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DESIGN, FABRICATION, AND FIELD EVALUATION OF A MICROCONTROLLER-BASED SOLAR–WEATHER MONITORING SYSTEM FOR MULTI-STRESSOR PHOTOVOLTAIC DEGRADATION ANALYSIS IN HARSH ENVIRONMENTS

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ABSTRACT

This study presents the design, fabrication, calibration, and field evaluation of a low-cost ATmega328-based solar–weather monitoring system for real-time photovoltaic (PV) degradation analysis under harsh environmental conditions. The system integrates irradiance, temperature, humidity, wind speed, voltage, current, and optical soiling sensors with a real-time clock and SD-card data logging unit. Field experiments were conducted in Mubi, Nigeria, from January to June 2025 using 250 W polycrystalline PV modules exposed to temperatures up to 75 °C, relative humidity above 85%, dust accumulation of 30 g/m², and wind speeds exceeding 25 m/s. Sensor calibration was performed using standard reference instruments, and analytical models were developed to assess the effects of individual and combined environmental stressors on PV performance. Results showed that isolated stressors caused efficiency losses ranging from 6.1% to 18.0%, while simultaneous exposure to multiple stressors produced cumulative degradation of 31.6%, indicating significant synergistic effects. Model

Keywords: Photovoltaic degradation, ATmega328, Embedded systems, Solar monitoring, Renewable energy reliability, multi-stressor analysis, Extreme weather conditions, Data acquisition.

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validation showed strong agreement between predicted and measured values, with coefficients of determination (R^2) ranging from 0.91 to 0.97. The developed monitoring platform provides an affordable and scalable solution for photovoltaic reliability assessment, predictive maintenance, and climate-resilient solar energy deployment, particularly in developing and remote regions.

INTRODUCTION

The global transition toward low-carbon energy systems has accelerated the adoption of solar photovoltaic (PV) technology, making it one of the fastest-growing renewable energy sources worldwide. Declining module costs, technological advancements, supportive policies, and increasing concerns about climate change have driven rapid expansion of PV installations across residential, commercial, industrial, and utility-scale applications (IEA, 2024). Consequently, solar PV has become a critical technology for achieving energy security and carbon neutrality goals (IEA, 2024; IRENA, 2024).

Despite its widespread deployment, the long-term reliability and performance stability of PV modules remain significant challenges. Although PV systems are typically designed for operational lifetimes of 25–30 years, environmental stressors such as high temperature, humidity, dust accumulation, wind loading, hail impact, and thermal cycling accelerate degradation processes that reduce energy yield and service life (Jordan & Kurtz, 2013; Köntges et al., 2017). Elevated temperatures reduce module efficiency by increasing carrier recombination and material degradation, while dust accumulation decreases solar irradiance transmission and can cause substantial energy losses (Skoplaki & Palyvos, 2009; Dubey et al., 2013; Sarver et al., 2013; Deceglie et al., 2018; Micheli et al., 2019). Similarly, humidity promotes corrosion and insulation deterioration, whereas wind and hail contribute to mechanical damage and microcrack formation (Köntges et al., 2017; Rahman et al., 2023; Kilikevičienė et al., 2019).

Most previous studies have focused on individual degradation mechanisms; however, PV modules in real operating environments are simultaneously exposed to multiple interacting stressors whose combined effects may exceed those of isolated degradation processes (Köntges et al., 2017; Rahman et al., 2023). For example, dust accumulation can increase module temperature, while elevated temperature accelerates moisture-related corrosion. These interactions highlight the need for integrated monitoring systems capable of simultaneously assessing environmental conditions and photovoltaic performance.

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Another challenge is the limited availability of affordable monitoring platforms that provide synchronized environmental and electrical performance measurements. Existing commercial systems often emphasize energy production monitoring and are frequently inaccessible to researchers and operators in developing regions due to cost constraints (Deceglie et al., 2018).

To address these challenges, this study presents the design, fabrication, calibration, and field evaluation of a low-cost ATmega328-based solar–weather monitoring system for real-time photovoltaic degradation analysis. The system integrates environmental sensing, photovoltaic electrical measurements, embedded data logging, and analytical modelling to evaluate thermal, optical, corrosion, and mechanical degradation mechanisms under real outdoor conditions. The proposed platform provides a practical and scalable framework for multi-stressor PV degradation assessment and establishes a foundation for future IoT-enabled predictive maintenance and intelligent photovoltaic asset management systems.

