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## Long-Term Trends in Solar Radiation and Climatic Variability Across Nigeria: Implications for Renewable Energy Potential

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### Abstract

The increasing demand for sustainable energy and the growing impacts of climate change have intensified the need for reliable assessments of solar energy resources across different regions of the country. Despite the abundant solar energy potential in Nigeria, limited studies have comprehensively assessed the combined influence of climatic variability on solar radiation and photovoltaic energy generation. This study examined the long-term trends of solar radiation and climatic variability across Nigeria and evaluated their implications for the country's renewable energy potential across selected climatic zones. Climatic datasets comprising Global Horizontal Irradiance (GHI), temperature, and relative humidity, spanning a total of 45 years (1981–2025) were obtained from the NASA POWER database for twelve selected locations representing the Warm Desert (Kukawa), Semiarid (Sokoto, Gombe, and Kano), Tropical Savannah (Abeokuta, Abuja, Minna, Jalingo, Jos, and Ibadan), and Monsoon (Ikot Akpaden and Asaba). The study adopted the Mann-Kendall trend test and Sen's slope estimator to assess long-term trends in solar radiation and climatic variables, while correlation analysis was employed to investigate the relationships between the study parameters. Additionally, a simplified photovoltaic energy estimation model based on a standardized 2kW photovoltaic system capacity was adopted in this study to estimate the solar photovoltaic energy output. The Mann-Kendall trend analysis revealed a statistically significant decreasing trend in solar radiation across all study locations ( $p < 0.05$ ), with Z-values ranging from -3.404 to -5.425 and Sen's slope values ranging from -0.005 to -0.009 kWh/m<sup>2</sup>/day. Temperature showed a significant increasing trend in most locations, with Z-values ranging from 2.299 to 5.645 and Sen's slope values ranging from 0.009 to 0.067 °C/year, indicating increasing regional warming pattern across the study area. Relative humidity revealed a strong spatial variability, with increasing trends observed in Ikot Akpaden, Asaba, Abeokuta, Ibadan, Sokoto, and Kukawa, while Abuja, Minna, and Jalingo revealed decreasing trends. The Z-values ranged from 1.595 to 5.204, while Sen's slope values ranged from -0.218 to 0.224 %/year. The correlation heat map revealed that solar radiation correlates negatively with relative humidity, with the strongest negative correlations observed in Abeokuta (-0.72), Ibadan (-0.63), Kukawa (-0.54), and Ikot Akpaden (-0.55). The estimated annual photovoltaic energy output ranged from approximately 2450 kWh/year to 3450 kWh/year for the standardized 2kW photovoltaic system, with northern locations such as Kukawa, Kano, Sokoto, and Gombe exhibiting the highest solar energy potential. These findings demonstrate the strong influence of long-term climatic variability on solar energy resources across the country.

The study reveals a clear north-south variation in solar energy potential, pointing out the potential of northern Nigeria for solar energy development and provides essential scientific information for renewable energy planning, sustainable energy policy development, and climate adaptation strategies in Nigeria.

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### 1.0 Introduction

The search for sustainable and renewable sources of energy has grown rapidly because of the outstanding need for clean energy to control global warming. Due to its abundance, sustainability, and environmentally friendly nature, solar energy has become one of the most reliable renewable energy sources. Energy is one of the vital forces behind modern societies leading to an increase in the standard of living, industrial growth, economic growth, and technological advancement (Stern et al., 2019).

The electromagnetic energy released by the sun onto the surface of the Earth is referred to as solar energy (Rhodes et al., 2010). It serves as the main energy source for climate systems, atmospheric processes, and renewable energy technologies like photovoltaic (PV) and solar thermal systems. The efficiency and sustainability of solar energy generation rely heavily on the amount of solar radiation present (Hassan et al., 2023). Furthermore, for a successful renewable energy planning and sustainable energy development, a detailed understanding of the temporal and spatial variability of solar radiation is essential.

Long-term solar radiation trends relate directly to climate change, atmospheric conditions, and renewable energy, due to the growing interest in

analyzing these trends globally (Wild et al., 2015). The performance and dependability of solar energy systems can be greatly impacted by variations in solar radiation. Climate variables such as temperature, relative humidity, rainfall, cloud cover, atmospheric particles, and greenhouse gas concentrations have an impact on the amount of solar radiation that reaches the Earth's surface. In some parts of the world, phenomena like "global dimming" and "global brightening" have occurred in recent decades, as a result of changes in atmospheric and climatic conditions (Hatzianastassiou et al., 2020). In Nigeria, these phenomena are strongly influenced by regional atmospheric processes. The Harmattan season, which is characterized by the transport of dust aerosols from the Sahara Desert into West Africa, increases the scattering and absorption of incoming solar radiation, particularly across northern Nigeria (Ayanlade et al., 2019). Similarly, the seasonal migration of the Inter-Tropical Discontinuity (ITD) influences cloud formation, rainfall distribution, humidity, and atmospheric moisture across the country. Southern Nigeria experiences higher cloud cover, rainfall, and humidity due to the influence of the Atlantic Ocean and the West African Monsoon system, which can reduce the amount of solar radiation reaching the surface. These atmospheric processes play a significant

role in the spatial and temporal variability of solar radiation across Nigeria and may influence the performance of solar energy systems (Ohunakin et al., 2015). These phenomena occur mainly as a result of the decrease and increase in solar radiation, respectively.

Climate change has become one of the most significant environmental problems the world is facing today, which has an effect on ecosystems, energy systems, and socioeconomic activity. The intensity of solar radiation can be influenced by an increase in temperatures, unstable precipitation patterns, increase in air pollution, and variation in cloud cover (Liu et al., 2019), which significantly impacts the production of solar energy, specifically in areas where solar resources are key factors for future energy growth. Therefore, studying the long-term trend in solar radiation and other climatic variables becomes an important factor to be considered in environmental management, renewable energy research, and climate science.

Nigeria, located within the tropical region, is endowed with abundant solar energy resources due to its geographical position (Mohammed, et al., 2013). Due to the nation's high levels of solar radiation reaching the earth per year, solar energy becomes one of the most acceptable renewable energy solutions needed to tackle the country's energy problems. Due to the rapid growth in industrialization, urbanization, and population in the country, the rate of energy consumption and demand has placed a massive strain on the power sector. Nevertheless, the country still struggles with poor electricity supply, unstable power production, and limited access especially in rural areas.

In various parts of Nigeria and other parts of the world, several studies have looked at climate patterns and solar radiation. Recent studies adopted statistical and empirical models to analyze the effect of some climatic variables like temperature, cloud cover, rainfall, aerosols, and humidity on solar radiation variability. Trend

analysis methods such as Sen's slope estimator and the Mann–Kendall trend test were adopted by previous studies in order to assess long-term climate changes (Mohammad et al., 2022). These studies however, covered limited localities, within a short-term period. Therefore, there remains a need for a comprehensive nationwide assessment of long-term solar radiation trends across Nigeria's climatic zones and their implications for renewable energy development. This study addresses this gap by integrating long-term solar radiation, temperature, and relative humidity datasets across multiple climatic zones in Nigeria and evaluating their implications for renewable energy potential, using statistical trend analysis techniques such as the Mann-Kendall Trend Test and Sen's Slope estimator. This study further evaluates the relationship between solar radiation and climatic variables such as temperature and relative humidity using the correlation heat map. The findings of this study provide valuable information for policymakers, renewable energy developers, researchers, and environmental planners in designing effective climate-adaptive solar energy strategies for sustainable development in Nigeria.

