



Veritatis Gaudium:

Multidisciplinary Journal of Postgraduate Studies

College of Postgraduate Studies,

Veritas University, Abuja, Nigeria

ISSN: 3043 - 5285

Volume 1, Number 3, July Special Edition, 2026

DOI: 10.13140/RG.2.2.27309.45286

INFLUENCE OF RELATIVE HUMIDITY, SOLAR RADIATION, CELL TEMPERATURE AND AMBIENT TEMPERATURE ON POLYCRYSTALLINE PHOTOVOLTAIC PERFORMANCE: A PHYSICS-BASED ASSESSMENT OF THREE COMMERCIAL MODULE BRANDS ACROSS THE DRY SEASON

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Abstract

This study examines how cell temperature (CT), ambient temperature (AT), relative humidity (RH) and global solar radiation influence the performance of three polycrystalline PV modules (Samples A, B and C) under the same outdoor conditions at Afaka, Kaduna. Global radiation data obtained from NiMet ranged from 18–29 MJ m⁻² day⁻¹, with weekly averages of 21–27 MJ m⁻² day⁻¹, reflecting Harmattan-driven seasonal transitions. CT rose from 26 °C in the morning to 45–52 °C at midday, while RH declined from 24% to 10%, demonstrating strong thermal humidity dynamics. Isc increased linearly with radiation, with slopes of 0.0698, 0.0453 and 0.0593 for Samples A, B and C, respectively, whereas Voc decreased with rising CT. Correlation analysis showed a moderate CT–AT relationship ($R^2 = 0.442$) and a weak AT–RH relationship ($R^2 = 0.0818$), confirming temperature as the dominant environmental driver. Sample A produced the highest Isc, Sample C the highest Voc but strong thermal sensitivity, and Sample B underperformed. Comparisons with international hot-climate studies show Afaka's thermal stress levels align with those in Rajasthan, Oman, the UAE, Morocco, Brazil and Australia. Overall, Afaka offers strong solar potential but imposes significant thermal loading that reduces voltage and efficiency, providing valuable long-term, multi-parameter data for global PV performance research.

Keywords: Cell temperature; ambient temperature; relative humidity; solar irradiance; global radiation; thermal stress; thermal loading

Introduction

Solar PV has expanded globally from 21 GW in 2009 to over 1.6 TW by 2025, driven by falling costs, improved efficiencies and strong climate policy frameworks such as the Paris Agreement and SDG 7. In Nigeria, where electricity shortages persist and solar resources reach 4–7.5 kWh m⁻² day⁻¹, PV offers a critical pathway for clean energy access and reduced generator-related emissions. However, real-world PV performance in hot, dry climates deviates significantly from Standard Test Conditions, with temperature emerging as the dominant limiting factor. Rising cell temperature (CT) reduces open-circuit voltage according to

$$V_{oc}(T) = V_{oc}(25^{\circ}\text{C}) + \beta(T - 25^{\circ}\text{C}) \quad (1)$$

and increases reverse saturation current following

$$I_0(T) = I_{00} T^3 \exp\left(\frac{-E_g}{kT}\right) \quad (2)$$

while band gap narrowing is described by

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta_g}. \quad (3)$$

Temperature also reduces maximum power output through

$$P_{\max}(T) = P_{\text{STC}} [1 - \gamma(T - 25^{\circ}\text{C})] \quad (4)$$

and elevates CT under high irradiance via the NOCT relation

$$T_c = T_a + \left(\frac{T_{\text{NOCT}} - 20}{800}\right) G. \quad (5)$$

Short-circuit current remains primarily irradiance driven, increasing approximately linearly as

$$I_{sc}(G, T) = I_{sc, \text{ref}} \left(\frac{G}{G_{\text{ref}}}\right) [1 + \alpha_{Isc}(T - 25^{\circ}\text{C})]. \quad (6)$$

These mechanisms highlight the need for long-duration and climate-specific PV studies. This research provides a 151-day assessment of radiation, AT, CT and RH impacts on three polycrystalline modules in Afaka, offering insights essential for optimising PV deployment in hot, dry regions.

Experimental Details

2.1 Study Location

The experiment was conducted at the Department of Physics, Nigerian Defence Academy (NDA), Afaka, Kaduna (10.61°N, 7.44°E), a region characterised by intense dry season solar radiation. Ambient temperatures commonly reach 30–38 °C, with cell temperatures exceeding 45 °C under low relative humidity of 10–20% and Harmattan conditions. Persistent dust, clear skies and low wind speeds limit convective cooling, creating strong thermal stress for PV modules. This environment provides a realistic test bed for evaluating PV performance in hot, arid climates.

2.2 PV Modules

Three 150 W polycrystalline silicon modules (Samples A, B, and C) were installed side-by-side on a fixed south-facing frame to provide uniform solar exposure (Figure 2.1). The electrical terminals were accessible for direct measurement of open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}). Cell temperature (CT), ambient temperature (AT) and relative humidity (RH) were monitored continuously to capture the thermal and environmental conditions affecting module behaviour. The installation area had no shading and the arrangement ensured that all modules operated under identical geometric and environmental conditions.



Figure 2.1

2.3 Measurement Parameters

Environmental and electrical parameters were recorded daily, weekly and hourly, including global radiation (from NiMet), cell temperature (CT), ambient temperature (AT), relative humidity (RH) and electrical outputs (Voc and Isc). Measurements were taken hourly from 08:00 to 17:00 to capture morning cooling, midday heating, afternoon warming and the onset of evening cooling, with all data logged and cross-checked for consistency. Weekly averages were computed to identify broader climatic patterns and support analysis of real outdoor PV behaviour. All procedures followed IEC 61724-1, IEC 60891 and IEC 61215 guidelines, using calibrated instruments to ensure reliable and reproducible results.

