of weather conditions on their performance. The researchers attributed this reaction to local weather conditions and the level of air pollution that does not support dust buildup (Ghazi and Ip, 2014). Returning to the city of Kraków, Jaszczur et al. observed more than 300 mg m^{-2} over one week without precipitation, causing a 2.1% PV efficiency loss (Jaszczur et al., 2019). Radonjić et al. investigated the effect of fly ash accumulated on rooftop PV modules based on 45 days of outdoor sunlight exposure in Serbia. They found an 87.2% reduction in the output power at the horizontal position and a 30.6% reduction at the optimally inclined position (Radonjić et al., 2021). Sayyah et al. conducted a literature review on quantifying the dust effect on PV systems and reported a 20% reduction in the energy produced by a PV system in Spain, which was the maximum reduction value in Europe at the time of the study. For comparison, the same research reported an 80% loss in energy for a PV system installed in California, USA. (Sayyah et al., 2014). Table 1 lists the most recent studies concerned with the dust deposition effect conducted in European countries.

The main task that is set to be accomplished in this study is to assess the electrical and thermal performance of two small PV cells, one made of poly-Si and the other of mono-Si, along with a mini a-Si module. These PV devices were subjected to both outdoor and laboratory operating conditions after intentionally applying a nonuniform layer of natural dust collected in Romania to their surfaces. The obtained degradation values in this research represent extreme scenarios of dust accumulation, surpassing some results observed in North African countries such as Mauritania, where a PV system in Nouakchott experienced a power loss of 21.57% (Lasfar et al., 2021). This heightened susceptibility to dust-related power loss is anticipated in Europe due to climate change, as indicated by Varga's study analyzing over 200 Saharan dust transport events in Central Europe from the last 40 years. The research revealed that these events, mainly occurring in Spring and Summer, intensified after 2014 (Varga, 2020). Conceição et al. reported, based on NASA satellite data, that the region of Portugal and Spain is expected to experience higher temperatures and less frequent rainfall by 2100. This projection implies an increase in dust buildup as natural cleaning becomes less effective (Conceição et al., 2018).

In more focused terms, the current state of the examined subject reveals that numerous global studies, with a specific emphasis on Europe, are investigating the impact of dust deposition on PV performance. Outcomes exhibit variability based on geographical factors, including dust deposition density, exposure duration, and prevailing weather conditions. Significantly, studies from Greece, Belgium, the UK, Poland, Serbia, Portugal, and Spain highlight diverse effects on PV efficiency, spanning from negligible to substantial reductions. In line with this context and aligning with the objectives of implementing and promoting Sustainable Development Goal 7 (SDG7) and achieving its underpinning target 7. a (United Nations, 2015), focused on clean energy research, this study aims to address a temporal and quantitative gap specific to important experimental studies on the impact of dust accumulation. This includes particularly thick layers of dust, representing extreme cases of gathering on PV surfaces installed in Europe. The research here seeks to fill a discernible void in recent and multiple studies in this area. Consequently, the results of this effort will equip energy planners with essential information for evaluating the efficacy of this crucial energy source, particularly on the European continent, which is always enthusiastic about generating clean and sustainable energy.

Moreover, this work effectively presents the I-V curves and their associated characteristic values, thermal images with corresponding PV front surface temperatures, and the recorded back surface temperatures of the three mini structures across various testing configurations. Also, the results are thoroughly discussed and interpreted. The comprehensive explanation of the results is facilitated by a substantial amount of data generated during the experimental work. These experiments are conducted using professional, scientific research equipment with high precision and accuracy. Hence, the uniqueness of this work lies in filling the identified gap by closely observing the effects of dust accumulation. In other words, the added value or significance of this study lies in contributing to the existing literature by providing updated performance analysis studies that delve into relatively extreme cases of dust accumulation. This contribution enhances the foundation for comparing results from different researchers, leading to more reliable and generalized observations, conclusions, or guidelines.

Henceforth, the remaining sections of this article are structured as follows: Section 2 outlines the experimental methodology, Section ↱3 presents and discusses the results, and Section 4 concludes the study while providing recommendations.

Table 1
Summary of the recent studies investigated the effect of dust deposition on PV performance in Europe.

Reference	Year	Location	Dust Deposition Density	Exposure time	Degradation measure	Loss percentage
(Kaldellis et al., 2010)	2009	Piraeus, Greece	0.09036 mg cm^{-2}	1 month	Power	5%
(Kaldellis and Fragos, 2011)	2011	Piraeus, Greece	0.4 mg cm^{-2}	1 h (artificial deposition)	Energy	30%
(Appels et al., 2012)	2012	Leuven, Belgium	–	5 weeks	Power	3 – 4%
(Ghazi and Ip, 2014)	2013	Brighton, UK	0.0003 - 0.00075 g	1-4 weeks	–	Neglectable effect
(Klugmann-Radziemska, 2015)	2015	Gdansk, Poland	1 µm (Layer thickness)	2 years	Maximum output power	3% per year
(Radonjić et al., 2021)	2016	Niš, Serbia	–	45 days	Power	30.6%
(Conceição et al., 2018)	2017	Évora, Portugal	–	Saharan Dust transport event	Maximum output power	8%
(Klugmann-Radziemska and Rudnicka, 2020)	2019	Gdansk, Poland	• – (Outdoor test) • 0 – 14 g m^{-2} (Indoor test)	• 1 year • –	Efficiency	• ≤15% • 6 – 10%
(Alonso-Montesinos et al., 2020)	2020	Almería, Spain	–	–	Power	5%