METHODOLOGY

Study Area

The field investigation was conducted at the Renewable Energy Research Test Site located within Adamawa State University, Mubi, Adamawa State, Nigeria. Mubi is geographically situated at approximately latitude 10.27°N and longitude 13.27°E within the Sudan Savannah ecological zone of northeastern Nigeria. The region experiences high solar irradiance throughout most of the year, making it highly suitable for photovoltaic (PV) performance and degradation studies.

The climatic conditions of the study area are characterized by elevated ambient temperatures, seasonal dust storms associated with the Harmattan period, moderate-to-high relative humidity during the rainy season, and occasional strong wind events. Average daily solar irradiance in the region ranges from 5.5 to 6.8 kWh/m²/day, while ambient temperatures during peak dry-season periods frequently exceed 40 °C. Under intense solar exposure, photovoltaic module surface temperatures can rise above 70 °C.

The area was specifically selected because the combination of high temperature, airborne dust, humidity variation, and wind exposure provides realistic environmental stress conditions for evaluating multi-stressor photovoltaic degradation mechanisms. Field experiments were conducted continuously between January and June 2025 in order to capture varying environmental conditions during both dry and transitional climatic periods.

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Research Design

An experimental field-based research design was employed to develop, calibrate, deploy, and evaluate a microcontroller-based solar–weather monitoring system for real-time photovoltaic degradation assessment under harsh environmental conditions. Two identical 250 W polycrystalline photovoltaic modules were installed under the same orientation and tilt conditions, with one serving as a reference module and the other exposed to environmental stressors including dust accumulation, elevated temperature, humidity, wind loading, and controlled hail impacts. Environmental parameters and photovoltaic performance variables were continuously monitored using the fabricated system, while data analysis was conducted through regression analysis, comparative statistical techniques, and analytical degradation modelling to quantify the effects of individual and combined stressors on photovoltaic performance.

System Architecture

The monitoring system was developed around an ATmega328 microcontroller configured as the central control and data acquisition unit. The overall architecture of the developed system consisted is shown in figure 1.

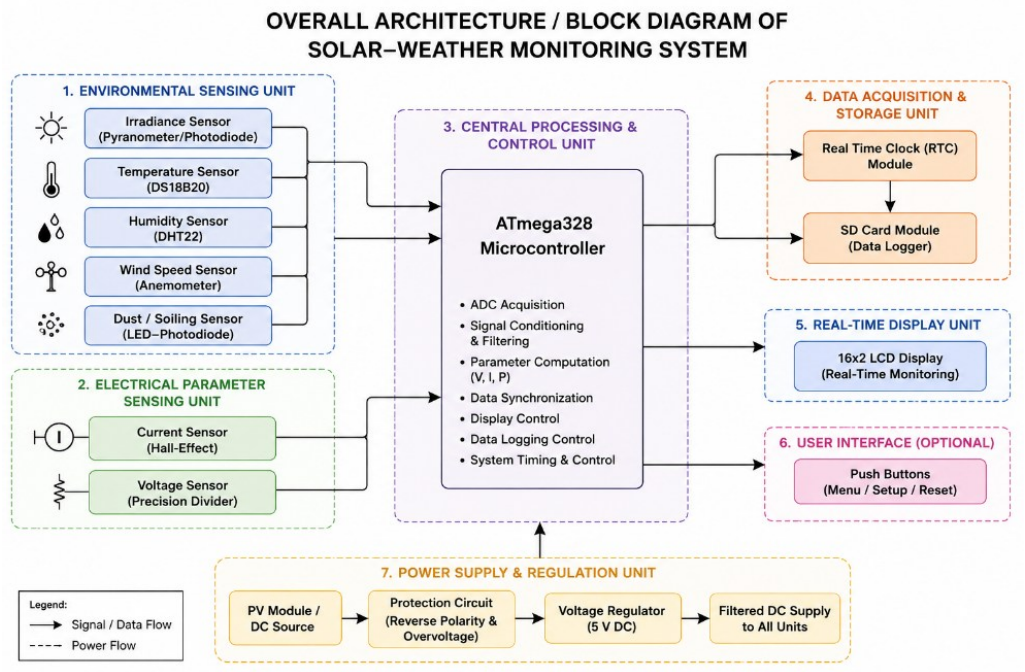

Figure 1. Overall Architecture / Block Diagram of the Solar–Weather Monitoring System

