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EXPERIMENTAL STUDY OF MODULE ELEVATION AND GROUND COVER TYPE ON PHOTOVOLTAIC PERFORMANCE

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This experimental study systematically explores the effects of elevation height and ground surface condition on the thermal and electrical performance of photovoltaic modules based on monocrystalline silicon photovoltaic modules under field conditions in a subtropical climate. Three identical 60 W monofacial PV modules were installed at heights of 0.7 m, 1.1 m, and 1.6 m above dried grass and vegetation-covered surfaces to assess the influence of airflow, albedo, and microclimatic cooling. Voltage, current, ambient air speed, ambient pressure, temperature, and irradiance were continuously recorded using high-precision dataloggers. Results show that module elevation strongly affects operating temperature and electrical efficiency, with the 1.1 m height yielding the highest power output (maximum 45.2 W) and conversion efficiency (7.0%). Vegetation reduced cell temperature through evapotranspiration, enhancing performance, while dried grass increased heat accumulation. Despite slightly higher irradiance above dried grass, modules over vegetation performed more efficiently. Overall, a moderate elevation and vegetative cover improve PV cooling and efficiency, offering an effective strategy for optimising agrivoltaic and eco-integrated PV systems.

Keywords: PV system configuration; elevation height; vegetation cover; dried grass surface

According to Ostvar et al. (2025), evaluating and improving the efficiency of energy consumption is a key prerequisite for longterm sustainability. The global expansion of photovoltaic (PV) technology demands system-level optimisation to maximise energy yield whilst minimising thermal losses that accommodate environmental factors influencing energy yield and module efficiency. While monofacial modules once dominated installations, the rapid growth of bifacial and advanced PV designs has shifted attention to rear-side irradiance, albedo, mounting height, and thermal effects (Su et al., 2024; Viriyaroj et al., 2024). Recent studies demonstrate that bifacial modules can achieve up to 30% higher energy yield than monofacial systems under optimal conditions (Yakubu et al., 2024). Experimental and modelling analyses highlight the influence of albedo, tilt, and module spacing on rear-side gain (Li et al., 2024; Tsuchida et al., 2024). Environmental and lifecycle assessments also reveal how temperature, dust, and surface reflectivity affect bifacial performance (Kumar et al., 2023; Maniscalco et al., 2024). Consequently, modern PV design must integrate environmental dynamics and advanced configurations to enhance long-term performance and economic feasibility. However, the rise of bifacial and advanced PV designs has highlighted the importance of factors such as albedo, microclimate, shading, and mounting configuration (Riedel-Lyngskær et al., 2022; Blakesley et al., 2023; Pirouz et al., 2025). Albedo, or surface reflectivity, strongly affects bifacial PV performance. Spectral properties vary across

surfaces, influencing backside energy generation (Haroun et al., 2025). Accurate albedo estimation is therefore critical. Satellite-based data, such as MODIS (Moderate Resolution Imaging Spectroradiometer), can introduce scaling errors for small or heterogeneous sites. This emphasises the need for ground-based validation or high-resolution datasets (Tonita et al., 2024). Such measures reduce uncertainty in bifacial gain calculations.

Bifacial PV modules utilise rear-side irradiance. This offers the potential for higher energy yields compared to monofacial panels. However, their efficiency is strongly influenced by environmental and design factors. These include panel elevation, tilt, orientation, row spacing, and ground reflectivity (Sun et al., 2018; Ganesan et al., 2024; Dincer and Ozer, 2025). Specifically, a strong negative correlation exists between tilt angle and PV energy output (-0.95). While tilt significantly impacts monthly energy production, annual energy yield differences are negligible for moderate adjustments around typical fixed angles (Madola et al., 2026). Field studies have examined these factors. Research in Brazil, Germany, and Costa Rica indicates that increasing module elevation reduces rear-side irradiance non-uniformity. This enhances power output and bifaciality factors (Sánchez et al., 2020; Braga et al., 2023). Global optimisation studies further demonstrate the combined influence of module height and albedo. Elevated modules over high-reflectivity surfaces can achieve up to 30% higher yields (Sun et al., 2018). Similarly, wind tunnel experiments

suggest benefits from taller array configurations. These configurations enhance convective heat transfer, mitigating thermal losses and improving module efficiency (Smith et al., 2022).

Parallel research focuses on agrivoltaic systems. These systems integrate crops beneath PV arrays. This research has demonstrated that ground cover type and vegetation can significantly affect module temperature, microclimate, and energy yield. Elevated PV panels over living crops can reduce module surface temperature by up to 10 °C. This improves energy efficiency while supporting agricultural production (Othman et al., 2023; Williams et al., 2023; Barron-Gafford et al., 2025). These findings indicate that both the physical height of PV modules and the characteristics of the ground surface play a critical role. Ground surfaces range from bare soil to cut grass or living plants. Moreover, the advanced design of the photovoltaic system enables dual land use, allowing simultaneous crop cultivation and electricity generation. Consequently, the increased electrical output from the photovoltaic installation contributes to a reduction in the overall carbon footprint (Libra et al., 2024).

