Cumulative aging effects of five-year intermittent exposure on flexible amorphous solar cells

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ABSTRACT

Amorphous silicon (a-Si) is rarely used for large scale photovoltaic energy production, it remains relevant in flexible electronic applications, where mechanical flexibility and lightweight design are prioritized, where exposure to sunlight is typically limited or irregular. This study conducts an experimental analysis of the long-term aging effects on the proprieties of an amorphous solar cells, under five years of intermittent outdoor climate conditions. Unlike conventional aging studies that focus on degradation over time, this research highlights the cumulative effects of environmental exposure, considering the discontinuous nature of exposure cycles and the non-linearity of degradation phenomena because of the abrupt transitions between outdoor exposure phases and indoor laboratory rest periods. The results show that nearly 50% of the panel's performances is reduced, with the losses observed as follows: a substantial decline in the fill factor from 55.3% to 30%, a decrease in energy conversion efficiency from 11.36% to 5.5%. This accelerated deterioration mainly attributed to harsh environmental transitions caused by intermittent exposure, which amplify aging mechanism compared to continuous exposure. Beyond the experimental findings, the approach presented here, constitutes a meaningful scientific contribution. By introducing a realistic and underexplored aging scenario, it lays the groundwork for a new line of research.

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1. INTRODUCTION

In recent years, flexible solar cells, particularly those based on amorphous silicon (a-Si), have garnered increasing attention due to their light weight, mechanical flexibility, and potential integration into portable and curved surfaces. These proprieties make them ideal for off-grid applications, wearable electronics, and foldable solar technologies, where conventional rigid panels are unsuitable [1], [2]. However, ensuring their durability and sustained performance under real-world operating conditions remains a significant challenge [3]–[5].

Most studies on solar cell aging have traditionally relied on accelerated laboratory protocols, such as continuous UV exposure, controlled thermal cycling, and damp-heat conditions, to predict long-term performance degradation within a short timeframe [6]–[9]. While these methods offer valuable insights, they do not fully capture the complexity of real outdoor environments. In practice, temperature swings, humidity fluctuations, UV radiation, and dust deposition often occur simultaneously, creating a combined effect that intensifies structural and interfacial instabilities [10]–[12]. Over time, these stresses lead to a gradual decline in key photovoltaic parameters, ultimately reducing the overall energy conversion efficiency [13]–[15].

Research has also explored aging effects over medium-term and long-term periods, with most studies focusing on crystalline silicon modules due to their widespread use in large-scale photovoltaic energy production [16]–[18]. Amorphous silicon panels have occasionally been examined under similar conditions for comparative purposes. However, despite their promising advantages for portable and flexible applications, studies addressing their stability and progressive degradation under realistic outdoor conditions remain virtually nonexistent, leaving a significant gap [19].

This gap is particularly significant because, unlike grid-connected systems, flexible a-Si modules are often used intermittently and under irregular conditions, leading to unique stress patterns that remain poorly understood. To address this issue, the present study investigates the cumulative effects of five-year intermittent exposure under Mediterranean environmental conditions on the morphological and electrical characteristics of flexible amorphous silicon solar cells. By combining detailed electrical measurements with advanced surface characterization, this work provides new insights into the mechanisms of environmental aging, contributing to a deeper understanding of their long-term stability and opening new perspectives for improving the durability of flexible photovoltaic technologies.

2. EXPERIMENTAL METHOD AND SETUP

This section presents the experimental method and setup used to evaluate the long-term aging behavior of the flexible amorphous solar cells. It first describes the study site in Oran, focusing on its specific environmental conditions. It then outlines the photovoltaic material and the outdoor exposure protocol implemented to monitor both electrical and morphological deterioration under real operating conditions.

2.1. Study site and environmental conditions

A precise characterization of the exposure environment is essential for understanding the mechanisms driving photovoltaic degradation. This subsection details the geographic location and coordinates of Oran, defining the specific site of aging. It also presents key meteorological parameters and local environmental stressors relevant to long-term photovoltaic performance losses.