Circuit schematic of the developed ATmega328-based solar–weather monitoring system as shown in figure 2 shows environmental sensor interfacing, electrical parameter sensing

circuitry, RTC module, SD card communication subsystem, LCD interface, and regulated power supply architecture.

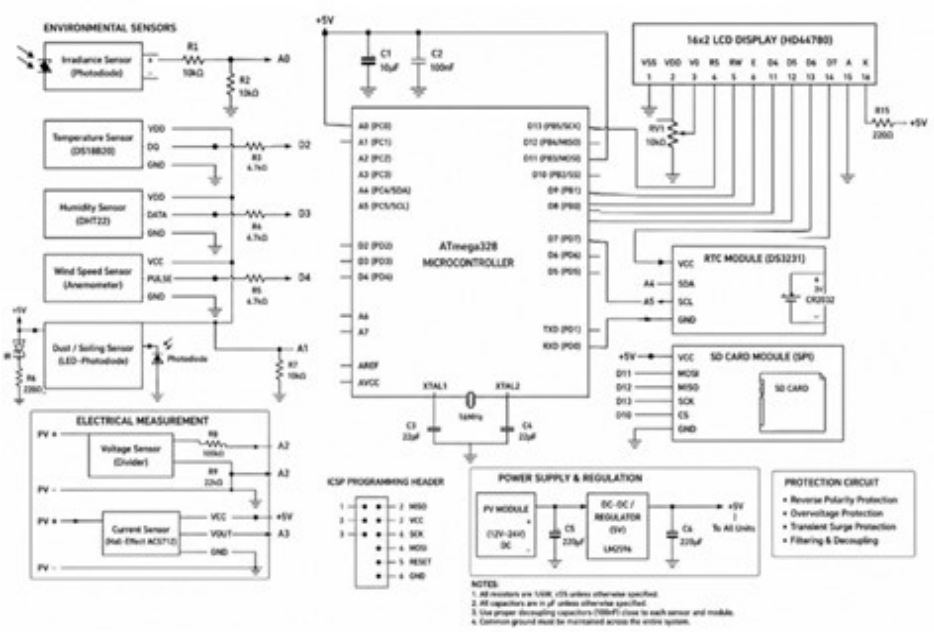

Figure 2. Circuit Diagram of the ATmega328-Based Solar–Weather Monitoring System

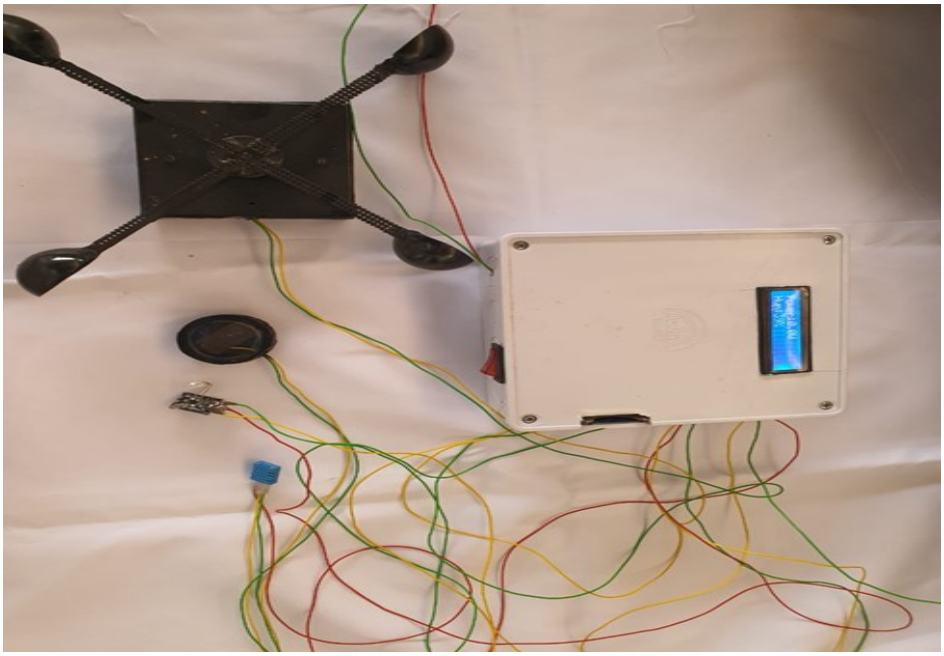

Figure 3. Fabricated Solar–Weather Monitoring System



Figure 4. Experimental Photovoltaic Test Rig Used for Multi-Stressor Degradation Evaluation

Environmental Sensing Subsystem

The environmental sensing subsystem was responsible for measuring atmospheric and operating conditions affecting photovoltaic performance. The subsystem incorporated A calibrated photodiode/pyranometer for solar irradiance measurement, A DS18B20 digital temperature sensor for module temperature monitoring, A capacitive humidity sensor for relative humidity measurement, A cup anemometer for wind speed measurement, and An optical LED–photodiode pair for dust and soiling estimation.

The sensors were strategically positioned around the photovoltaic test module to ensure accurate environmental representation during field operation.

Electrical Monitoring Subsystem

The electrical monitoring subsystem measured the photovoltaic output voltage, current, and instantaneous power. Current sensing was achieved using a Hall-effect current sensor, while a precision voltage divider network was used for voltage scaling and measurement.

The instantaneous photovoltaic output power was computed using:

$$P = VI$$

where:

P= photovoltaic output power (W), V= photovoltaic output voltage (V), and I= photovoltaic output current (A).

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Data Acquisition and Processing Subsystem

The ATmega328 microcontroller acquired analog and digital sensor outputs through its embedded Analog-to-Digital Converter (ADC) channels. Environmental and electrical measurements were sampled every 60 seconds under synchronized timing conditions. Signal conditioning and moving-average filtering algorithms were implemented in firmware to reduce measurement noise and improve data stability.

Real-Time Display Subsystem

A 16×2 Liquid Crystal Display (LCD) module was integrated into the system for real-time visualization of environmental variables and photovoltaic operating parameters. The display provided continuous updates of irradiance, temperature, humidity, voltage, current, and output power.

Data Storage Subsystem

A Real-Time Clock (RTC) module was incorporated to provide synchronized timestamping of all acquired measurements. The processed data were stored in comma-separated value (CSV) format using an SD card module for long-term analysis and degradation assessment.

Power Conditioning Subsystem

The monitoring system was powered using a regulated 5 V DC supply derived from the photovoltaic module output through a voltage regulation stage. Protection circuits were incorporated to prevent overvoltage and reverse-polarity damage to the embedded electronics.

Sensor Calibration

To ensure measurement reliability and reproducibility, all sensors used in the monitoring platform were calibrated against standard reference instruments before field deployment.