Despite growing recognition of environmental and structural influences on PV performance, the combined effects of module elevation and ground cover remain poorly understood. This gap is particularly evident in tropical and subtropical regions. Previous studies have mainly examined elevation or agrivoltaic configurations separately, overlooking their interactive effects on energy generation.

This study addresses this limitation by systematically analysing how PV module elevation and ground cover of dried grass and living vegetation jointly affect thermal behaviour, power output, and efficiency. Environmental and design parameters were integrated to quantify their combined influence on system performance. The novelty of this work lies in the simultaneous assessment of elevation height and diverse surface conditions. The findings provide

new insights for optimising PV installations in tropical climates and improving the design of efficient bifacial and agrivoltaic systems.

Material and Methods

Figure 1 presents the conceptual diagram that delineates the overall scope and methodology adopted in the PV performance analysis. It provides a clear visualisation of the sequential experimental and analytical procedures, illustrating the relationship between environmental parameters, electrical and thermal measurements, and the corresponding data processing and evaluation stages. This framework ensures a systematic approach to assessing the PV system's performance under varying operating and environmental conditions.

Furthermore, the experimental quantification of microclimatic interactions between vegetation surfaces and PV thermal dynamics remains limited, particularly in subtropical regions where evapotranspiration rates significantly influence module cooling.

Material

The experimental devices were selected based on the parameters measured in the current photovoltaic performance study. Table 1 summarises information on the measuring devices, specifying their roles in monitoring of electrical, thermal, and environmental variables such as voltage, current, PV surface and back cells temperature, solar radiation, air speed, pressure, and temperature. The corresponding measurement uncertainties are also included to ensure transparency and to assess the reliability and accuracy of the recorded data, as they represent the potential deviations associated with each instrument.

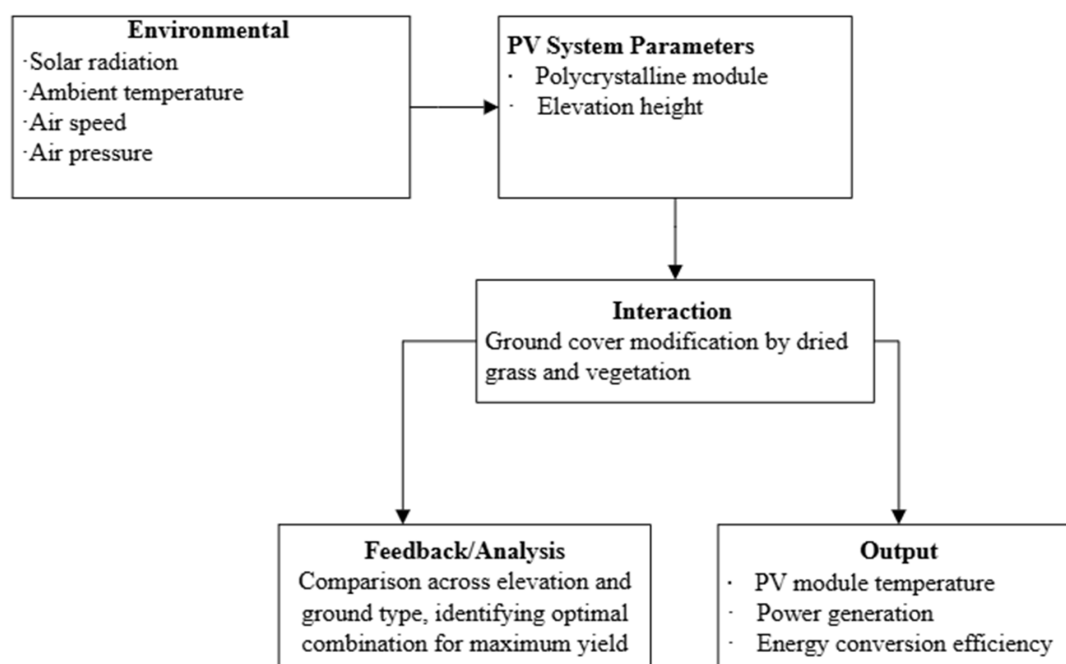


Fig. 1 Conceptual framework of the study

Table 1 The experimental instruments utilised in this study

Devices	Measurement accuracy	Function	Figure
ALMEMO-Ahborn-2890/9	depends on the digital ALMEMO-Ahlborn-2890/9 sensors used	recording data	
ALMEMO-ZA-9020-FS (K-type) and Denkovi	$\pm 0.5\text{ }^{\circ}\text{C}$	temperatures of: – ambient – PV surface and back cells	
MessKopF3.3 pyranometer	$< \pm 10\text{ W}\cdot\text{m}^{-2}$	solar radiation	
DENKOVI-SMART-32 channel	$\pm 0.5\%$ $\pm 0.5\%$	module voltage module current	
1-ohm resistors		voltage reduction	
ALMEMO-FVAD-35	$0.08\text{ m}\cdot\text{s}^{-1}$	air speed and pressure	

All sensors were calibrated prior to deployment according to manufacturers' specifications. Data acquisition was performed at one-minute intervals to ensure adequate temporal resolution for capturing transient thermal and electrical phenomena.

