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Correlation Analysis of Environmental Parameters and Photovoltaic Module Performance in a Tropical Savannah Climate

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This study investigates relationships between key environmental parameters and the performance of three commercially available polycrystalline photovoltaic (PV) modules operating under tropical savannah conditions in Afaka, Kaduna, Nigeria. A 151-day field experiment evaluated how cell temperature (CT), ambient temperature (AT), relative humidity (RH), and global solar radiation influenced module electrical behaviour. Environmental and electrical data collected under identical outdoor conditions were analysed using correlation and regression techniques. CT and AT showed a strong positive relationship (R^2 = 0.8583), identifying ambient temperature as a major driver of the module temperature. AT and RH showed a strong negative relationship (R^2 = 0.8772), while CT and RH exhibited a moderate negative relationship (R^2 = 0.6549). Global solar radiation ranged from 18 to 29 MJ m^{-2} day^{-1}, contributing to module output variations. Open-circuit voltage depended weakly on solar radiation, whereas short-circuit current increased with radiation despite relatively low coefficients of determination attributable to environmental variability. Comparative analysis revealed distinct electrical responses among modules under identical climatic conditions. These findings demonstrate that temperature-related environmental factors play a dominant role in photovoltaic performance and should inform PV system selection, performance prediction, and deployment in tropical climates.

Keywords: *solar energy conversion; cell temperature; solar irradiance; relative humidity; tropical savanna climate.*



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1. INTRODUCTION

The increasing global demand for clean and sustainable energy has intensified the deployment of renewable energy technologies, with solar photovoltaic (PV) systems emerging as one of the most promising options for electricity generation. Photovoltaic technology offers several advantages, including environmental sustainability, low operational costs, scalability, and suitability for both grid connected and standalone applications. In developing countries, particularly those located within the tropical belt, PV systems have become an important solution for addressing energy shortages and extending electricity access to remote and underserved communities. (Bamisile et al., 2025; Rehman et al., 2025).

Nigeria possesses abundant solar energy resources due to its geographical location within a region of high annual solar irradiance. Consequently, photovoltaic systems are increasingly being adopted for domestic, commercial, institutional, and agricultural applications. However, the performance of PV modules under actual outdoor conditions is strongly influenced by environmental factors. Unlike standard test conditions (STC), where module performance is evaluated under controlled laboratory environments, field-installed PV systems operate under continuously varying climatic conditions that can significantly affect their electrical output. (Owolabi et al., 2023; Awai et al., 2024).

Among the environmental parameters influencing PV performance, cell temperature, ambient temperature, relative humidity and solar radiation are particularly important. In tropical savannah

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regions, PV modules are frequently exposed to high solar irradiance and elevated temperatures, which can alter the electrical characteristics of solar cells and affect overall system performance. Understanding the interactions between these environmental variables and photovoltaic output is therefore essential for accurate performance prediction, optimal module selection, and efficient system design. (Santos et al., 2022; Rehman et al., 2025).

Numerous studies have identified temperature as one of the most influential environmental factors affecting photovoltaic performance. As cell temperature increases, the electrical characteristics of photovoltaic cells are altered, leading to reductions in open-circuit voltage and overall power output. Although short-circuit current tends to increase slightly with temperature, the increase is generally insufficient to compensate for the associated voltage losses, resulting in a net decline in module performance (Green, 1981; Skoplaki & Palyvos, 2009). The temperature dependence of photovoltaic electrical characteristics is fundamentally linked to semiconductor behaviour and the reduction of band-gap energy with increasing temperature (Sze & Ng, 2007). Consequently, elevated operating temperatures have been recognised as a major source of performance degradation in photovoltaic systems, particularly in hot and semi-arid regions where thermal stress is more pronounced. (Shaker et al., 2024; Keddouda et al., 2024; Awai et al., 2024).

Solar irradiance is another critical environmental parameter governing photovoltaic operation. An increase in incident solar radiation enhances photon absorption and promotes the generation of electron-hole pairs within photovoltaic materials, thereby increasing current production. Numerous studies have reported a strong positive relationship between irradiance and short-circuit current, identifying solar radiation as one of the principal drivers of photovoltaic energy generation. However, increased irradiance is often accompanied by a corresponding rise in module temperature, which may partially offset performance gains through temperature-induced voltage reductions. The distinction between laboratory-based module performance and actual field performance has been widely recognised in photovoltaic engineering, where environmental conditions deviate substantially from Standard Test Conditions (Messenger & Ventre, 2010; Duffie & Beckman, 2013). (Bamisile et al., 2025; Santos et al., 2022).

Relative humidity also influences photovoltaic performance, although its effects are generally indirect. Variations in atmospheric moisture can affect solar transmissivity, module cooling processes, and the deposition of dust and airborne contaminants on panel surfaces. Previous investigations have reported significant interactions among humidity, temperature, and photovoltaic performance, particularly within tropical and humid environments where atmospheric conditions exhibit considerable temporal variability. (Njok & Kamgba, 2023; Rehman et al., 2025).

Several studies have examined photovoltaic performance under tropical climatic conditions; however, many have concentrated on individual environmental variables or specific photovoltaic technologies. Research conducted in West Africa and other tropical regions has highlighted the importance of accounting for local climatic conditions when evaluating photovoltaic system behaviour, as environmental influences often differ significantly from those observed under controlled laboratory environments. These studies have consistently emphasised the need for long-term field investigations capable of capturing realistic environmental variability and providing reliable performance assessments under actual operating conditions. Such investigations are essential for improving performance prediction, module selection, system design, and the overall optimisation of photovoltaic deployment in tropical savannah environments. (Stankov et al., 2024; Ogbulezie et al., 2026).

Despite the growing adoption of photovoltaic systems in Nigeria, relatively few studies have conducted comparative evaluations of commercially available PV module brands operating under identical outdoor conditions in Northern Nigeria. Existing investigations have often focused on general performance assessment without providing detailed analysis of how environmental parameters interact and collectively influence module behaviour. (Owolabi et al., 2023; Ogbulezie et al., 2026).

Furthermore, limited attention has been given to correlation-based assessments that quantitatively examine the relationships among cell temperature, ambient temperature, relative humidity, solar radiation and electrical performance parameters. Such analyses are essential for identifying the dominant environmental factors affecting photovoltaic operation and for improving the

reliability of performance prediction models in tropical savannah climates. (Njok & Kamgba, 2023; Ogbulezie et al., 2026).

This study aims to investigate the relationships among cell temperature, ambient temperature, relative humidity, global solar radiation and photovoltaic module performance under tropical savannah conditions. A 151-day field experiment was conducted using three commercially available polycrystalline photovoltaic modules installed under identical environmental conditions at Afaka, Kaduna, Nigeria. Correlation and regression analyses were employed to quantify the interactions among environmental variables and to evaluate their influence on open-circuit voltage and short-circuit current. The findings provide insight into the environmental determinants of photovoltaic performance and contribute to the optimization of PV deployment in tropical regions.

2. METHOD

2.1 Study Area

The study was conducted at the Photovoltaic Experimental Site of the Physics Department, Nigerian Defence Academy (NDA), Afaka, Kaduna State, Nigeria. The geographical hierarchy of the study location is illustrated in Figure 1, showing the progression from Nigeria to Kaduna State, Afaka, the Nigerian Defence Academy and finally the specific experimental site used for the investigation.

