Pure Appl. Geophys. 180 (2023), 3385–3400

https://doi.org/10.1007/s00024-023-03330-x

Pure and Applied Geophysics

Estimation of Diffuse Solar Radiation Models for a Tropical Site in Nigeria

Olanrewaju Olukemi Soneye-Arogundade[1] and Bernhard Rappenglück[1]

Abstract—Knowledge of solar radiation and its components in a particular area is crucial in studying solar energy and constructing solar energy devices due to the many advantages solar radiation has over fossil fuels. In this two-year study, conducted at a tropical site in Ile-Ife, Nigeria, from January 2016 to December 2017, twenty-one empirical models were proposed to estimate diffuse solar radiation using continuous solar radiation data. The models were divided into five groups and developed using relative sunshine duration and/or clearness index as input variables. The performance of five models from the literature was also examined and compared to measured data. The models' performance was evaluated using the Akaike Information Criteria (AIC), the Global Performance Index (GPI), and various statistical errors. Model 11, a quadratic model with clearness index as an input variable, had the lowest AIC (1.8098), AIC_C (4.8099), ΔAIC_C (0.0000), and GPI (− 2.1796) values and was the most accurate model for estimating diffuse solar radiation at the study site and other locations with similar climatic conditions. None of the models selected from the literature was suitable for estimating diffuse solar radiation at the study site; hence, the proposed models performed better.

Keywords: Diffuse solar radiation, Empirical models, Solar energy, Clearness and cloudiness indices, Diffusion coefficient, Relative sunshine duration.

1. Introduction

The development and utilisation of renewable energy resources, which will serve as the fundamental future energy source for the world, is essential for generating sustainable energy technologies (Dincer, 2000; Elliott, 2000; Falayi & Rabiu, 2011; Ulgen & Hepbasli, 2009). Renewable energy resources, such as solar energy, offer critical advantages over fossil fuels, as they reduce the emission of greenhouse gases and a wide range of air pollutants and are a more sustainable source of energy. To fully utilise solar energy, it is important to have a precise knowledge of the amount of solar radiation and its components available at each location. This information is crucial for the design and optimisation of various solar energy systems, including those used in human-clothing-environment systems, and for biological studies of vitamin D. Additionally, this knowledge is essential for the development of solar energy conservation devices, such as water desalinators, concentrating collectors, solar furnaces, and solar dryers (Bakirci, 2009, 2015; Chandrashekara & Yadav, 2017; Falayi & Rabiu, 2011; Krzyścin et al., 2011; Salhi et al., 2020; Shimazaki et al., 2017; Taşdemiroğlu & Sever, 1991; Tiris et al., 1996; Zarezade & Mostafaeipour, 2016).

Despite the widespread availability of pyranometers, solarimeters, and pyrheliometers to measure incoming solar radiation, measuring diffuse solar radiation is not as common, even though it has significant applications in solar energy systems, home energy analysis, and building heat transfer (Berrizbeitia et al., 2020; Gopinathan & Soler, 1995; Jacovides et al., 1996; Soneye et al., 2019; Taşdemiroğlu & Sever, 1991; Ulgen & Hepbasli, 2009). Several factors contribute to the limited measurements of diffuse solar radiation, including the impact of geographic, climatic, and atmospheric conditions and the high cost of equipment maintenance (Ayoola et al., 2014; Jamil & Akhar, 2017; Soneye et al., 2019). As a result, many theoretical and empirical models have been developed to estimate this parameter (Bakirci, 2015; Duffie & Beckham, 2006; Khorasanizadeh et al., 2014).

In 1960, Liu and Jordan established the first empirical relationship for estimating diffuse solar

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00024-023-03330-x.

[1] Department of Earth and Atmospheric Sciences, University of Houston, Houston, TX 77204, USA. E-mail: olanrewaju.soneye@gmail.com

radiation, which has served as a baseline. Since then, many scientists (including Arslanoglu, 2016; Boland et al., 2008; Falayi & Rabiu, 2011; Gopinathan, 1988; Haydar et al., 2006; Iqbal, 1979; Jamil & Akhar, 2017; Jin et al., 2004; Karatasou et al., 2003; Khahro et al., 2015; Khalil & Shaffie, 2013; Oliveira et al., 2002; Salhi et al., 2020; Tarhan & Sari, 2005; Ulgen & Hepbasli, 2009; Wattan & Janjai, 2016; Yousuf & Umair, 2018, etc.) have proposed various empirical models for estimating diffuse solar radiation at different locations using input variables like pressure, temperature, humidity, clearness index, sunshine duration, and incoming solar radiation. Nevertheless, the most commonly used parameters include extraterrestrial solar radiation, clearness index, sunshine duration, and incoming solar radiation (Duffie & Beckham, 2006; Ulgen & Hepbasli, 2009; Yousuf & Umair, 2018). Various types of regression analysis, including linear, quadratic, cubic, exponential, logarithmic, and inverse, which all take into consideration the least squares method, are the most widely used techniques for developing diffuse solar radiation models (Yousuf & Umair, 2018).

In Nigeria, there are limited meteorological stations that measure diffuse solar radiation. Considering the significance of diffuse solar radiation in solar energy applications, this paper aims to develop empirical models for estimating monthly diffuse solar radiation for different classifications. These models are formulated based on the relationship between the cloudiness index and diffusion coefficient, which are functions of the clearness index and/or relative sunshine duration. In order to find the best model for estimating monthly diffuse solar radiation in the study area, we determine the accuracy of the developed empirical models through a comprehensive statistical error analysis between the modelled and observed data. Furthermore, the performance of five models chosen from existing literature based on their broad applicability and/or similarity to the climatic conditions is evaluated and compared against measured data.

2. *Methodology*

2.1. *Location of the Study Area*

This study utilised a two-year dataset (January 2016–December 2017) of incoming solar radiation obtained at a meteorological site in the Teaching and Research Farm of Obafemi Awolowo University in Ile-Ife (7.53° N; 4.54° E) in the southwestern region of Nigeria. According to Köppen's climate classification system, this region falls under the wet and dry climatic zones of West Africa and receives a high amount of solar radiation throughout the year, with sunrise and sunset occurring at approximately 07:00 and 19:00 local time (LT), respectively (Ayoola et al., 2014; Griffiths, 1974; Soneye et al., 2019; Soneye-Arogundade, 2021). The dry season runs from November to February, while the rainy season typically starts in March/April and ends in October, with average annual rainfall ranging between 1000 and 1500 mm. The mean relative humidity and temperature in the area are about 80% and 27 °C, respectively (Griffiths, 1974; Hayward and Oguntoyinbo, 1987; Ayoola et al., 2014; Soneye et al., 2019; Soneye-Arogundade, 2021). In general, the diffuse components of solar radiation increase during the wet months due to the increasing prevalence of clouds such as altostratus, thin cirrus, and altocumulus clouds (Iziomon & Aro, 1998; Okogbue et al., 2009; Soneye, 2021).

2.2. *A description of the Meteorological Sensors and Data Used for the Study*

The high-quality SR01 pyranometer (ISO-class) with a spectral range between 0.3 and 2.8 μm facing upward, incorporated into a four-component net radiometer (model NR01, Hukseflux, USA) sensor, was used to measure the incoming solar radiation. These measurements were recorded as one-minute values in Wm^{-2} and stored in a datalogger (model CR1000, Campbell Scientific, USA), as shown in Fig. 1. Additional information regarding sensor sensitivities, calibration, and maintenance can be found

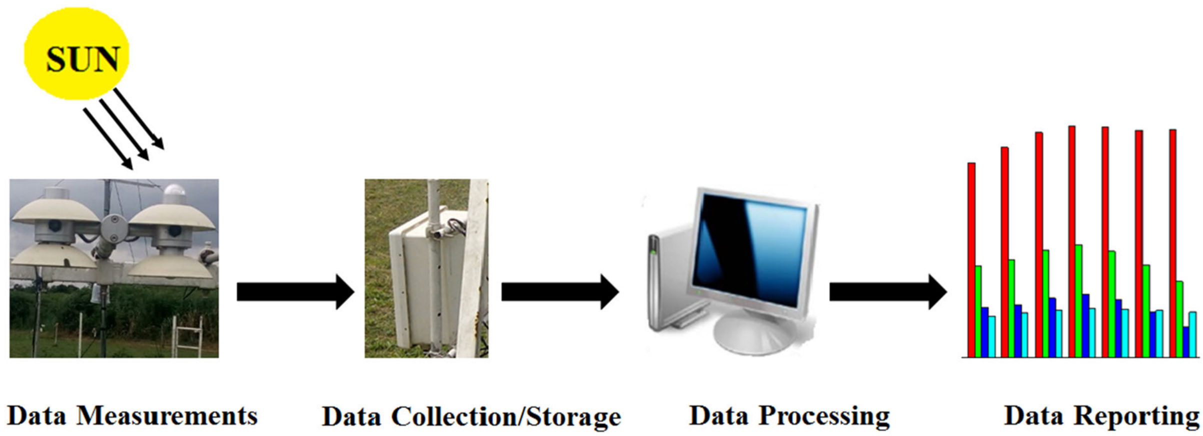

Figure 1
Acquisition and processing of radiation data at Ile-Ife, Nigeria

in Soneye et al. (2019) and Soneye-Arogundade (2021). The one-minute data was used to estimate the monthly average daily values of incoming solar radiation in MJ m^{-2} day^{-1}. The data was then divided into two annual sets.

