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Research Article

Estimation and Investigation of Photosynthetically Active Radiation over Benin, Nigeria

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Abstract

Photosynthetically active radiation (PAR) is an important input parameter for estimating plant productivity due to its key role in the growth and development of plants. In this study, the measured monthly average daily global solar radiation, relative humidity, wind speed, minimum and maximum temperature dataset was utilized to estimate and investigate the Photosynthetically active radiation (PAR) for Benin (latitude 6.32°N, longitude 5.10°E and 77.8 m) located in the coastal region of Nigeria. The meteorological parameters used in this study were obtained from the archives of National Aeronautics and space Administration (NASA) for a period of thirty-eight years (1984-2021). The newly developed temperature PAR based models were tested using statistical indicators of the coefficient of determination (R^2), Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t – test and index of Agreement (IA) to ascertain the suitability and applicability of the models. The results show that photosynthetically active radiation (PAR) is higher during the dry season and is low during the rainy season. Based on the regression models developed, the linear model equation that contains the mean temperature and temperature ratio was observed to be the best for PAR estimation in Benin with R^2, MBE, RMSE, MPE, t-test and IA value of 71.9 %, -0.0283 $MJm^{-2}day^{-1}$, 0.4842 $MJm^{-2}day^{-1}$, 0.0670 %, 0.1941 and 88.3428 % respectively.

Keywords: Benin, models, NASA, Photosynthetically active radiation (PAR), statistical indicators

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Introduction

Solar radiation can be considered as the most important meteorological element which affects all climatological and biological processes such as evaporation and transpiration, snowmelt (increase in sea level) and plant growth either directly or indirectly (Mojarrad *et al.*, 2015). Radiation of wavelength between 0.4 and 0.7 μm is most efficiently utilised in photosynthesis, and therefore it is called photosynthetically active radiation (PAR). It is the spectral range of solar light from 400 to 700 nanometers that is used by aquatic plants and algae in photosynthesis. PAR is also a measure of the photosynthetic photon flux density (PPFD), and is defined as the number of the incident photons per unit time per unit surface (McCree, 1972). Plants ultimately needs PAR as an energy requirement to convert carbon dioxide (CO_2) and water (H_2O) through photosynthesis into glucose which is used to synthesize structural and metabolic energy needed for plant growth, development. It is also needed for respiration and storing vegetative products that make up plant biomass (Nwokolo *et al.,* 2016; Nwokolo *et al.,* 2017). The chemical equation (1) determines the process in which plants synthesize their food.

$$6CO_{2(liquid)} + 12H_2O_{(liquid)} + photon \rightarrow C_6H_{12}O_{6(liquid)} + 6O_{2(gas)} + 6H_2O_{(liquid)} \qquad (1)$$

where the wavelength range of (0.4-0.7μm) of light here represents PAR that best causes photosynthesis.

PAR plays very important roles in plant growth, and it is the principal factor in regulating the rate of solar energy conversion into biological mediated energy. Therefore, it is a required parameter that must be estimated to predict the production of plant products and biomass (Goudriaan and van Laar, 1994; Asner and Wessman, 1997; and Mariscal *et al.,* 2000). The silicon photovoltaic detector can be used to measures PAR within the light wavelength range of 400 to 700 nm. The photosynthetic photon flux density (PPFD) of photosynthetically active radiation can be measured with most of the PAR sensors which can also be used to compute PAR. Photosynthetically Active Radiation can be measured directly using pertinent instruments or estimated from solar radiation (SR) (Qin *et al.,* 2012). However, in most places, the diurnal variations of SR and PAR are not available. Hence, there is a need to develop models for simulating the diurnal variation of PAR and SR. PAR changes seasonally and varies during the day, and depends on the latitude. Factors affecting the intensity of PAR are sunlight intensity, cloud cover, shading by trees, and buildings. PAR changes from one particular geographical location to another. PAR is a function of the local sky clearness index that depends on the cloud cover, solar declination angle, water vapor concentration, time of the day, and latitude of the location (Chukwujindu *et al.*, 2018).

Numerous types of research have been carried out on studies that involved the estimation of photosynthetically active radiation for different locations, these include the study by Anjorin et al. (2014) carried out a study the on the estimation of hourly photosynthetically active radiation (PAR) from hourly global solar radiation in the University of Jos Nigeria. Sunday et al. (2016) carried out a study on modeling and estimating photosynthetically active radiation from measured global solar radiation at Calabar, Nigeria. Etuk et al. (2016) carried out a study on the analysis of Photosynthetically active radiation over six tropical ecological zones in Nigeria. Nwokolo et al. (2017) investigated the photosynthetically active radiation estimations and modelling over different climatic zones in Nigeria. In another study, Nwokolo et al. (2018) investigated the relationship between photosynthetically active radiation (PAR) and global solar radiation (H) for 22 years of data from (July 1983 to June 2005) over selected climatic zones in Nigeria. Akpootu et al. (2019a) developed empirical models for Estimating Photosynthetically Active Radiation over Akure, South Western, Nigeria. Other studies include Ibrahim and Usman (2012), Nwokolo et al. (2022), Nwokolo et al. (2023) to mention but a few.