Experimental setup

The experimental setup was designed to evaluate the PV system's performance under controlled conditions. The experiment was conducted on 19–20 September 2025. It includes instruments for measuring voltage, current, module temperature, ambient air speed, ambient pressure, and solar irradiance, ensuring accurate data collection and reliable analysis. Figure 2 illustrates the experimental setup designed to assess the influence of elevation and ground surface conditions on PV module performance. The configuration involved three identical PV modules installed at elevations of 0.7 m, 1.1 m, and 1.6 m to systematically examine the impact of convective air circulation and surface heat dissipation on module efficiency.

A pyranometer, coplanar with the modules, measured incident solar irradiance to ensure accurate quantification of received solar energy, while an ambient temperature sensor simultaneously recorded environmental conditions, providing a reference for evaluating thermal gradients between the air and module surfaces. Each PV module was connected to

a resistive load bank, enabling controlled current flow and comprehensive voltage current (V–I) characterisation under dynamic irradiance and temperature conditions. Electrical performance parameters (voltage, current, and power output) were continuously monitored and logged using a Denkovi datalogger, while environmental parameters (ambient air speed, ambient pressure, temperature, and irradiance) were simultaneously recorded via an Almemo datalogger. Both dataloggers were interfaced with a computer system for real-time data acquisition, synchronisation, and visualisation throughout the experiment. This integrated setup provided a robust framework for accurately correlating module elevation with thermal behaviour, energy conversion efficiency, and environmental parameters, thereby enabling a comprehensive analysis of the influence of installation height on PV system performance.

To evaluate the influence of ground surface conditions on the thermal and electrical performance of PV modules, two distinct experimental cases were established. Case 1 utilised a dried grass surface, simulating semi-arid ground conditions with moderate thermal conductivity and minimal surface moisture, as shown in Fig. 3a. In Case 2, the module was mounted above a surface covered with living vegetation, providing a naturally cooled environment due to enhanced evapotranspiration and reduced surface temperature, as illustrated in Fig. 3b.

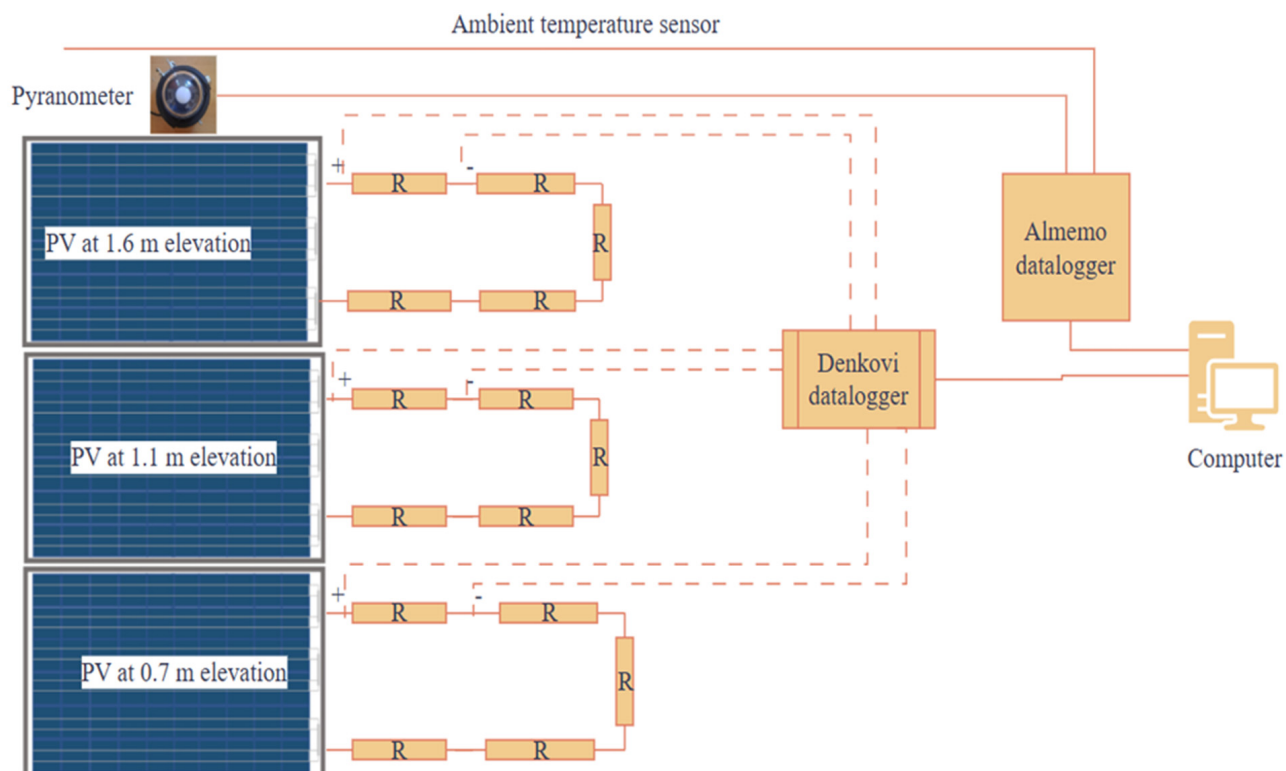


Fig. 2 Experimental setup



Fig. 3 Covering the PV module ground with: a) dried grass; b) vegetation

Each case was tested independently under identical meteorological conditions. Comprehensive datasets, including voltage, current, module temperature, ambient temperature, and solar irradiance, were collected. The data were then analysed and compared using defined performance metrics: energy output, conversion efficiency, and temperature coefficients to assess the impact of surface characteristics on PV module performance.