## 2.0 Materials and Methods

### 2.1 Study Area

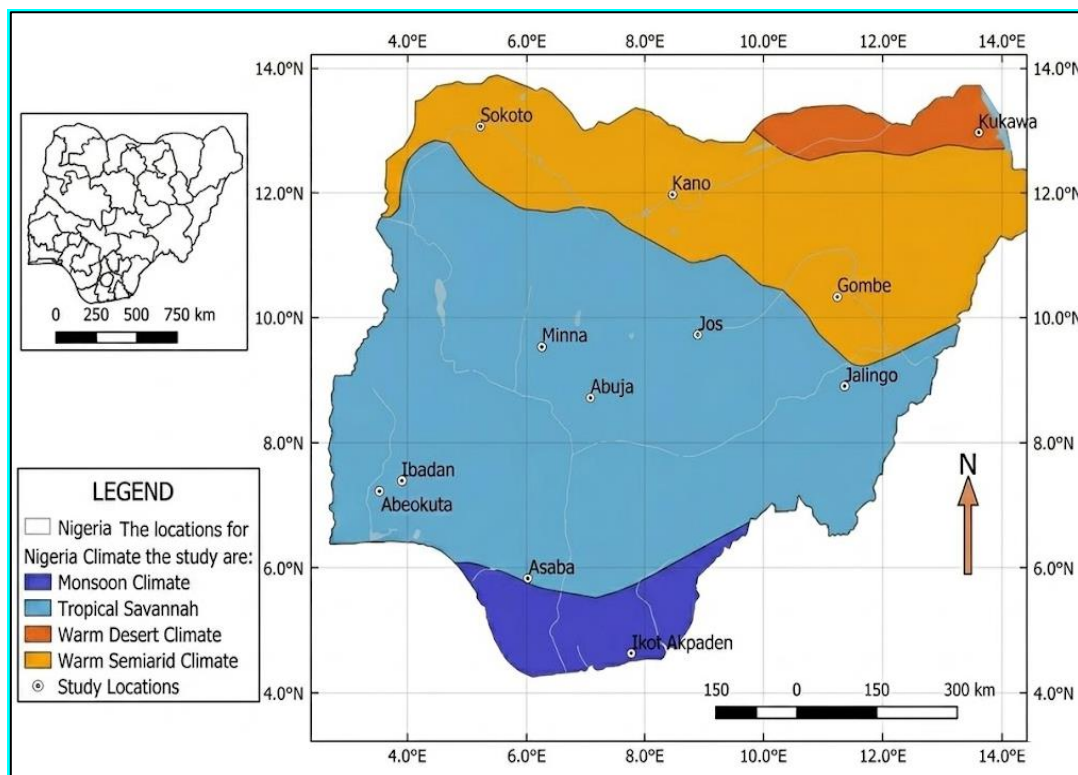
The study area stretches through an area measured at 923,769 km<sup>2</sup> with a population of 187 million in 2016 (Merem et al., 2017). It is the most populous country in Africa, and the world's sixth-most populous country. Nigeria, located in West Africa between latitudes 4° and 14°N, and longitudes 3° and 15°E, is bordered by Niger in the north, Chad in the northeast, Cameroon in the east, and Benin in the west, with the Atlantic Ocean to the south. It consists of 36 states, the Federal Capital Territory (FCT), and six geopolitical zones (North Central, North East, North West, South East, South-South, and South West). There are two seasons, the dry and the wet seasons, the length of which vary from north to south (George et al., 2022a, b; Udosen

et al, 2024a, b, c). The dry season usually accompanied by the dusty northeast winds has a very high temperature during midday and low temperatures at night, reduced rainfall, low humidity, and the influence of the dry and dusty Harmattan winds, especially between December and January. The wet season, also referred to as rainy season is associated with moist air masses from the Atlantic Ocean. In the southern part of Nigeria, the rainy season extends from March to October/November, but only from mid-May to September in the far north. In the southern part, there is usually a short break in the rain resulting in a short dry season also referred to as the “August break” (George et al., 2020; Agbo et al., 2021a, b; Ekanem et al., 2024).

According to the Köppen climatic classification system, Nigeria is composed of four major

climatic zones: Warm Desert Climate, Warm Semi-Arid Climate, Tropical Savannah Climate, and Monsoon Climate (Agbo et al., 2023). These climatic zones differ significantly in terms of temperature, humidity, rainfall distribution, atmospheric moisture, and cloud dynamics.

Figure 1 shows the distribution of the 4 major climatic zones of Nigeria. In this study, twelve representative stations were selected across the climatic zones based on spatial coverage, climatic characteristics, and data availability. Kukawa represented the Warm Desert Climate; Sokoto, Gombe, and Kano represented the Warm Semi-Arid Climate; Abeokuta, Abuja, Minna, Ibadan, Jalingo, and Jos represented the Tropical Savannah Climate; while Asaba and Ikot Akpaden represented the Monsoon Climate.



**Figure 1:** Map of Nigeria showing the climate zones and locations of stations

## 2.2 Solar radiation data

In this study, long-term climatic datasets obtained covers a 45-year period from 1981-2025. These data were obtained from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources

(NASA POWER) database. The data were obtained in CSV format and imported into Microsoft Excel (Version 2013) for preprocessing and organization before statistical analysis. The NASA POWER database was selected because it provides globally consistent

and validated satellite-derived climatic datasets primarily developed to aid researchers in renewable energy, environmental science and atmospheric sciences. The datasets used in this study were annual mean values generated from monthly climatic observations. Missing values observed in solar radiation data and represented by "999" in the NASA POWER database were identified and removed during preprocessing to ensure data consistency and reliability. The proportion of missing observations was minimal and represented less than 5 % of the dataset. These values were removed prior to analysis to prevent bias in the trend estimation procedures. Given the small proportion of missing observations, their exclusion was not expected to significantly affect the continuity or reliability of the Mann-Kendall trend analysis. The dataset collected for this study includes All Sky Surface Shortwave Downward Irradiance, Earth skin temperature and relative humidity within the study locations across the different climatic zones considered.

### 2.3 Climate variables

Other climatic variables were also included in the study to aid in evaluating their impacts on solar energy variability. These variables are temperature, and relative humidity. Temperature contributes significantly to the atmospheric conditions as it plays a major role in influencing the atmospheric conditions and solar radiation intensity. At high temperatures, the skies appear to be clearer in arid regions. Cloud cover is one of the factors that affects solar radiation, since increased cloudiness decreases the amount of solar energy reaching the Earth's surface. Relative humidity influences atmospheric transparency and it is most times related with cloud formation, thereby indirectly affecting solar radiation levels.

### 2.4 The Mann-Kendall (MK) Test

The Mann-Kendall trend test (sometimes called the M-K test) is a non-parametric test used to statistically assess if there is a monotonic (upward or downward) trend in a time series

data. It is a non-parametric test which does not demand the analyzed data to correspond to any particular distribution, which entails that it works for all distribution (Ashraf et al., 2021). The M-K trend test is adopted when a series of data acquired aligns with a linear relationship. It is usually used when analyzing climatological, meteorological, and hydrological time series data (Kendall, 1948; Mann, 1945).

The Mann-Kendall test (Mann 1945; Kendall 1975) is calculated using equations 1 and 2

$$sgn(x_j - x_k) = \begin{cases} +1; & \text{if}(x_j - x_k) > 0 \\ 0; & \text{if}(x_j - x_k) = 0 \\ -1; & \text{if}(x_j - x_k) < 0 \end{cases} \quad (1)$$

$$VAR(S) = \frac{1}{18} [n(n-1)(2n+5) - \sum_{p=1}^g t_p(t_p-1)(2t_p+5)] \quad (2)$$

where  $x_j$  and  $x_k$  are sequential data values in the series,  $n$  represents the total number of observations,  $sgn$  represents the sign function and the variance of ( $S$ ) is calculated using equation 2,  $t_p$  denotes the ties of the  $p^{th}$  value, and  $g$  represents the number of the tied value. The standard trend test statistics ( $Z$ ) is calculated from equation 3.