Figure 1 shows that the experimental site is located within the Physics Department of the Nigerian Defence Academy in Afaka, Kaduna State, Northern Nigeria. Afaka lies within the tropical savannah climatic zone, which is characterised by high solar irradiance, elevated ambient temperatures and distinct wet and dry seasons. These climatic conditions make the area suitable for investigating the influence of environmental parameters on photovoltaic module performance under real outdoor operating conditions.

The study area experiences abundant solar energy throughout most of the year, making it representative of locations with significant photovoltaic energy potential in Northern Nigeria. During the dry season, ambient temperatures are generally high, while relative humidity remains moderate to low. Such conditions significantly influence photovoltaic operating temperatures and electrical output, thereby providing an appropriate environment for examining the interactions among cell temperature, ambient temperature, relative humidity, solar radiation and photovoltaic module performance.

Conducting the experiment unZder natural environmental conditions enabled the photovoltaic modules to be evaluated under actual field operating circumstances rather than controlled laboratory conditions. Consequently, the results obtained are more representative of the environmental challenges and performance characteristics likely to be encountered during photovoltaic deployment in tropical savannah environments.

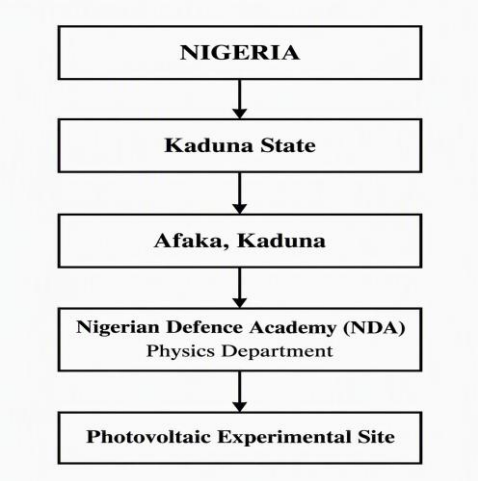


Figure 1. Hierarchical representation of the study location from Nigeria to the Photovoltaic Experimental Site at the Nigerian Defence Academy (NDA), Afaka, Kaduna State.

2.2 Photovoltaic Modules

Three commercially available polycrystalline photovoltaic modules were selected for the study. The modules were designated as Sample A (Bona), Sample B (Komas) and Sample C (Mpower). It should be noted that only one module from each brand ($n = 1$) was included in the experiment. Therefore, the results obtained represent the performance characteristics of the individual modules tested and should not be interpreted as definitive performance indicators of all modules manufactured under the respective brands.

All modules were installed on wooden support structures and mounted at the same tilt angle and orientation facing true south to maximise solar exposure and ensure uniform environmental conditions throughout the study period. The modules were deployed in an open outdoor environment free from significant shading and physical obstructions. This arrangement minimised geometric effects and enabled a direct comparison of the responses of the individual modules to environmental variations under identical operating conditions.

The manufacturer specifications of the investigated photovoltaic modules under Standard Test Conditions (STC) are presented in Table 1. Although all three modules possessed the same rated power output of 80 W, differences existed in their voltage and current characteristics. Sample C exhibited the highest open-circuit voltage (22.32 V), whereas Sample A exhibited the highest short-circuit current (4.85 A). These differences provided a basis for investigating how module-specific electrical characteristics influence outdoor performance under tropical savannah climatic conditions.

2.3 Measurement Instruments

Environmental and electrical parameters were measured using calibrated instruments throughout the experimental period to ensure accurate data acquisition and reliable performance evaluation. Open-circuit voltage (Voc), current and cell temperature were measured using an MS2101 digital multimeter, while short-circuit current measurements were obtained using a DC clamp meter. Ambient temperature and relative humidity were monitored using an HTC-1 digital thermometer-hygrometer positioned adjacent to the photovoltaic modules to ensure that the recorded environmental conditions accurately represented the operating environment of the panels.

The photovoltaic modules were mounted on wooden support structures and oriented toward true south using a compass to maximise solar radiation exposure. Electrical connections were established using 1-mm gauge cables, while temperature sensors were attached to the rear surfaces of the modules using paper tape to enable continuous monitoring of cell temperature. Environmental and electrical measurements were recorded electronically using Microsoft Excel and simultaneously documented in a field logbook for verification and backup purposes.

Table 1. Manufacturer specifications of the investigated photovoltaic modules under standard test conditions (STC).

Parameter	Sample A	Sample B	Sample C
Rated Power, Pmax (W)	80	80	80
Open-circuit Voltage, Voc (V)	21.50	21.67	22.32
Short-circuit Current, Isc (A)	4.85	4.80	4.49
Voltage at Maximum Power, Vmp (V)	17.50	17.93	18.00
Current at Maximum Power, Imp (A)	4.58	4.48	4.44
Power Tolerance (%)	±5	±5	±5
Maximum System Voltage (V)	1000	750	1000
Standard Test Conditions	AM 1.5, 1000 W m^{-2}, 25 °C	AM 1.5, 1000 W m^{-2}, 25 °C	AM 1.5, 1000 W m^{-2}, 25 °C

Weatherproof covers were used to protect the monitoring equipment and associated connections from environmental exposure during the study period. Additional installation accessories, including cable ties, electrical tape, screwdrivers, marker pens, and identification labels, were employed to ensure proper installation, maintenance, and identification of the experimental system. Safety measures were also observed throughout the study period, including the availability of a first-aid kit during installation and data collection activities.

2.3.1 Measurement Uncertainty

To improve the reliability of the experimental results, all environmental and electrical measurements were obtained using calibrated instruments and repeated observations throughout the 151-day monitoring period. Instrument readings were periodically checked to minimise systematic errors and ensure measurement consistency. Environmental variables, including cell temperature, ambient temperature, and relative humidity, as well as electrical parameters such as open-circuit voltage and short-circuit current, were recorded under identical operating conditions for all three photovoltaic modules.

Repeated measurements, consistent installation procedures, and routine verification of instrument readings helped to reduce random measurement errors and improve data reliability. Furthermore, the use of identical experimental conditions for all modules minimised external sources of variability and enabled meaningful comparison of module performance. Consequently, the reported values represent the best estimates of the environmental and electrical parameters under actual field operating conditions.

2.4 Data Collection Procedure

The field investigation was conducted over a period of 151 consecutive days under natural outdoor conditions. Throughout the monitoring period, environmental data and photovoltaic performance parameters were recorded under identical operating conditions for all three photovoltaic modules. Measurements were obtained hourly between 08:00 h and 17:00 h. Cell temperature (CT), ambient temperature (AT), and relative humidity (RH) were recorded using environmental monitoring instruments positioned close to the photovoltaic modules to ensure representative measurements of the surrounding microclimate. Temperature sensors attached to the rear surfaces of the modules provided real-time measurements of cell temperature. Open-circuit voltage (Voc) was measured using the digital multimeter, while short-circuit current (Isc) was measured using the DC clamp meter by briefly closing a switch across the module terminals.

Global solar radiation data were obtained from the Nigerian Meteorological Agency (NiMet). Daily radiation records were subsequently organised and averaged into weekly datasets to facilitate trend identification and minimise short-term fluctuations arising from transient atmospheric conditions such as cloud cover, haze, and dust. To improve data interpretation, hourly measurements were first averaged to obtain representative daily values. The daily observations were subsequently aggregated into weekly means, resulting in twenty-two weekly datasets that were used in the correlation, regression, and comparative performance analyses.