Table 2 summarises the main performance characteristics of the monofacial PV module used in this study, as defined under standard test conditions (STC).

Table 2 The PV module's specifications used in this experiment

Parameters	Value
Voltage at maximum power (V_{mp})	17.1 V
Current at maximum power (I_{mp})	3.5 A
Maximum power (P_{max})	60 W
Short-circuit current (I_{sc})	3.8 A
Open circuit voltage (V_{oc})	21.1 V
PV module area (A_m)	0.55 m ²
Temperature coefficient of power	(0.5 + 0.05) % °C ⁻¹

Data reduction

The performance of the PV modules was rigorously evaluated and compared using a specific equation designed to quantify their efficiency and power output under varying operational and environmental conditions. This approach allowed for a precise understanding of how effectively the modules convert solar energy into electricity.

Electrical power of the selected module can be evaluated using the following equations (Alshibil et al., 2023; Abdelwahab et al., 2025):

$$P_{el} = VI \quad (1)$$

where: P , V , and I – represent the output power (W), voltage (V), and current (A) of the PV module, respectively

Electrical efficiency of the selected module is defined by (Salameh et al., 2021):

$$\eta_{el} = \frac{P_{el}}{GA_m} \quad (2)$$

$$SE = \sqrt{\frac{\text{variance}}{n}} \quad (3)$$

where: η_{el} – represents the electrical conversion efficiency of the PV module, G is the incident solar irradiance (W·m⁻²); A_m – the active surface area of the module (m²); SE – denotes the standard error. A statistical study was performed using the analysis of variance (ANOVA) to determine the significance of elevation effects on PV performance metrics. Standard error (SE) quantifies the uncertainty in mean values, enabling assessment of measurement reliability

Results and discussion

Dried grass case

The dried grass surface contributed to higher temperatures because of its low moisture content and reduced evaporative cooling. This caused more heat reflection toward the PV module underside.

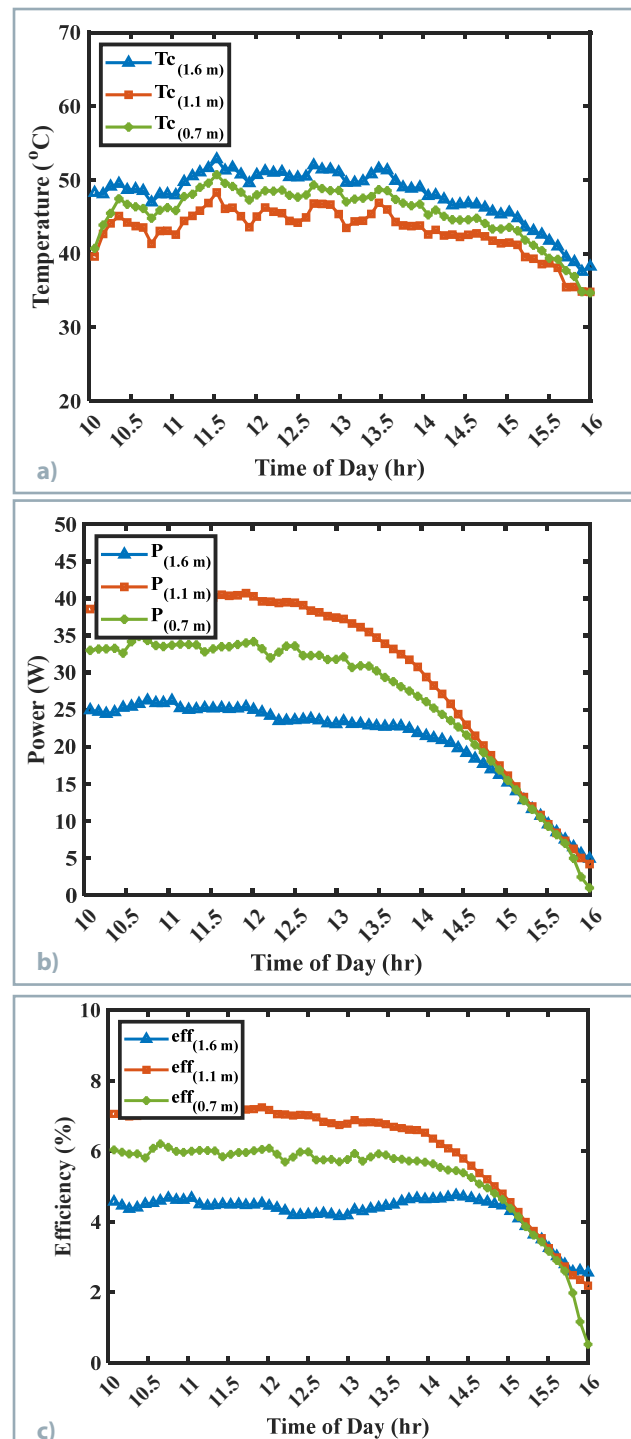


Fig. 4 PV module for dried grass surface coverage
a) cell temperature; b) power; c) efficiency

Figure 4a shows the variation in PV module cell temperature (T_c) at installation heights of 0.7 m, 1.1 m, and 1.6 m above a dried grass surface from 10:00 to 16:00 h. The cell temperature rose rapidly in the morning with increasing solar radiation, peaked around noon, and gradually declined in the afternoon as irradiance decreased.