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}; & S > 0 \\ 0; & S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}; & S < 0 \end{cases} \quad (3)$$

The extent to which the trend is either positive or negative depends on the magnitude of the  $S$  statistic value, either positive or negative. An upward trend is indicated by a positive  $S$  value, and a downward trend is represented by a negative  $S$  value. The  $Z$ -statistic (normal approximation) is defined if the number of data values ( $n$ ) exceeds 10. This further implies that if the number of data points in the series is near or below 10, the accuracy of the  $Z$  statistic decreases. The variance of  $S$ , "VAR( $S$ )," is defined using equations 2 in order to determine the  $Z$  value. The trends direction is determined by the sign of  $Z$ -value, where a negative value of  $Z$  indicates a decreasing trend while a positive

Z represents an increasing trend. Hence at the 5% significance level for a two-tailed test, the null hypothesis of no trend is rejected when  $|Z| > 1.96$ .

Sen's slope estimator was further employed to determine the magnitude and rate of change in the climatic variables over time. The Mann–Kendall test was selected because it is non-parametric, robust against outliers, and does not require normally distributed datasets.

### 2.5 Estimating Solar Energy Potential

In order to evaluate the solar energy potential across Nigeria's various climate zones, this study used a simplified photovoltaic energy estimation approach by utilizing 45 years of Global Horizontal Irradiance (GHI) data in kWh/m<sup>2</sup>/day from 1981 to 2025 that were taken from the NASA POWER. Global Horizontal Irradiance is one of the primary sources of solar photovoltaic (PV) power generation, which is the sum of all solar radiation that is incident on the Earth surface (Agbo et al., 2021b). The estimate is given in equation 4.

$$E = 365 \cdot P_K \cdot \text{GHI} \cdot \text{PR} \quad (4)$$

where  $P_K$  is the installed PV system capacity in kW, E is the expected annual electricity output (in kWh/year), and PR is the performance ratio, a dimensionless constant that account for system losses which could be as a result of faulty connections, system malfunction or temperature. In order to enable uniform comparison of solar energy potential across the different climatic zones, a fixed system of 2kW and a performance ratio of 0.80 were adopted in this study. This standardized capacity ensures that variations in the estimated annual energy output are primarily attributed to climatic differences rather than differences in PV system size. Furthermore, a 2 kW PV system represents a moderately sized residential scale solar installation commonly applicable in household and rural areas in Nigeria. A moderately efficient PV system is assumed to have a constant performance ratio of roughly 0.80. The product of 365 and GHI

represents the total annual solar energy incident on the surface per square meter.

### 2.6 Analysis Tools: MS Excel and Python Programming

The data obtained from NASA POWER were saved in CSV format and was sent to MS Excel (version 2013) where it was cleaned and prepared for analysis. In this study the climatic datasets obtained from NASA POWER were analyzed using Python programming language (Version 3.8.1). Python is one of the most outstanding tools that is widely used for performing the Mann-Kendall test as a result of its vast libraries which support data analysis, and statistical modelling. It is often used in research studies due to its efficiency, accuracy, flexibility and reliability, and its numerous numbers of built-in functions available and ready for complex datasets.

Python programming was employed in this study to perform trend analysis, statistical modelling, and predictive analysis. Several Python packages such as the pymann-kendall, and Pandas were imported and used in this study. The pymann-kendall library was used to perform the Mann-Kendall trend test, and Sen's slope estimation, which gave results for the equations (1) through (3), including p-values, and Z-statistics. The pandas library was imported and used for data manipulation, enabling systematic management of meteorological datasets for sites across Nigeria's climate zones. Matplotlib and Seaborn were imported and used for visualization and graphical representations of climatic trends. The generated outputs included; Time series plots, Box plots, Correlation heat maps and Solar energy potential chats. These visualizations such as the time series graph give a visual explanation of the Mann-Kendall test result given in Tables 1, 2, and 3. These visualizations improved the interpretation of climatic variability and renewable energy implications across all studied locations.

### 3.0 Results of the Study

The results of the Mann-Kendall trend test for all parameters across the study area (solar radiation, relative humidity, and temperature) are presented in Tables 1, 2, and 3 respectively. While Figures 2, 3 and 4 are time series plot (3 × 4 subplots) and Figures 5, 6 and 7 represents the box plots showing the graphical representation of the Mann-Kendall trend test result, for solar radiation, temperature and relative humidity from 1981-2025 across all studied locations. These visualizations such as the time series graph gives a visual explanation of the Mann-Kendall test result given in Tables 1, 2, and 3 showing the trend direction according to the results, also contributing to an improved interpretation of climatic variability and renewable energy implications across all studied locations.

Figure 8 represents the correlation heat map illustrating the relationship between solar radiation, relative humidity, and temperature across selected locations in Nigeria. Figure 9 represents the estimated annual solar photovoltaic energy output across selected locations in Nigeria's climatic zones, derived from Eq. (4).

#### 4.0 Discussion of the Results

##### 4.1 Long Term Trend Analysis of Solar Radiation and Climatic Variables

Tables 1, 2, and 3 shows the Mann-Kendall trend test for all variables across the study area respectively. The time series plots in Figure 2, 3, 4 and the box plots in Figure 5, 6, and 7 illustrate the graphical representations of the data in these tables.

The Mann-Kendall trend analysis revealed a statistically significant decreasing trend in solar radiation across all study locations in Nigeria. The negative Z-statistics and Sen's slope values observed across the stations indicate a persistent decline in solar radiation over the 45-year study period. This declining trend may be associated with increasing atmospheric aerosols, cloud

cover variability, atmospheric moisture, and climatic fluctuations affecting atmospheric transmissivity. The observed reduction in solar radiation aligns with the global findings of (Singh et al., 2016) who reported a significant declining trend in solar radiation, which may be associated with climatic conditions like aerosols and cloud cover. In addition, figure 2 gives a clear visualization of solar radiation trends across the study area exhibiting a decreasing trend across all stations, which aligns closely with the Mann-Kendall results presented in Table 1, while in Figure 5, the box plot shows variability in solar radiation in all studied locations, revealing the differences that correspond to the country's climatic zones. Lower solar radiation levels were observed in Ikot Akpaden, Asaba, Abeokuta, and Ibadan ranging from 4.1 kWh/m<sup>2</sup>/day to 4.8 kWh/m<sup>2</sup>/day due to repeated rainfall, high humidity and cloud cover, which influenced the solar radiation reaching the earth's surface. Abuja, Minna, Jalingo, and Jos showed moderate solar radiation from 5.2 kWh/m<sup>2</sup>/day to 5.6 kWh/m<sup>2</sup>/day; this is due to its seasonal variation (wet and dry seasons). Sokoto, Gombe, Kano, and Kukawa exhibit the highest values ranging from 5.8 kWh/m<sup>2</sup>/day to 6.3 kWh/m<sup>2</sup>/day as a result of low humidity, lesser cloud cover and its dry atmospheric conditions. In Nigeria, Harmattan dust aerosols transported from the Sahara Desert may also contribute to atmospheric scattering and absorption of solar radiation, particularly in northern regions.

Additionally, rainfall distribution, cloud formation, and atmospheric humidity across Nigeria can also be significantly influenced by the migration and seasonal fluctuation of the Inter-Tropical Discontinuity (ITD). Southern regions characterized by persistent cloud cover and high atmospheric moisture exhibited comparatively lower solar radiation values compared to the northern regions.