2.1.1. Geographic coordinates of Oran

Oran is geographically located at approximately 35.7028°N Latitude and -0.649256°W Longitude (35° 42’ 10’’ N, 0° 38’ 57’’ W), with an elevation of around 91 meters above sea level. It is a dynamic Mediterranean city and the second largest Algerian agglomeration, lying in the northwestern part of the country [20], [21]. Figure 1 presents the geographic location of Oran within the Algerian territory.

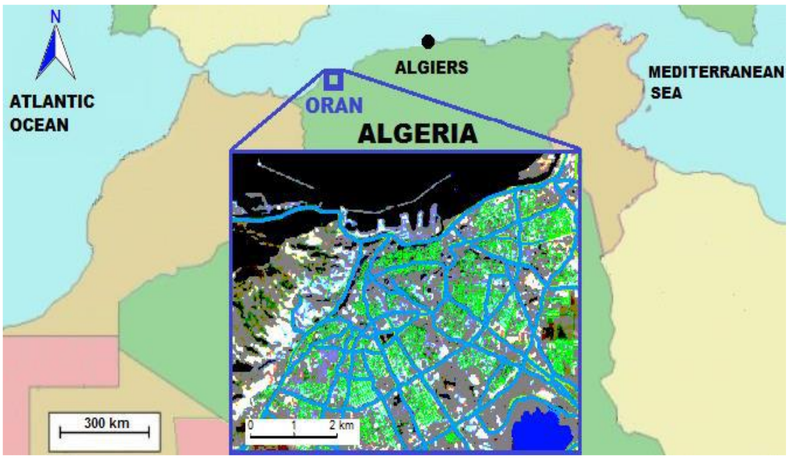


Figure 1. Geographic position of Oran city in Algeria [22]

2.1.2. Meteorological factors and local environmental stressors

Oran is characterized by a Mediterranean-type climate, featuring hot and dry summers contrasted with mild and moderately humid winters. During summer, average daytime temperatures usually range between 30 °C and 32 °C, occasionally surpassing 40 °C during intense heatwaves. In winter, the mean minimum temperature varies from 7 °C to 9 °C, while brief cold episodes may cause temporary drops to around 2 °C to 3 °C. Frost events are exceptionally rare in this coastal zone [23]

The Oran region benefits from nearly 3000 hours of annual sunshine, with solar irradiance often reaching 900–1000 W/m² during summer and remaining around 400–600 W/m² in winter under clear skies. Such high irradiation levels, combined with intermittent exposure cycles, intensify thermal and photonic stresses on photovoltaic materials, thereby promoting early signs of degradation [3], [24].

Humidity in Oran shows strong seasonal variations, ranging from about 50%–60% in summer to 70%–90% in winter. Under intermittent outdoor exposure, these fluctuations in humidity and temperature may influence the long-term stability of photovoltaic materials, especially those with flexible or non-hermetically sealed structures [23], [25]. Understanding and quantifying these meteorological and environmental conditions is essential to evaluate the real-world aging mechanism and long-term stability of photovoltaic modules deployed in region such as Oran.

2.2. Experimental materials and exposure protocol

This section details the materials and methodology used to assess the performance of the flexible amorphous solar panel. The experimental procedure was conducted in two successive phases. In the reference phase, current and voltage measurements were performed using multimeters, with a variable resistor connected across the panel terminals. In the automated phase, the panel was interfaced with a datalogger incorporating a variable electronic load. During this stage, voltage, current, temperature, and irradiance were automatically recorded in the memory and subsequently transferred to a computer for data processing and for plotting curves. The specific procedures for each phase are described in the next subsections.

