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ASSESSING SOLAR RADIATION PATTERNS IN THREE ZONES OF NIGERIA AND APPLICATION IN AGRICULTURE, WATER AND ENERGY

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ABSTRACT

Solar radiation is an electromagnetic waves of light from the sun, which can be visible, infrared and ultraviolet light. The impact of sunlight is directly proportional to the temperature experienced on earth, which in turn affect plant production and power generation via photovoltaic principles. The objective of this study is to assess the patterns of solar radiation (SR) in three zones of Nigeria and its application in Agriculture, water and Energy. In assessing the natural phenomenon, studies were carried out in Ibadan, Onne, and Kano agro-ecological zones in Nigeria. The International Institute of Tropical Agriculture (IITA) stations in Ibadan provided thirty-six (36) years of meteorological data, Onne provided thirty (30) years, and Kano provided twenty-seven (27) years. The trend direction, and the degree of change over time, the variables were subjected to basic parametric linear and quadratic regression analysis procedures as well as non-parametric Mann-Kendall trend analysis to determine the Sen.'s slope. Ibadan's SR was found to have dramatically dropped between January and December. The summary descriptive statistics of the long-term solar radiation dataset revealed significant fluctuation, with a Z test score of -3.84% in November at 0.001 significant levels and -2.87% in March at 0.01 significant values in Ibadan. The test summary statistics also reveal a large variance in Onne's SR, ranging from -0.41 to -2.59%. The months from January to December shows there was a notable decline in Onne's SR, with July seeing the highest value of -0.41%. Every month in the year has a notable variation in monthly SR, which decreases monotonically across the entire year. Changes in aerosol concentration, increased cloudiness and changes in earth orbits parameter are likely to be the potential reasons for the decrease in SR in the study areas. The sun radiation in Kano increased significantly from 0.41 in January to 2.99 % in July. The decrease in solar radiation (solar dimming) in Ibadan and Onne may help to reduce the cost of irrigation owing to reduction in Evapotranspiration thereby reducing irrigation water use efficiency (WUE) of the crop. Evaporation of water from dam will also reduce as a result of decrease in solar radiation thereby reducing the cost of water production while other area with increasing SR will enjoy more energy for both agricultural, water and energy purposes for processing, drying, refrigeration, electricity, water pumping and also for photosynthesis in crop production.

KEYWORDS: Solar radiation; Agro – ecological zones; Mann – Kendall trend; Agriculture; Energy

INTRODUCTION

Sunlight is the main source of energy for a variety of chemical, biological, and physical activities on the surface of the earth. Comprehensive and precise data on solar radiation at a given location are extremely important for study and application areas like ecology, hydrology, agrology, meteorology, limnology, industry, architecture, and environment (Bulut & Büyükalaca, 2007). In addition, statistics on solar radiation are an essential component of solar energy applications, including photovoltaic systems for electricity production, solar collectors for heating, solar air conditioning systems for building climate management, and passive solar devices (Sfetsos et al., 2000). Nigeria is endowed with an annual average daily sunshine of 6.25 hours, ranging from 5.25 hours at the coastal area to 9.0 hours at the far northern boundary (Ejiko, 2015; Ejiko et. al., 2020). It has an annual average daily solar radiation of about 5.25

$kW/m^2/day$ which varies from 3.5 $kW/m^2/day$ at the coastal area to 7.0$kW/m^2/day$ at the Northern boundary (Louis, 2003; Haydar et al., 2006). The solar radiation per station is directly related to the power generated with respect to the collector such as photovoltaic panels (Ejiko, 2021). In establishing an appropriate specification for power generation, Ejiko et. al. (2018) developed models for battery banking capacity. Modeling base on altitude and azimuth were utilized for appropriate positioning of solar ray collector. Data obtained from daily readings of Nigeria locations were used to develop mathematical models for determining the sun's position (Ejiko et. al., 2015; Ejiko et. al., 2019). The mathematical model is an equation with varying input parameters or formula derived to simplify complex situations into simple equations through which the variable replacement will lead to the varying output of the azimuth (Muneer et al., 2007; Ulgen & Hepbasli, 2004; Younes & Muneer, 2006).

For the purpose of global marketing, designers and manufacturers of solar equipment must be aware of the average global solar radiation available in various and specific regions. This requires knowledge of radiation data in various countries for the global study of the world distribution of global solar radiation. Due to its significance in supplying energy for the earth's climate system, global solar radiation has recently been examined. Global solar radiation is economically significant as a renewable energy alternative. The climate of a place affects the amount of solar radiation that reaches the earth's surface, and this information is crucial for modeling and forecasting solar radiation systems.

Installing pyranometers at numerous sites within a specific region and managing their daily maintenance and recording is the most effective method of determining the total solar radiation amount of a place, but this is an extremely expensive endeavor. Correlating solar radiation with meteorological characteristics at the location where the data is taken is an alternate method. When solar data are unavailable, the resulting correlation can be used to places with comparable geographical and climatic features.