Results and Discussion

3.1.1 Daily Ambient Temperature

Daily ambient temperature (AT) showed strong diurnal and seasonal variation, ranging from 26 - 40 °C as illustrated in Figure 1, with higher values during the late Harmattan. Rising AT progressively increased thermal loading on the modules, driving sharper cell-temperature (CT) rises seen in Figure 3. Midday AT peaks aligned with CT spikes in Figure 12 and weekly maxima in Figure 15, contributing to the voltage reductions shown in Figures 8–10 and Figure 14. Overall, the AT pattern defines the hot, dry-season conditions that shaped PV thermal behaviour throughout the study period.

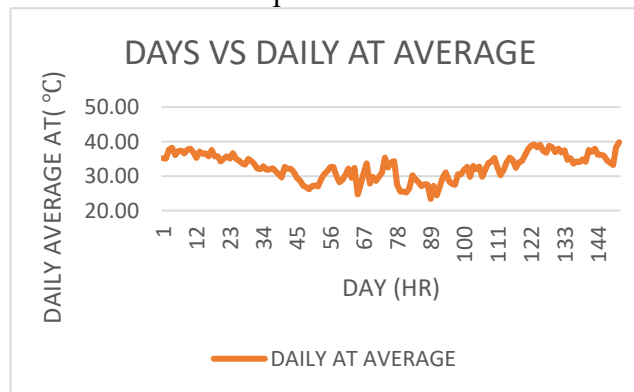


Figure 1. Daily Average Ambient Temperature

3.1.2 Daily Relative Humidity

Daily relative humidity (RH) varied widely between 10 - 33%, with occasional peaks near 40%, as shown in Figure 2, and remained very low (10 - 15%) through the core Harmattan. These dry conditions correspond to the high ambient temperatures (AT) in Figure 1 and strongly reduce convective cooling, allowing cell temperature (CT) to rise rapidly under irradiance, consistent with the CT peaks in Figure 3 and the hourly rise in Figure 12. Low RH combined with high AT intensifies

thermal stress, contributing to the midday voltage depressions seen in Figures 8 - 10 and Figure 14. Overall, the RH pattern highlights its indirect but important role in PV heating, amplifying temperature-induced losses in Afaka's hot, dry climate.

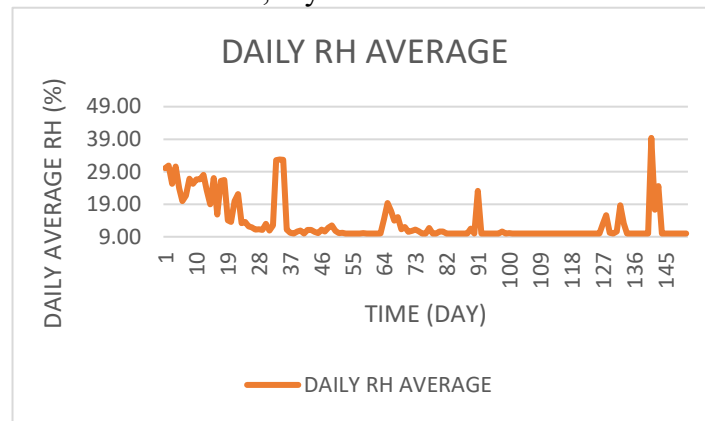


Figure 2. Daily Average Relative Humidity

3.1.3 Daily Cell Temperature

Cell temperature (CT) remained consistently higher than ambient temperature due to strong solar absorption and limited cooling, ranging from 32–47 °C with peaks near 50 °C as shown in Figure 3, following the warming trend in Figure 1. CT rose sharply during mid-season and Harmattan, reaching 38 - 45 °C and producing the voltage depressions seen in Figures 8–10 and Figure 14. The CT rise was most pronounced during low-humidity periods (Figure 2), supported by the CT - AT and CT - RH relationships in Figures 22 and 23. Overall, CT behaviour highlights the need for thermally resilient PV designs in Afaka's hot, dry climate.

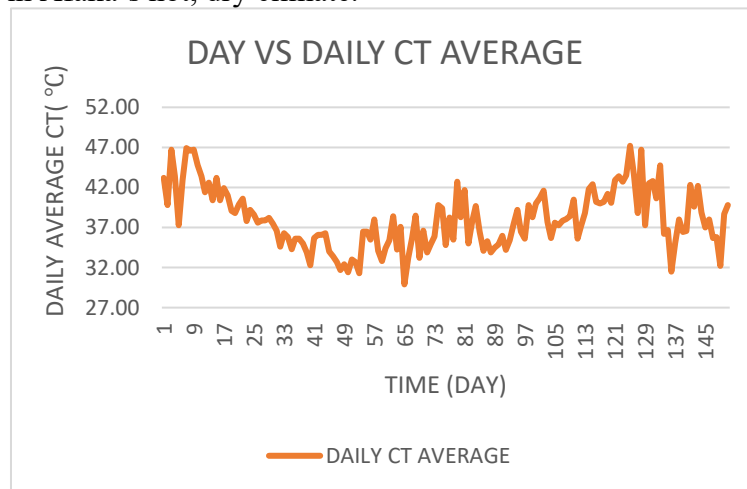


Figure 3. Daily Average Cell Temperature

3.1.4 Daily Global Radiation

Daily global radiation ranged from 18 - 29 MJ m⁻² day⁻¹, with pronounced peaks during Harmattan as shown in Figure 4, reflecting enhanced atmospheric transmissivity. These high-irradiance periods align with elevated cell temperatures (CT) in Figure 3 and the midday CT rise in Figure 12, which drive the voltage reductions seen in Figures 8 - 10 and Figure 14. Radiation also governed the current generation, matching the daily I_{sc} trends in Figures 5 - 7, the hourly behaviour in Figure 13, and the positive regression in Figure 18. Overall, Afaka's strong solar resource boosts current output but simultaneously intensifies thermal stress, shaping PV performance through both radiative and thermal effects.

