Estimation and Investigation of Photosynthetically Active Radiation using Meteorological Parameters over Ikeja, Nigeria

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ABSTRACT

Photosynthetically active radiation (PAR; 0.4 - 0.7μm) is a key driver in ecosystem biochemical processes, and thus a critical factor in agriculture productivity, ecosystem-atmosphere energy, and CO_2 fluxes.In this study, the measured monthly averaged 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 Ikeja (latitude 6.58°N, longitude 3.33°E and 39.4 m above sea level) located in the coastal region ofNigeria. The meteorological parameters used in this work 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 statisticallytested using 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 accuracy and applicability of the models.The results show that, the highest and lowest values of PAR were found during the rainy season with8.3426 MJ$m^{-2}day^{-1}$ and6.4936 MJ$m^{-2}day^{-1}$ in the months of April and July respectively. Based on the developed models, the model equation(16g) is the most suitable for estimating PAR for Ikeja with R^2, MBE, RMSE, MPE, t-test and IA values of 80.9 %, 0.0062 MJ$m^{-2}day^{-1}$, 0.3415 MJ$m^{-2}day^{-1}$, -0.1974 %, 0.0601 and 92.8712 % respectively.

Keywords: Ikeja, models, NASA, PAR, statistical indicators

1. INTRODUCTION

Solar radiation is the primary energy source for life on Earth [1]. The portion with wavelengths ranging from 400 to 700 nm is known as photosynthetically active radiation (PAR). It is often regarded as the spectral range of global solar radiation at wavebands spanning from approximately 0.4 μm through 0.7μm [2 – 4]. In general, plants use PAR as an energy source to convert CO_2 and water through photosynthesis into organic compounds (typically sugars) that are then used to synthesize structural and metabolic energy required for plant growth and respiration, as well as stored vegetative products that result in plant biomass [2], [5 – 6]. This radiation component (PAR) can be seen in the process plants used in synthesizing their food as given by the chemical equation.

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

where the photon (PAR) represents light energy wavelength range (0.4-0.7 μm) that is best fit for photosynthesis to occur.

This component of solar radiation spectrum (PAR) is extremely essential, because it isthe solar energy source for vegetativephotosynthesis to provide us with products suchas food and fiber (fiber) sources, biofuel carriers and additional material sources that support industrial process. It also plays very important roles in plant growth, and it is the principal factorin the rate of solar energy conversion intobiological mediated energy. Proper predictionand understanding of this radiometric parameter, PAR are needed for numerous applications,such as studies of radiation climate, remotesensing of vegetation, radiation regimes of plantcanopy and photosynthesis, an essential input inmodels estimating plant productivity, and carbonexchange between ecosystem and atmosphere.The silicon photovoltaic detector can be used to measures Photosynthetically Active Radiation (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.

Several researches have been carried out on studies that involved estimation of Photosynthetically active radiation for different locations these include the study by Nwokolo et al. [7] where they investigate the photosynthetically active radiation estimations and modelling over different climatic zones in Nigeria. In another study Akpootu et al. [8] developed empirical models for Estimating Photosynthetically Active Radiation over Akure, South Western, Nigeria. Nwokolo et al. [9] carried out a study on the impacts of climate change and Mateo - solar parameters on Photosynthetically active radiation prediction using hybrid machine learning with physics-based models. Nwokolo et al. [10] carried out a study on machine learning and physics-based hybridization models for evaluation of the effects of climate change and urban expansion on Photosynthetically active radiation. Other studies include, Sunday et al. [11], Etuk et al. [12], Nwokolo et al. [13] to mention but a few
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The aim of this study is to estimate and investigate the variability of Photosynthetically active radiation and to develop new temperature based models capable of estimating PAR for Ikeja.