A precise understanding of the distribution of solar radiation at a certain place is crucial for the construction of various solar energy devices as well as for performance estimations. Regretfully, the cost of solar radiation data and the comparatively advanced technologies needed prevent many developing nations from accessing it. Thus, it is preferable to elaborate on the procedures that make modeling with meteorological data simple. This study aims to assess solar radiation trends and variability, appraise certain global radiation models specifically for Ibadan, and create new models based on sunshine for the research region.

MATERIALS AND METHOD

Study area

These studies were carried out in three International Institute of Tropical Agriculture (IITA) stations: Ibadan, Onne, and Kano all located in Nigeria.

Ibadan: This is the biggest city in Black Africa and is located in southwest Nigeria. It is situated close to the border of the South Western Forest Grassland in Nigeria, at latitude 7º 30' N and longitude 3º 55'E. Additionally, it has a sub-humid climate with rainforests and sporadic torrential downpours. With a mean yearly rainfall of 1250 mm, it has bimodal rainfall.

Onne: This area, which is 10 meters above sea level and is situated at latitude 4° 46' N and longitude 7° 10' E, is another one with a lot of rainfall. It is a town in the South-South region of the nation in River State. The majority of the local population works as fishermen. Its humid environment is typified by mangrove trees, wetlands, and a lot of rainfall. With a maximum temperature between 28 and 32 degrees Celsius and a minimum temperature between 21 and 23 degrees Celsius, it has an annual mean rainfall of 2400 mm and a unimodal rainfall pattern. It has two distinct seasons: the long, intensely rainy season and the brief, dry season.

Kano: is located in the nation's northern area. Its semi-arid or savanna climate is typified by sporadic bushes and trees. Large amounts of sand particles are carried by strong winds and deposited in areas where erosion is removing soil. With an average annual rainfall of 748.1 mm, it has ferric latosol soils. There are two distinct seasons in the region: the wet or rainy season, which spans from May to September and has temperatures between 24 and 29 degrees Celsius, and the dry season, which is from October to April and has maximum temperatures between 28 and 42 degrees Celsius and minimum temperatures between 25 and 27 degrees Celsius.

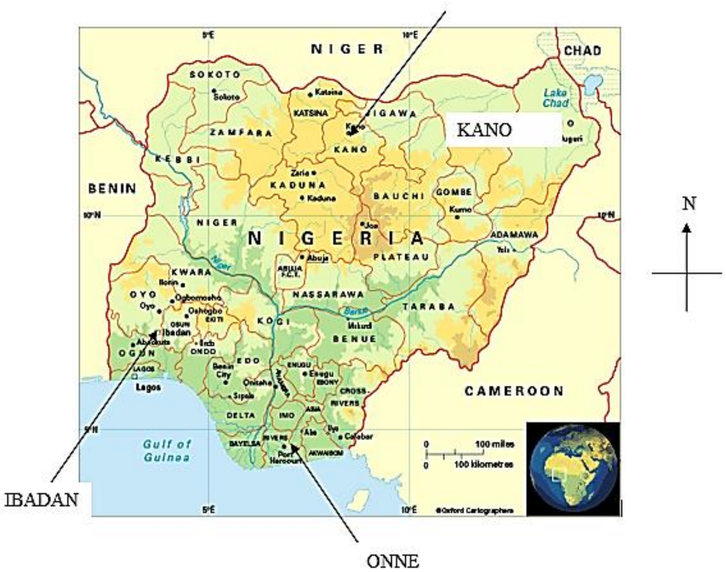

Figure 1: Geographical Location of the Study Areas on the Map of Nigeria

Data sources

The meteorological data; Solar Radiation used for the study was obtained from the Archives of the International Institute of Tropical Agriculture (IITA), stations in Ibadan, Onne, and Kano, Nigeria. The data collected covered a period of 36, 30, and 27 years for Ibadan, Onne, and Kano respectively. Onne is a station with latitude 4°43′N Longitude 7°01′E with an altitude of 19.55m above sea level. Ibadan has a latitude 7^0 30'N and longitude 3^0 54'E and Kano with latitude 12° 00' 47''N / 8° 31' 0''E.