Table 2. Instruments used for environmental and electrical measurements.

Instrument	Model	Purpose
Digital Multimeter	MS2101	Measurement of open-circuit voltage (Voc), current, and cell temperature
Digital Thermometer-Hygrometer	HTC-1	Measurement of ambient temperature and relative humidity
DC Clamp Meter	Model not recorded	Measurement of short-circuit current (Isc)
Solar Radiation Source	Nigerian Meteorological Agency (NiMet) Data	Kaduna Global solar radiation measurements

2.5 Data Analysis

The collected environmental and electrical data were analysed using descriptive statistical techniques, correlation analysis, and linear regression methods. Correlation analysis was employed to quantify the strength and direction of relationships among cell temperature, ambient temperature, relative humidity, and photovoltaic performance indicators. Attention was given to the relationships between:

- Cell temperature and ambient temperature (CT-AT);
- Cell temperature and relative humidity (CT-RH); and
- Ambient temperature and relative humidity (AT-RH).

Linear regression analysis was further employed to evaluate the influence of environmental parameters on photovoltaic electrical performance. Regression models were developed to examine the relationships between global solar radiation and the measured electrical parameters, namely open-circuit voltage (Voc) and short-circuit current (Isc).

The coefficient of determination (R^2) was used to evaluate the extent to which variations in one variable could be explained by changes in another variable. Higher R^2 values indicate stronger relationships between variables, whereas lower values suggest that additional environmental or operational factors contributed to the observed variability.

The resulting statistical analyses provided the basis for assessing the interactions among environmental parameters and for comparing the performance characteristics of the three photovoltaic module brands under tropical savannah climatic conditions.

2.6 Research Flowchart

The overall research methodology adopted in this study is illustrated in Figure 1. The flowchart summarizes the major stages of the investigation, beginning with site selection and module installation and ending with statistical analysis and comparative performance evaluation.

Figure 2 presents the methodological framework adopted for the study. Three commercially available polycrystalline photovoltaic modules were installed under identical outdoor conditions at Afaka, Kaduna. Environmental parameters, including cell temperature (CT), ambient temperature (AT), relative humidity (RH), and global solar radiation, were monitored throughout the 151-day study period.

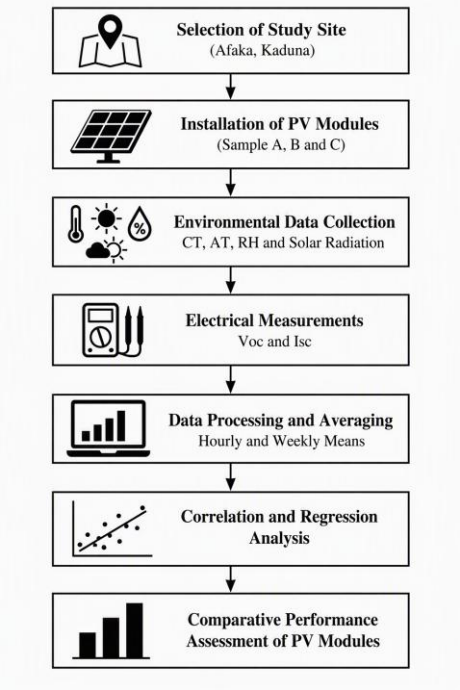


Figure 2. Research flowchart for data collection, correlation analysis and performance evaluation of photovoltaic modules

Simultaneously, the electrical performance parameters of the modules, namely open-circuit voltage (Voc) and short-circuit current (Isc), were measured. The collected data were processed through hourly and weekly averaging procedures before correlation and regression analyses were applied to quantify relationships among environmental variables and photovoltaic performance indicators. Finally, a comparative assessment was conducted to evaluate the response of the three module brands under tropical savannah climatic conditions.

3. RESULTS AND DISCUSSION

3.1 Global Solar Radiation Characteristics

Figure 3 presents the daily variation of global solar radiation recorded during the 151-day monitoring period. The observed radiation values ranged from approximately 18 to 29 MJ m^{-2} day^{-1}, indicating substantial variability in solar energy availability throughout the study period. The fluctuations observed in the figure are typical of tropical savannah environments, where cloud cover, atmospheric aerosols, humidity variations, and changing weather conditions influence the amount of solar radiation reaching the earth's surface. Periods of higher radiation were generally associated with clearer atmospheric conditions, while lower radiation values reflected increased cloudiness and atmospheric attenuation. Solar irradiance variability and atmospheric effects on PV output are consistent with the mechanisms reviewed by Bamisile et al (2025).

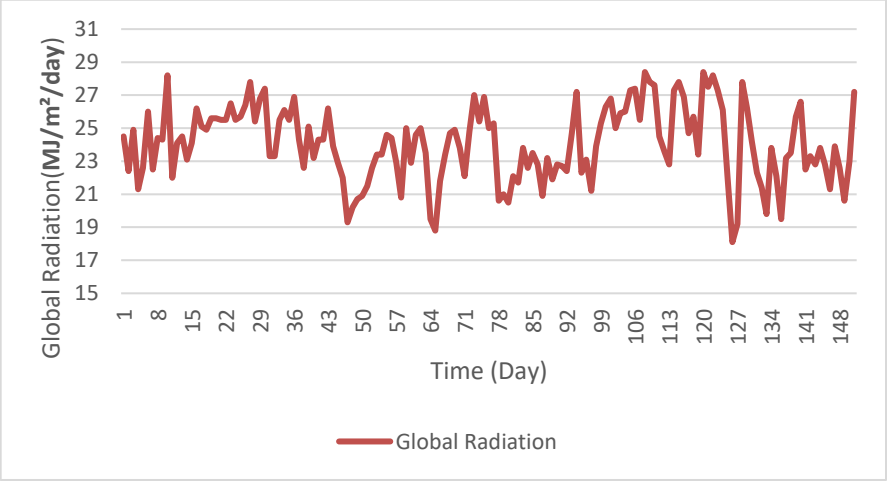


Figure 3. Daily Global Solar Radiation Distribution

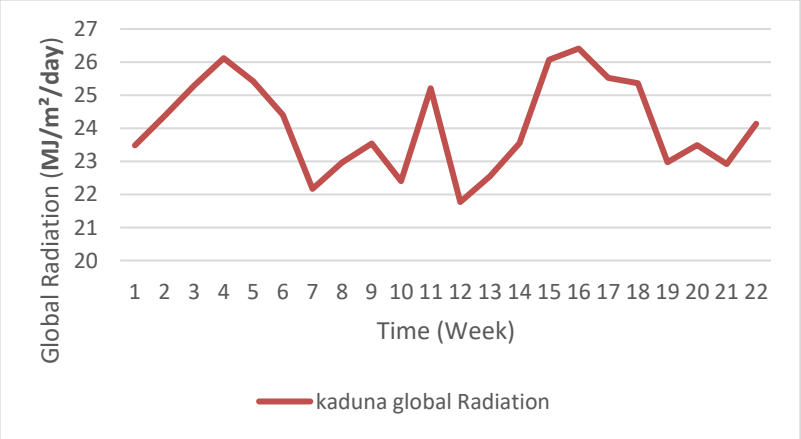


Figure 4. Weekly Global Solar Radiation Trends

Although day-to-day fluctuations were evident, Figure 3 shows that solar radiation remained consistently high throughout most of the monitoring period, confirming the favourable solar energy

potential of the study area. Such high radiation levels are advantageous for photovoltaic electricity generation because solar radiation constitutes the primary energy source driving photovoltaic conversion processes.