2. 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 Ikeja, 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 [14 – 15],

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

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 [14 – 15],

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

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

For a given month, the maximum possible sunshine duration (monthly average day length (S_O)) can be computed [14 – 15], 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 Ikeja, Therefore, PAR was obtained using the formula [16 – 17],

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

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 [18]. 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 [19]. The extraterrestrial photosynthetically active radiation, PAR_0 was estimated using the expression [7 - 8]

$$PAR_0 = 0.4\, H_0 \qquad (7)$$

The PAR and PAR_0 are in MJ/m^2/day

The Mean temperature (T_{mean}) was obtained using [20 – 21]

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

The temperature ratio (T_r) was obtained using [22]

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

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 was calculated using the equation [23].

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

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

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

As reported by Akpootu et al. [24]. The t-test as defined by student Bevington [25] is among the tests for mean value; and the random variable t. with n – 1 degrees of freedom can be given by the relation as

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

The index of agreement (IA) was calculated using the below equation [26 – 27]

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

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 [14] and Chen et al. [28] 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 is 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. For a better model performance, a low value of MPE is desirable and the percentage error between – 10% and + 10% is considered acceptable [29]

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 [30 – 31]. MBE and RMSE are in MJ/m^2/day, MPE, and IA are in % while t – test is non-dimensional

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

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

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

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

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

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

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

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

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

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.

3. RESULTS AND DISCUSSION

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

$$\frac{PAR}{PAR_0} = 0.186 + 0.182\ ln\Delta T \quad (16a)$$

$$\frac{PAR}{PAR_0} = 0.193 + 0.130\ \Delta T^{0.5} \quad (16b)$$

$$\frac{PAR}{PAR_0} = 0.382 + 0.261\left(\frac{\Delta T}{S_o}\right) \quad (16c)$$

$$\frac{PAR}{PAR_0} = -1.04 + 0.842\ \Delta T^{0.5} - 0.0436\ exp(\Delta T^{0.5}) \quad (16d)$$

$$\frac{PAR}{PAR_0} = -3.50 - 1.40\ \Delta T + 0.0395\ (\Delta T)^2 + 6.16\ ln\Delta T \quad (16e)$$

$$\frac{PAR}{PAR_0} = -14.8 + 6.77\left(\frac{\Delta T}{S_o}\right) - 14.7\left(\frac{\Delta T}{S_o}\right)^2 + 13.6\ exp\left(\frac{\Delta T}{S_o}\right) \quad (16f)$$

$$\frac{PAR}{PAR_0} = -0.85 + 0.012\ \Delta T + 0.0372\ T_{mean} + 0.24\text{Tr} \quad (16g)$$

$$\frac{PAR}{PAR_0} = 2.22 - 1.67\left(\frac{\Delta T}{S_o}\right) + 1.23\ ln\left(\frac{\Delta T}{S_o}\right) \quad (16h)$$

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

Models	R^2	MBE	RMSE	MPE	t	IA
Eqn16a	54.5	-0.0082	0.5433	-0.4035	0.0504	70.0628
Eqn16b	52.5	-0.0139	0.5544	-0.3474	0.0831	68.0792
Eqn16c	52.7	-0.0028	0.5535	-0.4961	0.0169	67.7504
Eqn16d	66.4	-0.0236	0.4732	-0.0517	0.1658	81.3077
Eqn16e	71.4	0.4717	0.6538	-6.5012	3.4558	75.2840
Eqn16f	71.4	0.5478	0.7160	-7.4961	3.9405	72.7580
Eqn16g	80.9	0.0062	0.3415	-0.1974	0.0601	92.8712
Eqn16h	69.8	0.1073	0.4646	-1.7574	0.7876	82.5765

Table 1b. Ranking of the evaluated PAR temperature based models for Ikeja based on the Statistical test

Models	R^2	MBE	RMSE	MPE	t	IA	Total

Eqn16a	5	3	4	4	2	6	24
Eqn16b	7	4	6	3	4	7	31
Eqn16c	6	1	5	5	1	8	26
Eqn16d	4	5	3	1	5	3	21
Eqn16e	2	7	7	7	7	4	34
Eqn16f	2	8	8	8	8	5	39
Eqn16g	1	2	1	2	3	1	10
Eqn16h	3	6	2	6	6	2	25