Method of analysis

An Excel template MAKESENS (Mann-Kendall test for trend and Sen's slope estimates) which was developed for detecting and estimating trends in the time series was used to evaluate the trend and variability of solar radiation and sunshine duration in the area under study. The Mann-Kendall test statistic S is given by Salmi et al. (2002) as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \quad \text{Eq.1}$$

where n is the length of the time series $x_i \ldots x_n$, and sgn (.) is a sign function, x_j and x_k are values in years j and k, respectively. The expected value of S equals zero for series without trend and the variance is computed as:

$$\sigma^2(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \quad \text{Eq. 2}$$

Here q is the number of tied groups and t_p is the number of data values in p^{th} group. The test statistic Z is then given as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\sigma^2(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \dfrac{S+1}{\sqrt{\sigma^2(S)}} & if \quad S < 0 \end{cases} \quad \text{Eq. 3}$$

As a non-parametric test, no assumptions as to the underlying distribution of the data are necessary. The Z statistic is then used to test the null hypothesis, H_o that the data is randomly ordered in time, against the alternative hypothesis, H_1, where there is an increasing or decreasing monotonic trend. A positive (negative) value of Z indicates an upward (downward) monotone trend. H_o is rejected at a particular level of significance if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables. Hobbins et al. (2001) noted that the Mann-Kendall test is non-dimensional and does not quantify the scale or the magnitude of the trend but the direction of trend. To estimate the true slope of an existing trend the Sen's non-parametric method was used (Salmi et al., 2002; Omotayo et al., 2024).

RESULTS AND DISCUSSION

Descriptive statistics for Ibadan

The descriptive statistics summary of the long-term series of solar radiation SR for Ibadan is presented in Table 1. SR varied significantly with Z test value of -3.84 MJ/m^2 in November at 0.001 significant levels to -2.87 MJ/m^2 in March at 0.01 significant levels. There was a significant decrease in SR in Ibadan in all months (January – December). This is consistent with the widely observed decline in solar radiation known as "global dimming," as documented by Stanhill and Cohen (2001). Similar findings regarding a decline of 10% every decade were also observed by Stanhill and Kalma (1995) in their examination of local series in Hong Kong. Increased cloud cover, changes in solar activity resulting from modifications to Earth's orbital parameters, and alterations in aerosol concentrations, whether naturally occurring from volcanic eruptions or man-made from population growth and industrialization, can all contribute to this.

Thus, reductions in solar radiation are expected to result in less water use and evapotranspiration, except for circumstances where a fall in solar irradiance increases plant canopy conductance to water vapor. Alongside the reported decline in solar radiation, a global decrease in open-water surface evaporation has also been detected (Xu et al., 2006). Furthermore, if no other climatic factors are present, a 10–20% reduction in solar energy reaching the earth's surface seems to have little impact on plant production and crop yield (Stanhill & Cohen, 2001).

Table 1.: Non-parametric Mann-Kendall and Sen's test summary statistics for Ibadan

Time series	Slope/yr	Solar radiation (MJ/m^2)	
		Test Z	Sig.
January	-0.09806	-3.45	***
February	-0.12531	-4.05	***
March	-0.09135	-2.87	**
April	-0.12222	-4.05	***
May	-0.09495	-3.69	***
June	-0.10703	-3.80	***
July	-0.11452	-3.61	***
August	-0.11528	-3.28	***
September	-0.11953	-3.75	**
October	-0.11782	-3.42	***
November	-0.12255	-3.84	***
December	-0.09113	-3.56	***
Annual	-0.1035	-4.862	***

* Significant at 0.001, **Significant at 0.01, * Significant at 0.05, $^+$ Significant at 0.1

Descriptive statistics for Ibadan

According to Table 2 at Onne's descriptive test summary data, there is a substantial fluctuation in SR ranging from -0.41 to -2.59 MJ/m2. From January to December, there was a significant decline in SR, with July seeing the highest value of -0.41%. Every month in the year has a notable variation in monthly SR, which decreases monotonically across the entire year. It is generally acknowledged that the concentration of carbon (IV) oxide (CO_2) is the primary factor limiting leaf photosynthesis at high photon flux densities. Photosynthesis is the primary factor determining plant productivity, and it becomes limited when photon flux densities drop to roughly 30% of those in full sunlight (Oguntunde et al., 2012). Thus, assuming other climatic factors are not present, a reduction of roughly 10 - 20% in solar energy reaching the earth's surface seems to have little impact on agricultural yield and plant productivity (Stanhill & Cohen, 2001). Nevertheless, when certain plants are exposed to high light levels, there is a decrease in leaf conductance to the gas exchange due to soil water availability and the plant's capacity to transfer water to active leaves. This moisture constraint is common in the arid and semi-arid sections of the latitudes as well as in tropical latitudes.