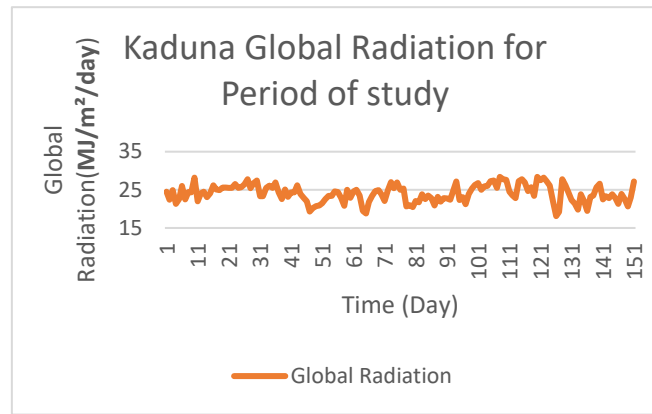


Figure 4. Daily Global Radiation Distribution

3.1.5 Daily Short-Circuit Current (Isc)

Daily short-circuit current (Isc) closely followed irradiance, showing the bell-shaped solar response seen in Figures 5 - 7, with Sample A reaching peaks near 4.8 A around Day 83 in line with the radiation spike in Figure 4. Samples B and C produced lower and more variable currents, but their profiles still mirrored radiation trends, reinforcing irradiance as the dominant driver. Despite high cell temperatures (CT) in Figure 3, Isc remained stable because its temperature coefficient is small, consistent with the hourly behaviour in Figure 13. The strong alignment between Isc and radiation is further confirmed by the positive regression slopes in Figure 18, highlighting Isc as a reliable indicator of irradiance availability.

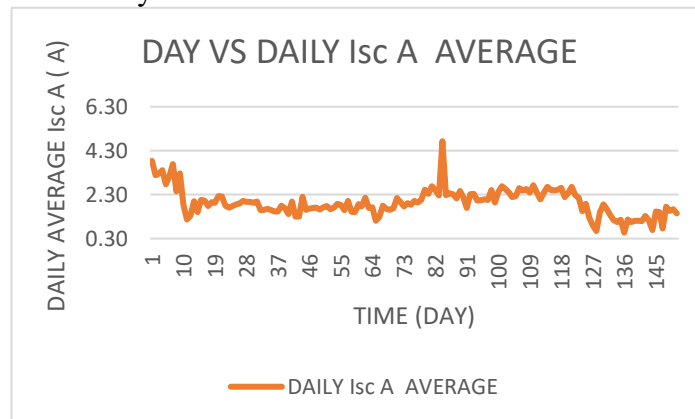


Figure 5. Daily Average Isc (Sample A)

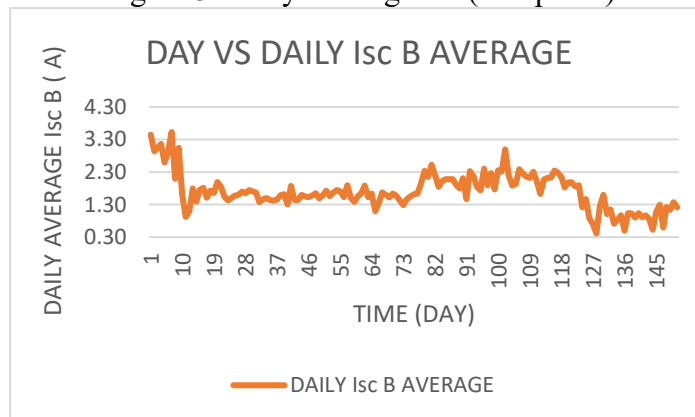


Figure 6. Daily Average Isc (Sample B)

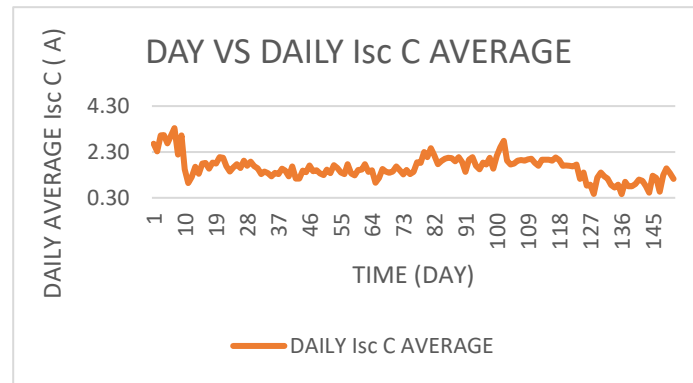


Figure 7. Daily Average Isc (Sample C)

3.1.6 Daily Open Circuit Voltage (Voc)

Daily open-circuit voltage (Voc) showed strong temperature dependence, with all modules exhibiting midday and seasonal voltage depressions in Figures 8 - 10 that correspond to elevated cell temperatures (CT). Samples A, B and C followed this pattern, with cooler days producing voltage peaks seen in Figures 1 and 3, while hotter periods drove the reductions highlighted in Figure 14 and the weekly trends in Figure 16. Sample C showed the largest swings, reflecting its stronger thermal sensitivity and the CT behaviour in Figure 3 and Figure 12. Overall, the daily Voc trends and the radiation - Voc correlation in Figure 17 confirm that temperature, not irradiance, is the dominant factor limiting voltage output in Afaka's climate.