2.2.1. STEP 1: Intermittent exposure methodology and PV panel specifications

Intermittent vs. continuous exposure: toward a cumulative aging approach: flexible amorphous silicon solar cells are increasingly integrated into mobile and wearable electronic applications, including smart textiles, medical monitoring devices, autonomous sensors, and portable global positioning system (GPS) beacons. In such contexts, exposure to sunlight is highly variable, governed by user mobility, random device orientation, and fluctuating weather and environmental conditions. Consequently, illumination is neither continuous nor regular, and cannot be modeled by a deterministic law. Under these discontinuous operating conditions, assessing degradation based solely on chronological time is scientifically inappropriate. Instead, aging must be understood as the cumulative effect of exposure cycles, comprising alternating phases of activation and rest that differ in duration, light intensity, temperature, and humidity.

Strategy and installation conditions: to reproduce the intermittent exposure protocol as realistically as possible, we alternated between sunlight and rest phases in the following way. We first placed the panel outdoors and exposed it for several consecutive days, especially during summer when solar irradiation was at its maximum. At other times, we exposed it only for a few hours before bringing it back into the laboratory, where it remained for several days. In some cases, the panel was kept indoors in the laboratory for nearly a month without any exposure, particularly during the winter season when solar radiation was low. As a result, the panel was stored indoors more often than it was exposed during winter. It is important to note that we did not systematically record the exact duration of each exposure or rest phase, since this information was not relevant to our main objective.

For the experimental setup, the flexible amorphous solar panel was installed on the roof of the Electronics Department in our university. To ensure rigidity and stability, the panel was first fixed attached to wooden plate, which was then mounted on an adjustable support. The tilt angle was set to 38° and oriented due south to maximize solar received irradiation and minimize shading from the surrounding environment. No cooling or cleaning system was applied, in order to reproduce real operating conditions as faithfully as possible.

For full transparency, it should be noted that the studied flexible a-Si solar module was originally obtained at the prototype stage through academic collaboration, without detailed information on its internal structure, encapsulation process, or official STC specifications. Initially intended for small laboratory tests, it was later subjected to successive intermittent outdoor exposures, which progressively oriented our research toward assessing cumulative aging effects. No intermediate measurements were recorded, as this was not part of the initial experimental plan. Table 1 summarizes the key electrical parameters of the module.

2.2.2. STEP 2: Measurement procedure and data acquisition system

Instrumentation for reference measurements: In a first step, reference measurements were carried out to validate the proper functioning of the automatic data acquisition system. The parameters Voc and Isc were manually determined through independent measurements performed with two instruments: a digital voltmeter (AMPROBE/30XR-A), and a digital ammeter (FLUKE/111). The I–V characteristic was obtained using a high-power, low-value variable resistor employed as the load. A pyranometer was also occasionally employed to compare and confirm the irradiance measurements provided by the sensors integrated into the datalogger. Figure 2. presents a real photograph of the experimental setup used in this study, illustrating the reference measurement phase. It shows the flexible PV panel mounted on its support (1), the pyranometer (2), the measuring instruments (voltmeter (3) and ammeter (4)), the variable load (5), and the datalogger (6) (inactive at this stage). This figure also provides an overall view of the experimental arrangement adopted in this work.

Figure 2. Photograph of the experimental setup used in this study

These reference measurements, restricted to this initial phase, were used to verify the consistency and reliability of the data. However, manual measurements did not allow the acquisition of a dense set of data along the I–V characteristic, unlike the datalogger, which automatically recorded one measurement per second, providing accurate and continuous tracking of voltage and current variations. Therefore, while the reference measurements were necessary to validate the approach, the scientific analysis relies primarily on the data obtained from the acquisition system.

After this reference measurement phase, the acquisition system was implemented. The flexible solar panel was connected to a datalogger, which continuously recorded voltage and current at a rate of one measurement per second. This setup provided a large number of accurate data points that cannot be obtained manually, ensuring both precision and reliability for the subsequent analysis.

Data acquisition system: A low-cost data acquisition system was implemented to ensure real-time monitoring and recording of the panel’s key electrical parameters during outdoor operation. Its design and components were carefully selected to suit the characteristics of the tested panel, enabling accurate and consistent monitoring [26]. Figure 3 shows the block diagram of the data acquisition system, outlining the main functional units and their interconnections.