Table 1a displays the several different statistical tests used in this study. As shown in the table above, based on the R^2 the model, equation 16g has the highest value of 80.9 % and is the best model. On the MBE, the model equation 16c has the lowest value with underestimation of 0.0028 MJ$m^{-2}day^{-1}$ in its estimated value which is judged as the best model. Based on the RMSE the model equation 16g has the least value of 0.3415 MJ$m^{-2}day^{-1}$ and is the best model. Based on the MPE the model, equation 16d has the minimum value with underestimation of 0.0517 % in the estimated value and is judged the best model, it is clear that all the models falls within the acceptable range of ($MPE \leq \pm 10\%$). On the t – test, the model equation 16c has the lowest value with 0.0169 and is the best model. Then based on the IA the model, equation 16g has the maximum value of 92.8712 % and is judged the best model.

Table 1b shows the ranking of the models which was done based on the validation of the models in (Table 1a). The total ranks gained by the different models ranged from 10 to 39. Hence, it is obvious according to the result obtained, the model equation 16g was observed to be the best for estimating Photosynthetically active radiation (PAR) for Ikeja.

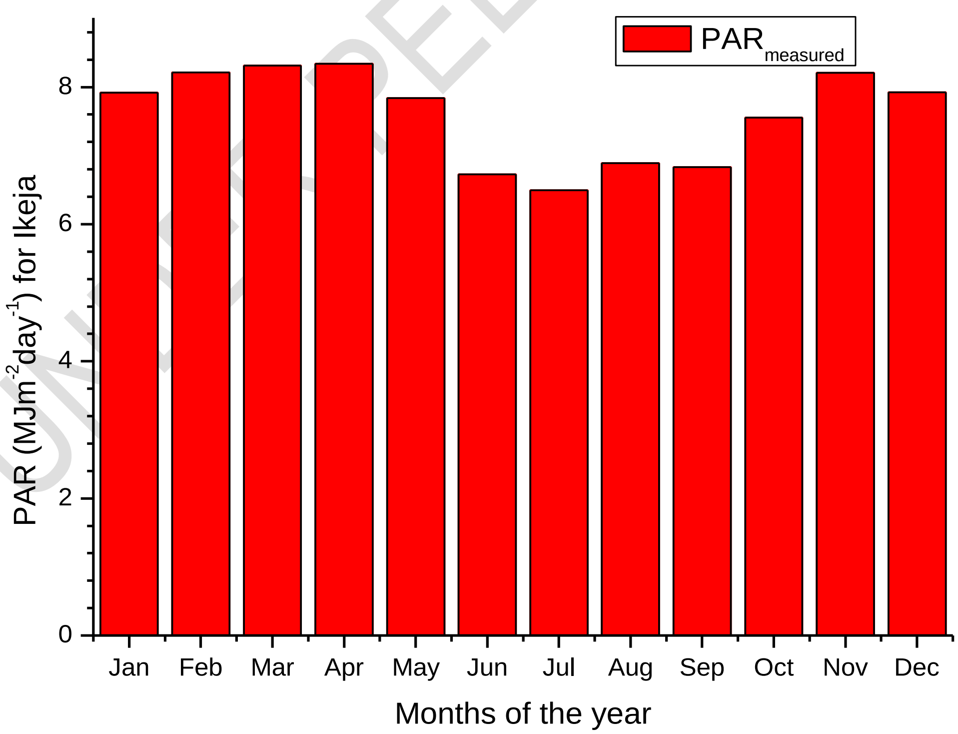

Fig 1. Monthly Variation of PAR for Ikeja

Fig. 1 displays the monthly variation of PAR for Ikeja during the investigation period (1984 – 2021). As shown above, the peak and the least value occurred in the month of April and July with 8.3426 MJ$m^{-2}day^{-1}$ and 6.4936 MJ$m^{-2}day^{-1}$ respectively. However both the peak and the least value falls under rainy season, and based on the dry season months like November, February and March have almost closed values with 8.2074 MJ$m^{-2}day^{-1}$, 8.2121 MJ$m^{-2}day^{-1}$ and 8.3166 MJ$m^{-2}day^{-1}$ respectively.