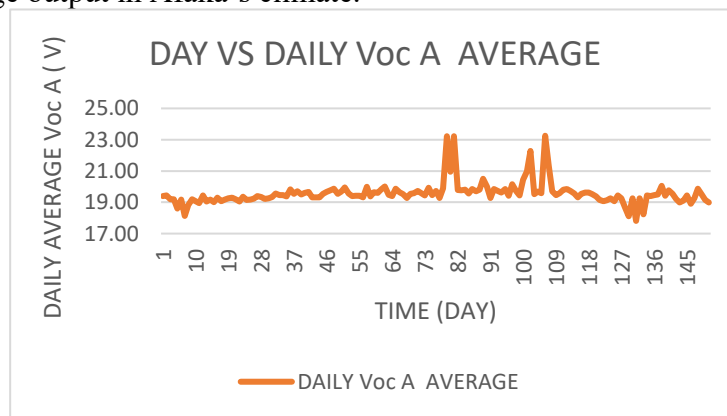


Figure 8. Daily Average Voc (Sample A)

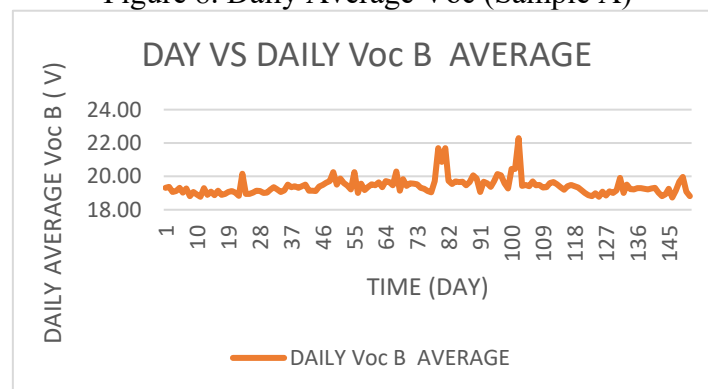


Figure 9. Daily Average Voc (Sample B)

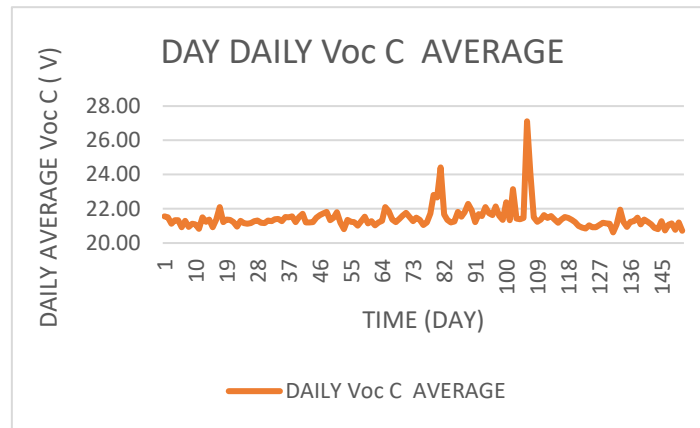


Figure 10. Daily Average Voc (Sample C)

3.2 Hourly and Weekly Temperature Effects

3.2.1 Weekly Global Radiation Trends

Weekly averaged global radiation (Figure 11) ranged from 21 - 26 MJ m⁻² day⁻¹, with peaks in Weeks 4, 11 and 15 reflecting intensified Harmattan transmissivity. These peaks align with the elevated weekly cell temperatures (CT) in Figure 15, while the later decline corresponds with the weekly Voc rise in Figure 16. The stable weekly radiation range highlights Afaka's reliable solar resource and its role in sustaining long-term thermal loading on the modules. Overall, this pattern provides essential context for interpreting the weekly CT and Voc behaviour in hot, dry environments.

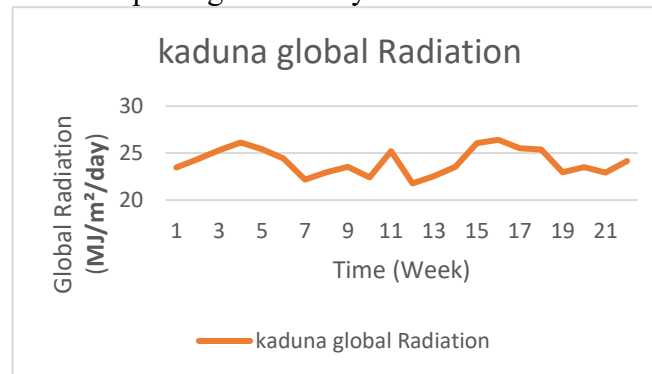


Figure 11. Weekly Global Radiation Trends

3.2.2 Combined Hourly Variation of Ambient Temperature (AT), Cell Temperature (CT), and Relative Humidity (RH)

Hourly measurements (Figure 12) showed AT rising from ≈22 °C to ≈38 °C and CT increasing more sharply from ≈27 °C to ≈45 °C, while RH dropped from ≈22% to ≈11% by midday. This combination of high CT, elevated AT and very low RH produced the strongest thermal loading, consistent with the irradiance patterns in Figures 4 and 11. The midday CT peak directly explains the voltage drops in Figure 14, reflecting the negative temperature coefficient of Voc. Overall, these hourly interactions align with the correlations in Figures 22 - 24, confirming temperature as the dominant driver of PV efficiency losses in Afaka's hot, low - humidity climate.

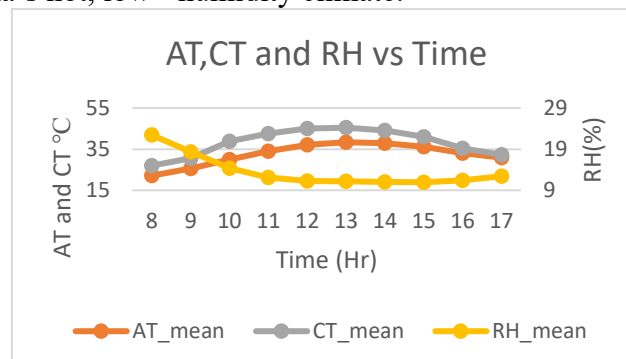


Figure 12. Hourly AT, CT, RH

3.2.3 Hourly Short-Circuit Current

Hourly short-circuit current (I_{sc}) followed the irradiance-driven bell-shaped pattern in Figure 13, rising from morning values to midday peaks before declining toward late afternoon. Sample A consistently produced the highest currents, with Samples C and B showing intermediate and lower outputs, matching the daily trends in Figures 5 - 7. Despite the strong rise in cell temperature (CT) shown in Figure 12, I_{sc} remained stable because its temperature coefficient is small and positive. The close alignment between hourly I_{sc} peaks and irradiance is further supported by the radiation - I_{sc} regression in Figure 18, confirming irradiance as the primary driver of current generation.