2. Experimental method

Natural dust collected from the surroundings in Brasov, Romania, was applied to the silicon solar cells and module to assess the impact of dust deposition on their performance. Fig. 2 displays a sample of this dust. The accumulation of dust on the PV surface can occur uniformly or non-uniformly under outdoor conditions, influenced by site characteristics, dust properties, wind speed, ambient temperature and humidity, tilt angle, and dimensions and material properties of the surface (Memiche et al., 2020). However, there is no scientific consensus supporting the uniformity or homogeneity of dispersion, as it occurs randomly in the natural world. In this study, a mini a-Si module (30 mm × 30 mm), and two mini-cells cut from larger commercial ones—a mono-Si cell (41.6 mm × 33.9 mm) and a poly-Si cell (33 mm × 40.4 mm)—were utilized in the experimental work. These precise dimensions of mini units mentioned here were measured using an electronic digital Vernier caliper (Powerfix Z22855F with accuracy 0.02 mm). These small PV devices were affixed to a heat sink using thermoconductive adhesive tape. A K-type thermocouple was used to measure the temperature on the back of each PV unit, falling within the range of the sensors' resolution (Guk et al., 2018). Subsequently, a sieve or strainer was employed to deposit a nonhomogeneous dust layer over the PV surfaces, as depicted in Fig. 3. According to the literature, the sieve significantly contributed to achieving a uniform or homogeneous distribution, with less emphasis on the mesh size (Darwish et al., 2021; Younis et al., 2017). As the next step, a K6-C with Ferrous/Non-Ferrous (FNF) probe multifunctional dry film non-destructive ultrasonic thickness gauge manufactured by NDT1 KRAFT was utilized to measure the depth of the dust layer. This device relies on the Combined Magneto-Inductive and Eddy Current parametric techniques, offering a measurement range of 0 – 1000 μm corresponding to the probe model (ndtone, 2023).

On the data collection side, an acquisition and control system based on the National Instruments (NI) cRIO 9074 8-slot embedded controller (National Instruments, 2023) was employed to record the I-V characteristics and back surface temperatures. Each set of readings took approximately 3.2 min, consisting of 8 data points with a 24-second interval. Table 2 provides a list of the NI modules fixed in the controller chassis. For a more detailed exploration of the modules' accuracies, interested readers can visit https://www.ni.com/docs/en-US/bundle/. Additionally, a capacitor-based dynamic load was connected to the controller to assist in obtaining the I-V data. The current and voltage sensors measured the parameters during the charging process of the capacitor directly connected to the PV mini-units (Mahmoudinezhad et al., 2019). Finally, a Testo 875–1i manual focus portable thermal imager with 19,200 temperature measuring points, thermal sensitivity of less than 50 mK, and a measuring range from −30 to +350 °C (Testo Thailand, 2023) was used to measure the front surface temperature. It is worth mentioning that Table 3 includes details about the accuracy of the instruments employed in various measurement procedures, whether in indoor or outdoor experiments.

Fig. 2. Natural dust sample collected in Brasov City, Romania.

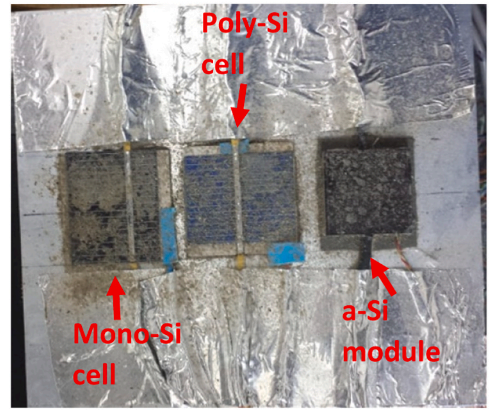

Fig. 3. Dusty silicon-based PV mini devices.

Table 2
List of NI data acquisition system parts (National Instruments, 2023).

Module	Description
NI- cRIO-9074	Embedded controller
NI-9227	Current Input Module
NI-9215	Voltage Input Module
NI-9211	Temperature Input Modules
NI-9213	

2.1. Outdoor experimental setup

The field experiments were conducted on the rooftop of a building in the Colina campus at Transilvania University of Brasov, Romania. For reference, the annual sum of global irradiation falling on an optimally inclined surface in Brasov equals 1400 kWh/m^2 (European Commission, 2019). The PV mini devices were affixed to an adjustable tripod, and readings were taken under clear sky conditions for both clean and dusty cases. Fig. 4 illustrates an image diagram of the experimental rooftop setup, while Fig. 5 displays photographs of the same arrangement. Solar irradiance was measured in the same test setup using the DELTA-T SPN1 Sunshine pyranometer. Researchers relied on this instrument to confirm if the appropriate irradiances of 800, 900, and 1000 W/m^2 were achieved, subsequently saving the relevant data.

2.2. Indoor experimental setup

The experiments were conducted in the Electronics and Computers department laboratory on the Colina campus. Fig. 6 illustrates an image

Table 3
Accuracies of measurement instruments used in the experiments.