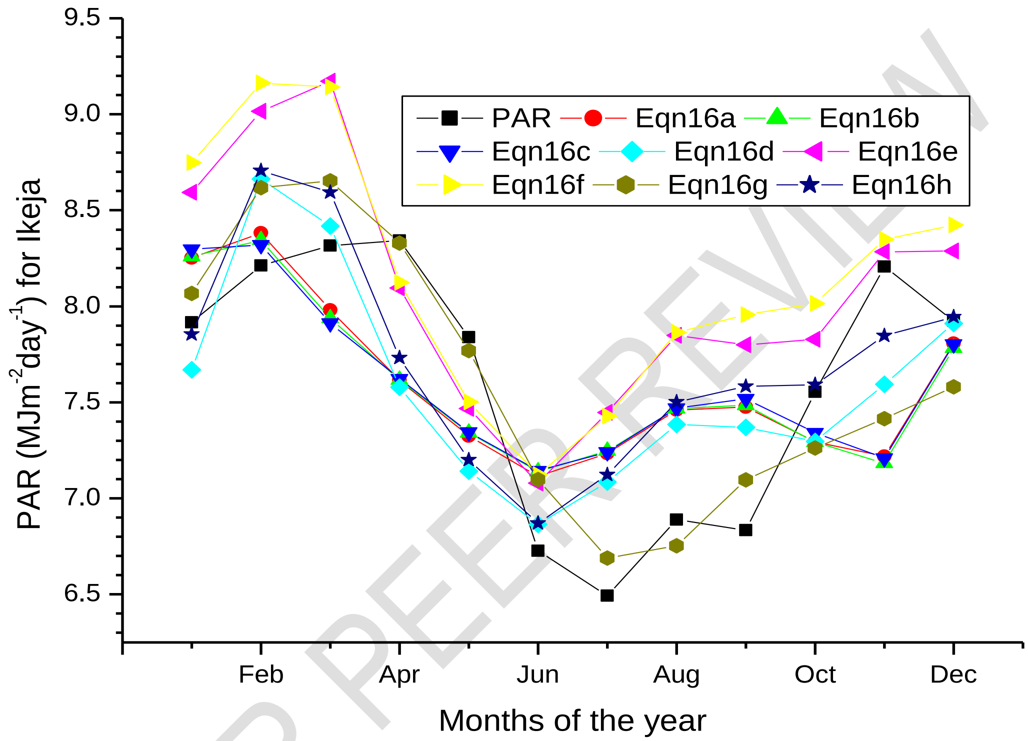

Fig. 2. Comparison between the measured PAR and estimated temperature photosynthetically active radiation (PAR) based models for Ikeja

Fig. 2 shows comparison between the measured PAR and the estimated temperature Photosynthetically active radiation based models for Ikeja. It is clear from the figure that the model, equation 16f overestimated the measured PAR and other estimated temperature PAR based model in the months of January to February and in September to December with the peak value of 9.1619 MJ$m^{-2}day^{-1}$ in February. The model, equation 16d underestimated other estimated temperature PAR based models and the measured PAR in January and April to May. Then the model, equation 16g underestimated the measured PAR and the rest of the estimated temperature PAR based models in August, October and December. The model, equation 16c also underestimated the measured PAR and other estimated temperature PAR based models in March. However the measured PAR underestimated the estimated temperature PAR based model in February that falls within the dry season and also in June, July and September that occurred in the rainy season with the minimum value of 6.4936 MJ$m^{-2}day^{-1}$ in July. Furthermore, the measured PAR overestimated the estimated temperature PAR based models in the months of April and May.