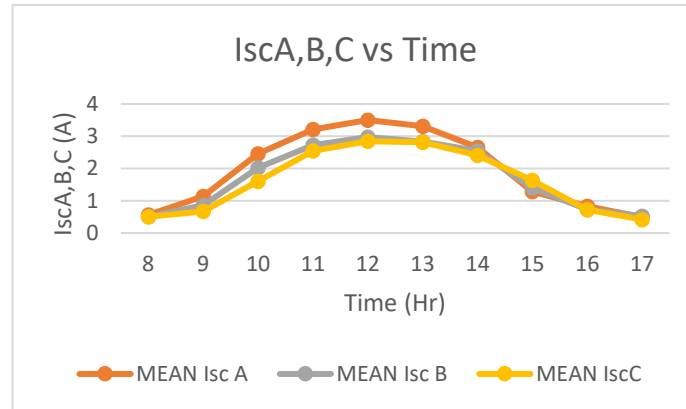


Figure 13. Hourly I_{sc} for Samples A, B, C

3.2.4 Hourly Open-Circuit Voltage

Hourly open-circuit voltage (V_{oc}) showed a strong temperature-dependent pattern, with Samples A and B remaining relatively stable around 19.0 - 19.5 V, as illustrated in Figure 14. Sample C exhibited higher voltages and a pronounced midday decline, rising to ≈ 22.2 V at 10:00 before dropping to ≈ 20.0 V by 17:00, directly reflecting the sharp CT increase in Figure 12. This inverse CT - V_{oc} relationship aligns with the daily and weekly voltage behaviour in Figures 8 - 10 and Figure 16, driven by the negative temperature coefficient of V_{oc} . The near-flat radiation - V_{oc} regression in Figure 17 further confirms temperature, not irradiance, as the primary limiter of voltage output in Afaka's hot, low - humidity climate.

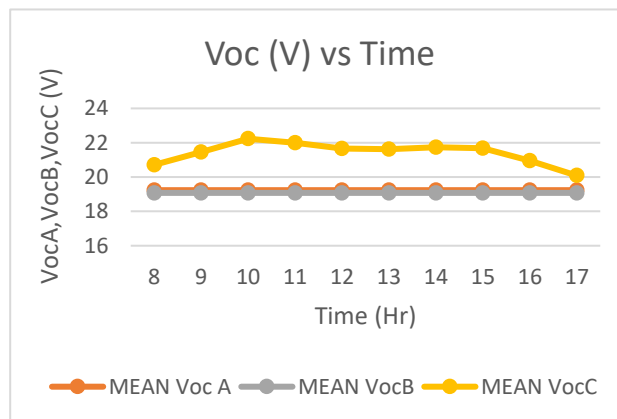


Figure 14. Hourly V_{oc} for Samples A, B, C

3.2.5 Weekly Cell Temperature

Weekly averaged cell temperature (CT) remained well above ambient levels, ranging from 34 - 44 °C as shown in Figure 15, with peaks in Weeks 1, 14 - 16 and 19 - 20 driven by strong Harmattan heating. These high CT intervals align closely with the weekly radiation peaks in Figure 11, confirming the strong irradiance - heating linkage. The same CT peaks correspond to the weekly voltage reductions

in Figure 16, consistent with the negative temperature coefficient of V_{oc} . Overall, the weekly CT pattern highlights sustained thermal stress on the modules and underscores the need for thermally resilient PV designs in hot, dry climates.

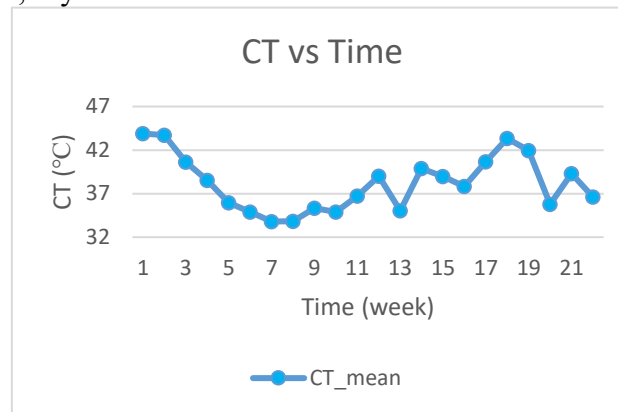


Figure 15. Weekly Cell Temperature

3.2.6 Weekly Open-Circuit Voltage

Weekly open-circuit voltage (V_{oc}) showed strong temperature dependence, with Sample C recording the highest values ($\approx 21.0 - 23.5$ V) and a peak in Weeks 14 - 16 when weekly CT was lower, as shown in Figures 16 and 15. Samples A and B remained more stable around 19.0 - 20.5 V, reflecting similar material characteristics and moderate thermal sensitivity. V_{oc} declined after Week 16 as CT increased, aligning with the sustained irradiance levels in Figure 11 and reinforcing the inverse CT - V_{oc} relationship. Overall, the weekly V_{oc} trends highlight the thermal vulnerability of PV modules in Afaka's hot, low - humidity climate and the importance of selecting technologies with low temperature coefficients.