Table 2.: Non-parametric Mann-Kendall and Sen's test summary statistics for Onne

Time series	Slope/yr	Solar radiation (MJ/m^2)	
		Test Z	Sig.
January	-0.080	-2.59	**
February	-0.081	-2.19	*
March	-0.075	-2.19	*
April	-0.068	-1.99	*
May	-0.052	-2.07	*
June	-0.093	-2.42	*
July	-0.035	-0.41	
August	-0.051	-1.16	
September	-0.099	-3.10	**
October	-0.045	-1.43	
November	-0.060	-2.04	*
December	-0.069	-2.43	*
Annual	-0.879	-3.08	***

* Significant at 0.001, **Significant at 0.01, * Significant at 0.05, $^+$ Significant at 0.1

Descriptive statistics for Kano

The test summary statistics trend of SR in Kano is presented in Table 3. The table shows there is a significant variation and increase in solar radiation in Kano from 0.4 to 2.99 MJ/m^2. This confirms the simulation studies, which showed that solar brightening, persists in many high-latitude areas (Kishcha et al., 2007). Also, there is an increase in SR as we tend to the northern part of the country.

However, the rate of solar radiation in the surrounding environment determines how much water a crop needs for irrigation. These establish the amount of water that needs to be used for irrigation. More water will be needed to irrigate crops in areas with strong sun radiation. The mechanisms of transpiration and evaporation are significantly influenced by solar radiation. Transpiration is the process of evaporation that happens across various plant organs, primarily leaves, whereas evaporation primarily occurs from the soil's surface. Due to their close relationship, evapotranspiration and water consumption are frequently evaluated jointly. Crop water needs, on the other hand, are a crucial component of irrigation strategy planning and design and are tied to the crop itself.

Table 3: Non-parametric Mann-Kendall and Sen's test summary statistics for Kano

Time series	Slope/yr	Solar radiation (MJ/m^2)	
		Test Z	Sig.
January	0.035	0.41	
February	0.051	0.73	
March	0.145	2.59	**
April	0.096	1.95	+
May	0.145	2.52	*
June	0.090	2.57	*
July	0.081	2.99	**
August	0.067	2.10	*
September	0.121	2.78	**
October	0.172	2.93	**
November	0.119	1.86	+
December	0.005	0.19	
Annual	0.081	1.09	

* Significant at 0.001, **Significant at 0.01, * Significant at 0.05, $^+$ Significant at 0.1

Application of solar radiation in agriculture, water, and energy

One of the earliest and most popular uses of solar energy is crop drying, which involves utilizing the sun to dry grains and other crops. Solar radiation is applied to many other fields, including agriculture. The easiest and least expensive method is to spread grain and fruit outside in the sun after harvesting or to let crops dry naturally in the field. In comparison to open-air methods, more advanced solar dryers preserve grain and fruit, minimize losses, dry faster and more evenly, and yield a higher-quality product (Avinash et al., 2008). Another field is space and water heating, which is related to dairy and livestock enterprises, which have high needs for heating their air and water. To optimize the health and growth of the birds, modern poultry farms rear them in enclosed buildings where temperature and air quality must be closely regulated. Regular indoor air replacement is necessary for these establishments to get rid of dust, smells, moisture, and harmful gasses. When it comes to heating this air, a lot of energy is needed.

Another way that solar radiation is used in agriculture is for greenhouse heating. Generally, commercial greenhouses get their lighting from the sun. On the other hand, solar greenhouses are made to use solar energy for lighting as well as heating. Thermal mass and insulation are two features of a solar greenhouse that enable it to gather and store solar heat energy for usage at night and on overcast days (Avinash et al., 2008). Water pumping: Photovoltaic (PV) water pumps are incredibly dependable and low maintenance when installed and sized correctly. The quality of solar energy available at the site, the pumping depth, the water demand, and the costs associated with system acquisition and installation all affect the size and cost of a PV water pumping system. Numerous businesses produce solar-powered water pumping systems for ponds, streams, and wells. In general, theoretical and practical research shows that substantial increases in photosynthesis can be achieved in many climates by a slight drop in direct radiation when combined with an increase in the fraction of diffuse radiation (Healey, 1998). In contrast to crop productivity, evapotranspiration and crop water balance are strongly correlated with solar radiation (Oguntunde et al., 2012). Therefore, reductions in solar radiation are expected to result in less water use and evapotranspiration, except for circumstances when a fall in solar irradiance enhanced plant canopy conductance to water vapour.

CONCLUSIONS AND RECOMMENDATIONS

The patterns of solar radiations in three agro-ecological zones of Nigeria were assessed in this study with its application in Agriculture, water and energy. However, the primary energy source for all physical, chemical, and biological processes on Earth's surface is solar radiation. The decrease in solar radiation (solar dimming) in Ibadan and Onne may help to reduce the cost of irrigation owing to reduction in Evapotranspiration thereby reducing irrigation water use efficiency (WUE) of the crop. Evaporation of water from dam will also reduce as a result of decrease in solar radiation thereby reducing the cost of water production while other area with increasing SR will enjoy more energy for both agricultural, water and energy purposes for processing, drying, refrigeration, electricity, water pumping and also for photosynthesis in crop production. This will enhance the planning and construction of greenhouses, livestock buildings, heating, cooling, and crop drying systems, as well as in the design of agricultural projects and systems.

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