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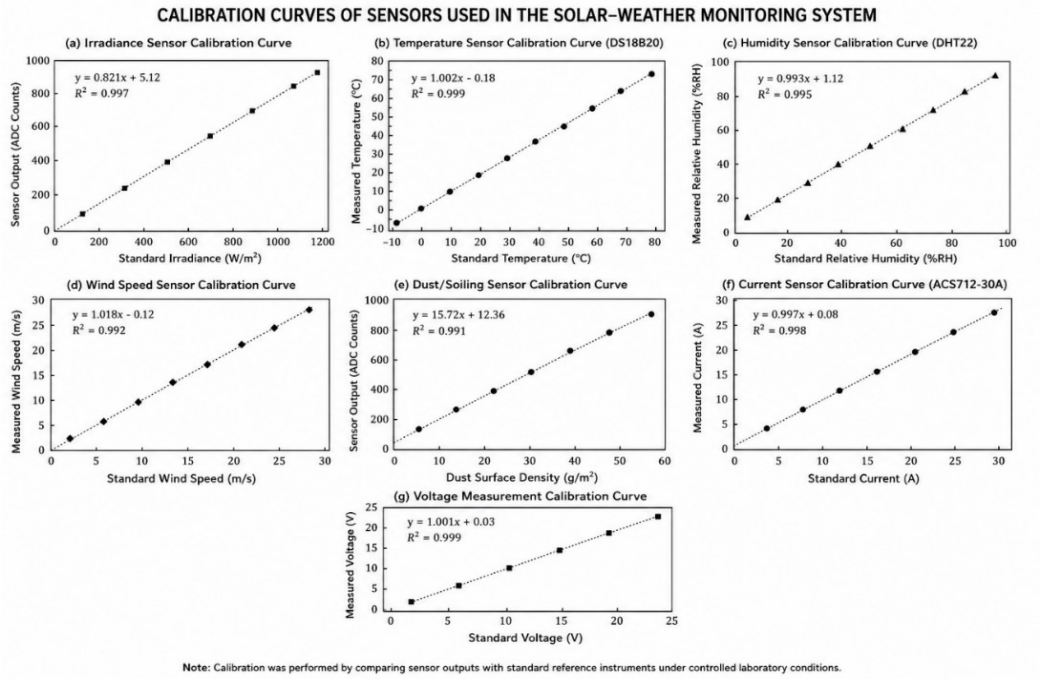

Figure 5. Calibration Curves of Sensors Used in the Solar–Weather Monitoring System
Calibration characteristics of the irradiance, temperature, humidity, wind speed, dust/soiling, current, and voltage sensors used in the developed solar–weather monitoring system.

The curves demonstrate strong linear agreement between measured sensor outputs and standard reference instruments.
The regression equations and coefficients of determination obtained during calibration are summarized as follows:

- Irradiance sensor:

$$y = 0.821x + 5.12, R^2 = 0.997 \quad (1)$$

- Temperature sensor (DS18B20):

$$y = 1.002x - 0.18, R^2 = 0.999 \quad (2)$$

- Humidity sensor (DHT22):

$$y = 0.993x + 1.12, R^2 = 0.995 \quad (3)$$

- Wind speed sensor:

$$y = 1.018x - 0.12, R^2 = 0.992 \quad (4)$$

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- Dust/soiling sensor:

$$y = 15.72x + 12.36, R^2 = 0.991 \quad (5)$$

- Current sensor (ACS712-30A):

$$y = 0.997x + 0.08, R^2 = 0.998 \quad (6)$$

- Voltage sensor:

$$y = 1.001x + 0.03, R^2 = 0.999 \quad (7)$$

The high coefficients of determination obtained during calibration indicate excellent linearity and measurement reliability for all sensing units incorporated into the developed monitoring platform.

RESULTS

The field experiments provided valuable data on the efficiency losses in photovoltaic (PV) modules under extreme environmental conditions. These losses were caused by both individual and combined stressors, and the results are summarized in Table 1.

Table 1: Measured PV Efficiency Losses under Extreme Weather Conditions

Stressor	Exposure Condition	Efficiency Loss (%)	Dominant Degradation Mechanism
High temperature	75 °C operating temperature	12.5	Increased series resistance
Dust accumulation	30 g/m² surface density	18.0	Optical shading/soiling
High humidity	RH > 85%	7.2	Contact corrosion
Hail impact	25 mm hail diameter	9.4	Cell microcracks
Strong wind	>25 m/s gusts	6.1	Mechanical stress
Combined stressors	All above	31.6	Synergistic degradation

Efficiency Losses Due to Individual Stressors

The individual contributions of various environmental stressors to PV performance degradation are as follows:

- **High Temperature:** Exposure to 75°C operating temperature resulted in a **12.5% efficiency loss,** primarily due to increased series resistance, which is a common issue under high-temperature conditions.
- **Dust Accumulation:** Dust deposition of up to 30 g/m² caused an **18.0% efficiency loss**. This loss was primarily due to optical shading and soiling, as dust reduces the

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amount of sunlight reaching the PV surface and also exacerbates thermal degradation by raising the module temperature.