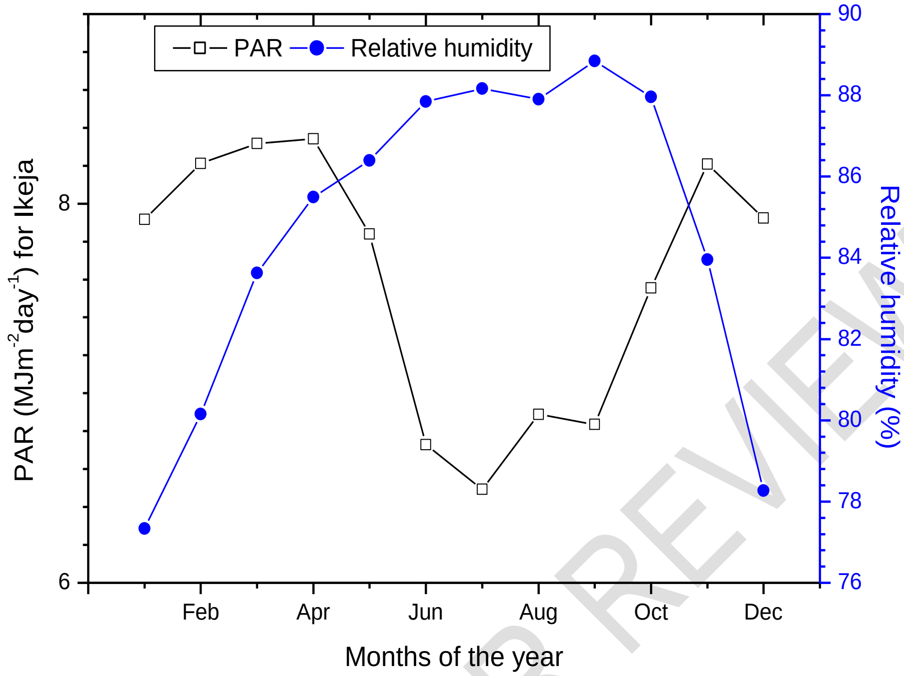

Fig. 3. Monthly variation of PAR with relative humidity over Ikeja during the period of thirty-eight years (1984 – 2021).

Fig. 3 shows the monthly variation of Photosynthetically active radiation (PAR) with relative humidity for the study area under investigation. The PAR increases from January to its peak value of 8.3426 MJ$m^{-2}day^{-1}$ in April and then decreases to July with the minimum value of 6.4936 MJ$m^{-2}day^{-1}$. The Relative humidity rises from January to July then decreases to August and further increases to its peak value of 88.8432 % in the month of September, then started descending from September down to December. The PAR then rises from July to August and slightly decreases to September and then increases sharply to November and fall to December.