**Table 1:** The Mann-Kendall Trend test results for solar radiation parameter for all the study location

| Location     | Trend      | P-value  | Tau    | S        | Var(S)   | Z      | Sen's Slope |
|--------------|------------|----------|--------|----------|----------|--------|-------------|
| Ikot Akpaden | Decreasing | 4.02E-4  | -0.385 | -316.000 | 7924.667 | -3.539 | -0.006      |
| Asaba        | Decreasing | 6.60E-4  | -0.371 | -304.000 | 7924.667 | -3.404 | -0.005      |
| Abeokuta     | Decreasing | 1.81E-06 | -0.520 | -426.000 | 7926.667 | -4.774 | -0.006      |
| Abuja        | Decreasing | 5.79E-07 | -0.544 | -446.000 | 7926.667 | -4.998 | -0.008      |
| Minna        | Decreasing | 6.32E-06 | -0.491 | -403.000 | 7925.667 | -4.516 | 0.007       |
| Jalingo      | Decreasing | 6.54E-08 | -0.588 | -482.000 | 7924.667 | -5.403 | -0.008      |
| Jos          | Decreasing | 1.15E-06 | -0.529 | -434.000 | 7926.667 | -4.863 | -0.006      |
| Ibadan       | Decreasing | 1.81E-06 | -0.520 | -426.000 | 7926.667 | -4.774 | -0.006      |
| Sokoto       | Decreasing | 3.54E-4  | -0.389 | -319.000 | 7925.667 | -3.572 | -0.005      |
| Gombe        | Decreasing | 5.79E-08 | -0.590 | -484.000 | 7926.667 | -5.425 | -0.008      |
| Kano         | Decreasing | 4.39E-4  | -0.383 | -314.000 | 7926.667 | -3.516 | -0.005      |
| Kukawa       | Decreasing | 1.99E-07 | -0.566 | -464.000 | 7926.667 | -5.200 | -0.009      |

**Table 2:** The Mann-Kendall Trend test results for temperature parameter for all the study location

| Location     | Trend      | P-value | Tau   | S        | Var(S)    | Z      | Sen's Slope |
|--------------|------------|---------|-------|----------|-----------|--------|-------------|
| Ikot Akpaden | Increasing | 0.000   | 0.505 | 500.000  | 10442.000 | 4.883  | 0.014       |
| Asaba        | Increasing | 0.000   | 0.568 | 562.000  | 10448.000 | 5.488  | 0.027       |
| Abeokuta     | Increasing | 0.021   | 0.238 | 236.000  | 10446.000 | 2.299  | 0.009       |
| Abuja        | Increasing | 0.000   | 0.566 | 560.000  | 10448.000 | 5.469  | 0.064       |
| Minna        | Increasing | 0.000   | 0.584 | 578.000  | 10448.000 | 5.645  | 0.067       |
| Jalingo      | Increasing | 0.000   | 0.520 | 515.000  | 10449.000 | 5.028  | 0.064       |
| Jos          | Increasing | 0.001   | 0.332 | 329.000  | 10447.000 | 3.209  | 0.035       |
| Ibadan       | No Trend   | 0.050   | 0.203 | 201.000  | 10444.333 | 1.957  | 0.009       |
| Sokoto       | No Trend   | 0.168   | 0.143 | -142.000 | 10448.000 | 1.379  | -0.010      |
| Gombe        | No Trend   | 0.053   | 0.201 | 199.000  | 10447.000 | 1.937  | 0.018       |
| Kano         | Increasing | 0.000   | 0.416 | 412.000  | 10448.000 | 4.021  | 0.046       |
| Kukawa       | No Trend   | 0.434   | 0.082 | -81.000  | 10445.000 | -0.783 | 0.009       |

The observed north-south variation in solar radiation and solar energy potential across Nigeria may also be influenced by regional atmospheric circulation systems. The Harmattan wind regime and seasonal movement of the Inter-Tropical Discontinuity (ITD) strongly affect the northern part of Nigeria. During the dry season, large quantities of dust and aerosols from the Sahara Desert are usually transported by the Harmattan winds, which can alter atmospheric transmission and influence the amount of solar radiation reaching the Earth's

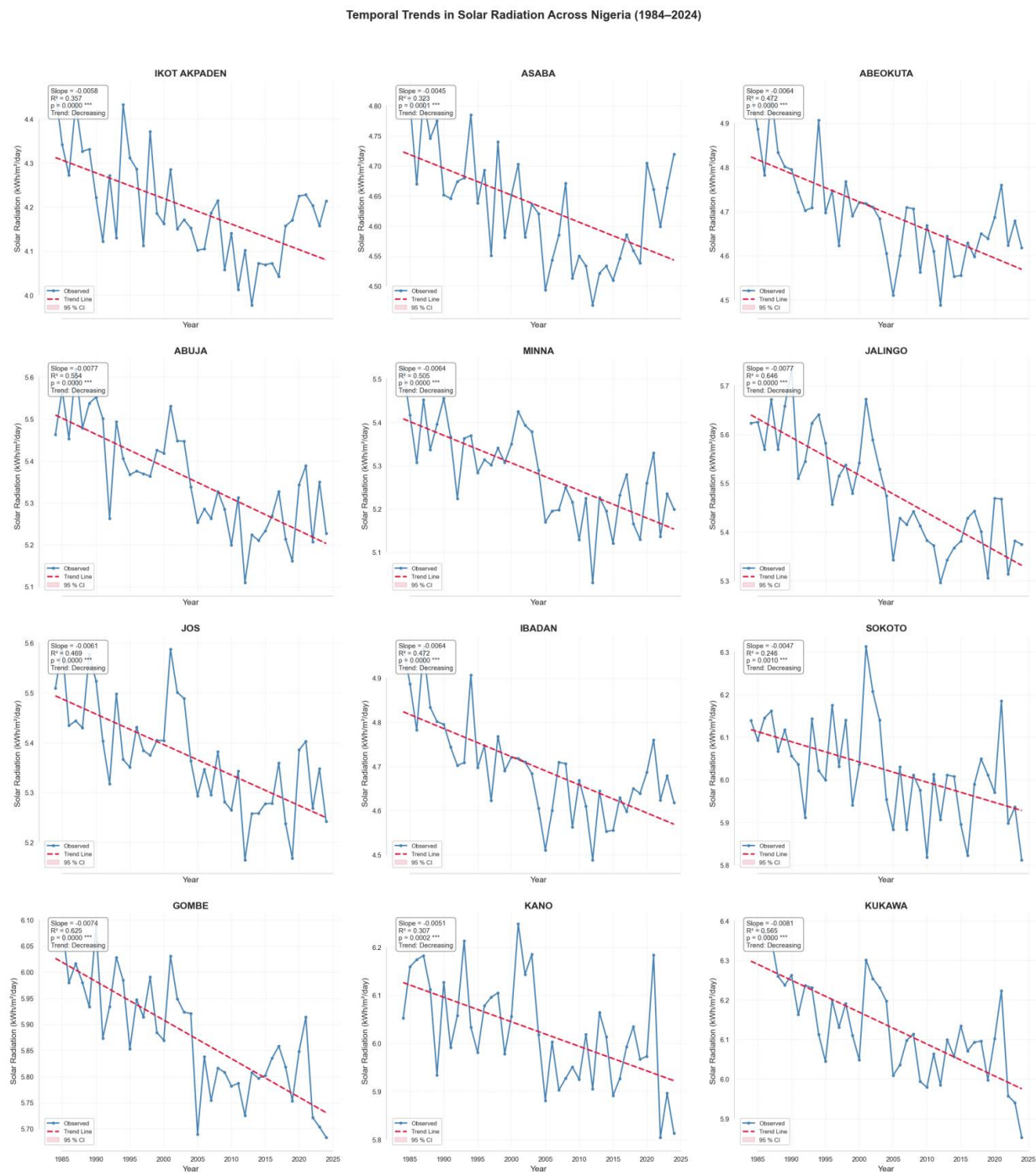
surface. Conversely, southern Nigeria experiences prolonged cloud cover, higher rainfall intensity, and elevated atmospheric moisture associated with the West African Monsoon. These conditions contribute to increased attenuation of incoming solar radiation through cloud scattering and absorption processes. Therefore, the combined effects of aerosol loading, cloud fraction, and atmospheric moisture likely play a significant role in the spatial variability of solar radiation observed across Nigeria's climatic zones.