Figure 4b presents the corresponding electrical power output. Power increased sharply in the morning, reached its maximum at solar noon, and then declined steadily toward the afternoon. The module at 1.1 m produced the highest power throughout the day, followed by those at 0.7 m and 1.6 m. This superior performance reflects an optimal balance between convective cooling and irradiance capture. At 0.7 m, heat accumulation from the ground raised cell temperatures and reduced efficiency, while at 1.6 m, enhanced airflow improved cooling but slightly reduced power generation.

Figure 4c illustrates PV module efficiency at the same heights. Efficiency followed a diurnal pattern, rising in the morning, stabilising near noon, and declining later in the day. The 1.1 m module maintained the highest efficiency (7%), confirming the advantage of balanced cooling and irradiance. In contrast, the 0.7 m module suffered from heat buildup, while the 1.6 m module received less reflected radiation.

Overall, elevation height significantly affected PV performance. Energy conversion under hot, dry circumstances was improved by a moderate height (1.1 m), which allowed for effective cooling without significant loss. These findings confirm that mounting height is a critical design parameter, as earlier studies also reported that increasing clearance enhances convective cooling and reduces cell temperature, thereby improving energy yield (Sánchez et al., 2020; Smith et al., 2022). The superior performance at 1.1 m in the present work is consistent with parametric analyses of bifacial modules, which showed that intermediate elevations often offer the best compromise between airflow, rear-side irradiance, and structural complexity (Ganesan et al., 2024).

The temperature differential between the 0.7 m and 1.6 m configurations averaged $3.2 \pm 0.5^\circ\text{C}$ during peak irradiance hours (11:00–13:00), demonstrating the significant thermal impact of mounting height on convective heat transfer. This corresponds to an estimated power difference of approximately 1.6% based on the temperature coefficient of power ($-0.5\%^\circ\text{C}^{-1}$).

Vegetation case

The vegetation cover influences both the thermal environment and the albedo. Vegetation transpiration cools the surrounding air, while the albedo affects the amount of reflected solar radiation. These factors collectively impact the cell temperature, and consequently, the power output.

Figure 5 illustrates the influence of installation height on the thermal and electrical performance of PV modules above a vegetation-covered surface. As shown in Fig. 5a, the cell temperature varied throughout the day across the three elevations (0.7 m, 1.1 m, and 1.6 m). The module installed at 1.1 m consistently exhibited lower cell temperatures compared to those at 0.7 m and 1.6 m, indicating a favourable interaction between airflow and irradiance. Moderate air velocity at this height likely enhanced convective heat