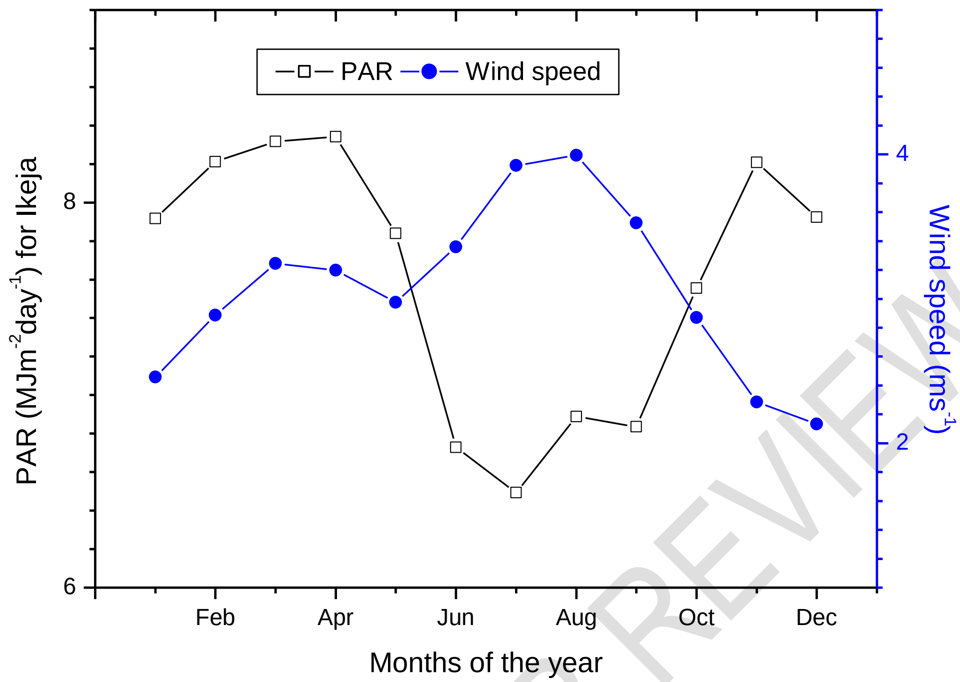

Fig. 4. Monthly variation of PAR with wind speed over Ikeja during the period of thirty-eight years (1984 – 2021).

Fig. 4 shows the monthly variation of photosynthetically active radiation (PAR) with wind speed for the study Area. It can be seen clearly that as the wind speed increases from January to March then decreases to May. The PAR rises from January to its maximum value of 8.3426 MJ$m^{-2}day^{-1}$ in April and started descending from April to its lowest value of 6.4936 MJ$m^{-2}day^{-1}$ in the month of July. However the wind speed increases from May to its highest value of 3.9939 ms^{-1} in August and then dropped sharply to its minimum value of 2.1337 ms^{-1} in December. The PAR also increases from July to August and decreases slightly to September, then further increases to November and drop to December.

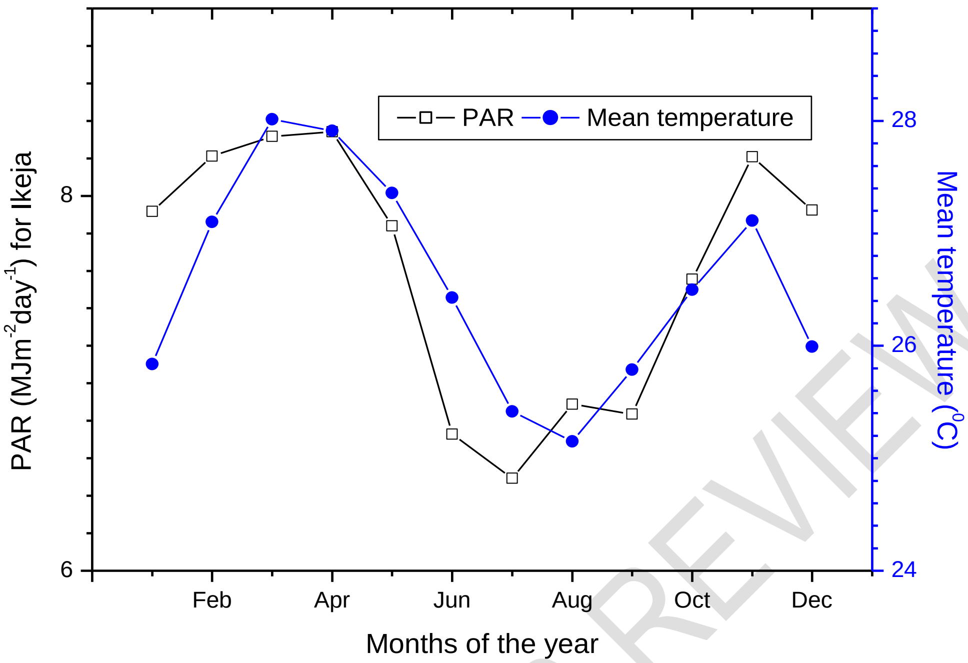

Fig. 5. Monthly variation of PAR with Mean temperature over Ikeja during the period of thirty-eight years (1984 – 2021).