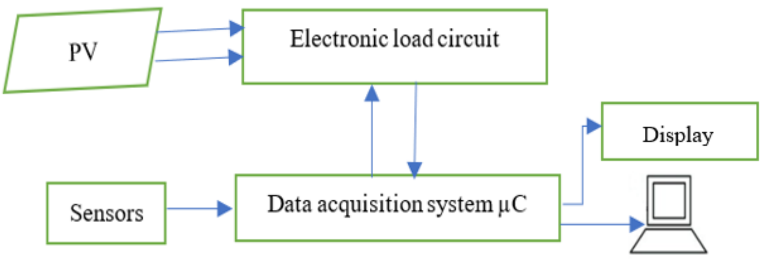
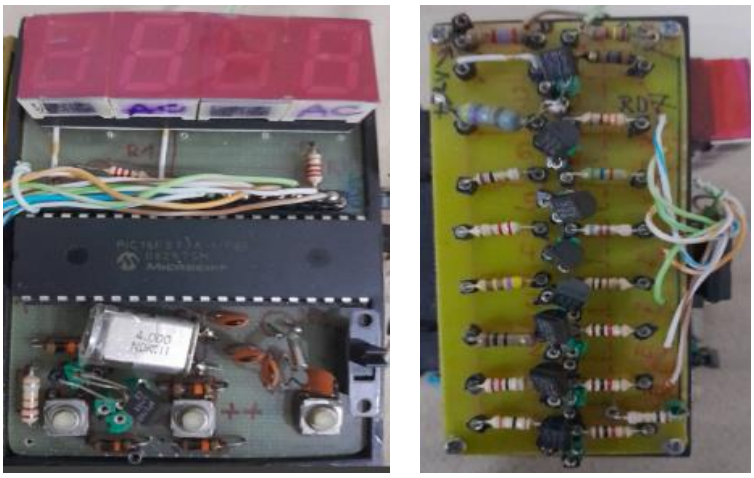


Figure 3. Block diagram of system design for data acquisition system

The measurement system is built around a microcontroller and integrates multiple sensors for accurate data acquisition. It includes two irradiance sensors: a photoresistor (LDR05) and a photodiode (BPW21), to monitor light intensity, an LM35 analog temperature sensor for thermal readings, and a voltage divider combined with a low-resistance shunt for precise measurement of the photovoltaic module's voltage and current. This configuration enables full-range operation of the panel and ensures accurate representation of its I–V behavior.

An electronically controlled variable load was designed to ensure stable and finely detailed I–V characterization across the entire operating range. Controlled by a microcontroller, it performs an automatic sweep of current and voltage through programmable electronics consisting of eight bipolar transistors operating in switching mode, combined with carefully selected resistors distributed quasi-uniformly along the load range. The detailed design details of the data acquisition system, including sensor selection, component configuration, and technical schematics of each module, have been presented in a dedicated paper [26], here, only the essential aspects are summarized to avoid diverting the reader's attention from the main objective of this study. Figure 4 provides a real view of the developed data acquisition system, Figure 4(a) showing the implemented setup and Figure 4(b) shows the variable electronic load integrated into the characterization device.



(a) (b)

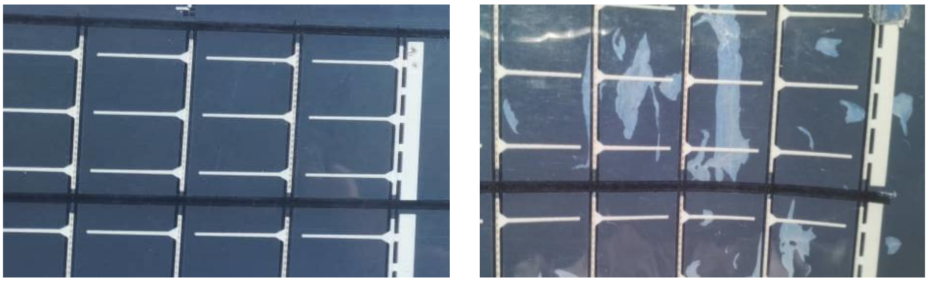
Figure 4. Illustration of the developed acquisition system (a) photograph of the implemented system and (b) view of the variable electronic load