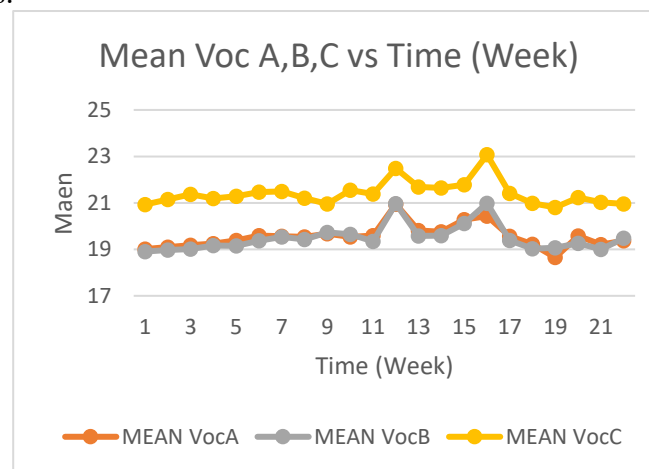


Figure 16. Weekly Voc for Samples A, B, C

3.3 Correlation Analysis

3.3.1 Relationship Between Global Solar Radiation and Open-Circuit Voltage (V_{oc})

Open-circuit voltage (V_{oc}) showed virtually no dependence on global radiation, as the near-zero regression slopes and very low R^2 values in Figure 17 confirm for all three modules. Instead, V_{oc} behaviour is dominated by cell temperature (CT), which rises sharply with irradiance as shown in Figures 3, 12 and 15. This thermal effect explains the midday and late-season voltage depressions in Figures 8 - 10, Figure 14 and Figure 16, consistent with the negative temperature coefficient of V_{oc} . Overall, the radiation - V_{oc} scatter reinforces that temperature, not irradiance, is the primary environmental factor limiting voltage output in Afaka's climate.

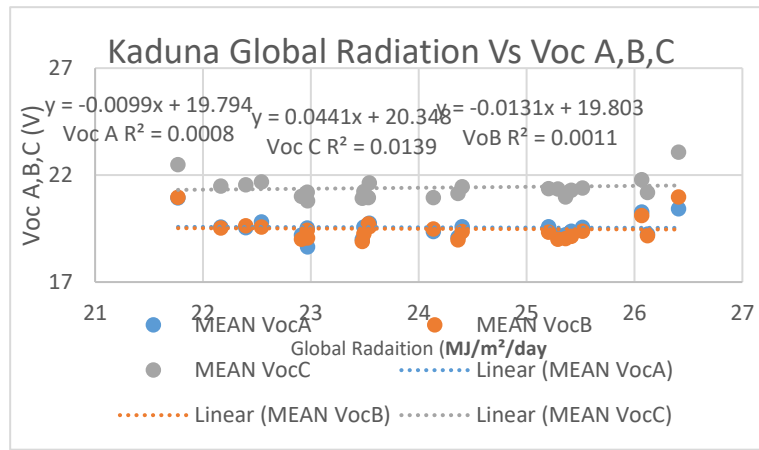


Figure 17. Global Radiation vs Voc

3.3.2 Relationship Between Global Solar Radiation and Short-Circuit Current (Isc)

Short-circuit current (Isc) increased with global radiation, as the positive regression slopes in Figure 18 show for all three modules, confirming irradiance as the dominant driver. Sample A displayed the strongest radiation sensitivity, followed by Sample C, while Sample B showed the weakest response, consistent with material differences. These trends align with the daily and hourly Isc patterns in Figures 5 - 7 and Figure 13, where current peaks coincide with maximum irradiance. Overall, the radiation - Isc relationship confirms that irradiance controls current output, while temperature plays only a minor secondary role.

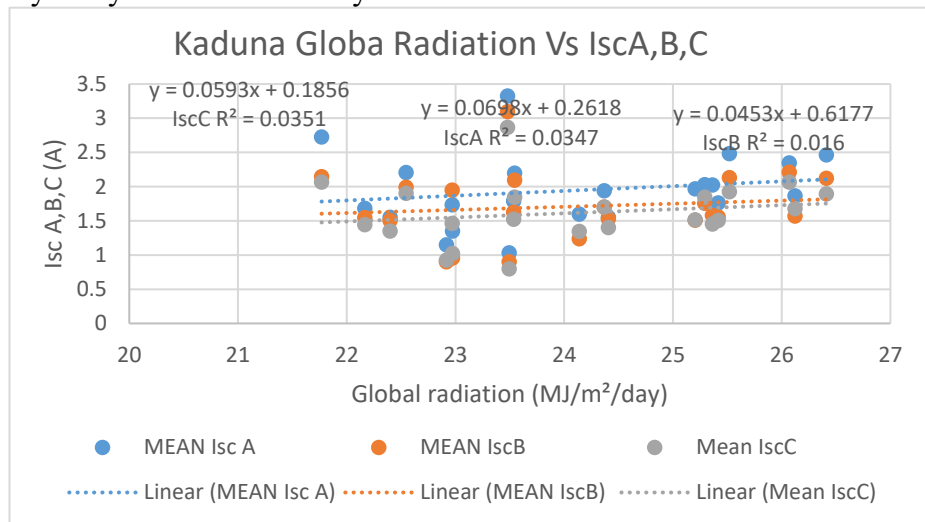


Figure 18. Global Radiation vs Isc

3.3.3 Relationship Between Global Solar Radiation and Ambient Temperature (AT)

Ambient temperature (AT) showed only a weak positive correlation with radiation, as the small slope and low R² value in Figure 19 indicate. The large scatter reflects additional influences such as wind, cloud cover, dust and moisture variability, which modulate AT independently of irradiance. This weak relationship contrasts with the much stronger irradiance-driven heating of cell temperature (CT) seen in Figures 3 and 12. Overall, the radiation - AT pattern shows that AT alone does not fully represent the thermal environment experienced by PV modules.

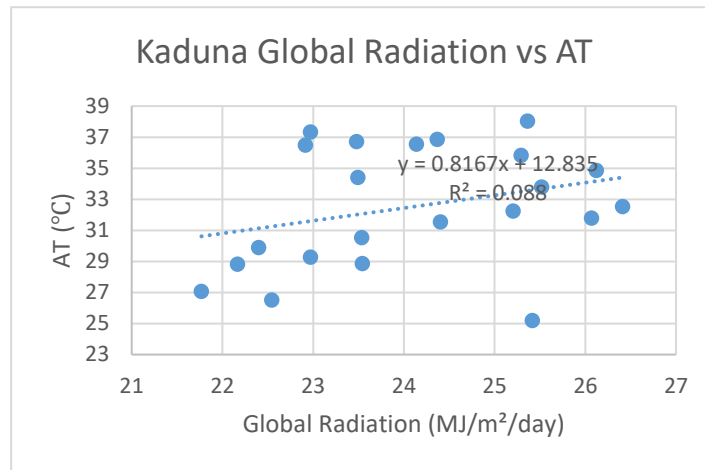


Figure 19. Global Radiation vs AT

3.3.4 Relationship Between Global Solar Radiation and Cell Temperature (CT)

Cell temperature (CT) showed a stronger positive correlation with radiation than ambient temperature, as the higher regression slope in Figure 20 demonstrates compared with Figure 19. CT rose more noticeably with irradiance because PV modules absorb light and heat directly, often exceeding AT by 10 - 15 °C, consistent with Figures 3 and 12. These higher CT values explain the voltage depressions in Figures 8 - 10, Figure 14 and Figure 16, reflecting the negative temperature coefficient of V_{oc} . Overall, the radiation - CT relationship highlights thermal loading as a central driver of PV performance in Afaka's climate.