2.3. Atmospheric and Astronomical Parameters

The clearness index (C_t) is the ratio of the measured global solar radiation at the surface of the Earth to the extra-terrestrial solar radiation at the top of the atmosphere. This index is used to determine the transparency of the Earth's atmosphere to solar energy and how clouds and aerosols in the atmosphere affect the amount of solar radiation reaching the Earth's surface (Akhlaque et al., 2009; Augustine & Nnabuchi, 2009; Kuye & Jagtap, 1992; Liu & Jordan, 1960; Okogbue et al., 2009; Poudyal et al., 2012; Soneye, 2021). The clearness index also takes into account changes in atmospheric conditions and the amount of solar radiation at a given location. Theoretically, the index ranges between 0 and 1, but in practise, it varies from almost 0 on cloudy days to about 0.8 in clear-sky conditions (Soneye, 2021). The daily values of the clearness index were computed using:

$$C_t = \frac{S_i}{S_0} \quad (1)$$

where S_i is the measured incoming solar radiation (Wm^{-2}) and S_0 is the daily extra-terrestrial solar radiation at the top of the atmosphere (Wm^{-2}).

The daily extra-terrestrial solar radiation is the intensity of the solar radiation at the top of Earth's atmosphere, and it varies throughout the year due to the elliptical orbit of the Earth (Iqbal, 1983; Duffie & Beckham, 2006; Soneye, 2021). The intensity of the extra-terrestrial solar radiation was computed using:

$$S_0 = \frac{24 \times 3600}{\pi} \times G_0 \times E_0 \times \left(\sin\omega_s \cos\phi \cos\delta + \frac{\pi\omega_s}{180} \sin\phi \sin\delta \right) \quad (2)$$

where G_0 is the solar constant ($1367Wm^{-2}$), E_0 is the eccentricity correction factor of the Earth's orbit, ϕ is the latitude (positive north), ω_s is the sunrise hour angle, δ is the solar declination angle and $\pi = 3.14286$. The units of ϕ, λ_e and δ are degrees (°).

The solar declination angle is the angle between the equatorial plane and the line connecting the centres of the sun and Earth. This angle constantly changes, with a value of zero during the autumnal and vernal equinoxes, and approximately equal values of $-23.5°$ and $+23.5°$ at the winter and summer solstices, respectively (Iqbal, 1983). The solar declination angle was determined using the equation developed by Cooper (1969) and (Soneye, 2021):

Table 1

Models used for obtaining sunshine duration (N) *data*

Author(s)	Models
Mani et al. (1962)	$C_t = 0.30 + 0.46R_S$
	$C_t = 0.26 + 0.61R_S$
Turton (1987)	$C_t = 0.30 + 0.40R_S$
Gopinathan (1988)	$C_d = 0.931 - 0.814R_S$
	$C_d = 1.194 - 0.838C_t - 0.446R_S$
Taşdemiroğlu and Sever (1991)	$C_d = 0.622 - 0.350R_S$
Veeran and Kumar (1993)	$C_t = 0.34 + 0.32R_S$
	$C_t = 0.27 + 0.65R_S$
Aras et al. (2006)	$C_d = 0.663 - 0.4883R_S$
Pandey and Katiyar (2009)	$C_d = 0.9891(R_S)^{-0.4014} - 0.7839$
Katiyar and Pandey (2010)	$C_t = 0.2229 + 0.5123R_S$
	$C_t = 0.2286 + 0.5309R_S$
Jamil and Akhtar (2015)	$C_t = 0.0609 + 0.8646R_S$
Jamil and Akhtar (2017)	$C_d = 0.6484 - 0.3606R_S$
	$C_d = 0.3089(R_S)^{-0.606}$
	$C_d = 0.2932 + 1.8655C_t - 1.5114R_S$
	$C_d = 0.2191 + 2.3964C_t - 0.3877(C_t)^2 - 1.7828R_S + 0.1705(R_S)^2$
	$C_d = 0.8207 + 1.2720(C_t)^2 - 1.3276R_S$

$R_S$is the daily values of the relative sunshine duration calculated using $R_S = \frac{N}{N_0}$. N_0 is the maximum possible sunshine duration day length and N is the sunshine duration. The units of N_0 and N are hours. The maximum possible sunshine duration was calculated using $N_0 = \left(\frac{2}{15}\right)\omega_s$

$$\delta = \phi_L \sin\left[\frac{2\pi(d_n - d_r)}{d_y}\right] \quad (3)$$

where ϕ_L is the latitude of the Tropic of Cancer $= 23.45°$, $\pi = 180°$, d_n is the Julian day number of the year, which ranges from 1 on 1 January to 365 on 31 December, d_r is a constant = 284, d_y is the average number of days per year with a value of 365.

The eccentricity correction factor was computed using (Spencer, 1971; Iqbal, 1983; Soneye, 2021):

$$E_0 = 1.000110 + 0.034221\cos\Gamma + 0.001280\sin\Gamma + 0.000719\cos2\Gamma + 0.000077\sin2\Gamma \quad (4)$$

where Γ (unit is degrees) is the day angle and can be expressed as:

$$\Gamma = \frac{360(d_n - 1)}{365} \quad (5)$$

The sunrise hour angle was estimated using:

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (6)$$

The daily values of the diffuse solar radiation (S_d, unit Wm^{-2}), for the study area were calculated using Eq. (7) when $\omega_s > 81.4°$ and $0.3 \le C_{tAVG} \le 0.8$ (Duffie & Beckham, 2006):

$$C_d = \frac{S_d}{S_i} = 1.311 - 3.022C_{tAVG} + 3.427{C_{tAVG}}^2 - 1.821{C_{tAVG}}^3 \quad (7)$$

where C_d is the cloudiness index and C_{tAVG} is the average value of the clearness index.

The direct solar radiation was calculated from the difference between incoming solar radiation and diffuse solar radiation values.

To determine the daily sunshine duration (N) in the absence of measured data, eighteen solar radiation models, listed in Table 1, were utilised using the techniques of Aras et al. (2006), Ulgen and Hepbasli (2009), and Sabzpooshani and Mohammadi (2014). These methods involve selecting various diffuse solar radiation models from the existing literature to estimate this parameter. The resulting data was then averaged to estimate diffuse solar radiation, as

Table 2

Classes of the models developed in this paper for estimating monthly mean values of diffuse solar radiation

Class	Dependent variable	Type	Independent variable	Meteorological input	Mathematical expression
1	Cloudiness Index	Single input	Clearness Index	Incoming solar radiation	$C_d = f(C_t)$
2	Cloudiness Index	Two input	Clearness Index and Relative Sunshine Duration	Incoming solar radiation and sunshine duration	$C_d = f(C_t, R_S)$
3	Diffusion coefficient	Single input	Clearness Index	Incoming solar radiation	$C_{DD} = f(C_t)$
4	Diffusion coefficient	Single input	Relative Sunshine Duration	Sunshine duration	$C_{DD} = f(R_S)$
5	Diffusion coefficient	Two input	Clearness Index and Relative Sunshine Duration	Incoming solar radiation and sunshine duration	$C_{DD} = f(C_t, R_S)$

Diffusion coefficient, $C_{DD} = S_d/S_0$

Table 3

Solar radiation models selected from the literature

Model	Class	Author (s)	Models
Model 22	Class 1	Page (1961)	$C_d = 1.00 - 1.13(C_t)$
Model 23	Class 2	Gopinathan (1988)	$C_d = 1.194 - 0.838(C_t) - 0.446(N/N_0)$
Model 24	Class 3	Haydar et al. (2006)	$C_{DD} = 0.331 + 0.233(C_t)$
Model 25	Class 4	Barbaro et al (1981)	$C_{DD} = 0.2205 - 0.0126(N/N_0) - 0.1292(N/N_0)^2$
Model 26	Class 5	Jamil and Akhar (2017)	$C_{DD} = -0.2925 + 2.3591(C_t) - 0.5458(C_t)^2 - 1.0239(N/N_0)$

selecting the most appropriate model without experimental data can be challenging. The purpose of this approach was to eliminate variations between the estimates generated by the models (Aras et al., 2006; Ulgen & Hepbasli, 2009).

2.4. *Development of Diffuse Solar Radiation Models*

In the past, various empirical models have been developed by different authors, such as Aras et al. (2006), Gopinathan (1988), Ulgen and Hepbasli (2009), Katiyar and Pandey (2010), Jamil and Akhar (2017), and others, to estimate monthly mean values of diffuse solar radiation. These models typically use extra-terrestrial radiation, measured incoming solar radiation, and measured sunshine duration or relative sunshine duration as input variables. In this study, a correlation approach was used to develop 21 models that fall under five categories, as presented in Table 2. Multivariate regression analysis was used to generate these models. Models with several input variables and an order of up to two in each input variable were more accurate. However, higher-order models were not considered due to the increased complexity of the correlation equations. Five previously published models (listed in Table 3) were selected from the literature and compared with the measured diffuse solar radiation. These models were selected due to their broad applicability and/or similarity to climatic conditions.