- **High Humidity**: With relative humidity (RH) greater than 85%, a **7.2% loss** was observed. This degradation is largely attributed to contact corrosion, which affects the electrical materials within the PV cells.
- **Hail Impact**: The impact of 25 mm diameter hailstones caused a **9.4% efficiency loss**, primarily due to the formation of microcracks in the cells, which reduce their effective area for current generation.
- **Strong Wind**: Wind gusts exceeding 25 m/s led to a **6.1% efficiency loss**, mainly attributed to mechanical stress, which can cause physical damage or misalignment of the PV modules.

Combined Stressors and Synergistic Effects

When all stressors were combined, the cumulative efficiency loss increased significantly to 31.6%. This substantial degradation is indicative of synergistic effects, where the interaction of multiple stressors results in greater degradation than the sum of individual factors. For example, dust accumulation not only reduces irradiance but also increases module temperature, thereby amplifying thermal degradation. Similarly, hail-induced microcracks can accelerate humidity-driven corrosion, leading to more severe degradation than any single factor would cause in isolation.

Degradation Models

The degradation models presented explain the observed results:

Temperature-Induced Degradation Model

The temperature dependence of PV power output is given by:

$$P(T) = P_{ref}\left[1 - \beta\left(T - T_{ref}\right)\right] \quad (8)$$

where P(T) is the output power at operating temperature T, P_{ref} is the rated power at reference temperature T_{ref} = 25 °C, and β is the temperature coefficient (0.004–0.005 °C⁻¹). This model quantifies the reduction in PV power output due to elevated operating temperatures.

Soiling and Dust Loss Model

Soiling-induced efficiency reduction follows an exponential attenuation model:

$$\eta_s = \eta_0 e^{-k_d M_d} \quad (9)$$

where:

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η_s= soiled module efficiency, η_0= clean module efficiency, k_d= dust extinction coefficient, and M_d= dust mass density.

An exponential attenuation model was used to estimate efficiency reduction caused by dust accumulation, with dust mass density being a key factor.

Humidity-Induced Corrosion Degradation

Humidity-related degradation is modelled as:

$$\Delta P_H(t) = P_0(1-e^{-\gamma_H t}) \quad (10)$$

Where:

$\Delta P_H(t)$= humidity-induced power degradation, P_0= initial module power, γ_H= humidity corrosion rate constant, and t= exposure duration.

The model captures the gradual degradation of PV performance over time due to moisture exposure, emphasizing the role of high humidity in accelerating material corrosion.

Hail-Induced Microcrack Damage

The density of microcracks generated by hail impact was modelled as:

$$\rho_c = \alpha E_h^n \quad (11)$$

The corresponding photovoltaic power degradation relationship was expressed as:

$$\Delta P_c = \kappa \rho_c \quad (12)$$

where:

ρ_c= microcrack density, E_h= hail impact energy, and α, n, and κ are experimentally determined material constants.

The model produced an R^2value of 0.95.

Combined Degradation Model

The cumulative degradation under multiple stressors is approximated by:

$$P(t) = P_0 \exp\left[-(\lambda_T + \lambda_D + \lambda_H + \lambda_C + \lambda_W)t\right] \quad (13)$$

Where:

λ_T= thermal degradation constant, λ_D= dust-related degradation constant, λ_H= humidity-induced degradation constant, λ_C= cracking degradation constant, and λ_W= wind-induced degradation constant.

This integrated model demonstrates how temperature, dust, humidity, hail, and wind stress interact to cause cumulative degradation, providing a comprehensive view of PV performance under extreme weather conditions.

The effect of operating temperature on photovoltaic performance was evaluated using the developed temperature degradation model. As module temperature increased

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beyond standard operating conditions, a corresponding reduction in power output was observed due to increased carrier recombination losses and higher internal resistance. Figure 6 illustrates the reduction in photovoltaic power output with increasing operating temperature.

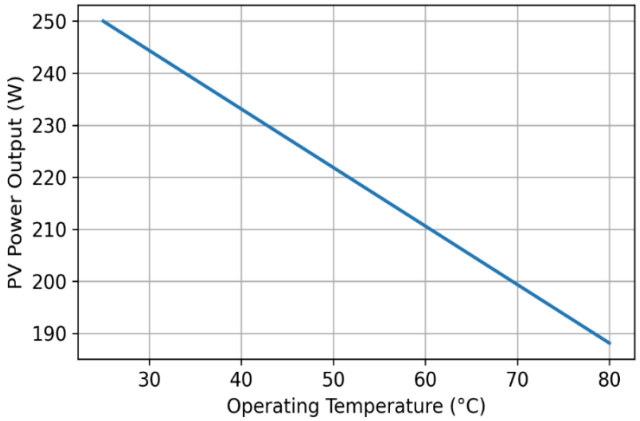

Figure 6. The effect of operating temperature on PV power output.