Instrument	Accuracy
k-type thermocouple	±1.5 °C (Wu, 2018)
K6-C FNF probe	±(0.015 T + 1), T = 0 – 1000 μm (ndtone, 2023)
Testo 875-1i manual focus thermal imager	±2 °C (Testo Thailand, 2023)
DELTA-SPN1	±5% (or ± 10 W/m^2) (Delta-T devices, 2023)
Daystar DS-05A	±3% (Raydec, 2022)

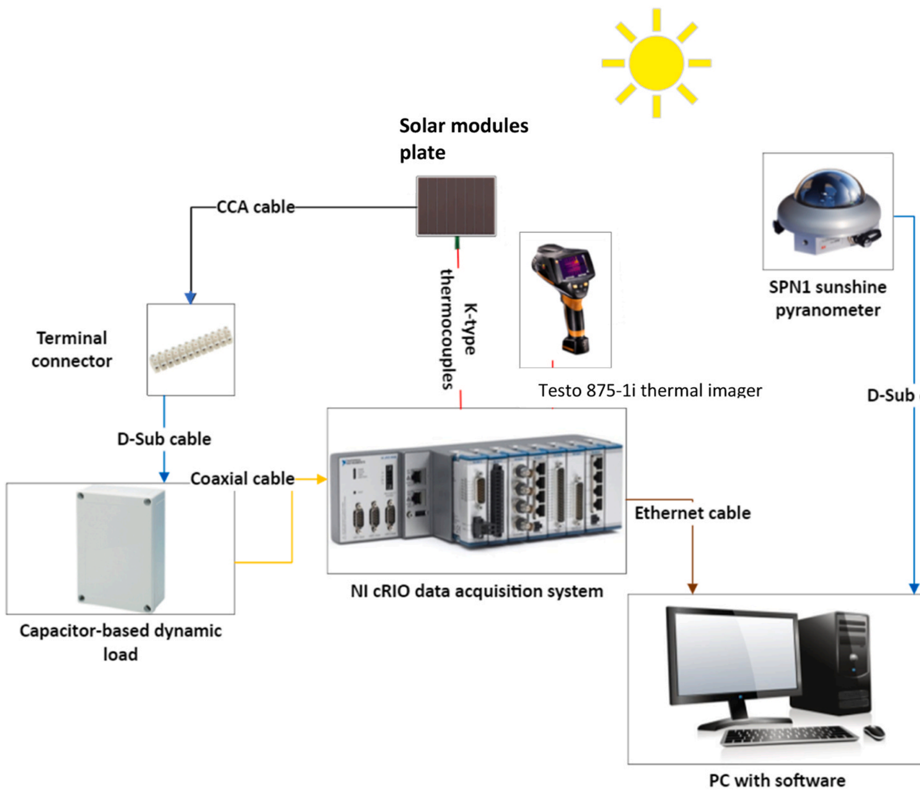

Fig. 4. Image diagram of the outdoor testing setup.

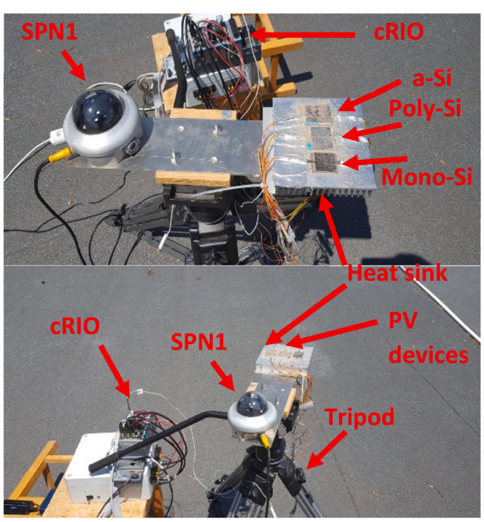

Fig. 5. Photographs of the outdoor testing setup with the PV mini units covered in dust.

diagram of the indoor testing setup used in this work, wherein a Daystar DS-05A solar meter measured light intensity in all trials to ensure solar irradiance was consistently at 800, 900, and 1000 W/m^2. Additionally, a 1000 W Sciencetech Solar LightLine A4 Xenon lamp simulator AAA was utilized, as shown in Fig. 7. The parameters of the Sciencetech solar simulator are detailed in Table 4. It is crucial to note that researchers prefer Xenon-based solar simulators due to their excellent quality in the visible band and the capability to filter out infrared light (Tawfik et al., 2018). This choice ensures that the obtained temperature values closely resemble real-world scenarios.

3. Results and discussion

The dust layer thickness averaged 25.8 μm (or 0.01936 μm mm^{-2}) when formed on the mono-Si mini cell surface and 32.25 μm (or 0.02287 μm mm^{-2}) when deposited on the poly-Si small cell surface, as illustrated in Fig. 8. However, the same measurement technique, which relies on the emission of ultrasonic waves, was not applicable to the a-Si mini-module. This is because a metallic substrate is required for the gauge to function, and such a substrate is typically not part of the module composition in the case of a-Si PV technology.

3.1. Electrical characterization

For the electrical characterization of the PV microstructures, the analysis method used here relied on indoor and outdoor measurements of the I-V curves and characteristics values to describe the performance at three different solar irradiance levels, beginning at 1000 W/m^2, progressing to 900 W/m^2, and finishing at 800 W/m^2. The I_{sc}, open-circuit voltage (V_{oc}), and maximum power (P_{max}) are always the emphasis of the I-V characteristics. It is noticeable from the I-V curves conveyed by Fig. 9 and Fig. 10 that at the three different irradiance levels, all the PV devices showed dissimilar responses between the clean and dusty situations, which is a typical outcome based on the difference in the PV technology. At the same time, there is no significant contrast between the outdoor and the indoor curves.