2.5. *Method of Statistical Evaluation*

The aim of this study is to determine the best model for estimating solar radiation at the study location. According to Sen (2008) and Gueymard (2012), previously developed solar radiation estimation models do not have a perfect correlation coefficient of R = 1 since the measured data are prone to calibration uncertainty. Hence, this study evaluates the accuracy and performance of all newly

Table 4

Statistical errors

Statitical error	Expression
Mean bias error (MBE)	$\frac{1}{n}\sum_{i=1}^{n}(E_i - M_i)$
Mean absolute error (MAE)	$\frac{1}{n}\sum_{i=1}^{n}\lvert E_i - M_i\rvert$
Root mean square error (RMSE)	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - M_i)^2}$
Relative root mean square error (RRMSE)	$100.\left[\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - M_i)^2}}{\overline{M}}\right]$
Mean percentage error (MPE)	$\frac{1}{n}\sum_{i=1}^{n}\left(\frac{(\overline{M_i} - \overline{E_i})}{\overline{M_i}}\right) \times 100$
Index of agreement (d)	$1 - \left[\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}\left(\lvert E_i - \overline{M}\rvert + \lvert(M_i - \overline{M})\rvert\right)^2}\right]$
Sum of the square of relative error (SSRE)	$\sum_{i=1}^{n}\left(\frac{(\overline{E_i} - \overline{M_i})}{M_i}\right)^2$
Relative standard error (RSE)	$\sqrt{\frac{SSRE}{n}}$
Uncertainty at 95% (U_{95})	$1.96\left(SD^2 + RMSE^2\right)^{1/2}$
T-statistic (t-stat)	$\sqrt{\left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]}$
Global Performance Index (GPI)	$MBE \times RMSE \times U_{95} \times t - stat \times \left(1 - R^2\right)$
Correlation coefficient (R)	$\frac{\sum_{i=1}^{n}\left(Et_i - \overline{Et}\right)\left(Md_i - \overline{Md}\right)}{\sqrt{\sum_{i=1}^{n}\left(Et_i - \overline{Et}\right)^2\sum_{i=1}^{n}\left(Md_i - \overline{Md}\right)^2}}$
Akaike information criterion (AIC)	$2K - 2\log\left(L\left(\hat{\theta}\middle\vert y\right)\right)$
Akaike information criterion corrected (AIC_C)	$AIC + \frac{2K(K+1)}{n-K-1}$
Change in Akaike information criterion corrected (ΔAIC_C)	$AIC_C(i) - AIC_{Cmin}$

M is the measured value, *E* is the estimated value, $\overline{M}$is the mean of the measured value, $\overline{E}$ is the mean of the estimated value, *n* is the number of observations, SD is the percentage standard deviation of the difference between the estimated and measured values; *K* is the is number of independent variables (degrees of freedom), $L\left(\Theta|y\right)$ is the log-likelihood at its maximum point of the model estimated; $AIC_c(i)$ is the individual AIC_Cscore for each model; AIC_{Cmin} is the minimum AIC_C score of the models tested (or the AIC_C score for the best model). In the U_{95} equation, 1.96 is the coverage factor corresponding to a 95% confidence interval. The lowest value of AIC and GPI shows the most accurate model, i.e., the more accurate a model is, the closer to zero is the value of its AIC and GPI (Behar et al., 2015; Snipes & Taylor, 2014). The application of AIC and GPI has helped rank all the proposed models correctly and identify the best-performing models, which could not be done using the other statistical errors

developed models using the statistical tools listed in Table 4.

3. Results and Discussion

The solar radiation data measured at Ile-Ife from January 2016 to December 2017 is presented in Fig. 2. The height of the bar chart corresponds to the average monthly solar radiation, while the red and green portions represent the monthly means of the diffuse and direct solar radiation components, respectively. The incoming solar radiation reached its maximum value of 19.36 MJ m^{-2} day^{-1} in April of the first year, while its minimum values of 13.75 MJ m^{-2} day^{-1} and 11.63 MJ m^{-2} day^{-1} were recorded in the wet months of July and August, respectively. In the second year, 2017, the values for July and September were practically the same, with approximately 13.40 MJ m^{-2} day^{-1}, with the lowest value of 11.53 MJ m^{-2} day^{-1} recorded in August and the maximum value of 18.267 MJ m^{-2} day^{-1} in March, followed by April and May. The increase in incoming solar radiation during these months (April 2016 and

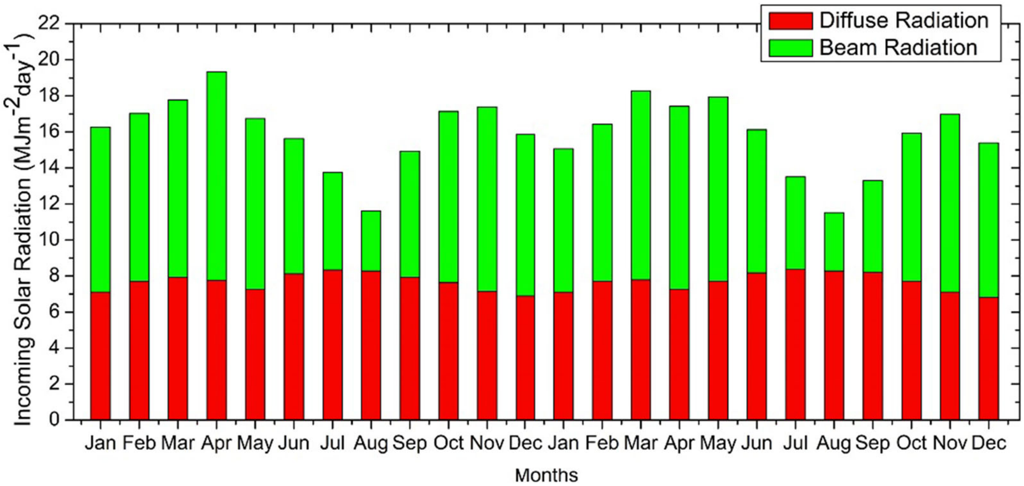

Figure 2
Variation of the monthly mean solar radiation for January-December 2016 and January–December 2017 at Ile-Ife, Nigeria

March 2017) can be attributed to the reduction in atmospheric turbidity resulting from the rain scavenging aerosol particles suspended in the atmosphere. This leads to a reduction in the attenuation of incoming solar radiation, less atmospheric cloud cover, and more direct solar energy reaching the earth's surface (Ayoola et al., 2014; Chukwuemeka & Asiegbu, 2017; Soneye, 2021; Soneye et al., 2019; Udo, 2000). The minimal values of incoming solar radiation in July and August for both years can be attributed to the predominance of high moisture content and high cloudiness throughout the rainy season (Afiesimama et al., 2006; Ayoola et al., 2014; Fagbenle, 1992; Maduekwe & Chendo, 1997; Ohunakin et al., 2015; Soneye, 2021; Soneye et al., 2019; Udo, 1978).

In 2016 and 2017, the variations in direct solar radiation followed the same pattern as the incoming solar radiation, with the minimum values occurring in August and the highest values recorded in April and March, respectively. The highest values of diffuse solar radiation, approximately 8.20 MJ m^{-2} day^{-1} were observed from June to September for both years, while the lowest values for both years were measured in December. The increase in cloud cover during the rainy months caused the high values of diffuse solar radiation observed between June and September of both years. This diffuse radiation is mostly caused by the intense forward scattering of

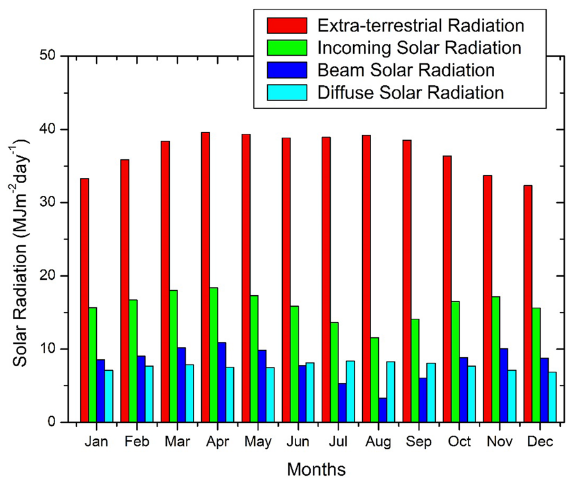

Figure 3
Variation of the monthly mean extra-terrestrial radiation, incoming solar radiation, and direct and diffuse solar radiation for January-December 2016 and January–December 2017 at Ile-Ife, Nigeria

solar radiation due to clouds such as altostratus, thin cirrus, and altocumulus (Ayoola et al., 2014; Iziomon & Aro, 1998; Okogbue et al., 2009; Soneye, 2021; Soneye et al., 2019). The lowest value obtained indicates that molecule scattering and, to a lesser extent, surface albedo are the primary causes of diffuse radiation that reaches the Earth's surface (Iziomon & Aro, 1998). These results are similar to those published for Abia, Nigeria, by Chukwuemeka