To investigate the influence of mitigation strategies on photovoltaic reliability, cumulative degradation behaviour was analyzed under both baseline and mitigated operating conditions. The results demonstrate that preventive measures such as dust removal, thermal management, and protective module design can significantly reduce long-term performance deterioration.

Figure 7 shows the cumulative degradation behaviour under baseline and mitigated operating conditions.

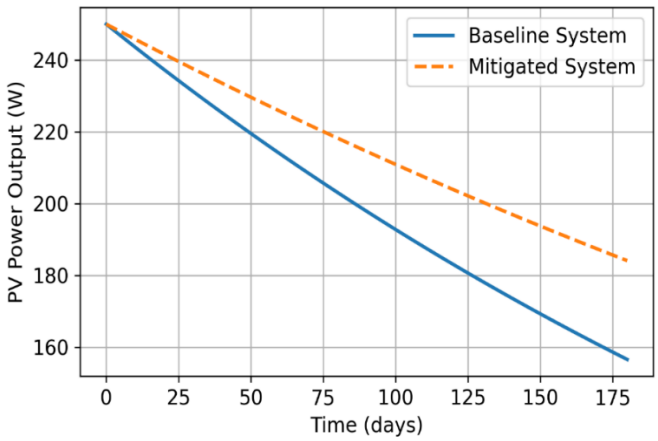

Figure 7. Cumulative degradation behaviour under baseline and mitigated operating conditions.

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Model validation was performed by comparing the predicted photovoltaic power output obtained from the developed degradation models with the measured field data. A close agreement between predicted and experimental values was observed, confirming the suitability of the proposed modelling framework for real-time photovoltaic degradation assessment.

Figure 8 compares measured and predicted photovoltaic power outputs and confirms the validity of the proposed degradation model.

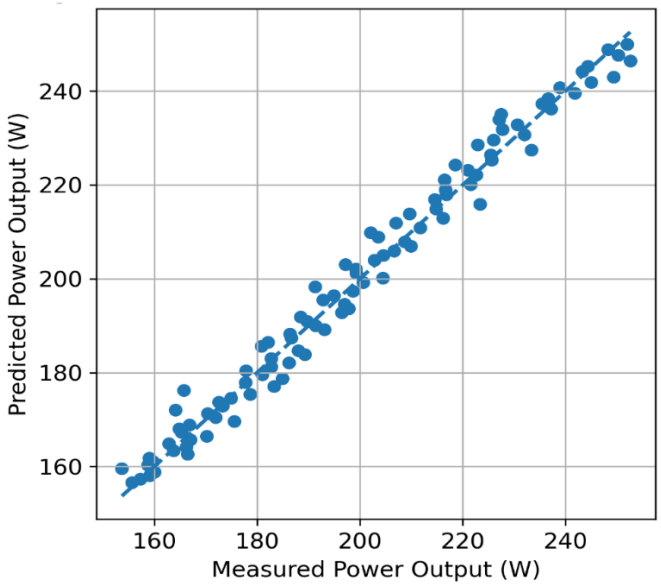

Figure 8. Measured and predicted PV power outputs, validating the degradation model.

Table 2. Validation Performance of Photovoltaic Degradation Models

Degradation Model	Primary Environmental Stressor	Coefficient of Determination (R^2)	Model Performance
Temperature Degradation Model	Module Temperature	0.91	Excellent
Dust/Soiling Degradation Model	Dust Accumulation	0.94	Excellent
Humidity Degradation Model	Relative Humidity	0.92	Excellent
Hail Impact Degradation Model	Mechanical Impact	0.95	Excellent
Wind Stress Degradation Model	Wind Loading	0.90	Very Good
Integrated Multi-Stressor Model	Combined Environmental Stressors	0.97	Outstanding

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The validation results demonstrate strong agreement between measured and predicted photovoltaic degradation behaviour. All individual degradation models achieved coefficients of determination greater than 0.90, while the integrated multi-stressor model achieved an R^2 value of 0.97. These results indicate that the developed analytical framework can reliably characterize photovoltaic degradation under varying environmental conditions and accurately represent synergistic interactions among environmental stressors.