Daily solar radiation data were averaged into weekly values to reduce short-term fluctuations (Figure 4). Weekly radiation ranged from approximately 21 to 27 MJ m^{-2} day^{-1}, with peaks exceeding 26 MJ m^{-2} day^{-1} in Weeks 4, 11, 15, and 16, and lower values in Weeks 7 and 12. These variations may have influenced photovoltaic operating conditions and electrical performance throughout the study period.

The results indicate that Afaka possesses favourable solar radiation characteristics for photovoltaic deployment. However, the observed fluctuations demonstrate that environmental variability should be considered when evaluating photovoltaic performance under outdoor operating conditions. Understanding the temporal distribution of solar radiation is particularly important because it influences cell temperature, electrical output, and the overall performance of photovoltaic systems operating under tropical savannah climatic conditions.

3.2 Environmental Parameter Variations

The hourly variations of cell temperature, ambient temperature, and relative humidity provide insight into the environmental conditions under which the photovoltaic modules operated during the monitoring period. These parameters are particularly important because they directly influence photovoltaic operating behaviour and electrical performance.

Figure 5 illustrates the variation of cell temperature with time. The average cell temperature increased steadily from approximately 27°C at 08:00 h to a maximum value of about 45.5°C at 13:00 h, after which it gradually declined to approximately 32°C by 17:00 h. The observed trend reflects the increasing intensity of solar radiation during the morning hours and the associated absorption of solar energy by the photovoltaic modules. Since only a portion of the incoming solar radiation is converted into electrical energy, a significant fraction is dissipated as heat, resulting in elevated cell temperatures. The peak temperature recorded around midday corresponds closely with the period of maximum solar irradiance and demonstrates the substantial thermal loading experienced by photovoltaic modules under tropical outdoor conditions.

A similar diurnal pattern was observed for ambient temperature, as shown in Figure 6. Ambient temperature increased from approximately 22°C at 08:00 h to a peak value of about 38°C at 13:00 h, before gradually decreasing during the afternoon hours. Although both temperatures followed similar temporal trends, ambient temperature remained consistently lower than cell temperature throughout the day. The difference between the two variables confirms the additional heating effect associated with direct solar exposure of the photovoltaic modules. This observation further supports the expectation that module temperatures exceed surrounding air temperatures during periods of intense solar radiation.

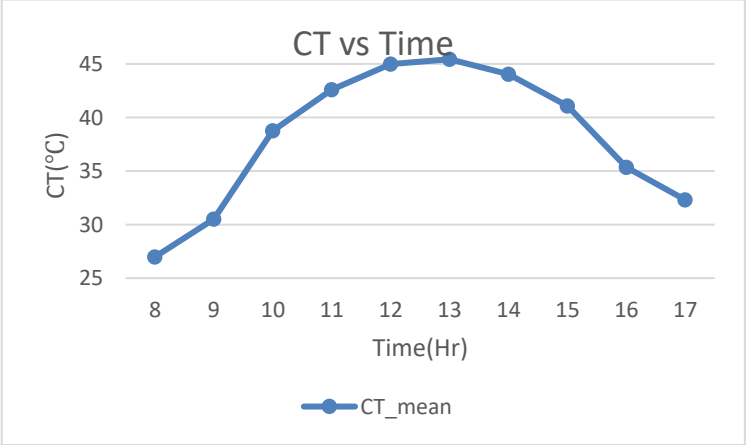


Figure 5. Variation of cell temperature with time.

In contrast, Figure 7 shows that relative humidity exhibited an inverse trend with respect to temperature. Relative humidity decreased from about 22% at 08:00 h to approximately 11% between

12:00 h and 15:00 h, after which a slight increase was observed towards the evening. This behaviour is characteristic of tropical savannah climates, where increasing air temperatures enhance the moisture-holding capacity of the atmosphere, resulting in lower relative humidity values during periods of maximum heating.

The combined behaviour of these environmental parameters demonstrates the strong thermal conditions that prevailed during the study period. The simultaneous occurrence of high cell temperatures, elevated ambient temperatures, and reduced relative humidity during midday periods indicates that photovoltaic modules operating in the study area are subjected to significant thermal stress. Such conditions are expected to influence photovoltaic electrical characteristics because elevated temperatures affect semiconductor properties and can alter voltage output, current generation, and overall module performance. These environmental trends therefore provide an important basis for understanding the correlation analyses and performance evaluations presented in the subsequent sections.

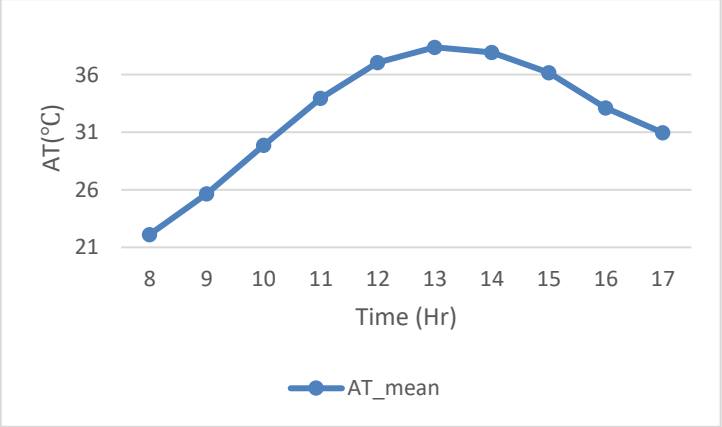


Figure 6. Variation of ambient temperature with time.

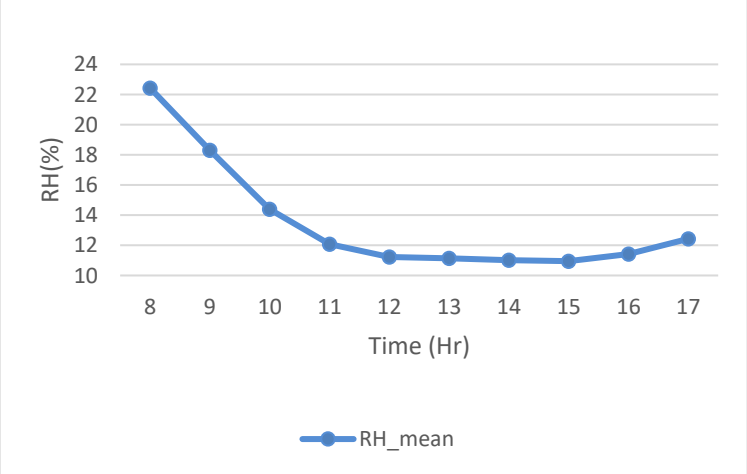


Figure 7. Variation of relative humidity with time.

3.3 Correlation Analysis of Enviromental Parameters

Correlation analysis was performed to quantify the relationships among the environmental parameters influencing photovoltaic module operation. Understanding these interactions is important because photovoltaic modules operate under continuously changing atmospheric conditions, where temperature, humidity, and solar radiation affect both module temperature and electrical performance. The analysis also provides a basis for identifying the strongest environmental relationships and assessing their potential implications for photovoltaic performance under tropical savannah conditions.