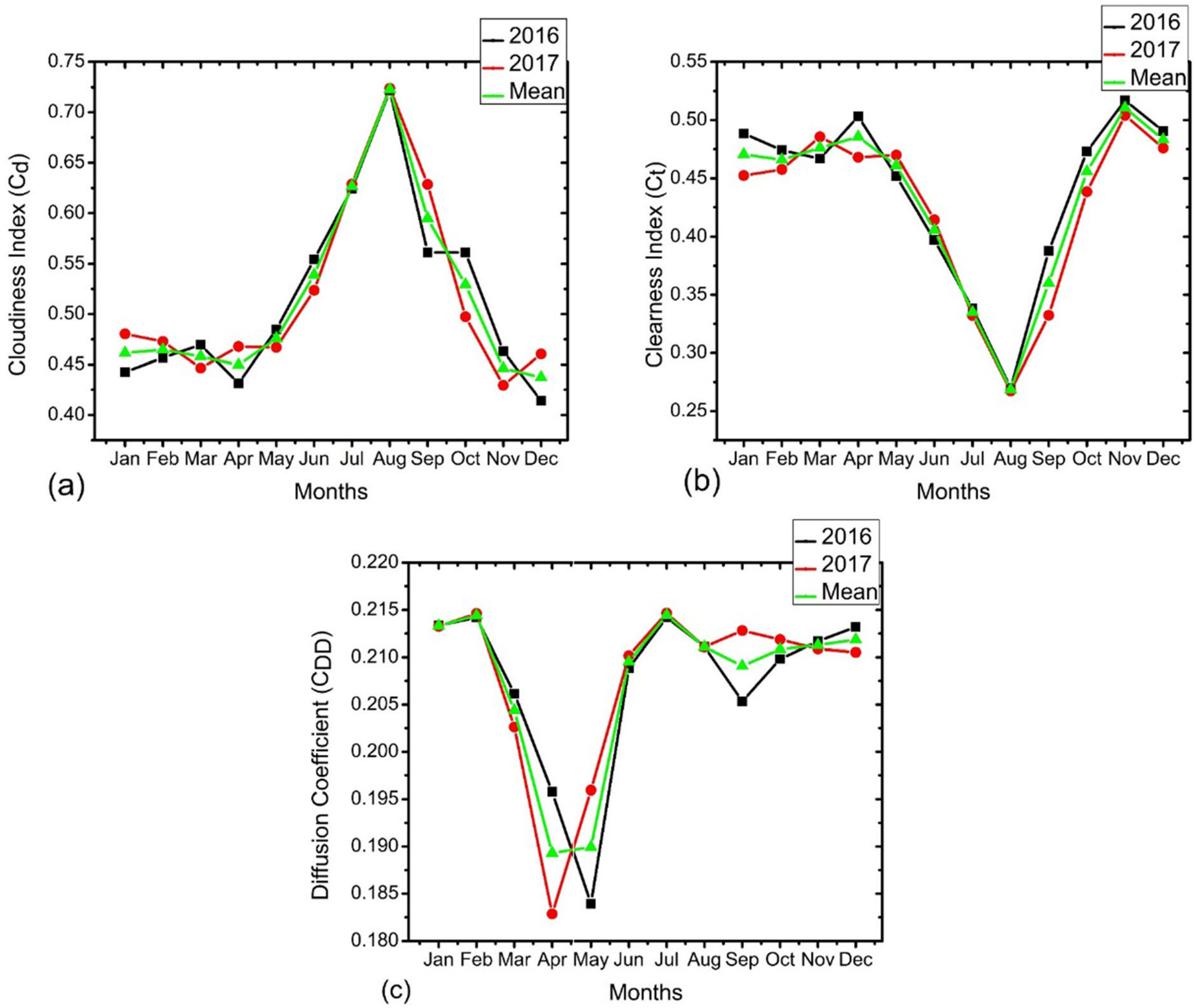

Figure 4
Variation of the monthly and yearly mean of cloudiness index, clearness index, and diffusion coefficient for January-December 2016 and January–December 2017 at Ile-Ife, Nigeria

and Asiegbu (2017), and Aligarh City, India, by Jamil and Akhtar (2017).

The monthly averaged values of extra-terrestrial radiation, incoming solar radiation, and direct and diffuse solar radiation for the period from January 2016 to December 2017 are shown in Fig. 3. A minimum value of 32.33 MJ m^{-2} day^{-1} was recorded in December, while a maximum value of 39.61 MJ m^{-2} day^{-1} was recorded in April for extra-terrestrial solar radiation. The low value in December is due to the high turbidity of the atmosphere, resulting from wind-borne harmattan dust of Saharan origin and smoke from bush burning activities (Butt et al., 2010; Falaiye et al., 2014; Maduekwe & Chendo, 1997; Ohunakin et al., 2015; Okogbue et al., 2009; Soneye et al., 2019). The average value of 11.58 MJ m^{-2} day^{-1} and the maximum value of 18.39 MJ m^{-2} day^{-1} of incoming solar radiation were recorded in August and April, respectively. The variation in direct solar radiation followed a similar pattern to that of incoming solar radiation, with a minimum average value of 3.30 MJ m^{-2} day^{-1} and a maximum average value of 10.89 MJ m^{-2} day^{-1} recorded in August and April, respectively. The maximum values of all three parameters were observed in April due to less attenuation of solar radiation caused by a reduction in aerosol particle concentration due to rainfall. The average minimum (6.85 MJ m^{-2} day^{-1}) and maximum (8.35 MJ m^{-2} day^{-1}) values of measured diffuse solar radiation were recorded in December and July, respectively. The decrease in direct and incoming solar radiation in August and an increase in diffuse solar radiation in July were due to increased cloudiness caused by an increase in the number, height, thickness, and type of clouds during those months (Ayoola et al., 2014; Butt et al., 2010; Soneye et al., 2019). This is also due to the effect of relatively moist air from the ocean due to the movement of the moist south-westerly wind from the ocean (Pal et al., 2000; Lawal, 2010; Ohunakin et al., 2015; Soneye, 2018). The yearly average values of extra-terrestrial, incoming, direct, and diffuse solar radiation at the research location were 37.05 MJ m^{-2} day^{-1}, 15.89 MJ m^{-2} day^{-1}, 8.21 MJ m^{-2} day^{-1} and 7.68 MJ m^{-2} day^{-1}, respectively.

The monthly and yearly average changes in the clearness index, cloudiness index, and diffusion coefficient during the observation period are shown in Fig. 4. The cloudiness index fluctuates in a similar manner to the diffusion coefficient, with the minimum and maximum values observed during the dry/transition and wet months, respectively. As shown in the figure, the cloudiness index had its lowest yearly mean value of 0.44 in December and its highest yearly mean value of 0.72 in August. Similarly, the diffusion coefficient exhibited its lowest yearly mean value of 0.19 in April and its highest yearly mean value of 0.21 in July. The high values for both the diffusion coefficient and cloudiness index seen in July and August can be attributed to the overcast conditions, an increase in relative humidity, and frequent thunderstorm activity, which are all related to the rainy season. These factors lead to significant attenuation of incoming solar radiation reaching the Earth's surface (Ayoola et al., 2014; Díaz-Torres et al., 2017; Soneye et al., 2019). Additionally, the concentration of diffuse coefficient values between 0.19 and 0.21 indicates that diffuse radiation accounts for only a small portion of extraterrestrial radiation (Che et al., 2006). The yearly averages for the clearness index, cloudiness index, and diffusion coefficient were 0.43, 0.52, and 0.21, respectively. These results are consistent with those reported by Udo (2000), Che et al. (2006), Okogbue et al. (2009), and Ohunakin et al. (2015). On the other hand, the clearness index, which depicts the availability of solar radiation and meteorological conditions at a particular area on the earth's surface, showed a minimum monthly mean value of 0.27 in

Table 5

Ranking of the models developed in this paper based on the Global Performance Index and Akaike Information Criteria

Model	Input variable	Rank
Model 11	One	1
Model 12	One	2
Model 13	One	3
Model 14	One	4
Model 15	One	5
Model 16	One	6
Model 17	One	7
Model 10	One	8
Model 6	One	9
Model 2	One	10
Model 3	One	11
Model 4	One	12
Model 5	One	13
Model 1	One	14
Model 21	Two	15
Model 9	Two	16
Model 7	Two	17
Model 20	Two	18
Model 18	One	19
Model 19	One	20
Model 8	Two	21

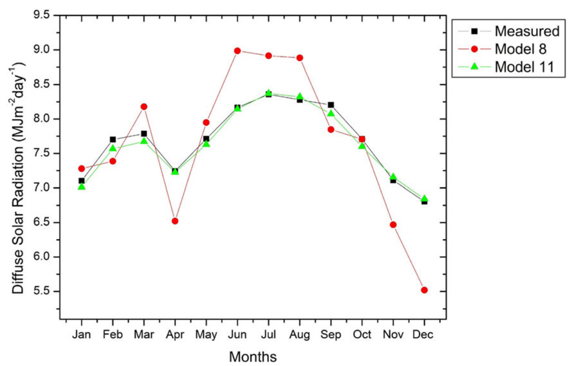

Figure 5
Variations of diffuse solar radiation, both measured and estimated using the best performing-model (Model 11) and the worst performing model (Model 8)