On the I-V characteristics side, Table 5 and Table 6, present drop percentage values, representing the percentage of the division between the difference of certain I-V characteristic values in dirty and clean conditions, and the clean condition value. These percentage values reveal that the poly-Si mini-cell experienced the most significant losses in I_{sc} and P_{max} when the dust settled on its surface, both indoors and outdoors, under 800 W/m^2. Contrary to the expected trend of increasing I_{sc} and P_{max} drop values with reduced light intensity, as observed in the outdoor results table and considered a well-known solar energy

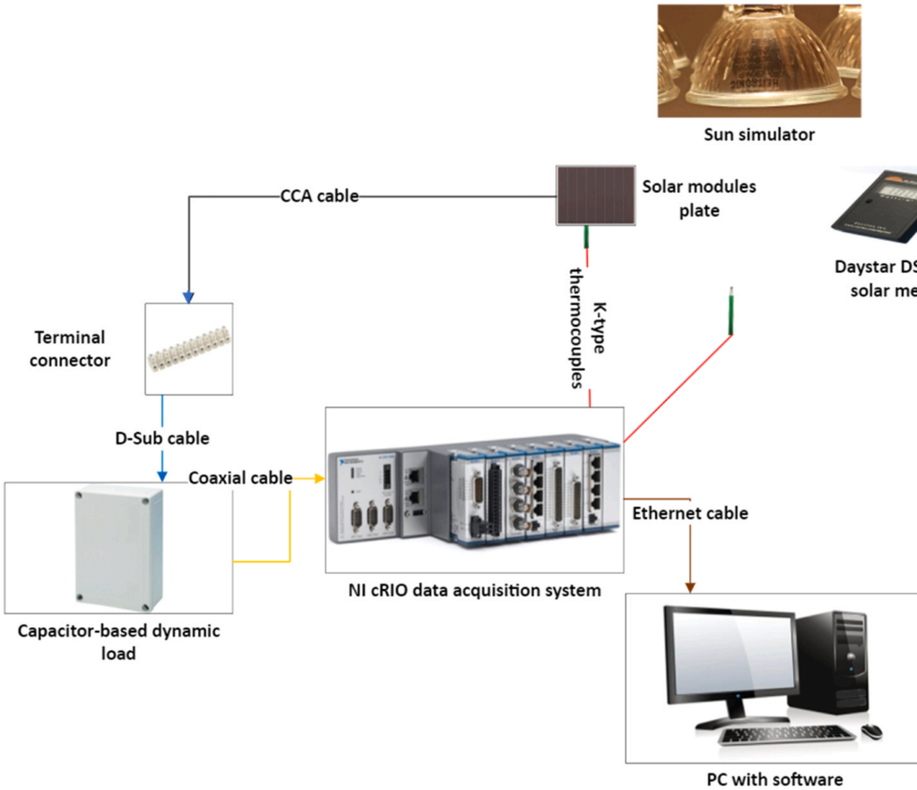

Fig. 6. Image diagram of the indoor testing setup.

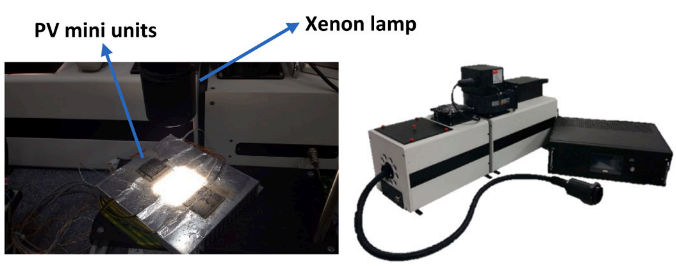

Fig. 7. LightLine A4 solar simulator: right) photograph of the equipment, left) the simulator under operation.

Table 4
LightLine A4 solar simulator specifications.

Model	Solar lightline A4
Manufacturer	Sciencetech
Wavelength range	350–1800 nm
Working distance	20 cm
Lamp type	1000 W Xenon
Dimensions (H × W × D)	900 mm × 250 mm × 450 mm
Weight	20 kg
Target size	50 mm × 50 mm
Uniformity	Class A
Projection Optic	-LA200-2
Sun level	1 Sun
Air Mass filter	AM 1.5 G
Environment	Temperature 10 – 35 °C, Humidity 20–80%

rationale, this pattern did not hold in the indoor experiment. Instead, a more erratic pattern emerged, reaching a peak with a negative V_{oc} loss percentage recorded for the a-Si mini-module at 800 W/m^2.

Although a-Si PV modules have a narrower spectral response, making them more vulnerable to dust-soiling effects, as claimed by Konyu et al. (2020), this analysis reveals that the a-Si mini-module exhibited better performance compared to other crystalline silicon mini-cells, as indicated by the numbers in the preceding tables. It demonstrated the least losses in P_{max} and I_{sc}, specifically at 900 W/m^2 across all testing conditions. Finally, as shown in the earlier tables, the reported losses and discrepancies in the V_{oc} values could be considered minor, aligning with the evidence-based common knowledge found in the relevant literature that dust primarily affects the I_{sc} (Rao et al., 2014).

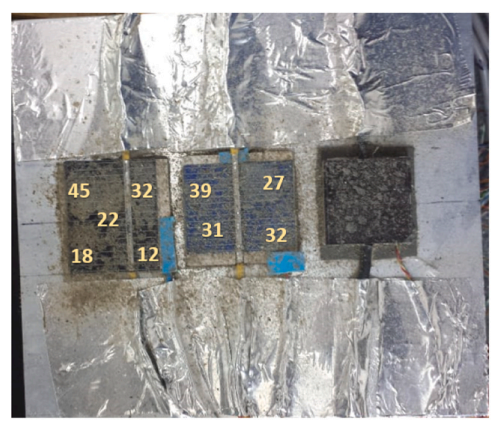

Fig. 8. Dust layer thicknesses in microns.