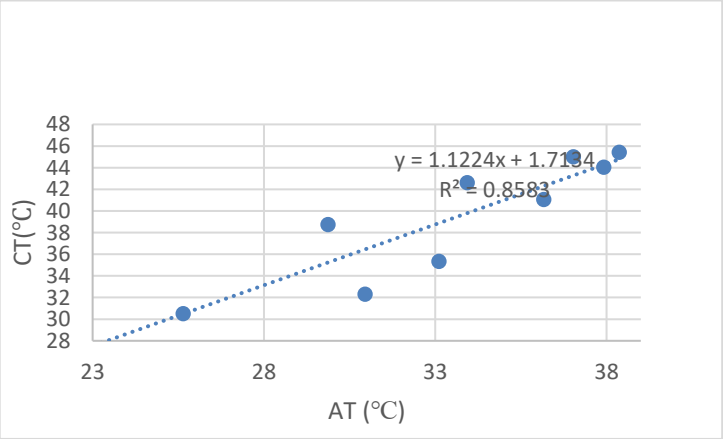


Figure 8. Relationship between cell temperature and ambient temperature.

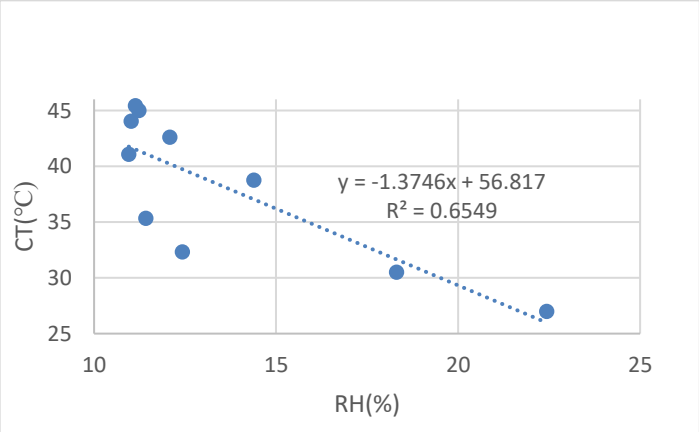


Figure 9. Relationship between cell temperature and relative humidity.

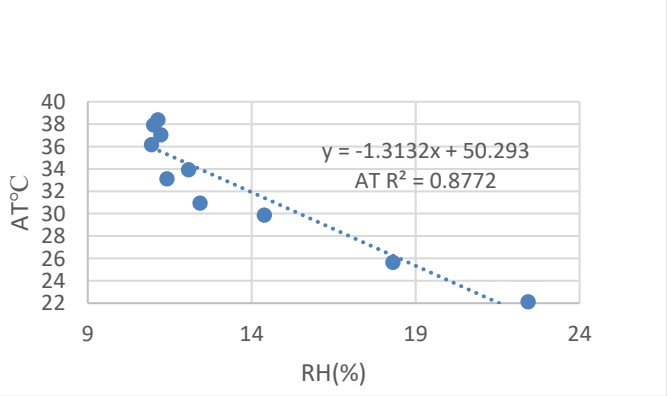


Figure 10. Relationship between ambient temperature and relative humidity.

Figure 8 illustrates the relationship between cell temperature and ambient temperature. A strong positive correlation was obtained, with a coefficient of determination of $R^2 = 0.8583$ and a regression equation of CT = 1.1224AT + 1.7164. This result indicates that approximately 85.83% of the variation in cell temperature can be explained by changes in ambient temperature. The strong correlation confirms that ambient temperature is one of the principal factors governing the thermal behaviour of photovoltaic modules. Similar observations have been reported in thermal modelling studies of photovoltaic modules operating under outdoor conditions, where module temperature was found to depend strongly on ambient conditions and solar loading (Faiman, 2008). However, cell temperatures remained consistently higher than ambient temperatures throughout the monitoring period, indicating the additional influence of direct solar heating. The regression slope greater than unity further suggests that increases in ambient

temperature are accompanied by proportionally higher increases in module temperature due to the absorption of solar energy by the photovoltaic cells. This finding highlights the significant thermal stress to which photovoltaic modules are exposed under tropical outdoor conditions. Similar dependencies of module operating temperature on ambient conditions have been reported by Santos et al (2022) and Keddouda et al (2024).

Figure 9 presents the relationship between cell temperature and relative humidity. The regression analysis yielded a moderate negative correlation with a coefficient of determination of R^2 = 0.6549 and a regression equation of CT = -1.3746RH + 56.817. The negative slope indicates that increases in cell temperature were generally associated with decreases in relative humidity. Approximately 65.49% of the observed variation in cell temperature can be explained by changes in humidity levels. This inverse relationship reflects the typical atmospheric conditions of tropical savannah environments, where higher temperatures are normally accompanied by lower humidity values. Although the correlation is weaker than that observed between cell temperature and ambient temperature, it nevertheless demonstrates a substantial interaction between thermal conditions and atmospheric moisture content. The remaining unexplained variability may be attributed to other environmental factors such as solar radiation intensity, cloud cover, and local atmospheric circulation. The relevance of humidity to outdoor photovoltaic behaviour has also been examined in Nigerian field conditions by Njok and Kamgba (2023).

The relationship between ambient temperature and relative humidity is shown in Figure 10. A strong negative correlation was observed, with a coefficient of determination of R^2 = 0.8772 and a regression equation of AT = -1.3132RH + 50.293. This represents the strongest environmental relationship obtained in the study, indicating that approximately 87.72% of the variation in ambient temperature can be explained by corresponding changes in relative humidity. The result reflects the fundamental thermodynamic behaviour of the atmosphere. As air temperature increases, the moisture-holding capacity of the atmosphere also increases, causing relative humidity to decrease when the amount of water vapour remains relatively unchanged. The strong inverse relationship observed is characteristic of tropical savannah climates and confirms the close coupling between temperature and atmospheric moisture conditions within the study area. Comparable field responses have been discussed in photovoltaic temperature-model investigations (Santos et al., 2022; Keddouda et al., 2024).