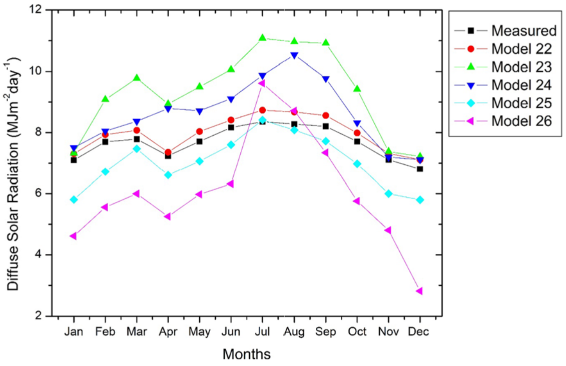

Figure 6
Variations of diffuse solar radiation, both measured and estimated using models obtained from the literature

August and a maximum monthly value of 0.51 in November, as shown in the figure. This shows that the study site is not fully overcast in November, since $C_t > 0.5$, but mostly cloudy in August ($C_t < 0.5$.) The trend observed mirrors that described by Adaramola (2012) at Akure, in the southern part of Nigeria, and Ohunakin et al. (2013). The highest clearness index value recorded in November suggested that the incoming solar radiation received at the Earth's surface consisted mainly of the direct radiation component due to minimal cloudiness and turbidity caused by the removal of suspended aerosol particles by rain showers (Babatunde & Aro, 1995; Iziomon & Aro, 1998; Soneye, 2021; Udo, 2000). This indicates that the sky conditions at the study area are favourable with high solar radiation, suggesting that there is possible utilisation and high performance of renewable energy systems at the location almost year-round, apart from only December and January. The minimum values recorded for the two parameters are attributed to the presence of strongly developed altostratus, thin cirrus, and altocumulus clouds during the peak of the rainy season (Iziomon & Aro, 1998; Okogbue et al., 2009; Soneye, 2021).

The new diffuse solar radiation models developed in this paper (see Table S1 in the supplementary material) use the curve estimate technique and the mathematical expressions for each class (Table 2). The details of the diffuse solar radiation models developed in this paper are discussed in the supplementary material (Figure S1 and Table S2). The estimated values from all the models follow a similar pattern to the measured values, with peak values ranging from 8.34 to 8.99 MJ m^{-2} day^{-1} in June and July and lower values between 5.19 and 7.27 MJ m^{-2} day^{-1} in December. The maximum measured value is 8.35 MJ m^{-2} day^{-1} in July, while the lowest is 6.81 MJ m^{-2} day^{-1} in December. Model 6 (Class 1), Model 9 (Class 2), Model 11 (Class 3), Model 16 (Class 4), and Model 21 (Class 5) perform the best, with high R- and d-values, the lowest errors, and the best statistics. Model 11 in Class 3 is the best-performing model among all the classes. The statistical results presented in Table S2 confirm that diffuse solar radiation is overestimated in Class 1, there is poor agreement between estimated and measured values in Classes 2, 4, and 5, and close variation and good agreement in Class 3.

The statistical results of all the models developed in this paper under the five classes are presented in

Table 6

Statistical results of the solar radiation models selected from the literature

Model	Class	MBE (MJ m^{-2} day^{-1})	MAE (MJ m^{-2} day^{-1})	RMSE (MJ m^{-2} day^{-1})	RRMSE (%)	MPE (%)	d	SSRE	RSE	U_{95} (MJ m^{-2} day^{-1})	t-stats	R
Model 22	Class 1	0.2783	0.2783	0.2906	3.7831	− 3.5984	0.9276	0.9290	0.2784	0.6762	11.0246	0.9922
Model 23	Class 2	1.4994	1.8846	2.0626	26.8502	− 19.4402	0.37644	0.6817	0.2384	5.3222	3.5113	0.4624
Model 24	Class 3	0.9341	0.9341	1.3385	17.4244	− 12.2721	0.4041	0.7872	0.2561	3.3667	3.2315	0.3878
Model 25	Class 4	− 0.6608	0.9065	0.9887	12.8711	8.5783	0.5607	1.1886	0.3147	3.2442	2.9801	0.4880
Model 26	Class 5	− 1.6186	1.9322	2.2434	29.2039	21.4669	0.3274	1.5067	0.3543	6.7045	3.4558	0.5097

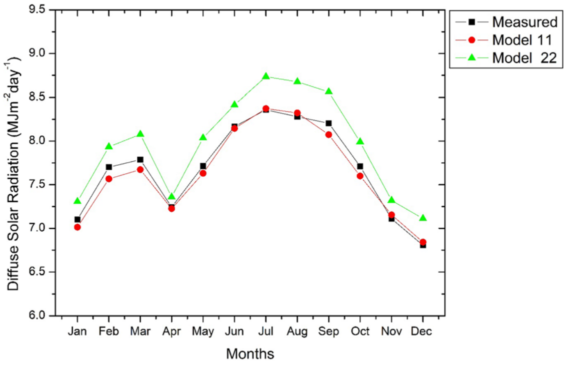

Figure 7
Variations of diffuse solar radiation, both measured and estimated using the best-performing-model (Model 11) developed in this paper and the best-performing model (Model 22) obtained from the literature

Table S2. The results show that most models have good correlation coefficients (R > 0.7), with about five models slightly below (0.5 ≤ R ≤ 0.7). Model 17, which has a significant value of MBE = 0.0247 MJ m^{-2} day^{-1}, performs best according to the MBE statistical evaluator. The values of MAE (0.0680–0.7207 MJ m^{-2} day^{-1}), RMSE (0.0825–0.8740 MJ m^{-2} day^{-1}), and RSE (0.2720–0.3067) indicate good agreement between estimated and measured values. Most models underestimated the diffuse solar radiation, as indicated by the negative values of MPE recorded, except for Model 16, with a value of 0.2884, which is close to zero. The Akaike Information Criteria (AIC) and Global Performance Index (GPI) methods were used to rank the models according to their suitability for estimating diffuse solar radiation at the study site, with the model having the lowest AIC and GPI values performing the best.

The results of the AIC and GPI values for all the models developed in this paper are presented in the supplementary material (Table S3), while the overall ranking of all the developed models based on their respective AIC and GPI values is presented in Table 5. As shown in Table S3, Model 11 (quadratic function) from Class 3 with the clearness index as the input variable performed better than all the other models developed in this study, with a GPI of − 2.17957 and AIC, AIC_C, and ΔAIC_C values of 1.8099, 4.8099, and 0.0000, respectively. In addition, as shown in Table 5, models with only one input variable performed better than those with two input variables.

The monthly variations of the measured and estimated diffuse solar radiation using the best-performing model (Model 11) and the worst performing model (Model 8) are presented in Fig. 5. As shown in the figure, the estimated values of the diffuse solar radiation obtained from Model 11 essentially duplicate the pattern of the measured radiation. The values of the measured data range between 6.81 and 8.36 MJ m^{-2} day^{-1}, while those estimated from Model 11 range between 6.84 and 8.37 MJ m^{-2} day^{-1}. The minimum and maximum values for both the measured and estimated data were observed in the months of December and July, respectively. However, Model 11 slightly underestimated the diffuse solar radiation between January and March, May, September, and October, while coinciding with the measured data in the other months. In contrast, the estimated values from Model 8 ranged from 5.52 MJ m^{-2} day^{-1} (December) to 8.99 MJ m^{-2} day^{-1} (July), with overestimation in January, March, May–August, and underestimation in February, April, September, November, and December. The only month where the

Table 7

Statistical results of Model 11, the best-performing model developed in this paper, and Model 22, the best-performing model selected from the literature

Model	MBE (MJ m^{-2} day^{-1})	MAE (MJ m^{-2} day^{-1})	RMSE (MJ m^{-2} day^{-1})	RRMSE (%)	MPE (%)	d	SSRE	RSE	U_{95} (MJ m^{-2} day^{-1})	t-stats	R	GPI	AIC	AIC_C
11	− 0.0469	0.0701	0.0825	1.0744	0.6023	0.9930	1.0123	0.2905	0.9853	2.2936	0.9906	− 2.1796	1.8098	4.8099
22	0.2783	0.2783	0.2906	3.7831	− 3.5984	0.9276	0.9290	0.2784	0.6762	11.0246	0.9922	0.6029	2.0744	4.8511

estimated values from Model 8 were similar to the measured data was October. The high correlation coefficient (0.9906) and index of agreement (0.9930) obtained for Model 11 indicate good conformity and agreement between the values estimated from this model and the measured data. Conversely, the low correlation coefficient (0.5335) and index of agreement scores (0.6188) for Model 8 suggest significant discrepancies and very poor agreement between the estimated and measured data.