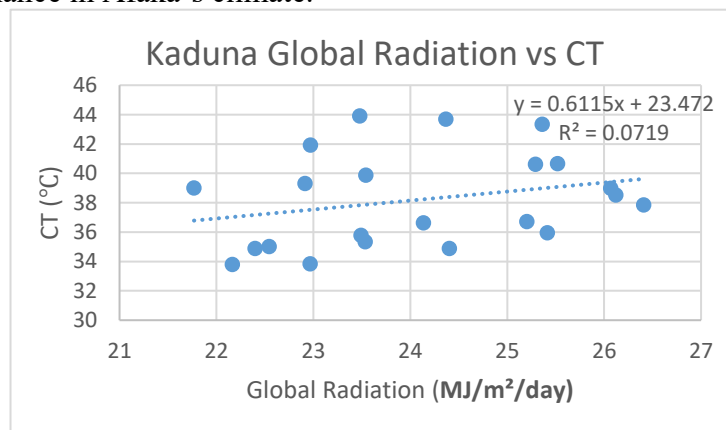


Figure 20. Global Radiation vs CT

3.3.5 Relationship Between Global Solar Radiation and Relative Humidity (RH)

Relative humidity (RH) showed virtually no dependence on radiation, as the near-zero slope and R^2 value in Figure 21 confirm. This independence matches the daily and hourly RH behaviour in Figures 2 and 12, where RH responds to temperature - driven changes in saturation vapour pressure rather than irradiance. RH nonetheless influences thermal performance by modulating convective cooling, with low RH contributing to the elevated CT values in Figures 3, 12 and 15. Overall, the radiation - RH relationship highlights humidity as a separate but influential factor in PV thermal behaviour.

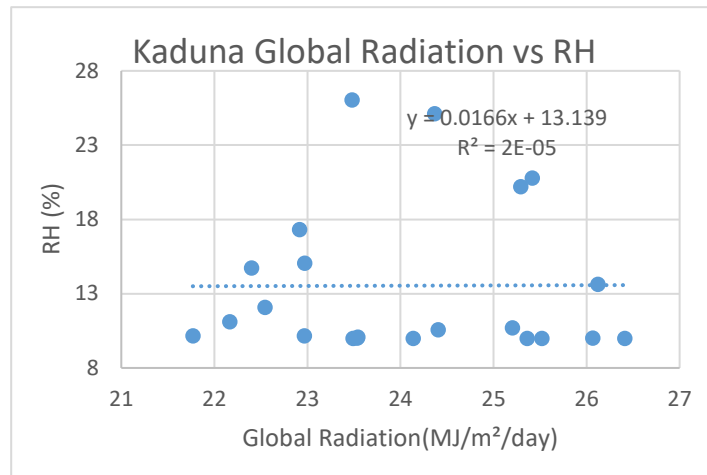


Figure 21. Global Radiation vs RH

3.3.6 Relationship Between Cell Temperature (CT) and Ambient Temperature (AT)

Cell temperature (CT) showed a moderate positive correlation with ambient temperature (AT), rising by about 0.55 °C per 1 °C increase in AT as indicated by the regression in Figure 22. CT consistently exceeded AT because modules absorb radiation directly, matching the daily and hourly patterns in Figures 3 and 12. This CT - AT coupling explains the midday voltage depressions in Figures 8 - 10, Figure 14 and Figure 16, driven by the negative temperature coefficient of V_{oc} . Overall, the relationship highlights how ambient conditions shape baseline thermal loading while irradiance drives additional heating in Afaka's climate.

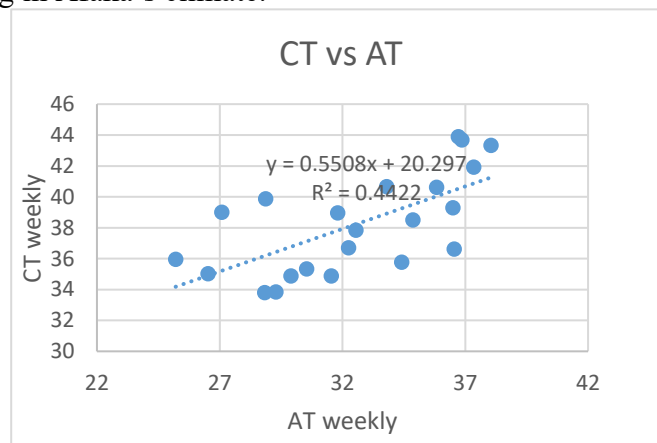


Figure 22. CT vs AT

3.3.7 Relationship Between Cell Temperature (CT) and Relative Humidity (RH)

Cell temperature (CT) showed only a weak positive correlation with relative humidity (RH), as the small slope and modest R^2 value in Figure 23 indicate. RH does not directly control module heating; instead, low RH suppresses convective cooling, contributing to the elevated CT values seen in Figures 3 and 15. The highest CT episodes occurred during very dry periods, explaining the pronounced voltage reductions in Figures 8 - 10, Figure 14 and Figure 16. Overall, the CT - RH relationship shows that while RH is not a primary driver of CT, low humidity amplifies thermal stress in Afaka's hot, dry climate.