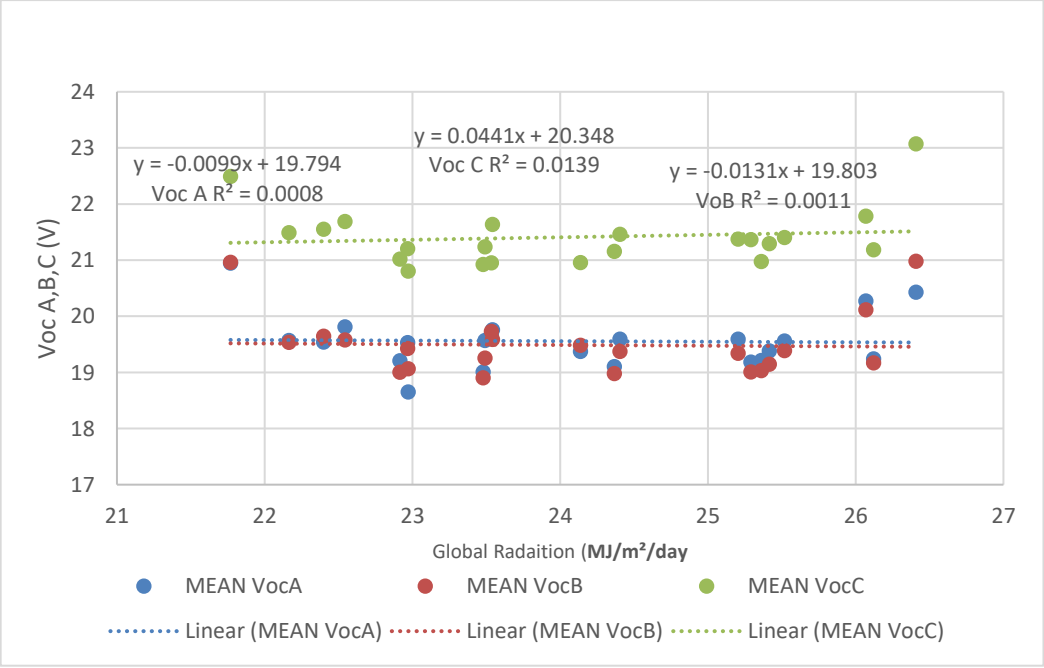


Figure 11. Relationship between global solar radiation and open-circuit voltage for samples A, B and C.

The correlation results demonstrate that the environmental variables investigated in this study are highly interconnected. The strongest relationship was observed between ambient temperature and

relative humidity (R^2 = 0.8772), followed closely by the relationship between cell temperature and ambient temperature (R^2 = 0.8583). The cell temperature-relative humidity relationship was comparatively weaker but remained statistically significant (R^2 = 0.6549). These findings indicate that temperature-related variables constitute the dominant environmental factors influencing photovoltaic operating conditions in Afaka. The strong correlations further demonstrate that photovoltaic performance in tropical savannah climates is governed by a combination of interrelated environmental parameters rather than by a single atmospheric variable. Consequently, accurate assessment of photovoltaic performance requires simultaneous consideration of temperature and humidity effects alongside solar radiation availability.

3.4 Relationship Between Solar Radiation and Photovoltaic Performance

3.4.1 Global Solar Radiation and Open-Circuit Voltage

The relationship between global solar radiation and open-circuit voltage (Voc) for the three photovoltaic modules is presented in Figure 11. The results show that Voc remained relatively stable throughout the observed radiation range of approximately 21–27 MJ m^{-2} day^{-1}. Linear regression analysis produced regression slopes of -0.0099, -0.0131, and 0.0441 for Samples A, B, and C, respectively. The corresponding coefficients of determination were very low, ranging from 0.0008 to 0.0139.

The low R^2 values indicate that changes in solar radiation explained less than 2% of the observed variation in open-circuit voltage. This finding suggests that solar radiation exerted minimal direct influence on voltage behaviour during the study period. The observed trend is consistent with photovoltaic theory, which states that Voc depends primarily on cell temperature and semiconductor material properties rather than irradiance. Although increasing solar radiation promotes charge-carrier generation, its influence on Voc is logarithmic and considerably weaker than the temperature effect. Similar temperature-dependent voltage behaviour has been reported in photovoltaic performance models developed for outdoor operating conditions (King et al., 2004).

The slight negative slopes observed for Samples A and B suggest that increases in solar radiation were accompanied by modest reductions in voltage, most likely due to radiation-induced heating of the modules. Higher solar radiation increases module temperature, and increasing temperature reduces the semiconductor band gap, thereby lowering the open-circuit voltage. Sample C exhibited a slight positive slope; however, the extremely low coefficient of determination indicates that the relationship lacks statistical significance.

These findings demonstrate that voltage behaviour in the investigated modules was controlled primarily by thermal conditions rather than irradiance variations. Consequently, temperature management remains a critical factor in maintaining stable voltage output in photovoltaic systems operating under tropical climatic conditions.

3.4.2 Global Solar Radiation and Short-Circuit Current

Figure 12 illustrates the relationship between global solar radiation and short-circuits current (Isc) for the three photovoltaic modules. Positive regression slopes were obtained for all modules, with values of 0.0688, 0.0453, and 0.0593 for Samples A, B, and C, respectively. The positive slopes indicate that current generally increased with increasing solar radiation.

The observed trend agrees with the fundamental operating principle of photovoltaic cells. As irradiance increases, more photons interact with the semiconductor material, generating a larger number of electron-hole pairs and consequently producing greater current output. Therefore, short-circuit current is expected to respond positively to increasing solar radiation. Such field-based climatic influences are also relevant to recent assessments in Nigeria (Owolabi et al., 2023; Njok & Kamgba, 2023).

However, despite the positive relationships observed, the corresponding coefficients of determination were relatively low, ranging from 0.016 to 0.0351. Reviewer concerns regarding these low R^2 values are valid because short-circuit current is theoretically expected to exhibit a stronger dependence on solar radiation. The weak statistical relationships observed in this study may be attributed to several environmental and operational factors acting simultaneously on photovoltaic performance.

Firstly, temperature variations occurred throughout the monitoring period and influenced the electrical characteristics of the modules. Secondly, atmospheric conditions such as dust loading, haze, humidity variations, aerosol concentrations, and cloud fluctuations may have affected the spectral composition of solar radiation reaching the module surfaces. In addition, the use of weekly averaged data reduced short-term irradiance fluctuations, thereby weakening the apparent linear relationship between radiation and current. Measurement uncertainties and module-specific responses may have also contributed to the scatter observed in the data.

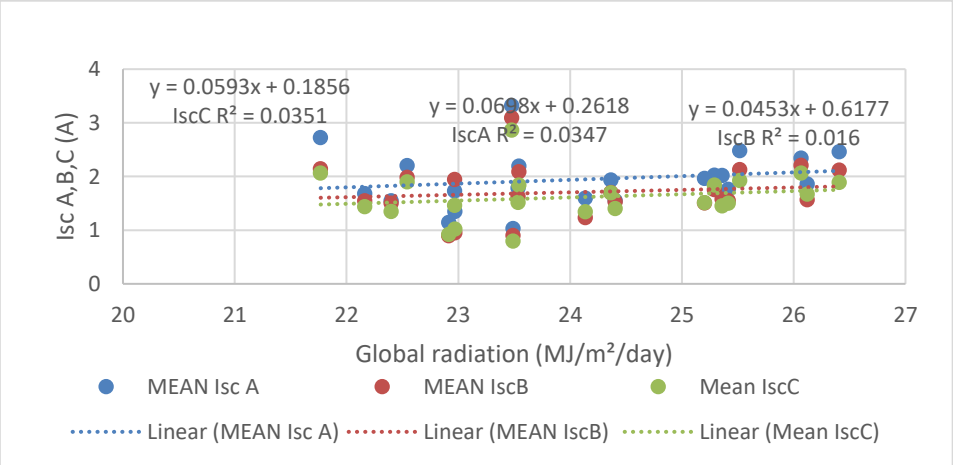


Figure 12. relationship between global solar radiation and short-circuit current for samples A, B and C.

Consequently, while solar radiation remains the primary driver of current generation, the electrical response of photovoltaic modules under outdoor tropical conditions is influenced by multiple interacting environmental variables. The low R^2 values therefore do not invalidate the positive influence of irradiance on current generation but rather demonstrate the complexity of outdoor photovoltaic operation.