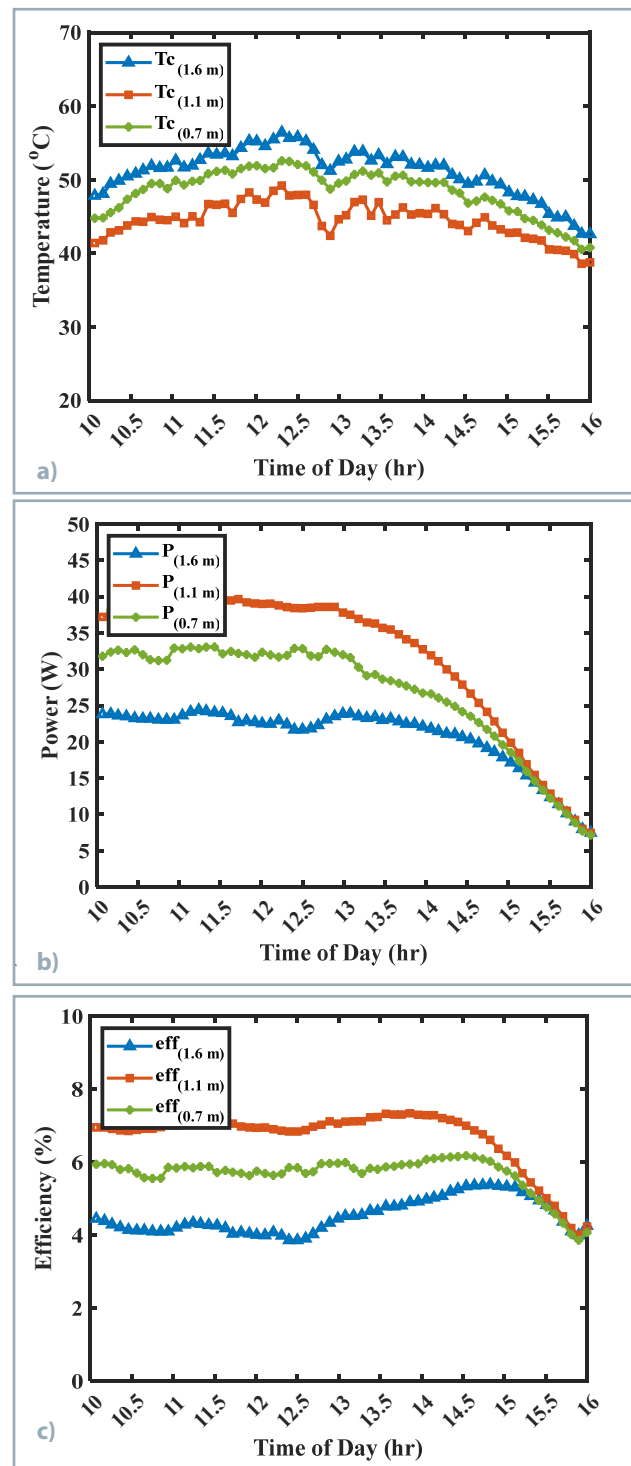


Fig. 5 PV module for vegetation surface coverage
a) cell temperature; b) power; c) efficiency

dissipation, while the 0.7 m module operated within a more stagnant air layer, and the 1.6 m module experienced less stable air currents. Additionally, the albedo of the vegetation and the module height influenced reflected solar radiation; the 1.1 m module likely absorbed less reflected energy, further reducing its temperature. All modules reached peak temperatures around midday, coinciding with the maximum solar irradiance.

Figure 5b shows the corresponding power output, with the 1.1 m module demonstrating the highest performance. This outcome directly correlates with its lower operating temperature, as PV power output decreases with increasing cell temperature due to the negative temperature coefficient. Vegetation moderated the microclimate through transpiration cooling and surface reflection, contributing to reduced module temperature and improved power generation.

Figure 5c presents module efficiency variations, revealing generally higher efficiencies over vegetation compared to dried grass surfaces. Among the three configurations, the 1.1 m module again exhibited superior efficiency, followed by those at 0.7 m and 1.6 m. These differences arise from elevation-dependent effects on convective cooling and reflected radiation. The cooling effect observed above vegetation agrees with agrivoltaic research, where crop or grass cover has been shown to lower module operating temperature through evapotranspiration and microclimate moderation, leading to higher PV efficiency (Othman et al., 2023). Moreover, the improved performance above vegetation supports the broader concept of agrivoltaics, in which vegetated ground cover simultaneously enhances energy production and contributes to more sustainable land use (Libra et al., 2024).

The results highlight that optimal module elevation, particularly around 1.1 m, enhances heat dissipation and maintains lower cell temperatures, thereby improving both power output and efficiency. Strategic elevation design is thus essential for maximising PV system performance in vegetated environments where airflow and albedo interactions play key roles.

Compared to the dried grass scenario, vegetation cover reduced average cell temperatures by 2.8 ± 0.7 °C across all elevations, resulting in a mean efficiency enhancement

of 1.4 ± 0.3 percentage points. This improvement underscores the passive cooling potential of strategically managed ground cover in agrivoltaic installations.

Comparison of the dried and vegetation ground coverage cases

The performance of PV modules was assessed on separate days for dried grass and vegetation-covered surfaces. To provide context for these results, the prevailing environmental conditions during each measurement period are detailed below, enabling an informed comparison of system performance under specific weather scenarios.

Figure 6a presents the airspeed profiles recorded over dried grass and vegetation surfaces. The results indicate consistently higher airspeeds above the dried grass throughout the measurement period, suggesting that this surface condition promotes greater airflow compared to the vegetation-covered area. Similarly, Fig. 6b shows the variation in ambient pressure during the respective measurement periods, with higher pressure values observed over the dried grass surface, consistent with the enhanced air movement recorded in Fig. 6a.

Figure 7a compares the incident solar radiation levels recorded for each surface type. The measurements indicate that higher radiation levels were present during the performance evaluation of the PV module over the dried grass surface. Figure 7b depicts ambient temperature measurements of dried grass and living vegetation from 10:00 to 16:00, revealing a distinct diurnal temperature pattern for both surfaces, characterised by increasing temperatures from morning to early afternoon, followed by a gradual decline.

Based on the presented data, the environmental conditions during the dried grass surface measurements were characterised by higher air speed, ambient pressure, ambient temperature, and incident solar radiation compared to the vegetation-covered surface measurements. These factors suggest that the dried grass measurements were conducted under more favourable weather conditions for PV module performance. The higher radiation directly translates to increased energy input, while the increased air speed could potentially aid in convective cooling, mitigating cell temperature increases. Therefore, any performance