The monthly variations of the diffuse solar radiation measured and estimated using the five published models selected from the literature (listed in Table 3) are presented in Fig. 6. As shown in this figure, Model 22 (Class 2) produces values that closely follow the pattern of the measured radiation but overestimate diffuse solar radiation in all months, including December, which had the lowest values for both the measured (6.81 MJ m^{-2} day^{-1}) and estimated (7.11 MJ m^{-2} day^{-1}) radiation. The highest values for both the measured and estimated (using Model 22) diffuse solar radiation, 8.36 MJ m^{-2} day^{-1} and 8.74 MJ m^{-2} day^{-1}, respectively, were recorded in July. The values estimated by the other models deviate significantly from the measured values. The lowest values, 7.22, 7.12, 5.80, and 2.81 MJ m^{-2} day^{-1}, were recorded for Models 23, 24, 25, and 26, respectively, in December. The highest values, 11.08, 8.41, and 9.61 MJ m^{-2} day^{-1} for Models 23, 25, and 26, respectively, were recorded in July, while the highest value of 10.54 MJ m^{-2} day^{-1} for Model 24 was recorded in August. Models 23 and 24 overestimated diffuse solar radiation in all the months, while Model 25 underestimated it. Additionally, Model 26 underestimated diffuse solar radiation between September and June but overestimated it in July and August. The under- and overestimation of diffuse solar radiation by these models is supported by the high values of MBE ($\sim$ 1.50 MJ m^{-2} day^{-1}), MAE ($\sim$ 1.93 MJ m^{-2} day^{-1}), RMSE ($\sim$ 2.24 MJ m^{-2} day^{-1}), RRMSE ($\sim$ 29.20%), MPE ($\sim$ 21.47%), SSRE ($\sim$ 1.51), RSE ($\sim$ 0.35), U_{95} ($\sim$ 6.71 MJ m^{-2} day^{-1}), and t-stat ($\sim$ 11.03), listed in Table 6. The table shows that most of the models have a correlation coefficient and index of agreement less than 0.5, indicating a high deviation of the estimated values from the measured values. Model 22 performed the best, with the highest correlation coefficient of 0.9922 and an index of agreement of 0.9276, as well as the lowest values of MAE (0.2783 MJ m^{-2} day^{-1}), RMSE (0.2906 MJ m^{-2} day^{-1}), RRMSE (3.7831%), and U_{95} (0.6762 MJ m^{-2} day^{-1}). The differences between the measured and estimated values may be due to various factors such as weather conditions, geographical location, precipitation, aerosol mass concentration, atmospheric turbulence, cloud formation, pollution levels, and differences in the intensity of global and diffuse solar radiation between Ile-Ife and the other sites, South Africa, Turkey, Italy, and India, where these models were developed (Alaa et al., 2017; Falayi et al., 2011; Soneye, 2021; Soneye-Arogundade, 2021).

The monthly variations of the measured and estimated diffuse solar radiation using the best-performing model (Model 11) developed in this paper and the best-performing model (Model 22) obtained from the literature are presented in Fig. 7. Also, the statistical results of Model 11 and Model 22 are presented in Table 7. As shown in the figure, the estimated values of the diffuse solar radiation obtained from the two models essentially duplicate the pattern of the measured radiation. The results show that Model 11 provided estimated values of diffuse solar radiation that closely matched the measured data (6.81 and 8.36 MJ m^{-2} day^{-1}), with values ranging from 6.84 to 8.37 MJ m^{-2} day^{-1}. On the other hand, Model 22 overestimated the diffuse solar radiation, with values ranging from 7.11 to 8.74 MJ m^{-2} day^{-1}. The minimum and maximum values of measured and estimated data were observed in December and July, respectively. However, Model 11 slightly underestimated the diffuse solar radiation between January and March, May, September, and October, but deviated only by 5.84–9.28% from the measured values. The statistical analysis presented in Table 7 indicates that Model 11 outperformed Model 22, with lower errors and better statistics, suggesting good conformity and agreement between the estimated and measured data. This implies that none of the models selected from the literature was suitable for estimating diffuse solar radiation at the study site; thus, the Model 11 developed in this study is recommended for estimating diffuse solar radiation not only at the study site but also at other locations with similar climatic conditions.

4. Conclusions

In this study, diffuse solar radiation models were developed and estimated using sunshine duration and clearness index data for Ile-Ife, a tropical site in Nigeria. Additionally, the best model suitable for estimating monthly diffuse solar radiation in the study area was identified using detailed statistical analysis.

The values of incoming solar radiation for 2016 and 2017 varied from 11.53 to 19.36 MJ m^{-2} day^{-1}, with minimum values in August and maximum values in April and March. Direct incoming solar radiation showed the same pattern. Diffuse solar radiation had its highest values from June to September and its lowest values in December, while extra-terrestrial solar radiation had low values during the dry months, with the lowest recorded in December. The study suggests that cloudiness, moisture content, and atmospheric turbidity have a significant impact on the variation of solar radiation.

The cloudiness index and diffusion coefficient have a similar pattern, with the lowest values occurring during the dry or transition months and the highest during the wet months. The diffusion coefficient had concentration values ranging from 0.19 in April to 0.21 in July, indicating that only a small part of the extra-terrestrial radiation is diffuse. In contrast, the clearness index had a minimum monthly value of 0.27 in August and a maximum monthly value of 0.51 in November, suggesting that the site is not overly cloudy. The yearly average values were 0.43, 0.52, and 0.21 for the clearness index, cloudiness index, and diffusion coefficient, respectively.

The best results were obtained from Model 6 (Class 1), Model 9 (Class 2), Model 11 (Class 3), Model 16 (Class 4), and Model 21 (Class 5). These models yielded MBE, MAE, and RMSE < 0.6 MJm^{-2} day^{-1}, RRMSE $< 7.0\%$, MPE $< 2.5\%$, and $d > 0.8$. In terms of the GPI (− 2.1796), AIC (1.8099), AIC_C (4.8099), and ΔAIC_C (0.0000) values, Model 11 (a quadratic function) from Class 3 with clearness index as the input variable performed better than all other models developed in this paper, while Model 8 (GPI = 3.0089, AIC = 15.9159, AIC_C = 24.7673, and ΔAIC_C = 19.9575) from Class 2 with clearness index and sunshine duration as input variables shows pretty poor performance. This implies that one input variable model performed better than the two input variable models. The use of a one-input variable model is recommended due to the increased complexity of models with two or more input variables and the high amount of requisite data. The clearness index is more significant than the relative sunshine duration in estimating diffuse solar radiation at the study site.

The monthly variations of the diffuse solar radiation estimated from the five published models selected from the literature deviate significantly from the measured values. However, the estimated values obtained from Model 22 (Class 2) duplicate the pattern of the measured radiation and show fairly good results, although they continuously overestimate the diffuse solar radiation.

The evaluated literature models were found to be unsuitable for estimating diffuse solar radiation at the study site. Therefore, the models developed in this paper performed better than the selected models. Among these models, Model 11 (Class 3) was found to be the best-performing model. It is a quadratic function with the clearness index as an input variable and provided estimated values of diffuse solar radiation that were in close agreement with the measured data. The estimated values ranged from 6.84 to 8.37 MJ m^{-2} day^{-1}, with measured data at 6.81 and 8.36 MJ m^{-2} day^{-1}. Conversely, Model 22 was found to overestimate the diffuse solar radiation, with values ranging from 7.11 to 8.74 MJ m^{-2} day^{-1}. The statistical analysis of Model 11, including GPI (− 2.1796), AIC (1.8099), AIC_C (4.8099), and ΔAIC_C (0.0000), demonstrated good conformity and agreement between the estimated and measured data. This suggests that Model 11 outperformed Model 22. The proposed Model 11 with the expression $C_{DD} = 0.0896 + 0.4790(C_t) - 0.4674(C_t)^2$, is recommended for estimating diffuse solar radiation not only at the study site but also at other locations with similar climatic conditions. Overall, it is suggested to use this Model 11 for sites in other climatic regions as well as to test its broader applicability and versatility for potential other applications where no radiation measurements are available. Our approach emphasises the usefulness of evaluating a suite of different diffuse solar radiation models to arrive at a statistically well-informed assessment for the recommendation of the best available model.

Data availability

The datasets that support the findings of this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors did not receive support from any organisation for the submitted work.

References

Adaramola, M. S. (2012). Estimating global solar radiation using common meteorological data in Akure. *Nigeria. Renew. Energ, 47*, 38–44.

Afiesimama, E. A., Pal, J. S., Abiodun, B. J., Gutowski, J. W. J., & Adedoyin, A. (2006). Simulation of West African Monsoon using the RegCM3. Part I: Model validation and interannual variability. *Theoretical and Applied Climatology, 86*, 23–37.

Akhlaque, A. M., Firoz, A., & Wasim, M. A. (2009). Estimation of global and diffuse solar radiation for Hyderabad, Sindh, Pakistan. *Journal of Basic and Applied Science, 5*, 73–77.