The purpose of this study is to estimate and investigate the variability of photosynthetically active radiation for Benin and to develop new temperature based models capable of estimating PAR for the studied location.

Methodology

The measured monthly average daily global solar radiation, relative humidity, wind speed, maximum and minimum temperatures covering a period of thirty eight years (1984 - 2021) for Benin, Nigeria was obtained from archives of the National Aeronautic and Space Administration (NASA).

The monthly average daily extraterrestrial radiation on a horizontal surface (H_0) in $MJ/m^2/day$, can calculated for days giving average of each month from the following equation (Iqbal, 1983; Zekai, 2008).

$$H_O = \left(\frac{24}{\pi}\right) I_{SC} \left[1 + 0.033cos\left(\frac{360n}{360}\right)\right]\left[cos\varphi cos\delta sin\omega_s + \left(\frac{2\pi\omega_s}{360}\right) sin\varphi sin\delta\right] \quad (2)$$

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where I_{SC} is the solar constant (=1367 Wm^{-2}), φ is the latitude of the site, δ is the solar declination and ω_s is the mean sunrise hour angle for the given month and n is the number of days of the year starting from 1st January to 31st of December. The solar declination, δ and the mean sunrise hour angle, ω_s can be calculated using the following equation (Iqbal, 1983; Zekai, 2008)

$$\delta = 23.45 sin\left\{360\left(\frac{284+n}{365}\right)\right\} \quad (3)$$

$$\omega_S = \cos^{-1}(-tan\varphi tan\delta) \quad (4)$$

For a given month, the maximum possible sunshine duration (monthly average day length (S_O)) can be computed (Iqbal, 1983; Zekai, 2008) by

$$S_O = \frac{2}{15}\omega_S \quad (5)$$

Since, there is no standard weather station that routinely measure PAR in Nigeria and in particular Benin, Therefore, PAR was obtained using the formula (Howell *et al.*, 1983; Li *et al.*, 2010)

$$PAR = 0.45 H_{mea} \quad (6)$$

where H_{mea} is the measured global solar radiation in MJ/m^2/day.
The extraterrestrial PAR_0 was estimated as 40% of the extraterrestrial global solar radiation as generalized by Monteith (1990). It was assumed that the sun – earth distance did not vary seasonally because the ratio of the distance between the earth and the sun on a specific day to the mean distance throughout the year is never more than 3.5% away from one (Gate, 1980). The extraterrestrial photosynthetically active radiation, PAR_0 was estimated using the expression (Nwokolo, 2017; Akpootu *et al.*, 2019a)

$$PAR_0 = 0.4\ H_0 \quad (7)$$

The PAR and PAR_0 are in MJ/m^2/day
The Mean temperature (T_{mean}) was obtained using (Akpootu *et al.*, 2019b; Akpootu *et al.*, 2022a)

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \quad (8)$$

The temperature ratio (T_r) was obtained using (Akpootu and Sanusi, 2015)

$$T_r = \frac{T_{max}}{T_{min}} \quad (9)$$

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The accuracy of the developed models was statistically tested by calculating the Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t-test, Index of Agreement (IA) and the coefficient of determination (R^2). The MBE, RMSE and MPE were calculated using the equation (El-Sabaii and Trabea; 2005; Akpootu and Momoh, 2014).

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(PAR_{i,cal} - PAR_{i,mea}\right) \quad (10)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(PAR_{i,cal} - PAR_{i,mea}\right)^2\right]^{\frac{1}{2}} \quad (11)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{PAR_{i,mea} - PAR_{i,cal}}{PAR_{i,mea}}\right) * 100 \quad (12)$$

As reported by Akpootu and Sulu 2015; Akpootu et al. (2022b). The t-test as defined by student Bevington (1969) in among the tests for mean value; and the random variable t. with n – 1 degrees of freedom can be given by the relation as

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}\right]^{\frac{1}{2}} \quad (13)$$

The index of agreement (IA) was calculated using the below equation (Akpootu and Abdullahi 2022; Akpootu *et al.*, 2023)

$$IA = 1 - \frac{\sum_{i=1}^{n}\left(PAR_{i,cal} - PAR_{i,mea}\right)^2}{\sum_{i=1}^{n}\left(\left|PA\ \ {}_{i,cal} - \overline{PAR}_{i,mea}\right| + \left|PAR_{i,mea} - \overline{PAR}_{i,mea}\right|\right)^2} \quad (14)$$