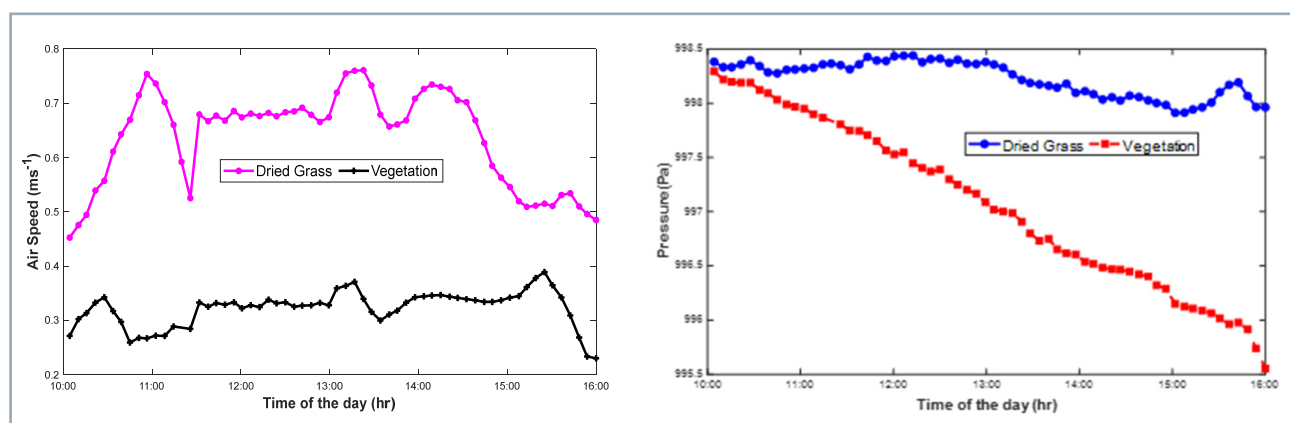


Fig. 6 Comparison for vegetation and dried grass surface coverage
a) ambient air speed; b) ambient pressure

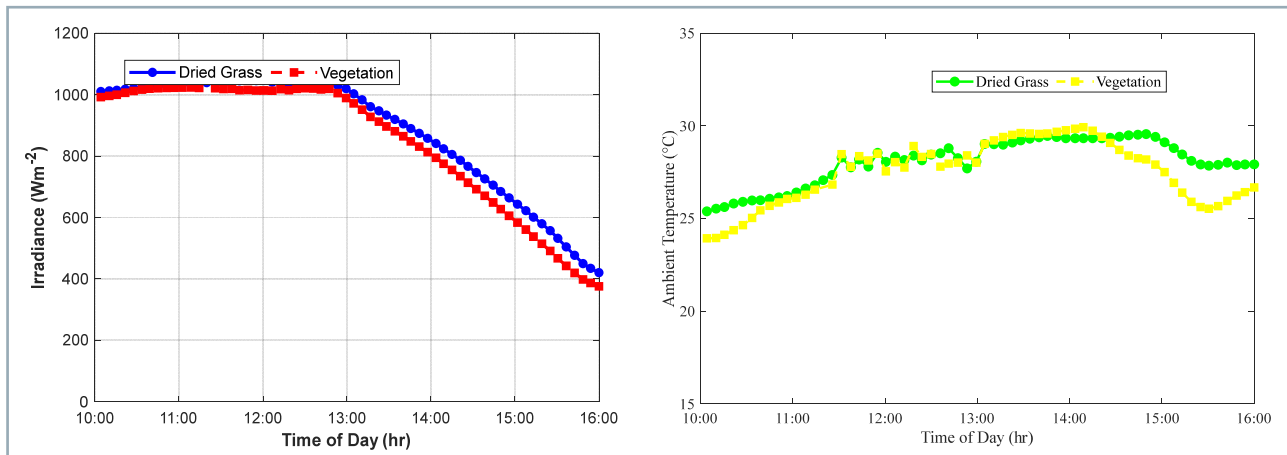


Fig. 7 Comparison for vegetation and dried grass surface coverage
a) irradiance; b) ambient temperature

comparisons must consider this disparity in environmental conditions.

Figure 8 illustrates the relationship between photovoltaic module performance and irradiance for dried grass and vegetation surfaces. Figure 8a depicts PV module efficiency versus irradiance, while Fig. 8b shows power output versus irradiance. These plots reveal the impact of surface type on PV module behaviour, even considering variations in environmental factors like air speed, ambient pressure, and solar radiation during measurements.

PV module efficiency increases with irradiance under both surface conditions. The vegetation-covered surface consistently demonstrates higher efficiency at lower irradiance levels ($350\text{--}700\text{ W}\cdot\text{m}^{-2}$). This advantage may stem from superior light capture due to enhanced reflection or scattering by the vegetation. Beyond $700\text{ W}\cdot\text{m}^{-2}$, efficiencies converge to approximately 5–6%, indicating a reduced influence of surface differences at higher irradiance. Power output also increases nearly linearly with irradiance in both scenarios. At lower irradiance, power output is lower for dried grass, mirroring the efficiency trends in Fig. 8a. The power curves converge at higher irradiance, signifying similar power performance as irradiance approaches maximum values. The error bars represent the variability of measurements, reflecting high confidence in the observed trends.

Effective irradiance reaching the PV module, and thus its efficiency, is modulated by surface reflection and scattering. The convergence

of efficiency at higher irradiance is likely due to internal resistance and saturation effects (ground surface coverage) within the PV cells, which limit efficiency regardless of surface type. The near-linear increase in power with irradiance is consistent with PV cell theory, where power output is directly proportional to photon absorption and conversion, and thus light intensity.