Temperature result showed a consistent increasing trend across most locations. The highest temperature increase was observed in Minna, Abuja, Jalingo and Asaba. Minna was observed to have the highest temperature with  $Z=5.64$ . Only a few locations such as Ibadan, Sokoto, Gombe and Kukawa showed no significant trend. This aligns with the findings of Alhaji et al. (2018), which reported a significant rise in temperature in Gombe State. Similarly, global studies such as Calma et al. (2025), also reported increasing temperature trends, which signify a wider trend of global warming. The Sen's slope later supports these findings, with positive slope values across several stations, also indicating a gradual increase in temperature overtime while only Sokoto and Kukawa depicts a negative Sen's slope. The magnitude of the slopes reflects the rate of warming, which differs across locations. Furthermore, Figure 3 and 6 visualize the time series plots and the box plots for temperature. A consistent increasing trend in temperature was observed across several locations. The time series plots showed a consistent increasing trend in (Ikot Akpaden, Asaba, Abeokuta, Abuja, Minna, Jalingo, Jos,

and Kano), while a few other locations like Ibadan, Sokoto, Gombe and Kukawa exhibits no significant trends as shown in table 2. Although slight upward-sloping regression lines were observed in the time series plots for Ibadan, Sokoto, and Gombe, the Mann-Kendall test showed that these trends were not statistically significant ( $p > 0.05$ ). Therefore, the increase observed in these locations may be associated to natural variability rather than a consistent long-term warming trend. The box plots in Figure 6 confirms the consistent increase in temperature from southern to northern regions, where the lowest temperature was observed in Jos ( $22^{\circ}\text{C}$ ), while Kukawa ( $32^{\circ}\text{C}$ ) exhibits the highest temperature. Therefore, the temperature analysis revealed significant warming trends across most stations. The strong positive Z-values observed in Minna, Abuja, Jalingo, and Asaba indicate increasing regional warming patterns consistent with global climate change projections. Rising temperatures may be linked to increasing greenhouse gas concentrations, urbanization, land surface modification, and regional climatic changes.

**Table 3:** The Mann-Kendall Trend test results for relative humidity parameter for all the study location

| Location     | Trend      | P-value | Tau    | S        | Var(S)    | Z     | Sen's Slope |
|--------------|------------|---------|--------|----------|-----------|-------|-------------|
| Ikot Akpaden | Increasing | 0.000   | 0.432  | 428.000  | 10448.000 | 4.177 | 0.053       |
| Asaba        | Increasing | 0.001   | 0.341  | 338.000  | 10450.000 | 3.297 | 0.153       |
| Abeokuta     | Increasing | 0.000   | 0.538  | 533.000  | 10449.000 | 5.204 | 0.093       |
| Abuja        | Decreasing | 0.000   | 0.477  | -472.000 | 10450.000 | 4.607 | 0.220       |
| Minna        | Decreasing | 0.000   | -0.440 | -436.000 | 10450.000 | 4.255 | 0.224       |
| Jalingo      | Decreasing | 0.000   | 0.441  | -437.000 | 10449.000 | 4.265 | -0.218      |
| Jos          | No Trend   | 0.111   | 0.166  | -164.000 | 10450.000 | 1.595 | 0.064       |
| Ibadan       | Increasing | 0.000   | 0.419  | 415.000  | 10447.000 | 4.050 | 0.065       |
| Sokoto       | Increasing | 0.001   | 0.341  | 338.000  | 10450.000 | 3.297 | 0.153       |
| Gombe        | No Trend   | 0.717   | 0.038  | -38.000  | 10450.000 | 0.362 | 0.013       |
| Kano         | No Trend   | 0.115   | 0.164  | -162.000 | 10448.000 | 1.575 | 0.101       |
| Kukawa       | Increasing | 0.003   | 0.313  | 310.000  | 10448.000 | 3.023 | 0.130       |



**Figure 2:** Time series plots for solar radiation for all locations (a) Ikot Akpaden (b) Asaba (c) Abeokuta (d) Abuja (e) Minna (f) Jalingo (g) Jos (h) Ibadan (i) Sokoto (j) Gombe (k) Kano (l) Kukawa

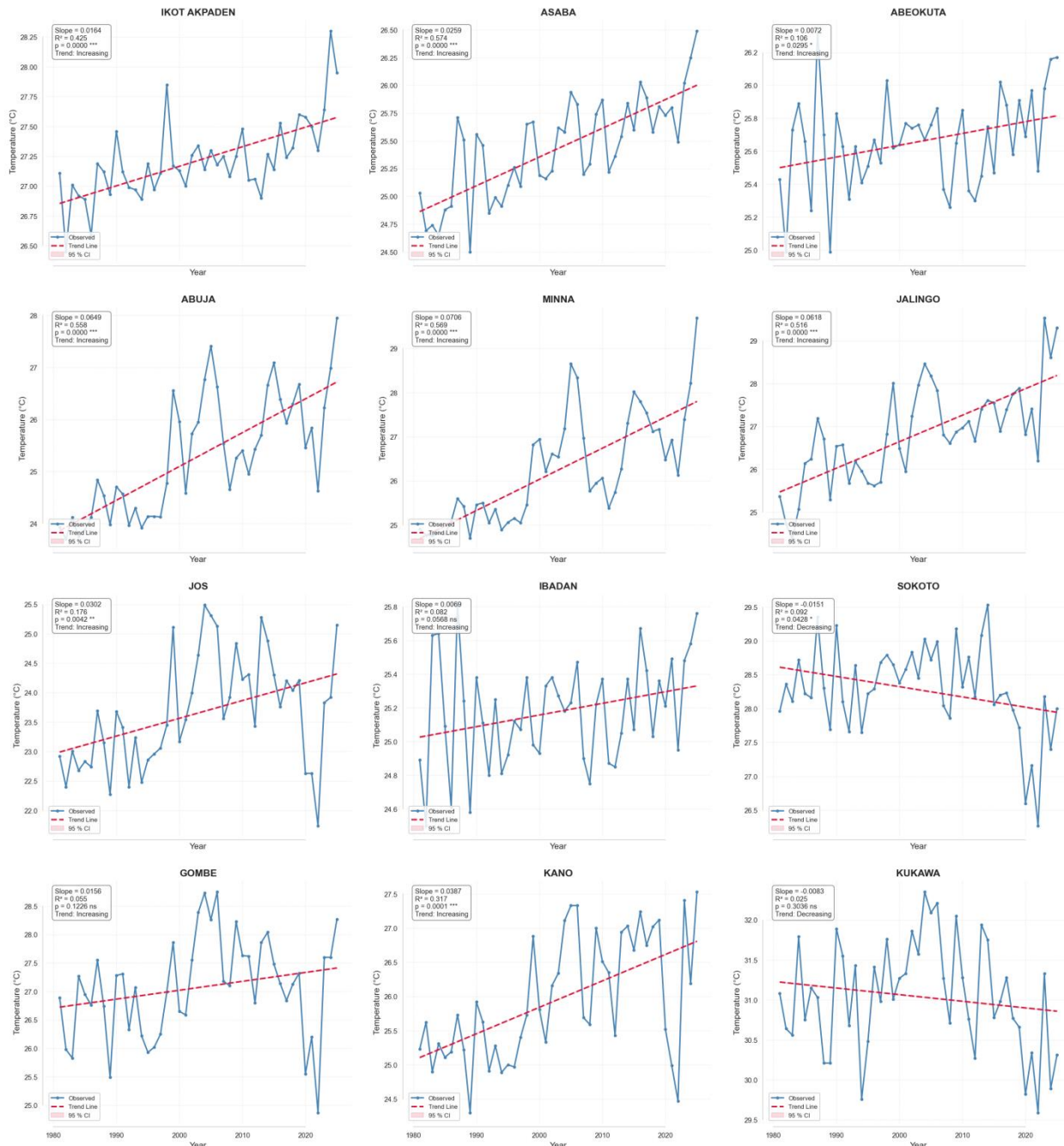
Relative humidity generally shows a spatial variability in humidity across the study area, where a decreasing or variable trend was observed specifically in the northern regions, while a consistently high humidity levels was maintained in the southern regions. However, increasing trend was observed in Ikot Akpaden, Asaba, Abeokuta, Ibadan, Sokoto, and Kukawa, while, Abuja, Minna, and Jalingo indicates significant decrease in humidity. A weak or no

trend was observed in locations such as Jos, Gombe, and Kano. This agrees with (Calma et al., 2025) where a decreasing trend in relative humidity was reported alongside rising temperatures. This highlights the inverse relationship between temperature and relative humidity, where warmer air aligns with lower humidity and a reduced moisture concentration aligns with increasing evaporation. Figure 4 showed a clear variability in relative humidity

across the study area with Ikot Akpaden, Asaba, Abeokuta, and Ibadan showing an increasing trend in Southern regions where the highest values above 80% were observed in Ikot Akpaden, Abeokuta and Ibadan. Abuja, Minna, and Jalingo exhibits decreasing trend over time.