3.2. *Thermal Characterization*

The thermal characterization was conducted by capturing thermal images of the solar PV mini-devices with and without dust deposition to obtain their front surface temperatures, both indoor and outdoor, as depicted in Fig. 11 and Fig. 12, which display images taken at 800 W/m^2, serve as samples representing all the images captured for the various

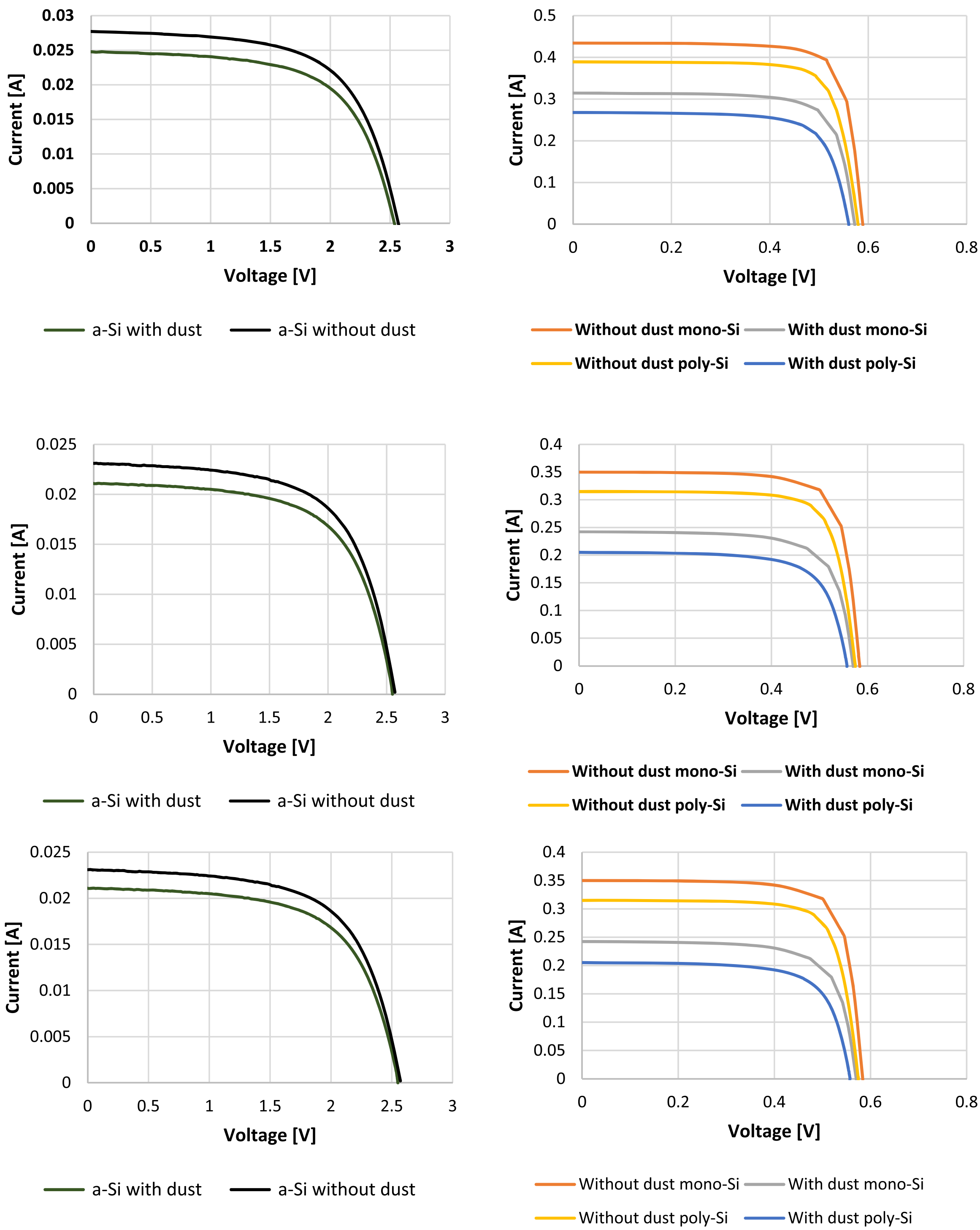

Fig. 9. I-V curves produced by outdoor tests: top) at 1000 W/m^2, middle) at 900 W/m^2, bottom) at 800 W/m^2.

irradiances used in this study. Additionally, K-type thermocouples were utilized to measure their back surface temperatures. In Table 7 and Table 8, the front surface temperature values, particularly the differences between the clean and dusty cases across the entire light intensity range, do not show a visible pattern. Notably, the a-Si mini-module consistently exhibited the highest temperature values. Interestingly, there were instances where the temperature rise was negative, indicating a colder surface under the dust cover, contrary to the general understanding that dust deposition heats the PV structure (Andrea et al., 2019). However, a systematic decline in the values of the back surface temperature rise corresponding to the solar irradiance gradient outdoors is evident in Table 9. In contrast, this arrangement is more chaotic for the laboratory-based results, as shown in Table 10. Remarkably, the a-Si mini-module is also the PV structure that was highly affected by the dust cover regarding the back surface temperature.