This study underscores the importance of ground cover selection and management for optimising PV deployment, especially in environments with variable irradiance. Similar conclusions were

reached in studies on bifacial and eco-integrated PV systems, which demonstrated that ground albedo and spectral reflectance significantly modify the irradiance field around the modules and thus the resulting power output (Riedel-Lyngskær et al., 2022). The fact that vegetation improved efficiency despite lower irradiance in this experiment is consistent with analyses showing that the net benefit of a given ground cover depends on the combined effects of albedo, thermal behaviour, and local climatic conditions rather than irradiance alone (Pirouz et al., 2025).

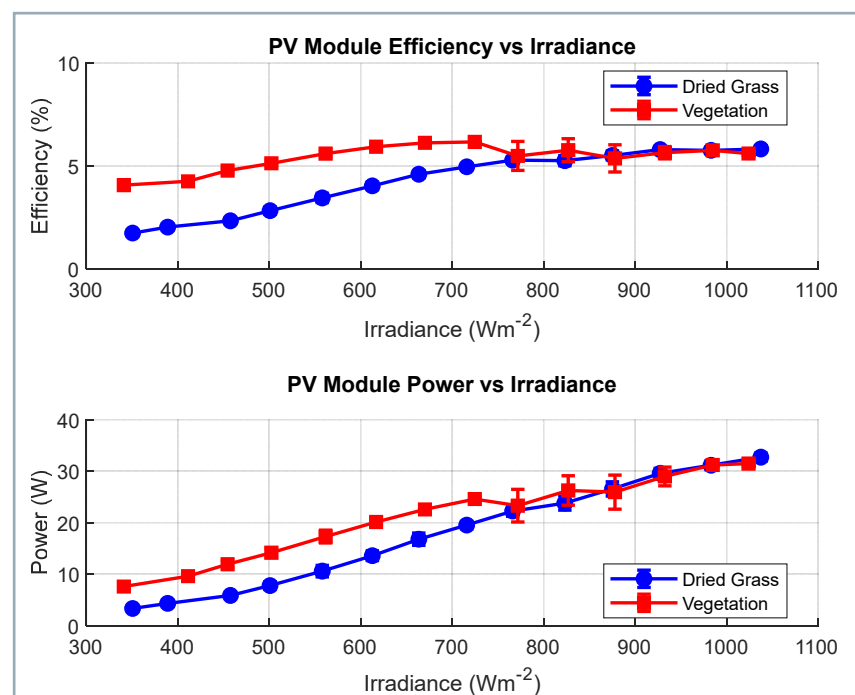


Fig. 8 PV module performance under different ground surface coverage
a) efficiency; b) power

The findings can guide the design of agrivoltaic and eco-friendly PV systems, emphasising the potential for enhanced energy yield through strategic ground cover management, even when external environmental factors vary.

Uncertainty analysis

An uncertainty analysis was performed for the instruments used in the experimental setup, as well as for the relevant physical quantities, to determine the measurement errors. To quantify and address these potential errors, Eq. 4 and 5 were utilised to determine the overall uncertainty in the measurements (Madhi et al., 2025):

$$\frac{\partial P}{P} = \sqrt{\left(\frac{\partial V}{V}\right)^2 + \left(\frac{\partial I}{I}\right)^2} \quad (4)$$

$$\frac{\partial \eta_{el}}{\eta_{el}} = \sqrt{\left(\frac{\partial V}{V}\right)^2 + \left(\frac{\partial I}{I}\right)^2 + \left(\frac{\partial G}{G}\right)^2} \quad (5)$$

where: ∂P , ∂V and ∂I – represent the measurement uncertainties associated with power, voltage, and current, respectively; $\partial \eta_{el}$ – denotes the uncertainty in electrical efficiency

An uncertainty analysis was performed to assess the accuracy and reliability of the measurement system and the instruments employed. The relative uncertainty of both power and efficiency was determined to be 0.18%, reflecting a high degree of measurement precision.

Conclusion

The experimental results demonstrated the combined influence of elevation height and ground surface on the electrical performance of PV modules under outdoor conditions. Modules above dried grass showed higher temperatures due to limited evaporative cooling and increased heat reflection. In contrast, vegetation-covered surfaces reduced cell temperature through evapotranspiration, improving electrical efficiency. An elevation of 1.1 m provided the best performance by maintaining a balance between convective cooling and irradiance capture. Modules at 0.7 m experienced heat build-up, while those at 1.6 m had minor power losses despite improved cooling. Both surface types exhibited a near-linear relationship between power output and irradiance, with efficiency converging at high irradiance levels due to cell saturation. Overall, mounting height and ground cover significantly affect PV performance by influencing heat dissipation, airflow, and reflected radiation. Maintaining a moderate elevation of around 1.1 m above vegetated or partially reflective surfaces enhances cooling and energy yield. These findings offer practical guidance for designing efficient agrivoltaic and eco-adaptive PV systems in various climatic conditions.

Future research should investigate long-term seasonal variations and extend this methodology to bifacial module configurations, where rear-side albedo effects may further amplify the performance benefits of strategic ground cover management and optimised mounting geometries.

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