3.5 Hourly Photovoltaic Module Performance

3.5.1 Hourly Variation of Short-Circuit Current

The hourly behaviour of short-circuit current is presented in Figure 13. All three photovoltaic modules exhibited similar bell-shaped profiles, with current increasing during the morning hours, reaching maximum values around midday, and declining towards the evening.

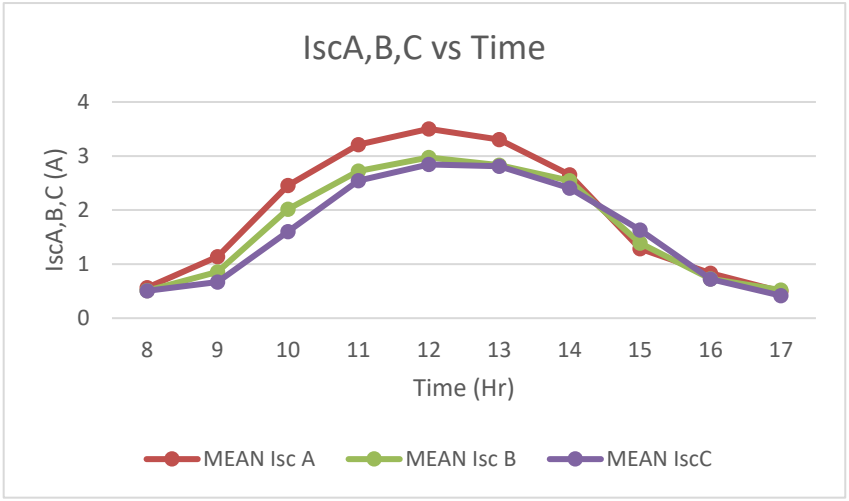


Figure 13. Hourly Variation of Short-Circuit Current for Samples A, B and C

The shape of the current profile closely followed the daily pattern of solar radiation. During the early morning, lower solar elevation angles reduced irradiance intensity and consequently limited

photon absorption by the cells. As solar radiation increased throughout the morning, electron-hole pair generation increased, producing higher current values. Peak current output occurred between 12:00 h and 13:00 h, coinciding with periods of maximum solar radiation.

Among the three modules, Sample A consistently produced the highest short-circuit current throughout the day. Sample B exhibited intermediate performance, whereas Sample C generally produced lower current values. This behaviour agrees with the manufacturer specifications presented in Table 1, where Sample A possessed the highest rated short-circuit current under standard test conditions.

The results confirm that current generation is strongly dependent on incident solar radiation and responds rapidly to changes in irradiance. Therefore, short-circuit current can be considered an effective indicator of solar energy availability under field operating conditions. This behaviour is consistent with established temperature sensitivities of photovoltaic cells (Shaker et al., 2024).

3.5.2 Hourly Variation of Open-Circuit Voltage

Figure 14 shows the hourly variation of open-circuit voltage (Voc) for the three photovoltaic modules. Unlike short-circuit current, voltage exhibited relatively small fluctuations throughout the day. Samples A and B maintained nearly constant voltage values, averaging approximately 19.24 V and 19.08 V, respectively.

Sample C consistently recorded higher voltages than the other two modules, with values ranging between approximately 20.09 V and 22.23 V. However, a reduction in voltage was observed during periods of elevated temperature, particularly during the midday hours.

The observed behaviour reflects the temperature dependence of photovoltaic voltage. Increasing module temperature causes a reduction in semiconductor band-gap energy, leading to a decrease in open-circuit voltage. Similar temperature-induced voltage reductions have been widely reported in photovoltaic performance studies and are recognised as one of the principal mechanisms responsible for thermal performance losses in photovoltaic modules (Chander et al., 2015). Consequently, although solar radiation reaches maximum values around midday, voltage output tends to be slightly lower because of increased thermal loading. The temperature-dependent response is consistent with the review by Shaker et al (2024).

The results demonstrate the competing influences of irradiance and temperature on photovoltaic operation. Whereas current output benefits from increased irradiance, voltage output is adversely affected by the corresponding increase in module temperature. Therefore, overall photovoltaic performance is determined by the balance between these opposing effects.

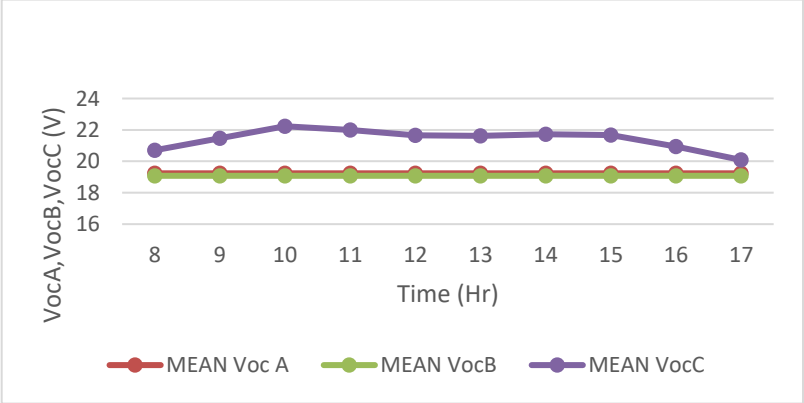


Figure 14. Hourly variation of open-circuit voltage for Samples A, B and C.

3.6 Comparative Performance of Photovoltaic Modules

3.6.1 Weekly Variation of Short-Circuit Current

Figure 15 shows the weekly variation of short-circuit current (Isc) for Samples A, B, and C during the monitoring period. All three modules exhibited similar temporal trends, indicating that their electrical responses were influenced by the same environmental conditions, particularly variations in solar radiation. Current output generally declined during the early weeks, increased towards the middle of the study period, and decreased again during the final weeks.

Sample A consistently recorded the highest short-circuit current, with values reaching approximately 3.35 A, while Sample B exhibited intermediate performance and Sample C generally produced the lowest current output. The peak current values observed between Weeks 12 and 17 coincided with periods of higher solar radiation availability, demonstrating the dependence of current generation on irradiance.

The superior performance of Sample A is consistent with its higher manufacturer-rated short-circuit current under Standard Test Conditions. Overall, the results indicate that both environmental conditions and module-specific characteristics influenced the current-generation capability of the investigated photovoltaic modules.

3.6.2 Weekly Variation of Open-Circuit Voltage

Figure 16 shows the weekly variation of open-circuit voltage (Voc) for Samples A, B, and C throughout the monitoring period. The three modules exhibited similar temporal trends; however, clear differences in voltage output were observed. Sample C consistently recorded the highest voltage values, ranging from approximately 20.8 V to 23.0 V, while Samples A and B maintained lower but relatively stable outputs between 18.8 V and 21.0 V.

The superior voltage characteristics of Sample C are consistent with its higher manufacturer-rated open-circuit voltage (22.32 V) under Standard Test Conditions. Temporary increases in voltage were observed around Weeks 12 and 16, corresponding to periods of favourable environmental conditions. In contrast, slight voltage reductions occurred during weeks associated with elevated module temperatures, reflecting the well-established inverse relationship between temperature and open-circuit voltage.