The instantaneous values of current and voltage were displayed and stored in the microcontroller's memory before being transferred to a computer via a serial connection. The collected data were processed and analysed to generate the I–V and P–V curves with MATLAB software. This fully automated protocol enabled accurate and reproducible experimental monitoring while reproducing the real operating conditions of intermittent use of flexible solar panels in mobile and portable applications. Key electrical parameters were obtained from the panel's current–voltage measurements. For clarity and direct comparison, the detailed presentation of these baseline results, along with the post-aging measurements, is provided in parallel in the following Results and discussion section.

2.2.3. STEP 3: Morphological characterization using atomic force microscopy (AFM)

The morphological characterization of the solar cells was carried out using an atomic force microscope (AFM) at the Laboratory of Electron Microscopy and Material Sciences (LMESM), within our University of Science and Technology of Oran. This tool provides high-resolution images of the sample surfaces, essential for analyzing the morphological structure of the solar cells before and after aging

A morphological analysis of the initial samples revealed a homogeneous surface structure, with no apparent signs of degradation or morphological defects, the Figures 5(a) and 5(b) shows a photograph of the flexible amorphous panel before and after intermittent natural aging, providing a visual overview of the cell's overall appearance. For a detailed comparison of the surface morphology at the microscopic level, the AFM images before and after aging will be presented in the Results and discussion section.



(a) (b)

Figure 5. Flexible amorphous panel, (a) before and (b) after intermittent natural aging

3. RESULTS AND DISCUSSION

This section summarizes the key outcomes of the five-year intermittent aging study and discusses their significance. It first evaluates the post-aging degradation of both electrical performance and morphological features, then compares these results with previous findings, examines the correlation between structural alterations and electrical losses, and finally outlines the implications for long-term performance and future optimization strategies.

3.1. Post aging evaluation of electrical performance degradation

A comparative analysis was conducted using the initial performance as a reference. Among several-time measurements, two representative recordings were selected, capturing the best observed values for Isc, and Voc and Pmax. These curves in Figures 6 and 7 were obtained on August 21st at 12:27 PM under irradiance of 995.33 W/m² and an ambient temperature of 29.6 °C.

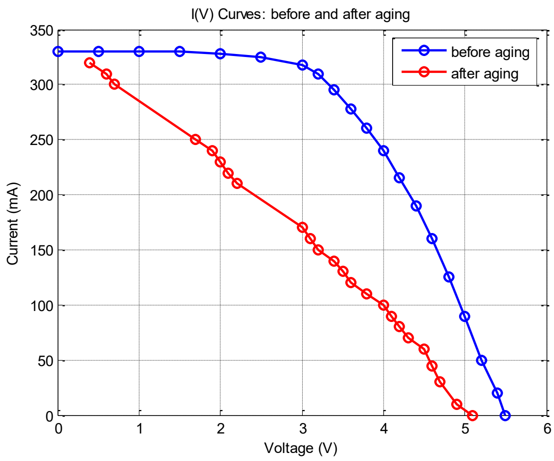


Figure 6. Evolution of the I–V characteristics of the flexible amorphous solar panel before and after five years of intermittent outdoor exposure

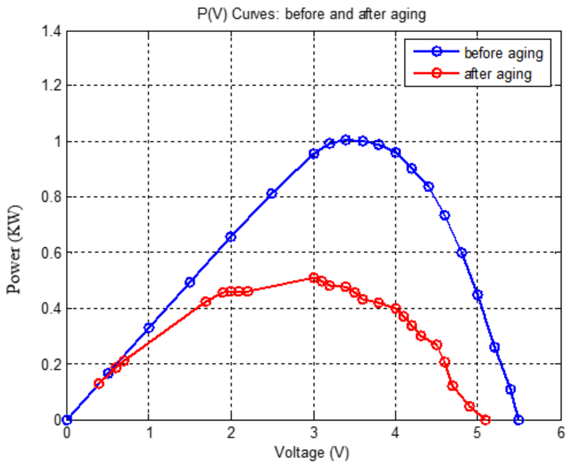


Figure 7. Evolution of the P–V characteristics of the flexible amorphous solar panel after five years of intermittent outdoor exposure, showing a decline in maximum power and fill factor