Alaa, M. A., Ali, M. A., & Yaseen, K. A. (2017). Parameterization of the downward long wave radiation under clearsky condition in Baghdad, Iraq. *Asian Journal of Applied Sciences, 10*, 10–17. https://doi.org/10.3923/ajaps.2017.10.17

Aras, H., Balli, O., & Hepbasli, A. (2006). Estimating the horizontal diffuse solar radiation over the Central Anatolia region of Turkey. *Energy Conversion and Management, 47*, 2240–2249. https://doi.org/10.1016/j.enconman.2005.11.024

Arslanoglu, N. (2016). Evaluation and establishment of diffuse solar radiation models for Bursa, Turkey. *Energy Sources, Part a: Recovery, Utilization, and Environmental Effects, 38*(18), 2788–2797. https://doi.org/10.1080/15567036.2016.1214640

Ayoola, M. A., Sunmonu, L. A., Bashiru, M. I., & Jegede, O. O. (2014). Measurements of net all-wave radiation at a tropical location, Ile-Ife, Nigeria. *Atmósfera, 27*, 305–315. https://doi.org/10.1016/S0187-6236(14)71118-X

Augustine, C., & Nnabuchi, M. N. (2009). Correlation of cloudiness index with clearness index for four selected cities in Nigeria. *The Pacific Journal of Science and Technology, 10*, 568–573.

Babatunde, E. B., & Aro, T. O. (1995). Relationship between clearness index and cloudiness index at a tropical station (Ilorin, Nigeria). *Renewable Energy, 6*, 801–805. https://doi.org/10.1016/0960-1481(94)00087-M

Bakirci, K. (2009). Correlations for estimation of daily global solar radiation with hours of bright sunshine in Turkey. *Energy, 34*(4), 485501.

Bakirci, K. (2015). Models for the estimation of diffuse solar radiation for typical cities in Turkey. *Energy, 82*, 827–838.

Barbaro, S., Cannato, G., Coppolina, S., Leone, C., & Sinagra, E. (1981). Diffuse solar radiation statistics for Italy. *Solar Energy, 26*(5), 429–435.

Behar, O., Khellaf, A., & Mohammedi, K. (2015). Comparison of solar radiation models and their validation under Algerian climate—the case of direct irradiance. *Energy Conversion and Management, 98*, 236–251. https://doi.org/10.1016/j.enconman.2015.03.067

Berrizbeitia, S. E., Gago, E. J., & Muneer, T. (2020). Empirical models for the estimation of solar sky-diffuse radiation. A review and experimental analysis. *Energies, 13*, 701. https://doi.org/10.3390/en13030701

Boland, J., Ridley, B., & Brown, B. (2008). Models of diffuse solar radiation. *Renewable Energy, 33*, 575–584. https://doi.org/10.1016/j.renene.2007.04.012

Butt, N., New, M., Malhi, Y., da Costa, A. C. L., Oliveira, P., & Silva-Espejo, J. E. (2010). Diffuse radiation and cloud fraction relationships in two contrasting Amazonian rainforest sites. *Agricultural and Forest Meteorology, 150*, 361–368. https://doi.org/10.1016/j.agrformet.2009.12.004

Chandrashekara, M., & Yadav, A. (2017). Water desalination system using solar heat: A review. *Renewable and Sustainable Energy Reviews, 67*, 1308–1330. https://doi.org/10.1016/j.rser.2016.08.058

Che, H. Z., Shi, G. Y., Zhang, X. Y., Zhao, J. Q., & Li, Y. (2006). Analysis of sky conditions using 40 year records of solar radiation data in China. *Theoretical and Applied Climatology, 89*, 83–94. https://doi.org/10.1007/s00704-006-0258-0

Chukwuemeka, O. S., & Asiegbu, A. D. (2017). Decline in global solar radiation with increased sunshine hour in Abia state Nigeria. *International Journal of Research in Engineering and Innovation, 1*(3), 150–154.

Cooper, P. I. (1969). The absorption of solar radiation in solar stills. *Solar Energy, 12*, 333–346. https://doi.org/10.1016/0038-092X(69)90047-4

Díaz-Torres, J. J., Hernández-Mena, L., Murillo-Tovar, M. A., León-Becerril, E., López-López, A., Suárez-Plascencia, C., Aviña-Rodriguez, E., Barradas-Gimatee, A., & Ojeda-Castillo, V. (2017). Assessment of the modulation effect of rainfall on solar radiation availability at the Earth's surface. *Meteorological Applications, 24*, 180–190.

Dincer, I. (2000). Renewable energy and sustainable development: A crucial review. *Renewable and Sustainable Energy Reviews, 4*(2), 157–175. https://doi.org/10.1016/S1364-0321(99)00011-8

Duffie, J. A., & Beckman, W. A. (2006). *Solar engineering of thermal processes*. Wiley.

Elliott, D. (2000). Renewable energy and sustainable futures. *Futures, 32*, 261–274. https://doi.org/10.1016/S0016-3287(99)00096-8

Fagbenle, R. O. (1992). A comparative study of some simple models for global solar irradiation in Ibadan, Nigeria. *International Journal of Energy Research, 16*, 583–595.

Falaiye, O. A., Babatunde, E. B., & Willoughby, A. A. (2014). Atmospheric aerosol loading at Ilorin, a tropical station. *The African Review of Physics, 9*, 527–535.

Falayi, E. O., & Rabiu, A. B. (2011). Estimation of global solar radiation using cloud cover and surface temperature in some selected cities in Nigeria. *Archives of Physics Research, 2*(3), 99–109.

Falayi, E. O., Rabiu, A. B., & Teliat, R. O. (2011). Correlations to estimate monthly mean of daily diffuse solar radiation in some selected cities in Nigeria. *Advances in Applied Science Research, 2*(4), 480–490.

Gopinathan, K. K. (1988). Empirical correlations for diffuse solar radiation. *Solar Energy, 40*, 369–370. https://doi.org/10.1016/0038-092X(88)90009-6

Gopinathan, K. K., & Soler, A. (1995). Diffuse Radiation models and monthly-average, daily, diffuse data for a wide latitude range. *Energy, 20*(7), 657–667. https://doi.org/10.1016/0360-5442(95)00004-Z

Griffiths, J. F. (1974). Climates of Africa. In H. E. Landsberg (Ed.), *World survey of climatology* (Vol. 10, pp. 167–187). Elsevier.

Gueymard, C. A. (2012). Clear-sky irradiance predictions for solar resource mapping and large-scale applications: Improved validation methodology and detailed performance analysis of 18 broadband radiative models. *Solar Energy, 86*(8), 2145–2169. https://doi.org/10.1016/j.solener.2011.11.011

Haydar, A., Balli, O., & Hepbasli, A. (2006). Estimating the horizontal diffuse solar radiation over the Central Anatolia region of Turkey. *Energy Conversion and Management, 47*(17), 2240–2249. https://doi.org/10.1016/j.enconman.2005.11.024

Hayward, D. F., & Oguntoyinbo, J. S. (1987). *The climatology of West Africa*. Rowan and Littlefield.

Iqbal, M. A. (1979). Study of Canadian diffuse and total solar radiation. II: Monthly average hourly horizontal radiation. *Solar Energy, 22*, 87–90. https://doi.org/10.1016/0038-092X(79)90063-X

Iqbal, M. (1983). *An introduction to solar radiation*. Academic Press.

Iziomon, M. G., & Aro, T. O. (1998). The diffuse fraction of global solar irradiance at a tropical location. *Theoretical and Applied Climatology, 61*, 77–84. https://doi.org/10.1007/s007040050053

Jacovides, C. P., Hajioannou, L., Pashiardis, S., & Stefanou, L. (1996). On the diffuse fraction of daily and monthly global radiation for the island of Cyprus. *Solar Energy, 56*(6), 565–572. https://doi.org/10.1016/0038-092X(96)81162-5

Jamil, B., & Akhtar, N. (2015). Statistical analysis of short-term solar radiation data over Aligarh (India). *Progress in Clean Energy, 2*, 937–948. https://doi.org/10.1007/978-3-319-17031-2_61

Jamil, B., & Akhtar, N. (2017). Comparative analysis of diffuse solar radiation models based on sky-clearness index and sunshine period for humid-subtropical climatic region of India: A case study. *Renewable and Sustainable Energy Reviews, 78*, 329–355. https://doi.org/10.1016/j.rser.2017.04.073

Jin, Z., Yezheng, W., & Gang, Y. (2004). Estimation of daily diffuse solar radiation in China. *Renewable Energy, 29*, 1537–1548. https://doi.org/10.1016/j.renene.2004.01.014

Karatasou, S., Santamouris, M., & Geros, V. (2003). Analysis of experimental data on diffuse solar radiation in Athens, Greece, for building applications. *International Journal of Sustainable Energy, 23*(1–2), 1–11. https://doi.org/10.1080/01425910310001485 97

Katiyar, A. K., & Pandey, C. K. (2010). Simple correlation for estimating the global solar radiation on horizontal surfaces in India. *Energy, 35*(12), 5043–5048. https://doi.org/10.1016/j.energy.2010.08.014

Khahro, S. F., Tabbassum, K., Talpur, S., & Alvi, M. B. (2015). Evaluation of solar energy resources by establishing empirical models for diffuse solar radiation on tilted surface and analysis for optimum tilt angle for a prospective location in southern region of Sindh, Pakistan. *Electrical Power and Energy Systems, 64*, 1073–1080. https://doi.org/10.1016/j.ijepes.2014.09.001