Fig. 5 shows the monthly variation of Photosynthetically active radiation (PAR) with mean temperature for Ikeja during the investigation period. As the PAR increases from January to its highest value of 8.3426 MJ$m^{-2}day^{-1}$in April and then falls down to its least value of 6.4936 MJ$m^{-2}day^{-1}$ in the month of July. The mean temperature also increases from January to its peak point in March with the value of 28.0133 ℃ and then decreases to its least value of 25.1489 ℃ in the month of August. However, the PAR rises from July to August and slightly decreases to September, then increases to November. Similarly the mean temperature increases from August uniformly to September and then both the PAR and mean temperature dropped from November to December.

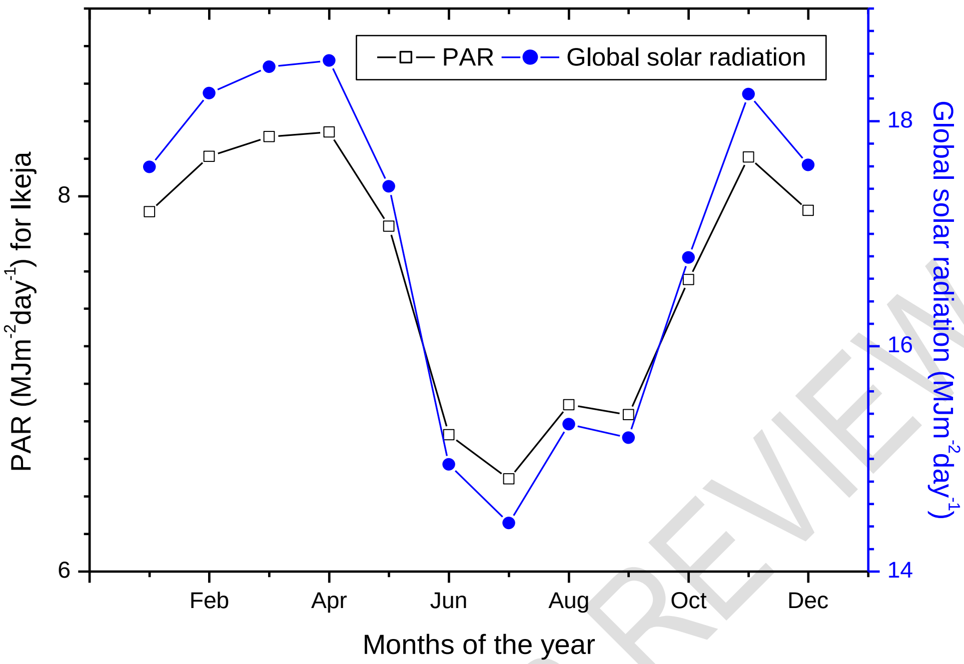

Fig. 6. Monthly variation of PAR with Global solar radiation over Ikeja during the period of thirty-eight years (1984 – 2021).

Fig. 6 displays monthly variation of photosynthetically active radiation (PAR) with global solar radiation for the study Area. It is well clear that the PAR and the global solar radiation vary similarly with each other, meaning that they are going or moving one behind the other. As show in the figure above, the global solar radiation increases from January to its maximum value of 18.5391 MJ$m^{-2}day^{-1}$in April and then moves down to its minimum value of 14.4303 MJ$m^{-2}day^{-1}$ in the month of July. The PAR similarly increases from January to its highest value of 8.3426 MJ$m^{-2}day^{-1}$ in April and then decreases to its lowest value of 6.4936 MJ$m^{-2}day^{-1}$ in July. As the global solar radiation rises from July to August the PAR also rises from July to August and then both of them slightly decreases from August to September showing that they are in tandem with each other. However almost similarly both the PAR and global solar radiation further increases sharply from September to November and at the same month from November they both dropped to December.

4. CONCLUSION

Photosynthetically active radiation 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 Ikeja (latitude 6.58°N, longitude 3.33°E and 39.4 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 Ikeja is higher with 8.3426 MJ$m^{-2}day^{-1}$ in April and is low with 6.4936 MJ$m^{-2}day^{-1}$ in July that occurred both in the rainy season. Based on the new temperature PAR based models developed, the best model for Ikeja is (model equation 16g). The variation of PAR with global solar radiation indicate that a direct relationship exist between them for the location.

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