From the above equation (10) – (14), the $PAR_{i,mea}$, $PAR_{i,cal}$ and n are referred to as the i^{th} measured, i^{th} calculated values of daily photosynthetically active radiation and the total number of observations respectively. Iqbal (1983) and Chen et al. (2004) have recommended that a zero value for MBE is the most suitable and a low RMSE is desirable. Moreover, the smaller the value of the MBE, RMSE and MPE the better the models performances. A positive MPE and MBE values gives the average amount of overestimation in the calculated values, while the negative values gives underestimation (Gana and Akpootu, 2013a, b; Akpootu and Gana, 2014; Olomiyesan *et al.*, 2021). For a better model performance, a low value of MPE is desirable and the percentage error between – 10 % and + 10 % is considered acceptable (Merges *et al.*, 2006)

The smaller the value of t the better is the performance. For better data modeling, the coefficient of determination R^2 should approach 1 (100%) as closely as possible (Akpootu and Iliyasu, 2015a; Akpootu and Iliyasu, 2015b). MBE and RMSE are in MJ/m²/day, MPE, and IA are in % while t – test is non-dimensional (Akpootu et al. 2019c, d, e, f).

The proposed temperature PAR based models developed in this study are of the form:

$$\frac{PAR}{PAR_0} = a + b\ ln\Delta T \quad (15a)$$

$$\frac{PAR}{PAR_0} = a + b\Delta T^{0.5} \quad (15b)$$

$$\frac{PAR}{PAR_0} = a + b\left(\frac{\Delta T}{S_o}\right) \quad (15c)$$

$$\frac{PAR}{PAR_0} = a + b\Delta T^{0.5} + c\ exp(\Delta T^{0.5}) \quad (15d)$$

$$\frac{PAR}{PAR_0} = a + b\Delta T + c(\Delta T)^2 + dln\Delta T \quad (15e)$$

$$\frac{PAR}{PAR_0} = a + b\left(\frac{\Delta T}{S_o}\right) + c\left(\frac{\Delta T}{S_o}\right)^2 + dexp\left(\frac{\Delta T}{S_o}\right) \quad (15f)$$

$$\frac{PAR}{PAR_0} = a + b\Delta T + cT_{mean} + d\mathrm{Tr} \quad (15g)$$

$$\frac{PAR}{PAR_0} = a + b\left(\frac{\Delta T}{S_o}\right) + cln\left(\frac{\Delta T}{S_o}\right) \quad (15h)$$

where PAR, PAR_O and S_o are as previously defined. ΔT Is the difference between the monthly average daily maximum and minimum temperature i.e., $T_{max} - T_{min}$ and the constants a, b and c are empirical coefficients determined by regression analysis and the other terms are the model correlation parameters.

Results and Discussion

The evaluated temperature based models with their respective PAR empirical coefficients developed in this study for Benin based on equations 15a – 15h are;

$$\frac{PAR}{PAR_0} = 0.090 + 0.194\ ln\Delta T \quad (16a)$$

$$\frac{PAR}{PAR_0} = 0.163 + 0.117\ \Delta T^{0.5} \quad (16b)$$

$$\frac{PAR}{PAR_0} = 0.364 + 0.197\left(\frac{\Delta T}{S_o}\right) \quad (16c)$$

$$\frac{PAR}{PAR_0} = -\ 0.392 + 0.363\ \Delta T^{0.5} - 0.00854\ exp(\Delta T^{0.5}) \quad (16d)$$

$$\frac{PAR}{PAR_0} = -\ 1.80 - 0.293\ \Delta T + 0.005\ (\Delta T)^2 + 2.06\ ln\Delta T \quad (16e)$$

$$\frac{PAR}{PAR_0} = -\ 1.55 + 0.730\left(\frac{\Delta T}{S_o}\right) - 2.03\left(\frac{\Delta T}{S_o}\right)^2 + 1.26\ exp\left(\frac{\Delta T}{S_o}\right) \quad (16f)$$

$$\frac{PAR}{PAR_0} = -\ 1.46 - 0.0196\ \Delta T + 0.0477\ T_{mean} + 0.635\ \mathrm{Tr} \quad (16g)$$

$$\frac{PAR}{PAR_0} = 1.07 - 0.481\left(\frac{\Delta T}{S_o}\right) + 0.621\ ln\left(\frac{\Delta T}{S_o}\right) \quad (16h)$$

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Table 1. Validation of the PAR Temperature based models for Benin under different statistical test