The results demonstrate that photovoltaic degradation under real outdoor conditions is governed by the combined influence of multiple environmental stressors. The developed monitoring platform successfully captured the effects of temperature, dust accumulation, humidity, wind loading, and hail-induced mechanical damage, showing that cumulative degradation is substantially greater than that caused by individual stressors.

Elevated temperatures reduced photovoltaic efficiency by up to 12.5%, primarily due to increased carrier recombination, reduced open-circuit voltage, and higher internal resistance. This finding agrees with previous studies that identified thermal stress as a major contributor to photovoltaic degradation (Dubey et al., 2013; Jordan & Kurtz, 2013). Dust accumulation produced the highest isolated efficiency loss (18.0%) by reducing solar irradiance transmission and increasing module operating temperature, consistent with the observations of Sarver et al. (2013), Micheli et al. (2019), and Deceglie et al. (2018).

Humidity-induced degradation resulted in efficiency losses of approximately 7.2%, mainly due to moisture ingress, corrosion, and deterioration of electrical interconnections, supporting findings reported by Köntges et al. (2017) and Rahman et al. (2023). Hail impact caused efficiency losses of about 9.4% through the formation of microcracks that disrupted current collection pathways, while wind loading produced smaller losses (6.1%) associated with cyclic mechanical stresses and structural fatigue (Jordan & Kurtz, 2013; Rahman et al., 2023).

A major outcome of this study is the confirmation of strong synergistic interactions among environmental stressors. Simultaneous exposure to multiple stress factors resulted in a cumulative efficiency loss of 31.6%, demonstrating that thermal, optical, electrochemical, and mechanical degradation mechanisms interact under real operating conditions. The integrated degradation model achieved the highest predictive accuracy (R^2 = 0.97), confirming the importance of multi-stressor approaches for realistic photovoltaic reliability assessment. The combined degradation loss was lower than the arithmetic sum of individual losses because degradation mechanisms interact nonlinearly and were evaluated under simultaneous rather than isolated conditions.

The ATmega328-based monitoring platform operated reliably throughout the six-month field deployment, providing accurate synchronized environmental and photovoltaic measurements. Its low cost and scalability make it suitable for photovoltaic reliability

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studies and monitoring applications in developing regions. Overall, the findings highlight the importance of climate-resilient photovoltaic designs, continuous environmental monitoring, and predictive maintenance strategies to improve long-term system performance and reliability (Rahman et al., 2023).

CONCLUSION

This study developed and successfully deployed a low-cost ATmega328-based solar–weather monitoring system for real-time assessment of photovoltaic degradation under harsh environmental conditions. The system effectively integrated environmental sensing, photovoltaic performance monitoring, synchronized data acquisition, and long-term data logging.

Results showed that environmental stressors significantly affect photovoltaic performance, with dust accumulation causing the highest individual efficiency loss (18.0%), followed by elevated temperature (12.5%). When multiple stressors acted simultaneously, cumulative efficiency losses increased to 31.6%, demonstrating strong synergistic interactions among thermal, optical, mechanical, and electrochemical degradation mechanisms.

The developed degradation models exhibited high predictive accuracy, achieving coefficients of determination (R^2) between 0.91 and 0.97, with the integrated multi-stressor model providing the best performance. The monitoring platform operated reliably throughout field deployment and proved suitable for photovoltaic reliability studies in harsh climates.

Overall, the study demonstrates that affordable embedded monitoring systems can support photovoltaic reliability assessment, predictive maintenance, and climate-resilient solar energy deployment, particularly in developing and remote regions. Future research should focus on long-term monitoring, IoT integration, cloud-based diagnostics, and machine-learning-enabled predictive maintenance for large-scale photovoltaic installations.

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Conflict of Interest

The author hereby declares no conflict of interest.

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