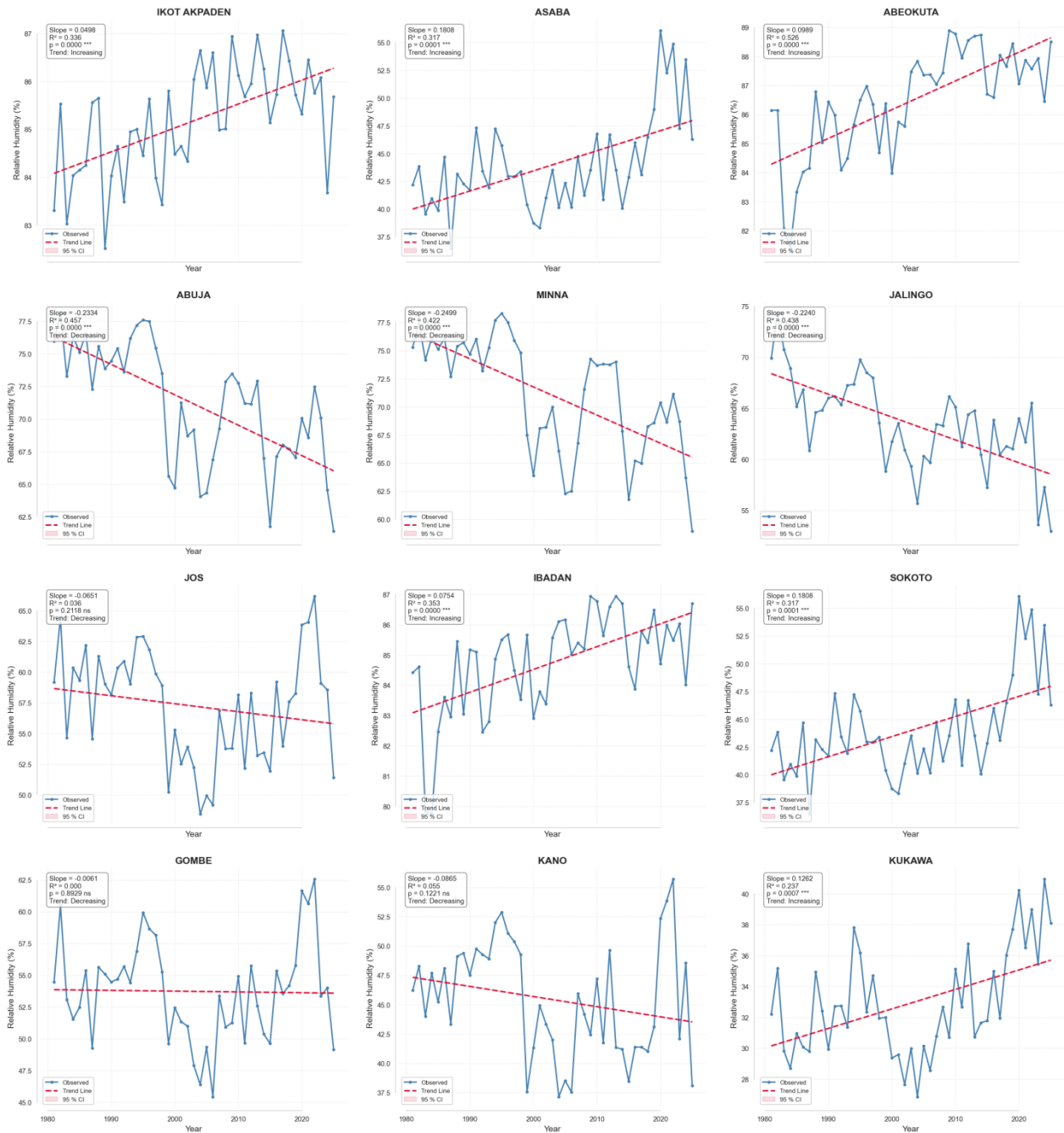
In the northern locations, Jos, Gombe and Kano possessed a high variability with no consistent upward or downward direction detected, which further indicates fluctuating humidity conditions.

Temporal Trends in Temperature Across Nigeria (1981–2024)



**Figure 3:** Time series plots for temperature across all study locations: (a) Ikot Akpaden, (b) Asaba, (c) Abeokuta, (d) Abuja, (e) Minna, (f) Jalingo, (g) Jos, (h) Ibadan, (i) Sokoto, (j) Gombe, (k) Kano, and (l) Kukawa. The red trend lines indicate the overall direction of variation in temperature over time. However, the presence of an upward-sloping trend line does not necessarily imply statistical significance. According to the Mann-Kendall test results, the trends observed in Ibadan, Sokoto, Gombe, and Kukawa were not statistically significant ( $p > 0.05$ ).

Temporal Trends in Relative Humidity Across Nigeria (1981–2024)



**Figure 4:** Time series plots for relative humidity for all locations (a) Ikot Akpaden (b) Asaba (c) Abeokuta (d) Abuja (e) Minna (f) Jalingo (g) Jos (h) Ibadan (i) Sokoto (j) Gombe (k) Kano (l) Kukawa

This aligns with the Mann-Kendall test results presented in Table 3. The box plot in Figure 7 aligns with this result, where Ikot Akpaden, Abeokuta, and Ibadan exhibit a high relative humidity. Abuja, Minna, Jalingo, and Jos showed a moderate level, while Asaba, Sokoto, Gombe, Kano, and Kukawa shows lower humidity with the lowest observed in Kukawa. Furthermore, Southern regions maintained

relatively high humidity conditions due to their proximity to the Atlantic Ocean and persistent maritime air masses, while northern regions generally exhibited lower humidity levels associated with dry continental air masses. The inverse relationship observed between temperature and relative humidity confirms that increasing temperature enhances atmospheric evaporation and reduces relative humidity

concentration. Although aerosol optical depth (AOD) and cloud fraction data were not directly examined in this study, the observed decline in solar radiation may be linked to increasing atmospheric aerosols, cloud cover variability,

and changes in regional climatic conditions. Future studies should incorporate NASA POWER aerosol and cloud parameters to quantitatively evaluate their contributions to the observed solar radiation trends.