The degradation of the electrical performance of the flexible amorphous solar panel, after five years of intermittent exposure to a Mediterranean climate, is evident in a significant reduction in its photovoltaic characteristics. Specifically, the maximum output power (Pmax) decreases by more than 50%, from 1.003 W to 0.484 W, accompanied by notable decline in the fill factor (FF) from 55.3% to 30.6% and drop in energy conversion efficiency (η) from 11.36% to 5.5%. The drop is most pronounced around Pmax, with Vm falling from 3.4 V to 2.2 V and Im from 0.295 A to 0.22 A. The observed degradation mainly results from the Staebler–Wronski effect, combined with real environmental stresses such as temperature and humidity fluctuations, and the impact of internal resistive losses. The increase in series resistance together with the decrease in parallel resistance significantly contribute to the observed reductions in current, voltage, and overall efficiency. These combined effects highlight the impact of aging on both the structural integrity and the electrical behavior of the cells. A summary of the electrical parameters derived from the I–V characteristics before and after aging is presented in Table 1. The performance degradation is evident across all indicators. This Table 1 compare key parameters, illustrates this degradation, with Pmax showing the most significant drop over 50%. These findings highlight the importance of enhancing material quality, encapsulation methods, and manufacturing processes to improve the durability of flexible photovoltaic devices under prolonged exposure to harsh environmental conditions.

Table 1. Electrical parameters and degradation rates of the a-Si solar module

Parameter	Before aging	After aging	Variation (%)
Isc	0,330A	0.310 A	- 6%
Voc	5,5V	5.1 V	- 7.3%
Pmax	1,003kW	0.484 W	- 51.7%
FF	55,3%	30.6%	- 44.6%
η	11,36 %	5.5%	- 51.5%

3.2. Morphological analysis

The morphological degradation of the flexible amorphous solar panel was examined using AFM and macroscopic imaging. The analysis focused on three critical zones: metal contacts, the sunlight-receiving surface, and interconnection wires. AFM analysis of the metal contacts, see Figure 8, reveals a pronounced morphological transition from a smooth and continuous surface in the intact region, see Figure 8(a) to a degraded structure after aging, see Figure 8(b), marked by increased surface roughness, microcracks, discontinuities, and oxidation patterns. These nanoscale alterations are corroborated by macroscopic observations, which display visible cracking, material loss, and fragmentation, all of which compromise the integrity and conductivity of the electrical contacts.

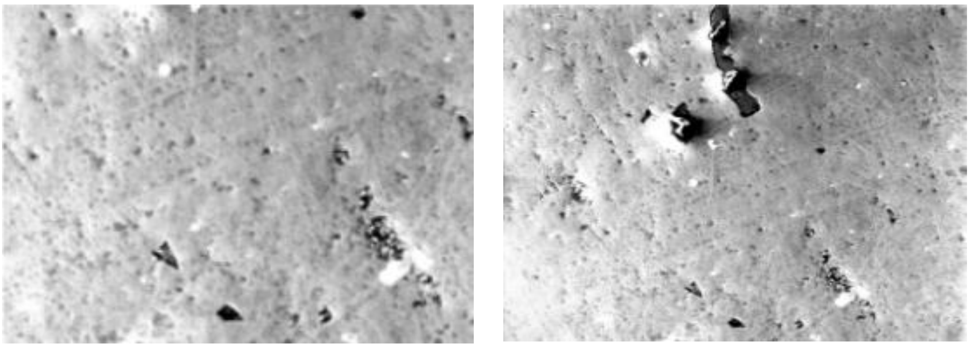
(a) (b)