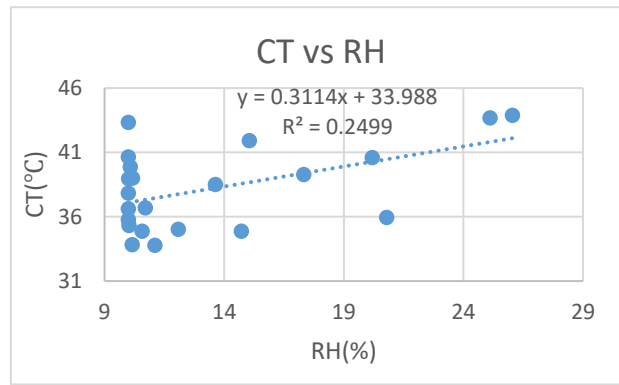


Figure 23. CT vs RH

3.3.8 Relationship Between Ambient Temperature (AT) and Relative Humidity (RH)

Ambient temperature (AT) showed only a very weak positive correlation with relative humidity (RH), as the small slope and low R^2 value in Figure 24 indicate. AT in Afaka is driven mainly by solar heating and atmospheric mixing, while RH responds to temperature-dependent changes in saturation vapour pressure rather than irradiance. Even with this weak statistical link, low RH still reduces convective cooling, contributing to the elevated CT values seen in Figures 3, 12 and 15. Overall, the AT - RH relationship shows that humidity does not control AT but helps shape the thermal conditions influencing PV module heating and performance.

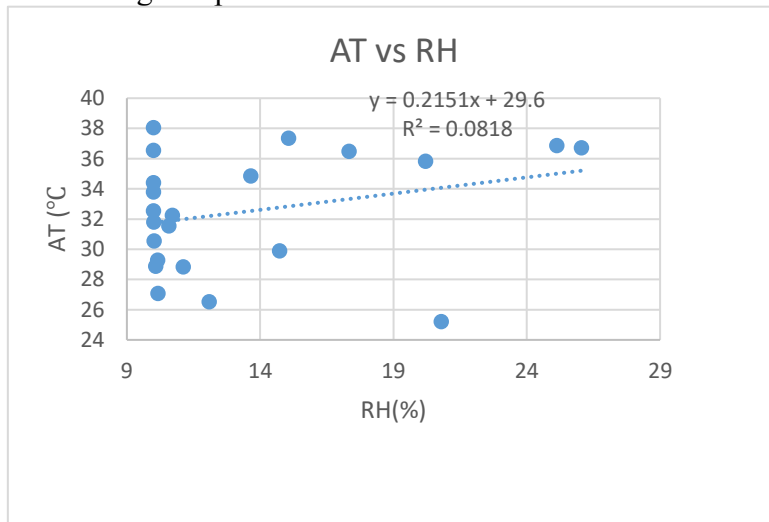


Figure 24. AT vs RH

3.4 Environmental and Electrical Behaviour of the PV Modules

Ambient temperature (AT) showed only a very weak positive correlation with relative humidity (RH), expressed by $AT = 0.2151 RH + 29.600$ ($R^2 = 0.0818$), confirming that humidity explains almost none of the variability in AT. This pattern mirrors observations from hot, arid regions such as Rajasthan, Oman and the UAE, where AT is driven mainly by solar heating and large scale air mass movement rather than moisture content. Low RH in Afaka reduces convective cooling, contributing to the elevated CT values seen in Figures 3, 12 and 15 which is like a desert climate behaviour reported in Morocco, Brazil and Australia. Rising CT increases intrinsic carrier concentration and reverse saturation current, reducing V_{oc} according to $V_{oc}(T) = V_{oc}(25^\circ C) + \beta(T - 25^\circ C)$, with Afaka's $>45^\circ C$ conditions producing 6 - 10% voltage loss, comparable to the 10 - 15% losses documented internationally in high-temperature PV environments. The strong inverse CT - V_{oc} trends in Figures 16 - 17 confirm that thermal loading not irradiance dominates voltage behaviour, consistent with global findings from hot, low humidity climates. These AT - RH - CT interactions explain the combined thermal environment that governs module heating and electrical response. Overall, Afaka's thermal stress profile aligns with international hot climate PV behaviour, reinforcing

the need for modules with low temperature coefficients, enhanced ventilation and thermally resilient designs to maintain performance in extreme environments.

Conclusions

This study shows that temperature not irradiance is the dominant factor controlling PV performance in Afaka's hot, low humidity climate, with CT consistently exceeding AT and driving voltage and efficiency losses. Module behaviour reflected these thermal constraints: Sample A produced the highest I_{sc} , Sample C the highest V_{oc} but with strong thermal sensitivity, while Sample B performed weakest overall. The observed CT peaks of 45–52 °C correspond to 8–12% efficiency losses, consistent with the temperature - dependent models

$$\eta = \eta_{ref}(1 - \beta(T_c - 25))$$

and

$$V_{oc}(T) = V_{oc}(25^\circ\text{C}) + \beta(T - 25).$$

These relationships confirm that thermal loading is the primary performance limiter, underscoring the need for modules with low temperature coefficients, enhanced ventilation, and designs that reduce heat accumulation. Overall, climate specific thermal management is essential for reliable PV deployment in hot, dry regions.

Recommendations

PV deployment in hot, dry climates must prioritize modules with low magnitude negative temperature coefficients, since voltage loss follows

$$V_{oc}(T) = V_{oc}(25^\circ\text{C}) + \beta(T - 25).$$

Thermal management is essential because efficiency decreases according to

$$\eta = \eta_{ref}(1 - \beta(T_c - 25)).$$

Elevated mounting, open rack designs, enhanced ventilation and reflective ground surfaces should be adopted to reduce T_c . Dense packing and restricted airflow must be avoided to prevent heat accumulation. Continuous monitoring of CT, AT and RH is recommended for real time thermal control and protective derating. PV models for hot regions should incorporate temperature-dependent derating, while future research should address long term thermal degradation mechanisms to improve module resilience.

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