Models	R^2	MBE	RMSE	MPE	t	IA
Eqn16a	59.8	0.0111	0.5982	-0.7877	0.0614	75.6835
Eqn16b	58.6	0.0105	0.6062	-0.7985	0.0573	74.6338
Eqn16c	58.5	0.0047	0.6072	-0.7303	0.0259	74.2964
Eqn16d	62.7	-0.0097	0.5791	-0.4447	0.0558	78.3866
Eqn16e	63.5	-0.0951	0.5815	0.7261	0.5500	79.3157
Eqn16f	64.0	-0.1245	0.5842	1.0844	0.7236	78.1889
Eqn16g	71.9	-0.0283	0.4842	0.0670	0.1941	88.3428
Eqn16h	63.6	0.0356	0.5753	-1.0427	0.2057	78.6913

Table 2. Ranking of the evaluated PAR temperature based models for Benin based on the Statistical test

Models	R^2	MBE	RMSE	MPE	t	IA	Total
Eqn16a	6	4	6	5	4	6	31
Eqn16b	7	3	7	6	3	7	33
Eqn16c	8	1	8	4	1	8	30
Eqn16d	5	2	3	2	2	4	18
Eqn16e	4	7	4	3	7	2	27
Eqn16f	2	8	5	8	8	5	36
Eqn16g	1	5	1	1	5	1	14
Eqn16h	3	6	2	7	6	3	27

Table 1 gives the summary of the statistical tests adopted in this period of study. As shown in the table, based on the R^2 the model, equation 16g has the highest value with 71.9 % and is the best model. Based on the MBE the model, equation 16c has the lowest value with overestimation of 0.0047 MJ$m^{-2}day^{-1}$ in its estimated value and is judged the best model. Based on the RMSE the model, equation 16g has the minimum value with 0.4842 MJ$m^{-2}day^{-1}$ and is judged the best model. Based on the MPE, despite the observed overestimation and underestimation exhibited by the models, they all fall within the acceptable range ($MPE \leq \pm 10\%$) with the model, equation 16g having the least value with overestimation of 0.0670 % and is the best model in the estimated value. Based on the t – test the model, equation 16c was judged the best model been it with the lowest value of 0.0259. Based on the IA the model, equation 16g is judged the best model having the highest value of 88.3428 %.

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The ranking of the models (Table 2) was done based on the validation of the models (Table 1). The total ranks obtained by the different models ranged from 14 to 33. Based on the overall results of the model, equation 16g was found the most suitable and the best for estimating photosynthetically active radiation for Benin.