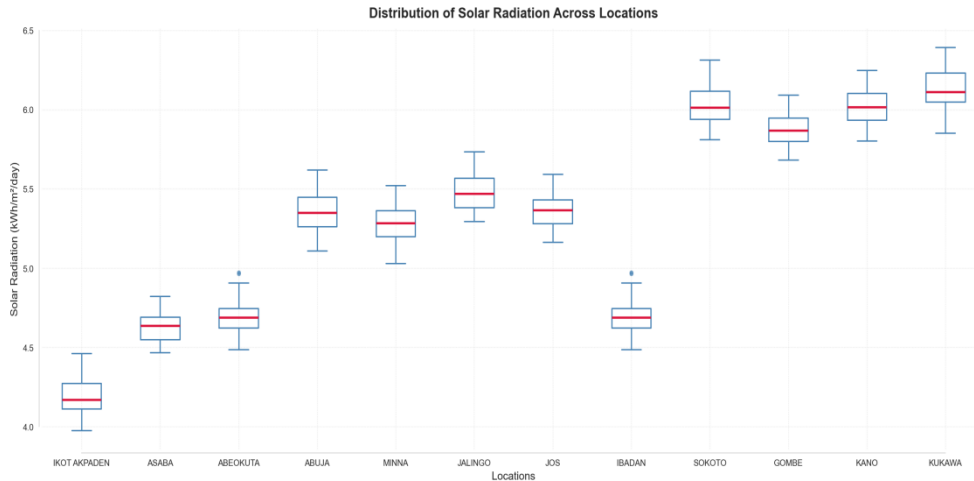


Figure 5: Box Plots Distribution of solar radiation across all locations

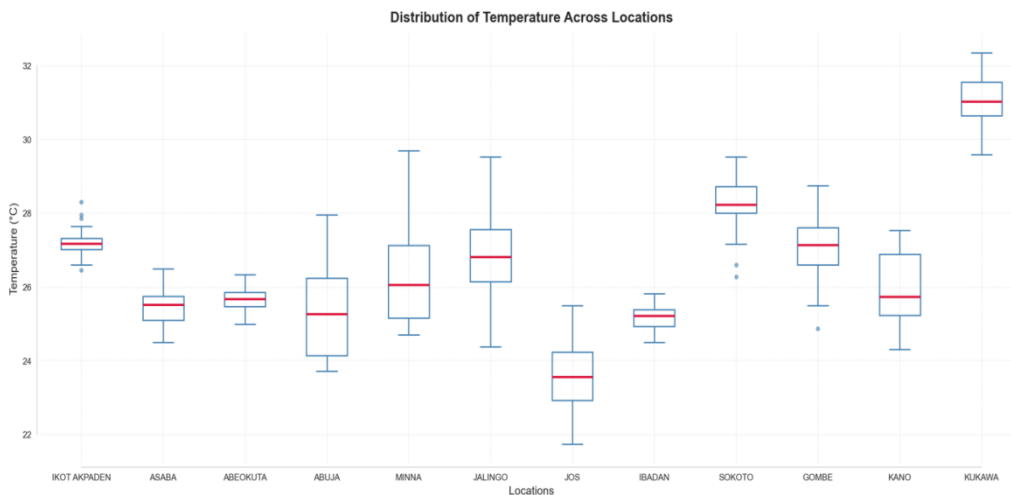


Figure 6: Box Plots Distribution of temperature across all locations

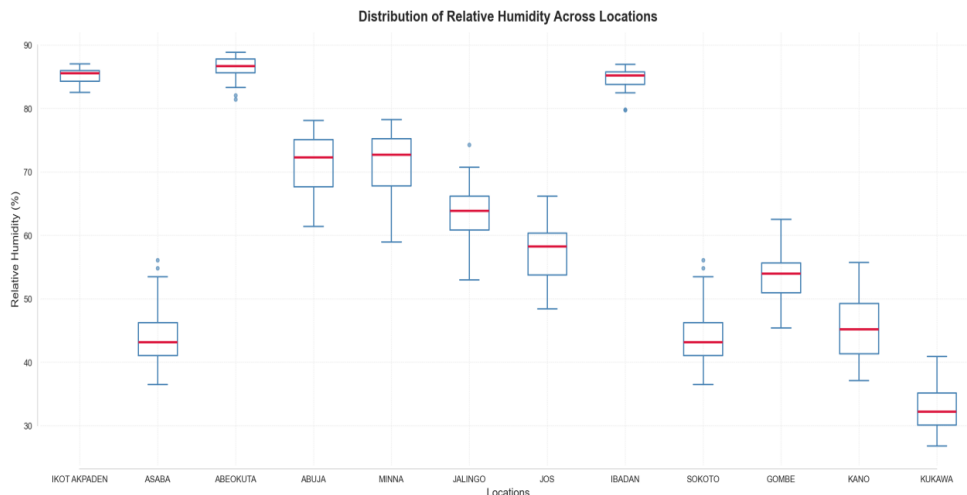
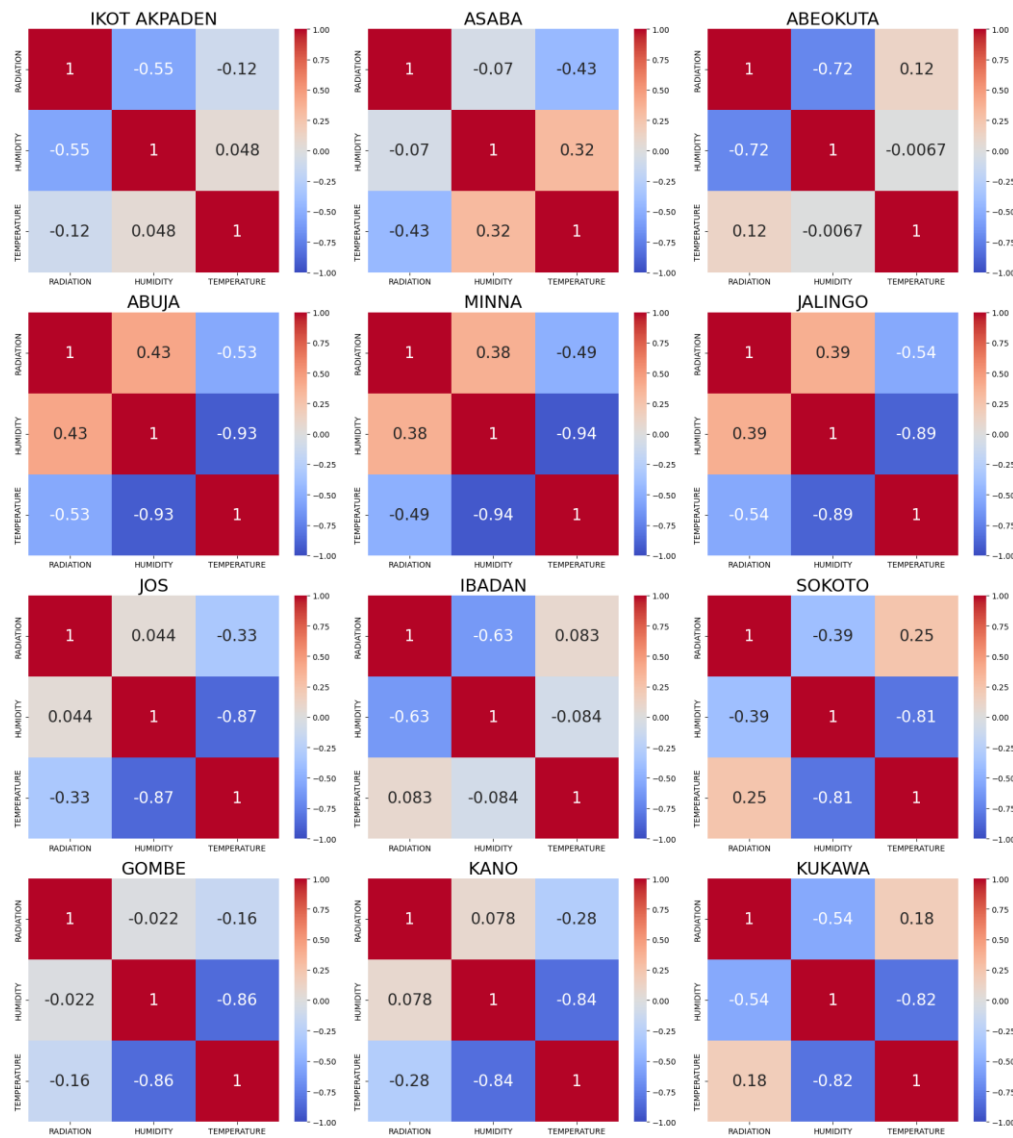