Khalil, S. A., & Shaffie, A. M. (2013). A comparative study of total, direct and diffuse solar irradiance by using different models on horizontal and inclined surfaces for Cairo, Egypt. *Renewable and Sustainable Energy Reviews, 27*, 853–863. https://doi.org/10.1016/j.rser.2013.06.038

Khorasanizadeh, H., Mohammadi, K., & Mostafaeipour, A. (2014). Establishing a diffuse solar radiation model for determining the optimum tilt angle of solar surfaces in Tabass, Iran. *Energy Conversion and Management, 78*, 805–814. https://doi.org/10.1016/j.enconman.2013.11.048

Krzyścin, J. W., Jarosławski, J., & Sobolewski, P. S. (2011). A mathematical model for seasonal variability of vitamin D due to solar radiation. *Journal of Photochemistry and Photobiology b: Biology, 105*(1), 106–112. https://doi.org/10.1016/j.jphotobiol.2011.07.008

Kuye, A., & Jagtap, S. S. (1992). Analysis of solar radiation data for Port Harcourt, Nigeria. *Solar Energy, 49*(2), 139–145. https://doi.org/10.1016/0038-092X(92)90148-4

Lawal, K. A. (2010). Statistical downscaling of climate change scenario over Nigeria. *B.Tech Thesis, submitted to the Department of Meteorology, Federal University of Technology, Akure, Nigeria*.

Liu, B. Y. H., & Jordan, R. C. (1960). The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy, 4*(3), 1–19. https://doi.org/10.1016/0038-092X(60)90062-1

Maduekwe, A. A. L., & Chendo, M. A. C. (1997). Atmospheric turbidity and the diffuse irradiance in Lagos Nigeria. *Solar Energy, 61*(4), 241–249. https://doi.org/10.1016/S0038-092X(97)00020-0

Mani, A., Chacko, O., & Venkiteshwaran, S. P. (1962). Measurements of the total radiation from sun and sky in India during the IGY. *Indian Journal of Meteorology, Hydrology and Geophysics, 13*(3), 337–366. https://doi.org/10.54302/mausam.v13i3.4367

Ohunakin, O. S., Adaramola, M. S., Oyewola, O. M., & Fagbenle, R. L. (2013). Generation of a typical meteorological year for North-East, Nigeria. *Applied Energy, 112*, 152–159. https://doi.org/10.1016/j.apenergy.2013.05.072

Ohunakin, O. S., Adaramola, M. S., Oyewola, O. M., Matthew, O. J., & Fagbenle, R. L. (2015). The effect of climate change on solar radiation in Nigeria. *Solar Energy, 116*, 272–286. https://doi.org/10.1016/j.solener.2015.03.027

Okogbue, E. C., Adedokun, J. A., & Holmgren, B. (2009). Hourly and daily clearness index and diffuse fraction at a tropical station, Ile-Ife, Nigeria. *International Journal of Climatology, 29*, 1035–1047. https://doi.org/10.1002/joc.1849

Oliveira, A. P., Escobedo, J. F., Machado, A. J., & Soares, J. (2002). Correlation models of diffuse solar radiation applied to the city of Sao Paulo, Brazil. *Applied Energy, 71*, 59–73. https://doi.org/10.1016/S0306-2619(01)00040-X

Page, J. K. (1961). The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40_N–40_S. In: *Proceedings of UN conference on new sources of energy*, vol. 598, no. 4, pp. 378–390.

Pal, J. S., Small, E. E., & Eltahir, E. A. B. (2000). Simulation of regional-scale water and energy budgets: Representation of subgrid cloud and precipitation processes within RegCM. *Journal of. Geophysical Research Atmospheres, 105*(29), 579–629. https://doi.org/10.1029/2000JD900415

Pandey, C. K., & Katiyar, A. K. (2009). A comparative study to estimate daily diffuse radiation over India. *Energy, 34*, 1792–1796. https://doi.org/10.1016/j.energy.2009.07.026

Poudyal, K. N., Bhattarai, B. K., Sapkota, B., & Kjeldstad, B. (2012). Estimation of global solar radiation using clearness index and cloud transmittance factor at Trans-Himalayan Region in Nepal. *Energy and Power Engineering, 4*, 415–421. https://doi.org/10.4236/epe.2012.46055

Sabzpooshani, M., & Mohammadi, K. (2014). Establishing new empirical models for predicting monthly mean horizontal diffuse solar radiation in city of Isfahan, Iran. *Energy, 69*, 571–577. https://doi.org/10.1016/j.energy.2014.03.051

Salhi, H., Belkhir, L., & Tiri, A. (2020). Evaluation of diffuse fraction and diffusion coefficient using statistical analysis. *Applied Water Science, 10*, 133. https://doi.org/10.1007/s13201-020-01216-0

Sen, Z. (2008). *Solar energy fundamentals and modelling techniques: Atmosphere, environment, climate change and renewable energy*. London: Springer.

Shimazaki, Y., Goto, S., Yoshida, A., & Yamamoto, T. (2017). The effect of solar radiation on temperature distribution in outdoor human-clothing-environment systems. *International Journal of Heat and Mass Transfer, 104*, 1–6. https://doi.org/10.1016/j.ijheatmasstransfer.2016.08.022

Snipes, M., & Taylor, D. C. (2014). Model selection and Akaike information criteria: an example from wine ratings and prices. *Wine Economics and Policy, 3*(1), 3–9. https://doi.org/10.1016/j.wep.2014.03.001

Soneye, O. O. (2018). Investigation of the effect of atmospheric aerosol loading on the surface radiation balance at Ile-Ife, Southwest Nigeria. *Ph.D. thesis. Obafemi Awolowo University, Ile-Ife, Nigeria*.

Soneye, O. O., Ayoola, M. A., Ajao, I. A., & Jegede, O. O. (2019). Diurnal and seasonal variations of the incoming solar radiation flux at a tropical station, Ile-Ife, Nigeria. *Heliyon*. https://doi.org/10.1016/j.heliyon.2019.e01673

Soneye, O. O. (2021). Evaluation of clearness index and cloudiness index using measured global solar radiation data: a case study for a tropical climatic region of Nigeria. *Atmósfera, 34*(1), 25–39. https://doi.org/10.20937/ATM.52796

Soneye-Arogundade, O. O. (2021). Evaluation and calibration of downward longwave radiation models under cloudless sky at Ile-Ife, Nigeria. *Atmósfera, 34*(4), 417–432. https://doi.org/10.20937/ATM.52843

Spencer, J. W. (1971). Fourier series representation of the position of the Sun. *Search, 2*, 162–172.

Tarhan, S., & Sari, A. (2005). Model selection for global and diffuse radiation over the Central Black Sea (CBS) region of Turkey. *Energy Convers Manag, 46*(4), 605–613. https://doi.org/10.1016/j.enconman.2004.04.004

Taşdemiroğlu, E., & Sever, R. (1991). Estimation of monthly average, daily, horizontal diffuse radiation in Turkey. *Energy, 16*(4), 787–790. https://doi.org/10.1016/0360-5442(91)90030-P

Tiris, M., Tiris, C., & Ture, I. E. (1996). Correlations of monthly-average daily global, diffuse and beam radiations with hours of bright sunshine in Gebze, Turkey. *Energy Convers Manag, 37*, 1417–1421.

Turton, S. M. A. (1987). The relationship between total irradiation and sunshine in humid tropics. *Solar Energy, 38*(5), 353–354. https://doi.org/10.1016/0038-092X(87)90007-7

Udo, R. K. (1978). *A comprehensive geography of West Africa* (pp. 1–50). London: Heinemann Educational Books. 112, 152 159.

Udo, S. O. (2000). Sky conditions at Ilorin as characterized by clearness index and relative sunshine. *Solar Energy, 69*(1), 45–53. https://doi.org/10.1016/S0038-092X(00)00008-6

Ulgen, K., & Hepbasli, A. (2009). Diffuse solar radiation estimation models for Turkey's big cities. *Energy Convers Manag, 50*(1), 149–156. https://doi.org/10.1016/j.enconman.2008.08.013

Veeran, P. K., & Kumar, S. (1993). Diffuse radiation on a horizontal surface at Madras. *Renewable Energy, 3*(8), 931–934. https://doi.org/10.1016/0960-1481(93)90053-J

Wattan, R., & Janjai, S. (2016). An investigation of the performance of 14 models for estimating hourly diffuse irradiation on inclined surfaces at tropical sites. *Renewable Energy, 93*, 667–674. https://doi.org/10.1016/j.renene.2016.02.076

Yousuf, M. U., & Umair, M. (2018). Development of diffuse solar radiation models using measured data. *International Journal of Green Energy*. https://doi.org/10.1080/15435075.2018.1525738

Zarezade, M., & Mostafaeipour, A. (2016). Identifying the effective factors on implementing the solar dryers for Yazd province, Iran. *Renewable and Sustainable Energy Reviews, 57*, 765–775. https://doi.org/10.1016/j.rser.2015.12.060

(Received November 11, 2021, revised June 15, 2023, accepted July 13, 2023, Published online July 25, 2023)