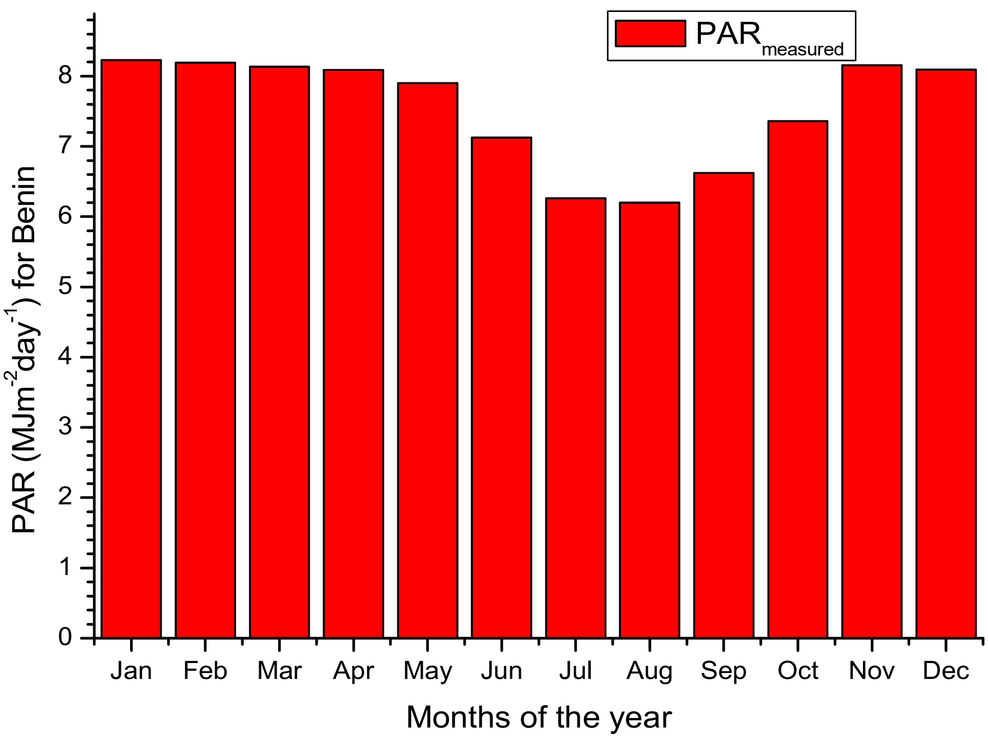

Figure 1: Monthly Variation of (PAR) for Benin

Figure 1 gives the monthly variation of PAR for Benin during the study period (1984 – 2021). It is clear that the highest value occurred in January with 8.2305 MJ$m^{-2}day^{-1}$ that falls within the dry season, while the lowest value occurred in August with 6.2003 MJ$m^{-2}day^{-1}$ which was found in the rainy season, other months like February, March and November are very closed to the maximum value in which they all occurred in the dry season with 8.1929 MJ$m^{-2}day^{-1}$, 8.1333 MJ$m^{-2}day^{-1}$ and 8.1541 MJ$m^{-2}day^{-1}$ respectively. The result in this study is in line with that of Akpootu et al. (2019a) where they reported that the highest value of the monthly average daily PAR of 9.38 MJ$m^{-2}day^{-1}$ occurred in the month of November and the lowest value of 6.04 MJ$m^{-2}day^{-1}$ occurred in August for Akure during the dry and rainy season respectively.

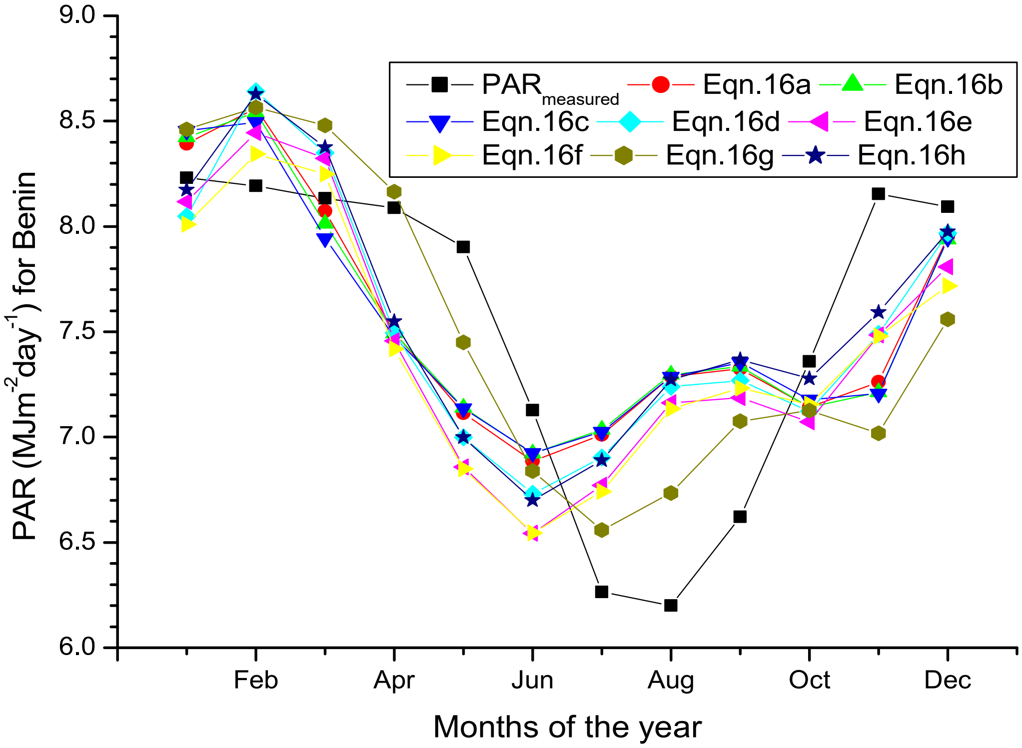

Figure 2: Comparison between the measured PAR and estimated temperature photosynthetically active radiation (PAR) based models for Benin

Figure 2 displays the comparison between the measured PAR and estimated temperature PAR based model for Benin. As shown above, the model, equation 16f underestimated the measured PAR and other estimated temperature PAR based models in the month of January. The model, equation 16c also underestimated the measured PAR and other estimated temperature based models in March. Then the measured PAR underestimated the estimated temperature PAR based models in the month of February which occurred under the dry season, and also in July to September with the lowest value of 6.2003 MJ$m^{-2}day^{-1}$ that falls under the rainy season. However the measured PAR also overestimated the estimated temperature PAR based models in May to June and in October which occurred in the rainy season, and also from November to December that falls within the dry season. The model equation 16g overestimated the PAR measured and other estimated temperature PAR based models in January, March and April which also underestimated the measured PAR and other estimated temperature PAR based models in the months of November and December. The model equation 16e underestimated the PAR measured and other estimated PAR temperature based models in the month of October that occurred in the rainy season.