Figure 8. Scanning electron microscopy profiles of the metallic contact regions (a) intact section before aging, showing smooth and continuous surface and (b) defective section after aging, exhibiting cracks and oxidation patterns

The sunlight exposed surface exhibits clear signs of degradation. AFM profiles in Figure 9 confirms this deterioration by revealing pronounced morphological changes. Figure 9(a) displays a uniform morphology before aging, whereas the aged section Figure 9(b) presents pronounced topographical irregularities, and increased surface roughness, likely resulting from prolonged UV exposure and environmental stress. These nanoscale features align with macroscopic observations, which show a cracked, heterogeneous surface that reduces light absorption efficiency.

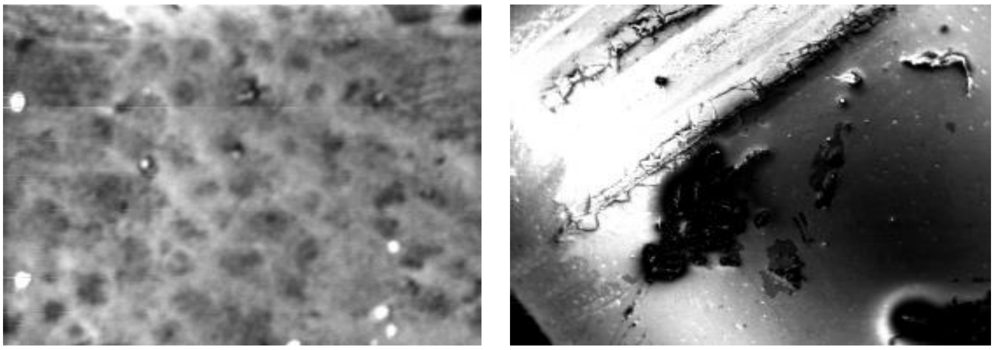
AFM analysis in Figure 10 highlights pronounced aging-related defects on the interconnection wires. The intact section before aging Figure 10(a) exhibits a regular and continuous structure, whereas the aged section Figure 10(b) shows corrosion marks and structural discontinuities. These degradations disrupt charge transport pathways and contribute to a decline in overall electrical performance.

The interconnection wires display surface irregularities, localized delamination, and oxidation marks following aging. These structural degradations, driven by UV exposure, humidity, and temperature fluctuations, compromise charge transport efficiency and long-term electrical stability by increasing series resistances reducing current collection efficiency.



(a) (b)

Figure 9. Scanning electron microscopy profiles of the sunlight-receiving surface (a) intact section before aging, with uniform morphology and (b) defective section after aging, with visible micro-cracks and increased surface roughness



(a) (b)

Figure 10. Scanning electron microscopy profiles of the interconnection wires between solar cells (a) intact section before aging, showing regular structure and (b) defective section after aging, with corrosion marks and structural discontinuities

3.3. Comparative analysis with previous studies and contextualization

A direct comparison with existing literature is difficult, as no prior study has examined the effects of intermittent outdoor exposure on amorphous solar cells. Most research focuses on continuous or accelerated aging under constant illumination, which does not reflect real usage conditions. Nevertheless, several recent studies provide valuable benchmarks on degradation rates and climatic influences.

Chen *et al.* conducted a meta-analysis of 168 outdoor studies (2019–2024), showing a global increase in photovoltaic (PV) degradation rates, where hydrogenated amorphous silicon cells were identified as highly sensitive to hot and arid climates (e.g., Algeria, UAE, India), where dry heat and thermal fluctuations reduce module lifetime from ~40 to 15–20 years [27]. Field studies in Saharan regions, such as Tadjer *et al.* reported 4%–12% performance losses over two years at Ghardaïa, in Algeria, confirming strong sensitivity of amorphous modules to harsh conditions [28]. Complementary accelerated aging studies (Santos *et al.* [14]; Rahayu *et al.* [3]) also demonstrated severe losses, up to 90% efficiency reduction after mechanical cracking and more than 35% Pmax decline after prolonged UV and humidity exposure — though such tests fail to reproduce real outdoor stress cycles. In Mediterranean environments, Mateo *et al.* observed moderate continuous degradation of a-Si:H modules in Valencia, with approximately 15% Pmax and nearly 10% FF reductions, while V_{oc} and I_{sc} exhibited reductions of about 6–7% and 4–5%, respectively, after eight years [15]. Similarly, Ymer *et al.* [29] reported cumulative losses of 10–15% in Mediterranean climates versus 20–25% in desert regions, highlighting humidity sensitivity and the lack of long-term data.