It is essential to highlight, by examining the comparative data in Table 11, that explaining the difference in temperature rises between indoor and outdoor experiments based on front surface temperature is challenging. On the other hand, a clear decreasing order, with fewer outliers (i.e., one negative value), is observed when evaluating the differences in back surface temperature rises between outdoor and indoor conditions. This leads to the conclusion that the back surface

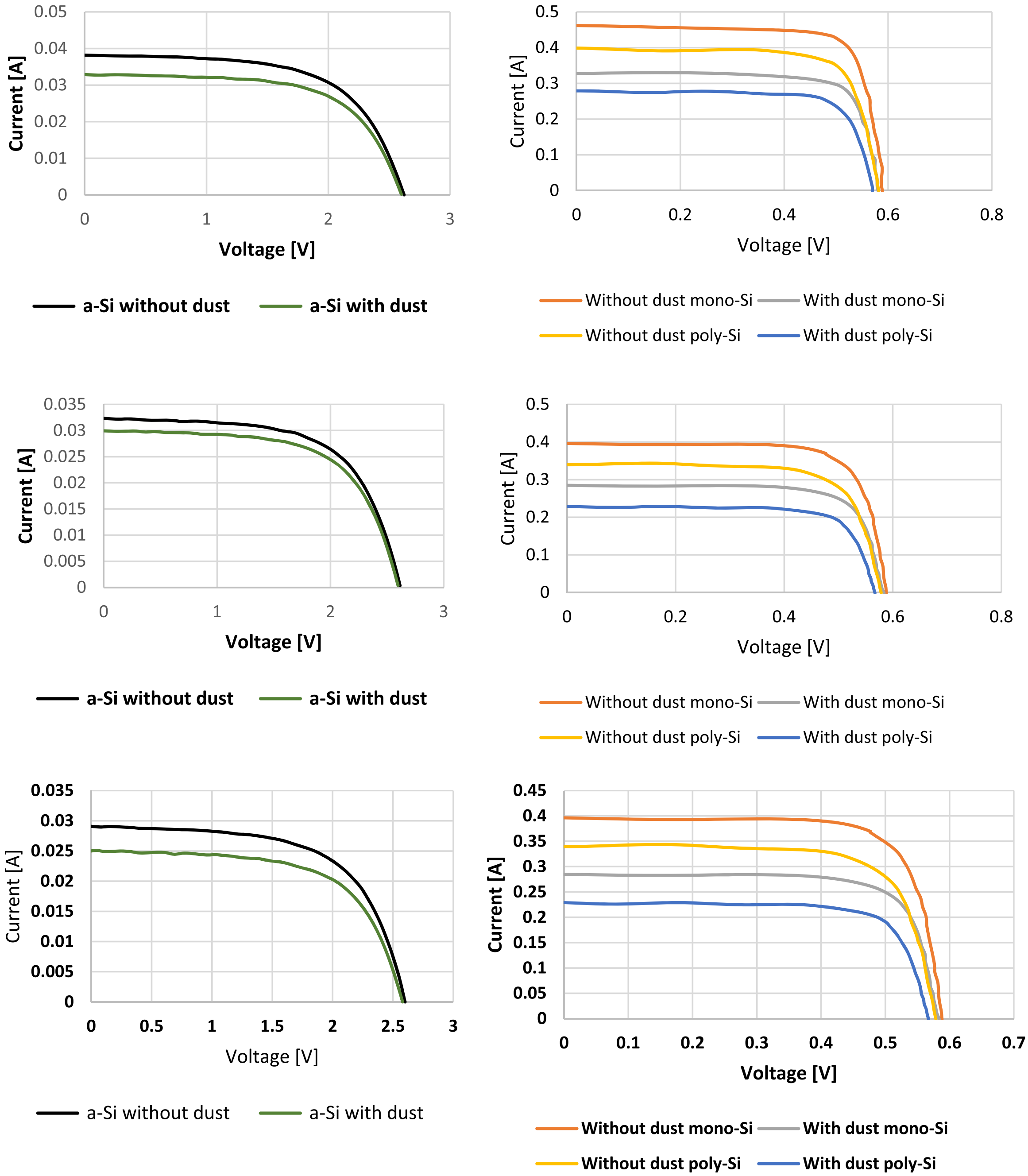

Fig. 10. I-V curves produced by the indoor test: top) at 1000 W/m^2, middle) at 900 W/m^2, bottom) at 800 W/m^2.

Table 5
Drop percentages in I-V characteristics due to dust deposition in the outdoor experiment.

PV technology	Light intensity [W/m^2]	Drop percentage (%)		
		P_{max}	I_{sc}	V_{oc}
Mono-Si	1000	33.22%	27.77%	2.91%
	900	33.60%	27.79%	2.80%
	800	40.90%	33.93%	2.87%
Poly-Si	1000	37.35%	31.36%	3.31%
	900	38.37%	31.68%	3.28%
	800	45.35%	38.14%	3.39%
a-Si	1000	10.10%	10.10%	1.17%
	900	9.39%	8.26%	1.28%
	800	13.71%	12.30%	6.20%

Table 6
Drop percentages in I-V characteristics due to dust deposition in the indoor experiment.

PV technology	Light intensity [W/m^2]	Drop percentage (%)		
		P_{max}	I_{sc}	V_{oc}
Mono-Si	1000	30.83%	28.61%	1.85%
	900	26.19%	25.21%	1.36%
	800	29.07%	28.37%	1.14%
Poly-Si	1000	31.49%	29.97%	1.83%
	900	30.41%	29.43%	1.78%
	800	32.02%	33.38%	1.78%
a-Si	1000	12.25%	13.62%	0.87%
	900	7.42%	7.12%	0.70%
	800	13.35%	14.12%	-0.79%