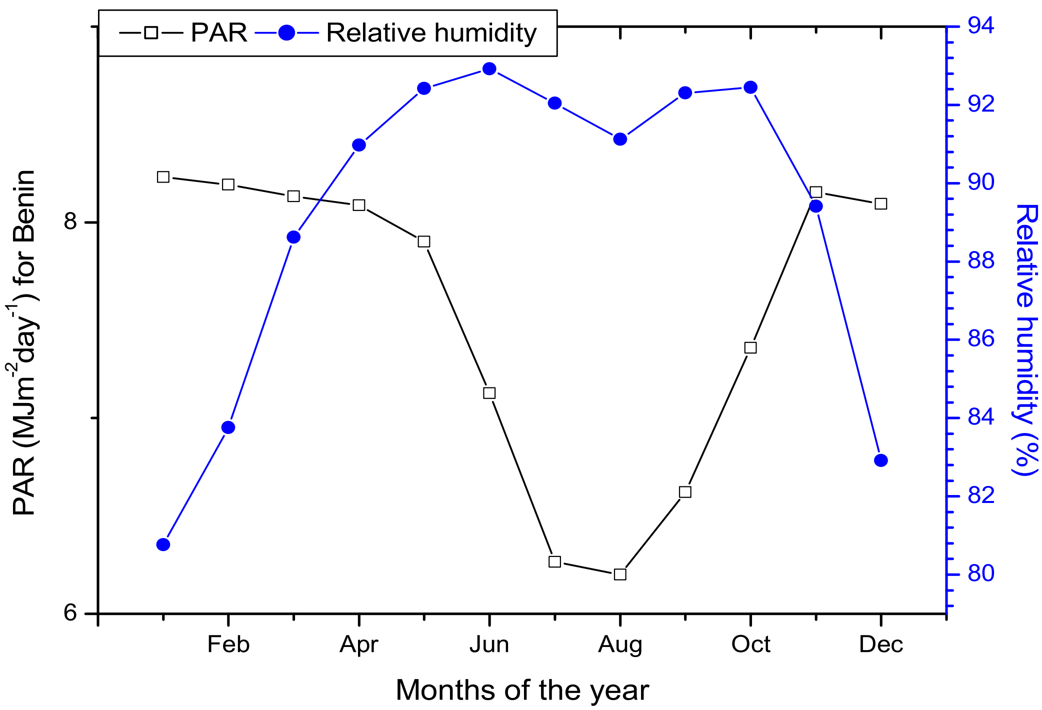

Figure 3: Monthly variation of PAR with Relative humidity during the Investigation period of thirty-eight years (1984 – 2021) for Benin

Figure 3 shows the monthly variation of PAR with relative humidity during the period of investigation. The PAR gradually decreases from it maximum value of 8.2305 MJ$m^{-2}day^{-1}$ in January to its minimum value in August with 6.2003 MJ$m^{-2}day^{-1}$. The relative humidity increases from its minimum value of 80.7629 % in January to its peak value in June with 92.9200 % and then decreases to August. The PAR also increases from August to November and drop in December. However, the relative humidity increases from August to October and then started descending from October down to December.