In contrast, our study uniquely examines five years of intermittent Mediterranean exposure, revealing far more severe degradation of flexible amorphous solar cells. These results underscore the combined impact of climatic stress and discontinuous exposure cycles, offering new insights relevant to real-world portable PV applications.

3.4. Correlation between morphological and electrical degradation

The AFM analysis and macroscopic imaging revealed pronounced morphological degradation in aged samples, particularly on metal contacts, the sunlight-receiving surface, and interconnection wires. Increased surface roughness, microcracks, delamination, and oxidation were observed, indicating structural instability induced by UV radiation, humidity, and thermal cycling.

These nanoscale and macroscale defects correlate directly with the electrical losses observed. For instance:

- Microcracks and discontinuities in metallic contacts increase series resistance (Rs), reducing current flow and FF.
- Surface roughness and cracking on the active layer lower light absorption and increase recombination, contributing to the efficiency drop.
- Oxidation and delamination on interconnections disrupt charge transport pathways, leading to voltage and power losses.

Thus, the morphological degradation mechanisms explain the severe decline in electrical performance and highlight the vulnerability of flexible amorphous solar cells to mechanical and environmental stresses.

3.5. Implications and future perspectives

The results of this study highlight the urgent need to reconsider the design and reliability strategies of flexible amorphous PV modules under real-world conditions. From an industrial perspective, improvements in encapsulation materials, barrier coatings, and interfacial stability are essential to mitigate moisture ingress, UV-induced defects, and delamination, which were identified as major contributors to long-term degradation. At the research level, these findings emphasize three key future directions:

- Material innovation: Develop new encapsulants and protective layers with improved thermal and humidity resistance.
- Accelerated aging protocols: Redesign laboratory tests to replicate intermittent exposure and cyclic stress conditions rather than relying solely on continuous irradiation.
- Predictive modeling: Establish reliability models that integrate cumulative cyclic effects to more accurately predict real-world performance.

By addressing these aspects, the present study provides insights that can guide both industry and academia in developing more durable flexible PV technologies, particularly for portable, off-grid, and wearable applications.

4. CONCLUSION

This work demonstrates the high vulnerability of flexible amorphous silicon solar modules to intermittent outdoor exposure in a Mediterranean climate. After five years of natural aging, the modules exhibited severe performance degradation, with power output losses exceeding 50% and efficiency decreasing from 11.36% to 5.5%, corresponding to an accelerated annual degradation rate of nearly 10%.

Unlike most previous studies that relied on continuous or accelerated protocols, this research introduces intermittent exposure as a cumulative aging factor, providing a more realistic framework for assessing durability. This methodological innovation fills a gap in the literature and sheds light on the specific degradation pathways affecting flexible thin-film PV modules. Overall, the study contributes to a deeper understanding of the real-world limitations of flexible a-Si technologies and opens new perspectives for improving their long-term stability and guiding future standardization efforts.

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AUTHOR CONTRIBUTIONS STATEMENT

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C	:	**C**onceptualization	I	:	**I**nvestigation	Vi	:	**Vi**sualization
M	:	**M**ethodology	R	:	**R**esources	Su	:	**Su**pervision
So	:	**So**ftware	D	:	**D**ata Curation	P	:	**P**roject administration
Va	:	**Va**lidation	O	:	Writing - **O**riginal Draft	Fu	:	**Fu**nding acquisition
Fo	:	**Fo**rmal analysis	E	:	Writing - Review & **E**diting			

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author S.D on request.

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