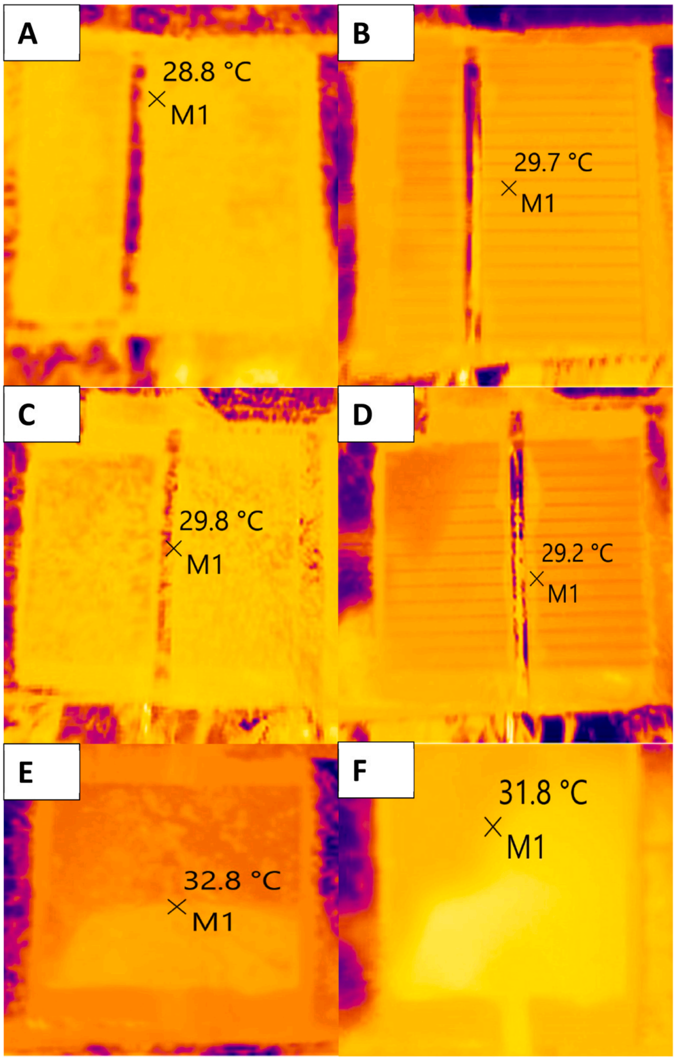

Fig. 11. Thermal images illustrating the temperature at the designated point M1 during the outdoor testing configuration at an irradiance level of 800 W/m^2: (A) mono-Si with dust, (B) mono-Si without dust, (C) poly-Si with dust, (D) poly-Si without dust, (E) a-Si with dust, (F) a-Si without dust.

temperature better represents the thermal status of the PV device, supporting the preliminary claim that the outdoor arrangement is the optimal testing environment due to the lack of standardized practices endorsed by any competent standardization authority.

4. Conclusion and recommendations

In this research, experimental work was conducted to investigate the impact of dust on the electrical and thermal performances of silicon-based PV technologies. The study utilized outdoor and indoor testing setups, employing PV mini-devices of mono-Si, poly-Si, and a-Si. A heterogeneous single layer of dust was applied to the surface of these mini-units, and an innovative methodology, the ultrasonic coating thickness gauge, was employed to measure this layer thickness. The study presented outcomes in the form of I-V curves and characteristics, thermal images, and front and back surface temperatures at different solar irradiance levels. It was observed that the outdoor setup yielded better results than the indoor setup due to the randomness and inconsistency in the latter's results. This abnormality was attributed to the lack of a standard method for conducting laboratory-based experiments on dust deposition, which would reduce the impact of uncontrollable errors.

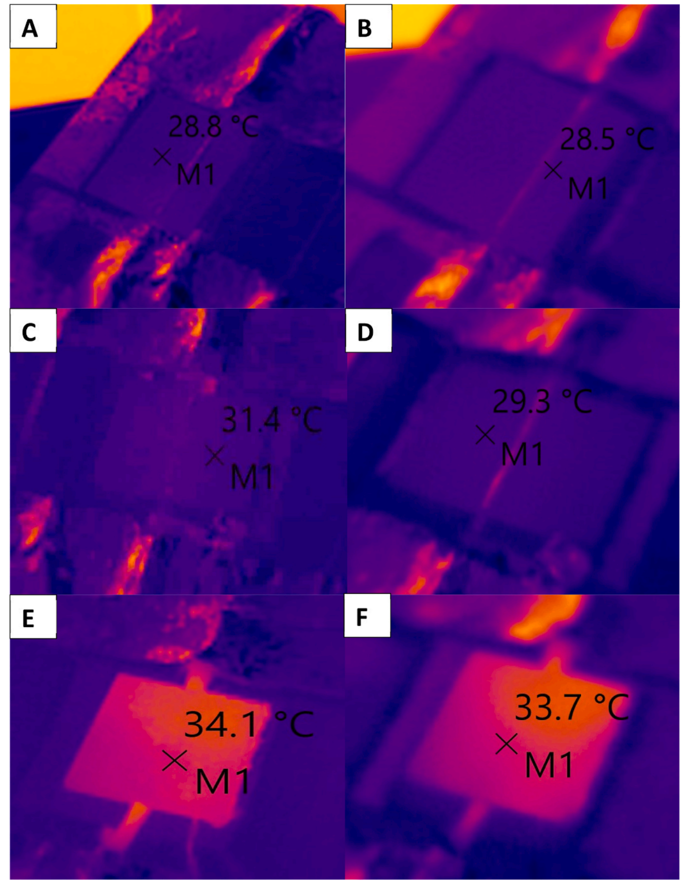

Fig. 12. Thermal images illustrating the temperature at the designated point M1 during the indoor testing configuration at an irradiance level of 800 W/m^2: (A) mono-Si with dust, (B) mono-Si without dust, (C) poly-Si with dust, (D) poly-Si without dust, (E) a-Si with dust, and (F) a-Si without dust.

Table 7
Front surface temperature extracted from thermal images at the outdoor experiment.