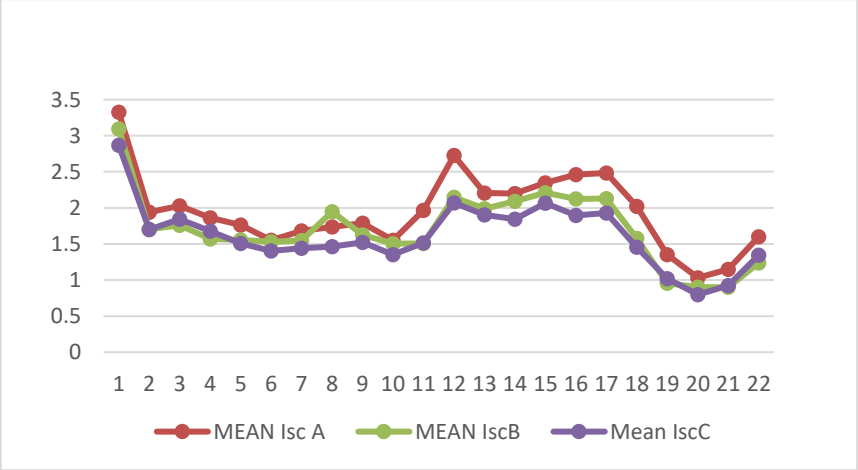


Figure 15. Weekly variation of short-circuit current for Samples A, B and C.

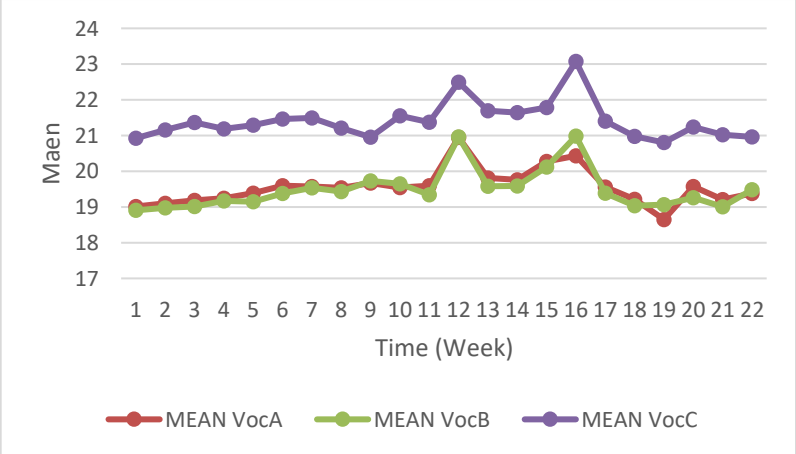


Figure 16. Weekly variation of open-circuit voltage for Samples A, B and C.

Overall, the results indicate that Sample C exhibited the strongest voltage performance, while Samples A and B demonstrated comparatively stable voltage behaviour under varying outdoor conditions. The observed differences confirm that module-specific electrical characteristics influence photovoltaic performance, even when modules operate under identical environmental conditions.

3.7 Implications for PV Deployment in Tropical Climates

The results obtained in this study have important implications for photovoltaic deployment in tropical savannah environments such as Northern Nigeria. The strong relationships observed among cell temperature, ambient temperature, and relative humidity indicate that thermal conditions constitute a major environmental constraint on photovoltaic performance. Cell temperatures frequently exceeded ambient temperatures by a substantial margin, highlighting the significant thermal stress experienced by photovoltaic modules during periods of intense solar radiation.

The strong correlation between cell temperature and ambient temperature confirms that elevated environmental temperatures contribute directly to increased module operating temperatures. Since higher module temperatures are associated with reductions in voltage output, thermal stress may lead to performance losses even under favourable solar radiation conditions. Consequently, thermal management should be considered an essential component of photovoltaic system design in tropical regions.

The comparative evaluation of the investigated modules further demonstrates the importance of module selection. Although all modules possessed similar rated power capacities under Standard Test Conditions, their outdoor electrical responses differed considerably. Sample A exhibited superior current-generation capability, whereas Sample C maintained higher voltage characteristics. These differences suggest that module selection should be based not only on manufacturer-rated power output but also on expected environmental operating conditions and thermal behaviour. Site-specific thermal effects and performance variability have similarly been emphasized in the recent literature (Bamisile et al., 2025; Ogbulezie et al., 2026). Comparisons of photovoltaic technologies under Nigerian climatic conditions have likewise been reported by Owolabi et al (2023).

The findings also highlight the importance of passive cooling strategies. Adequate ventilation beneath photovoltaic modules, elevated mounting structures, and the use of modules with favourable temperature coefficients can reduce thermal loading and improve long-term performance. Such measures are particularly relevant in Northern Nigeria, where high solar irradiance is frequently accompanied by elevated temperatures and low relative humidity.

Overall, the results demonstrate that successful photovoltaic deployment in tropical climates requires careful consideration of environmental conditions, module characteristics, and thermal management strategies to ensure reliable and sustainable energy production.

4. CONCLUSION

This study examined the relationships between environmental parameters and photovoltaic module performance under tropical savannah climatic conditions in Afaka, Kaduna, Nigeria, using a 151-day field investigation involving three polycrystalline photovoltaic modules. The results demonstrated that environmental variables are strongly interrelated and exert significant influence on photovoltaic operating conditions. Correlation analysis revealed a strong positive relationship between cell temperature and ambient temperature (R^2 = 0.8583), indicating that ambient temperature was a major determinant of module operating temperature. A strong negative relationship was observed between ambient temperature and relative humidity (R^2 = 0.8772), while cell temperature and relative humidity exhibited a moderate negative correlation (R^2 = 0.6549). These findings confirm that temperature-related variables are the dominant environmental factors affecting photovoltaic operation in the study area. The analysis further showed that open-circuit voltage exhibited very weak dependence on global solar radiation, with extremely low coefficients of determination for all modules. In contrast, short-circuit current increased with increasing solar radiation but displayed relatively weak statistical correlations, indicating that current generation was influenced not only by irradiance but also by temperature fluctuations and other environmental conditions. Comparative evaluation of the modules

revealed distinct performance characteristics. Sample A consistently produced the highest short-circuit current, reaching peak hourly values of approximately 3.50 A and demonstrating superior current-generation capability. Sample C maintained the highest open-circuit voltage, with values up to 23.07 V, while Sample B generally exhibited the lowest overall electrical performance throughout the monitoring period. The findings highlight the importance of module selection and thermal management for photovoltaic deployment in tropical climates. Future studies should incorporate direct power and efficiency calculations and extend the monitoring period to capture seasonal influences and long-term photovoltaic performance.

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AUTHOR CONTRIBUTIONS

Conceptualization, O.J.A. and I.O.; methodology, O.J.A., O.P. and I.M.; software, O.P. and A.J.O.; validation, I.O., R.A.T. and A.J.O.; formal analysis, O.J.A., O.P. and I.M.; investigation, O.J.A., I.O. and R.A.T.; resources, I.M. and A.J.O.; data curation, O.P. and R.A.T.; writing—original draft preparation, O.J.A. and I.O.; writing—review and editing, all authors; visualization, O.P. and A.J.O.; supervision, I.O. and I.M.; project administration, O.J.A. and R.A.T. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMENT

Confirm whether the 151-day field measurements and the NiMet solar radiation data are available from the corresponding author upon reasonable request, and specify any access restrictions or repository details as applicable.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE (AI) USAGE DECLARATION

During the preparation of this revised manuscript, ChatGPT (OpenAI) was used for editorial assistance, including the identification and formatting of literature citations and the drafting of publication declarations. The authors must review and verify all AI-assisted content and take full responsibility for the manuscript.

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