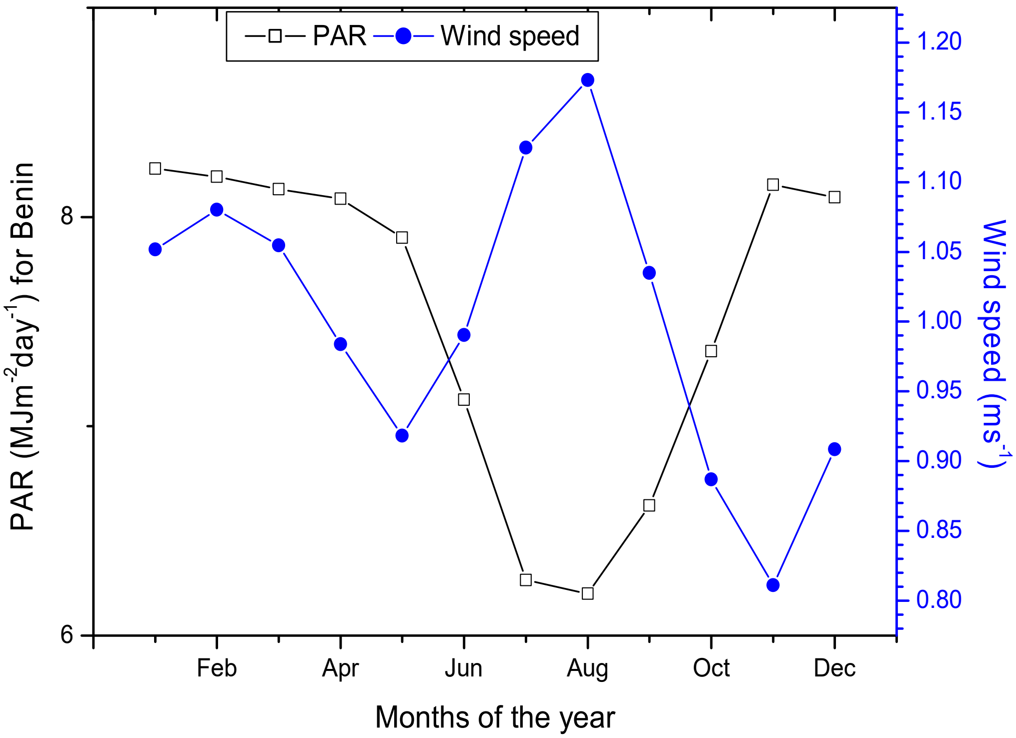

Figure 4: Monthly variation of PAR with wind speed during the investigation period of thirty-eight years (1984 – 2021) for Benin

Figure 4 displays the monthly variation of PAR with wind speed for Benin during the period of investigation. It is clear from the figure that the PAR started descending from its highest value of 8.2305 MJ$m^{-2}day^{-1}$ in January, down to its lowest value in August with 6.2003 MJ$m^{-2}day^{-1}$ and further increases from August to November and then drop to December. On the other hand, the wind speed increases from January to February and then gradually decreases to May. Also, the wind speed increases from May to its peak value in August with 1.1732 ms^{-1} and then moves down gradually to its least value in November with 0.8111 ms^{-1} and then increases to December. The highest value of wind speed corresponds to the lowest value of PAR in the month of August.

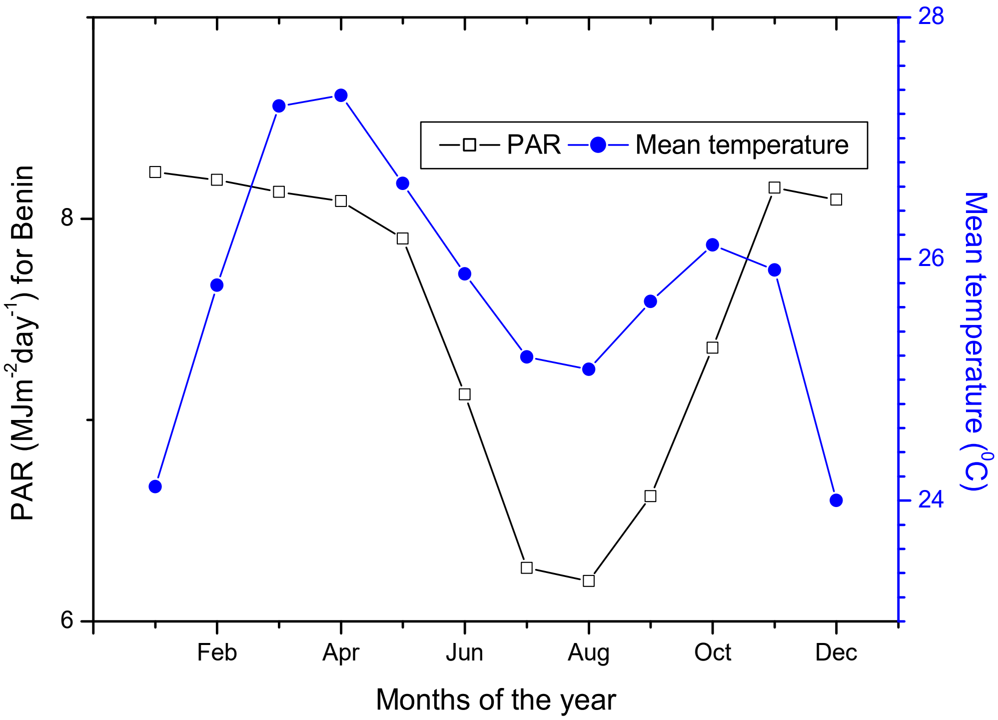

Figure 5: Monthly variation of PAR with mean temperature during the investigation period of thirty-eight years (1984 – 2021) for Benin.

Figure 5 shows the monthly variation of PAR with mean temperature during the investigation period. The mean temperature (℃) increases from January to its highest value of 27.3522 ℃ in the month of April and then decreases down to August. Furthermore, the mean temperature also increases from August to October then decreases to November and then falls sharply to its lowest value of 24.0000 ℃ in the month of December. On the other hand, the PAR started descending from its peak value of 8.2305 MJ$m^{-2}day^{-1}$ in the month of January down to its lowest value of 6.2003 MJ$m^{-2}day^{-1}$ in August and further increases from August to November then drop to December.