PV technology	Light intensity [W/m^2]	Front surface temperature (with dust) [°C]	Front surface temperature (without dust) [°C]	Temperature difference [°C]
Mono-Si	1000	33.5	32.5	1
	900	32.2	31.1	1.1
	800	28.8	29.7	-0.9
Poly-Si	1000	34.2	30.5	3.7
	900	31.7	30	1.7
	800	29.8	29.2	0.6
a-Si	1000	36.4	35.8	0.6
	900	34.4	33.2	1.2
	800	32.8	31.8	1

All PV devices exhibited varying responses between clean and dusty conditions, with the poly-Si mini-cell experiencing the most significant losses in I_{sc} and P_{max} under 800 W/m^2. Unexpectedly, the indoor experiment showed a more erratic pattern, with a negative V_{oc} loss for the a-Si mini-module at 800 W/m^2. Despite a-Si modules being more susceptible to dust, they outperformed crystalline silicon mini-cells, showing the least losses in P_{max} and I_{sc}, especially at 900 W/m^2. The findings confirm the common knowledge that dust primarily affects I_{sc}. In terms of thermal characterization, the front surface temperature differences between clean and dusty cases lacked a discernible pattern, but the a-Si mini-module consistently displayed the highest temperatures. Outdoors, back surface temperature values exhibited a systematic

Table 8
Front surface temperature extracted from thermal images at the indoor experiment.

PV technology	Light intensity [W/m^2]	Front surface temperature (with dust) [°C]	Front surface temperature (without dust) [°C]	Temperature difference [°C]
Mono-Si	1000	31.2	30.7	0.5
	900	30.1	29.8	0.3
	800	28.8	28.5	0.3
Poly-Si	1000	31.7	31.1	0.6
	900	31.1	30.3	0.8
	800	30.6	29.3	1.3
a-Si	1000	37.6	36.9	0.7
	900	36.8	35.5	1.3
	800	34.1	33.7	0.4

Table 9
Back surface temperature under outdoor testing conditions.

PV technology	Irradiance level [W/m^2]	Average back surface temperature [°C]		Temperature rise [°C]
		With dust	Without dust	
Mono-Si	1000	33.1	31.8	1.3
	900	32.1	30.7	1.4
	800	30.3	29.7	0.6
Poly-Si	1000	32.8	31.5	1.3
	900	31.4	30.1	1.3
	800	30.3	29.2	1.1
a-Si	1000	34.9	32.6	2.3
	900	33.3	31.2	2.1
	800	31.1	30.1	1

Table 10
Back surface temperature under indoor testing conditions.

PV technology	Light intensity [W/m^2]	Average back surface temperature [°C]		Temperature rise [°C]
		With dust	Without dust	
Mono-Si	1000	28.3	27.4	0.9
	900	29.5	29.1	0.4
	800	30.1	29.8	0.2
Poly-Si	1000	28.6	28.2	0.4
	900	29.8	29.3	0.5
	800	30.1	29.9	0.2
a-Si	1000	31.2	30.8	0.4
	900	32.1	31.6	0.5
	800	32.8	32.5	0.3

Table 11
Comparison between the outdoor and indoor temperatures.

PV technology	Light intensity [W/m^2]	Outdoor and indoor front surface temperature difference (with dust) [°C]	Outdoor and indoor back surface temperature difference (with dust) [°C]
Mono-Si	1000	2.3	4.8
	900	2.1	2.6
	800	0	0.2
Poly-Si	1000	2.5	4.2
	900	0.6	1.6
	800	-0.8	0.2
a-Si	1000	-1.2	3.7
	900	-2.4	1.2
	800	-1.3	-1.7

decline, contrasting with the more chaotic results from laboratory-based experiments. Notably, the a-Si mini-module was significantly impacted by the dust cover in terms of back surface temperature. When comparing indoor and outdoor experiments, differences in back surface temperature offered a clearer order, reinforcing the conclusion that outdoor arrangements are optimal for testing due to the absence of standardized laboratory practices. These insights contribute to a better understanding of the complex interplay between dust formation and PV performance, providing critical guidance for enhancing system efficiency and reliability in real-world applications. Some significant findings include:

1. The deposited dust layer has thickness densities of 0.01936 and 0.02287 μm mm^{-2} for the mono-Si and poly-Si mini cells, respectively. Meanwhile, the measurement process was not applicable to the a-Si mini module due to technical difficulties related to the absence of metallic substrate material in the latter module.
2. The maximum losses in I_{sc} and P_{max} were 38.14% and 45.35%, respectively, in the outdoor test and 33.38% and 32.02%, respectively, in the indoor test, all produced by the poly-Si mini-cell at 800 W/m^2.
3. The weak response of V_{oc} to the presence of dust aligns with expectations, as dust primarily deteriorates I_{sc}.
4. The a-Si mini-module exhibited the highest front and back surface temperatures in both clean and dusty conditions across the entire light intensity range.
5. Maximum temperature increases were 2.3 °C at the back surface outdoors and 0.9 °C indoors, while for the front surface, the respective maximum rises were 3.7 °C and 1.3 °C.

Finally, it is recommended that in-depth review studies analyzing relevant literature content be conducted. Consequently, standard practices for indoor experimentation on the effects of dust deposition on PV performance should be extracted and advocated for inclusion in competent international standards such as IEC and ISO.

CRediT authorship contribution statement

Younis Abubaker: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Cotfas Daniel Tudor:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization. **Rjafallah Abdelkader:** Writing – review & editing. **Cotfas Petru Adrian:** Validation, Supervision, Software, Methodology, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Abubaker Younis reports a relationship with Transilvania University of Brasov that includes: employment.

Data availability

Data will be made available on request.

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