Figure 7: Box Plots Distribution of relative humidity across all locations



**Figure 8:** Correlation Heat Maps across all locations for Solar Radiation, Temperature and Relative Humidity

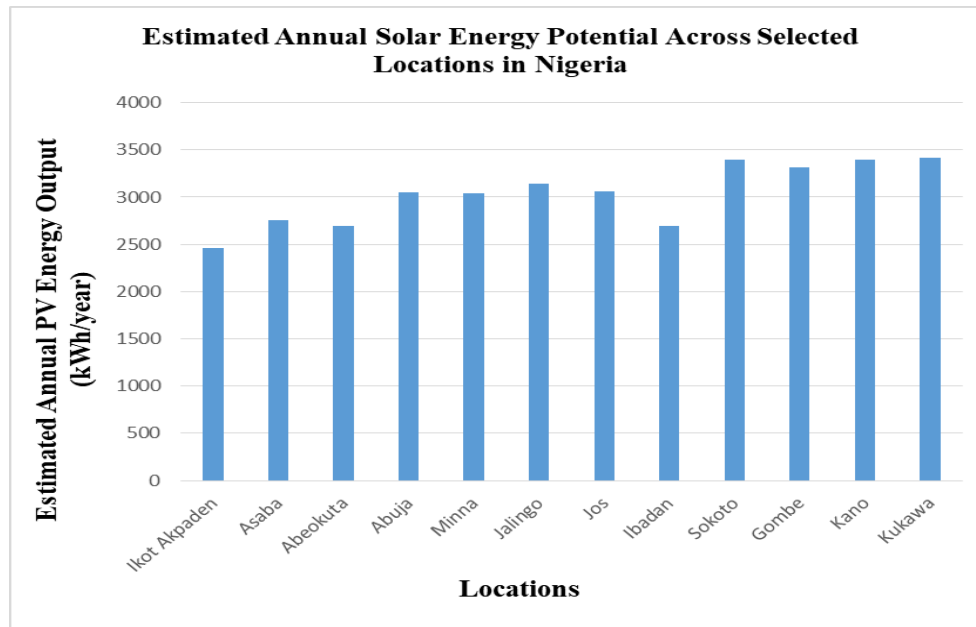
### 4.2 Relationship Between Climate Variables

The correlation analysis was used in this study to demonstrate the relationship between the climate variables. Figure 8 shows the correlation heat map of these variables for all studied locations. The correlation heat map showed a negative relationship between solar radiation and relative humidity, with strong negative correlations seen in Abeokuta (-0.72), Ibadan (-0.63), Kukawa (-0.54), and Ikot Akpaden (-0.55). This demonstrates the influence of climate variables on solar radiation, which indicates that increased atmospheric moisture and cloudiness significantly reduce the amount of solar radiation reaching the Earth’s surface. The strong negative correlations observed in Abeokuta, Ibadan, Ikot Akpaden, and Kukawa

suggest that atmospheric humidity plays a major role in controlling solar radiation variability. Increased cloud formation and atmospheric water vapor reduce atmospheric transparency through absorption and scattering processes. The relationship between solar radiation and temperature exhibited spatial variability across the study area. Negative relationships were observed in Abuja (-0.53), Minna (-0.49), and Jalingo (-0.54) while Sokoto (0.25), Kukawa (0.18), and Ibadan (0.08) exhibits a weak/positive correlation. While some northern stations showed weak positive relationships, several transitional regions exhibited negative correlations. This variability may be associated with regional atmospheric circulation systems, land surface processes, and cloud dynamics. The

correlation between temperature and relative humidity showed a strong negative relationship nearly across all studied locations. The strongest negative correlations were observed in Abuja (-0.93), Minna (-0.94), Jalingo (-0.89), Kano (-0.84), and Sokoto (-0.81). Thus, suggesting that an increasing temperature will result in a

decrease in relative humidity. These findings agree with Falayi et al. (2013), who reported that increased humidity and cloud cover reduce solar radiation, while temperature shows a positive correlation.



**Figure 9:** Bar charts showing the solar energy potential across selected locations in Nigeria's climatic zones

#### 4.3 Assessment of the Impact of Long-Term Climate Trends on Solar Energy Potential across Selected Locations in Nigeria's Climatic Zones

Figure 9 shows the estimated annual solar photovoltaic energy output across selected locations in Nigeria's climatic zones. The estimated energy output values reported in this study represent the annual electricity generation from a standardized 2kW photovoltaic (PV) system assumed in equation 4, and not the total large-scale solar energy capacity of the locations. Therefore, the estimated annual photovoltaic energy yield for the standardized 2kW PV system varies between 2450 kWh/year and 3450 kWh/year across the selected locations, indicating spatial variability in solar energy potential across Nigeria's climatic zones, which correspond to the expected annual energy yield of the assumed 2kW PV installation under the climatic conditions of each study location. The highest estimated solar photovoltaic energy

output was recorded in the Warm Desert Climate (Kukawa), and Semi-arid Climate (Kano, Sokoto, and Gombe). These findings may be linked to the climatic characteristics of these regions such as low humidity, lower cloud cover, minimal rainfall and extended periods of sunshine. These conditions enhance atmospheric transparency and increase solar radiation penetration, thereby increasing the performance and productivity of photovoltaic systems and electricity generation potential. This result is in line with the report that climatic conditions and vegetation significantly influence the distribution of solar radiation across Nigeria's climatic zones (Okono et al., 2022). Similarly, Falayi et al. (2013) reported that reduced cloud cover and low atmospheric moisture contribute positively to the availability of solar radiation in Nigeria. The Monsoon Climate (Ikot Akpaden, Asaba) and the Tropical Savannah Climate (Ibadan) recorded a lower estimated annual solar energy output value, with the lowest potential observed

in Ikot Akpaden. The results may be attributed to the nature of their climatic conditions, such as long rainfall duration, high humidity, and persistent cloud cover etc, highlighting the influence of climatic factors on the amount of solar energy reaching the surface. This finding is consistent with Falayi et al. (2013), who reported that solar radiation intensity in Nigeria reduces significantly with an increase in cloud cover and relative humidity. A moderate to high solar energy potential was recorded in Abuja, Minna, Jalingo, and Jos, because of its transitional climatic characteristics between the northern and southern regions of Nigeria. These regions experience mixed climatic conditions such as moderate rainfall, moderate humidity, and a stable sun duration.

The findings of this study therefore demonstrate a clear north-to-south variation in solar energy potential across Nigeria's climatic zones, with the northern region exhibiting an increasing solar energy potential across Nigeria's climatic zones, which shows that the northern part of Nigeria exhibits more suitable climatic conditions that is favourable for large-scale solar photovoltaic projects compared to the southern coastal regions. This spatial distribution pattern confirms the strong influence of long-term climatic variables on renewable energy resources and solar photovoltaic performance. Therefore, the results demonstrate the significant influence of long-term climatic conditions on solar energy potential, highlighting the importance of climatic considerations in solar energy planning and policy development in Nigeria.

## 5.0 Conclusion

This study successfully examined the long-term trends of solar radiation and climatic variables across selected climatic zones in Nigeria and evaluated their implications for renewable energy potential. The study revealed that temperature exhibits a consistent increasing trend across most locations which indicates a

consistent warming pattern across the study area. Relative humidity generally shows a spatial variability in humidity across the study area, where a decreasing or variable trend was observed specifically in the northern regions, while consistently high humidity levels were maintained in the southern regions, indicating that atmospheric moisture conditions differ considerably between northern and southern regions of Nigeria.

The correlation heat map showing the relationship between climatic parameters revealed that an increase in relative humidity causes a significant decrease in solar radiation intensity. This indicates that atmospheric conditions such as cloud cover, moisture concentration, and rainfall patterns influence solar energy availability. The estimated solar photovoltaic output energy demonstrates a clear north-to-south variation in solar energy potential across Nigeria's climatic zones. The northern region exhibits higher solar energy potential than the southern climatic zones because of lower humidity, reduced cloud cover, and greater solar radiation availability. This confirms the strong influence of long-term climatic variables on renewable energy resources and solar photovoltaic performance. Therefore, the study demonstrates that the northern part of Nigeria remains the most suitable region for large-scale solar photovoltaic development due to its favourable atmospheric and climatic characteristics.

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