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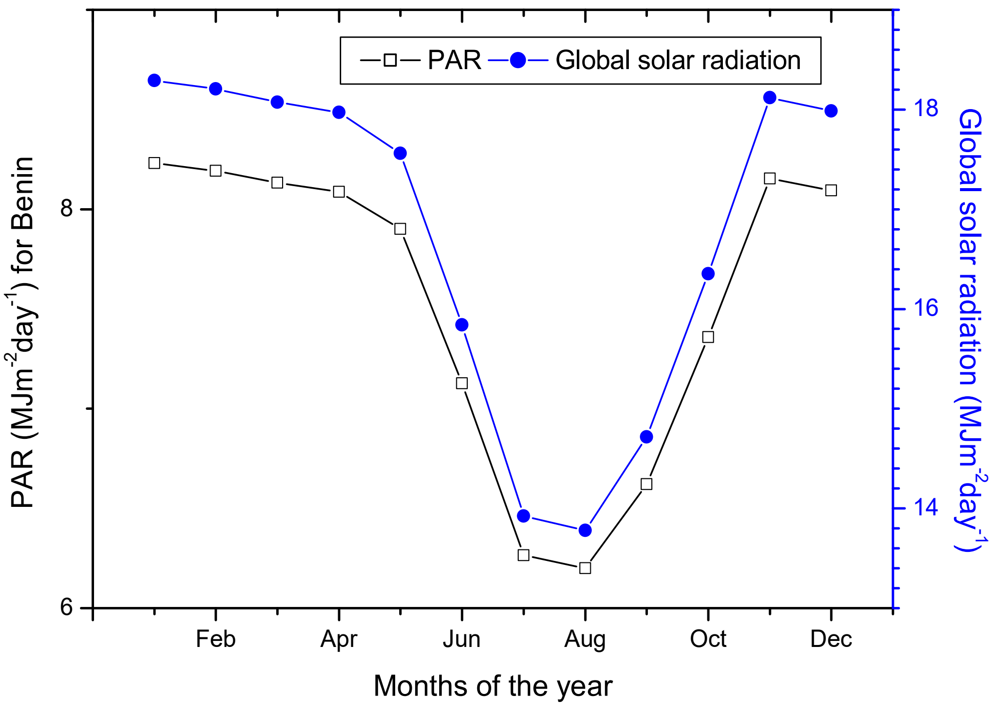

Figure 6: Monthly variation of PAR with global solar radiation during the investigation period of thirty-eight years (1984 – 2021) for Benin

Figure 6 shows the monthly variation of PAR with global solar radiation for Benin during the investigation period. Obviously as shown in the figure, as the PAR started decreasing from its maximum value of 8.2305 MJ$m^{-2}day^{-1}$ in the month of January down to its least value in August with 6.2003 MJ$m^{-2}day^{-1}$, similarly the global solar radiation also begin descending from its highest value of 18.2899 MJ$m^{-2}day^{-1}$ in January to its lowest value of 13.7785 MJ$m^{-2}day^{-1}$. Furthermore as the PAR also increases from August to November and then drop to December, the global solar radiation still increases from August to November and drop to December. This shows that the PAR and the global solar radiation has a direct relationship with each other, as they both decreases from the peak point in January to the least value in the same month of August, and similarly they both further increases from August in tandem to November and drop together in December. The implication of this result is that the global solar radiation can be used to estimate PAR as it gives an idea of its variation over the period under investigation for the location.

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Conclusion

Photosynthetically active radiation is a necessary input in application dealing with plant physiology, biomass production and natural illumination in greenhouses. It is the quantity of light energy that can be obtained for photosynthesis to take place and are usually within the wavelength range of 400 to 700 nm. This paper addresses the issue of estimation and investigation of photosynthetically active radiation (PAR) for Benin (latitude 6.32°N, longitude 5.10°E and 77.8 m above sea level) located in the coastal region of Nigeria. The data used in this study were obtained from the archives of National Aeronautics and space Administration (NASA). The monthly average daily global solar radiation, relative humidity, wind speed, minimum and maximum temperature during the period of thirty-eight years (1984-2021) were utilized in this work. In this present investigation, eight (8) new temperature PAR based models were developed and compared on the basis of statistical indicators of coefficient of determination (R^2), Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t – test and index of Agreement (IA). The result shows that photosynthetically active radiation (PAR) for Benin is higher during the dry season with 8.2305 MJ$m^{-2}day^{-1}$ in January and is low in the rainy season with 6.2003 MJ$m^{-2}day^{-1}$ in August. Based on the new temperature PAR based models developed, the best model, for Benin is (model equation 16g). The variation of PAR with global solar radiation indicate that a direct relationship exist between them for the location, the result of the PAR with wind speed showed that the wind speed has direct influence on the PAR as high value of wind speed corresponds to low value of PAR as indicated in the month of August.

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