Sudhaker *et al. International Journal of Energy and Environmental Engineering* 2013, **4**:21
http://www.journal-ijeee.com/content/4/1/21

International Journal of Energy and Environmental Engineering
a SpringerOpen Journal

ORIGINAL RESEARCH **Open Access**

Modelling and estimation of photosynthetically active incident radiation based on global irradiance in Indian latitudes

Kumarasamy Sudhakar[1*], Tulika Srivastava[1], Guddy Satpathy[1] and Manicam Premalatha[2]

Abstract

Photosynthetically active radiation (PAR) as a component of solar radiation plays a major role in different applications dealing with plant canopies, biomass production and microalgae growth. The amount of PAR energy depends upon location, time of the year and atmospheric conditions. Understanding the PAR and its availability is very essential for modelling biological growth system. The objective of this study is to estimate PAR for latitudes ranging from 9° to 34° and for the entire year based on hourly and monthly average of the daily global radiation (Hg). Based on the estimated data, a power regression model showing the relationship between PAR and Hg is presented for six Indian latitudes. The ratios of hourly sum of PAR to Hg and monthly average of hourly global radiations (Ig) vary smoothly with significant seasonal variations and are influenced by several other local climatic conditions. The power regression equation between PAR and Hg obtained are as follows: (a) For 9° latitude, PAR = 0.040 $(Hg)^{0.924}$, R^2 = 0.970, (b) 14° latitude, PAR = 0.029 $(Hg)^{0.952}$, R^2 = 0.894, (c) 19° latitude, PAR = 0.256 $(Hg)^{0.748}$, R^2 = 0.721, (d) 24° latitude, PAR = 0.159 $(Hg)^{0.775}$, R^2 = 0.896, (e) 29° latitude, PAR = 0.052 $(Hg)^{0.886}$, R^2 = 0.830 and (f) 34° latitude, PAR = 0.016 $(Hg)^{1.013}$, R^2 = 0.768.

Keywords: Photosynthetically active radiation, Solar radiation, Latitude, PAR modelling, India

Background

The amount of solar radiation reaching the top of the Earth's atmosphere is around 1,367 W m^{-2}, also called as solar constant [1]. On a bright sunny day, roughly around 800 to 1,200 W m^{-2} of total radiation reaches the Earth's surface owing to atmospheric scattering and absorption. The sun radiates energy in the spectral range from 280 to 4,000 nm (Figure 1), with a maximum in the blue-green (480 nm). The three major regions of the solar spectrum are (a) ultraviolet region (wavelength less than 400 nm): constitutes 9% of the irradiance, (b) visible region (wavelength ranging from 400 to 700 nm): constitutes 45% of the irradiance and (c) infrared region (wavelength greater than 700 nm): constitutes 46% of the irradiance.

The photosynthetically active radiation (PAR) in visible spectrum ranging from 400 to 700 nm is absorbed by plants to carry out photosynthesis. The PAR provides energy for photosynthesis and regulates plant growth and development. Within the PAR, the solar radiation peaks at 590 nm. The amount of PAR highly depends on environmental conditions. The measurement of the PAR is very important for environmental systems, agriculture, forest, architecture, solar greenhouse and many other applications. The PAR estimation based on simple methodologies would be highly useful for ecological modelling, algal photosynthesis, plant yield and land use efficiency. Therefore, a simple regression model that accurately predicts the PAR from global irradiance is necessary to design the growth system of phototropic microorganism.

The energy generation from solar radiation and performance correlations has been investigated by many authors [2–6]. The estimation of PAR based on solar global radiation has been studied by different authors for various specific locations [7–12]. The theoretical background and applications of PAR are described by [13]. Relatively, very little information regarding the availability of PAR in Indian context has been published in literature. Considering that the PAR measurement is very scarce in India,

* Correspondence: sudha_k@sify.com
[1]Energy Centre, Maulana Azad National Institute of Technology Bhopal, Madhya Pradesh 462 051, India
Full list of author information is available at the end of the article

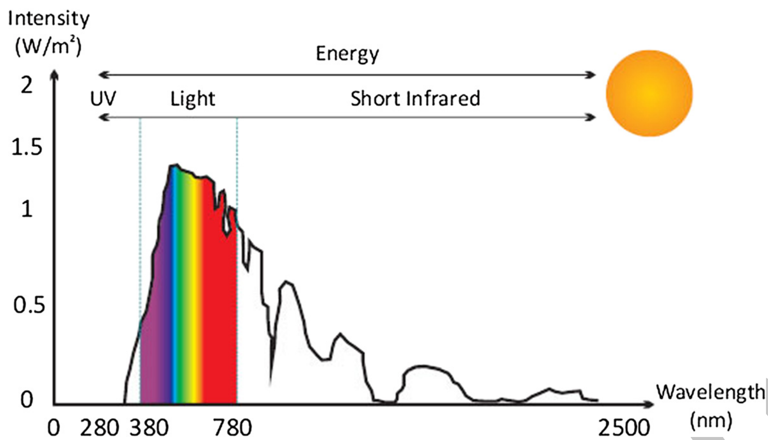

Figure 1 Solar spectrum.

it becomes more necessary to estimate PAR based on global solar radiation as a function of local climatic condition. The most probable idealised conversion coefficient (PAR/Total global solar radiation, μmol J^{-1}) of 1.814 has been reported [13].

The objective of this study is to estimate PAR based on hourly average and daily average of monthly solar radiation for the Indian latitudes ranging from 9° to 34°. This study is initiated to develop a simpler approach for estimating and validating the PAR and provide monthly estimates of solar radiation that can be used as input for biological growth model.

The specific activities of this study are as follows: to predict the monthly and daily average of global solar radiation, to estimate the daily average PAR at various Indian latitudes, and to evaluate the correlation between estimated monthly average of hourly global radiation and the PAR radiation at the Earth's surface based on regression model.

Methods

PAR modelling

The characteristics of studied location

India lies to the north of the equator between 6°44' and 37°30' north latitude and 68°7' and 97°25' east longitude. The Indian subcontinent undergoes four major climatic seasons when every season is about 2 months. These are winter (January to February), summer (March to May), a monsoon (rainy) season (June to September) and a post-monsoon season (October to December). Various climatic factors are responsible for the seasonal changes in India.

Estimation of daily average of monthly horizontal global radiation

The extraterrestrial solar radiation incident on a horizontal surface can be determined for any location and day of the year according to previous researchers [14,15]. Solar declination angle can be calculated for each day based on the Cooper equation. It varies throughout the year and is the function of the day number of the year (N) as shown in Table 1. N ranges from 1 to 365.

$$\text{del} = 23.45 \sin\left(\frac{360\,(284 + N)}{365}\right) \quad (1)$$

The solar hour angle for a location on Earth is zero when the sun is directly overhead, negative before noon and positive in the afternoon. The solar hour varies from 1 to 24.

$$\omega = 15\,(L\text{st}-12) \quad (2)$$

The sunrise hour angle for a location is a function of solar declination angle and the latitude.

$$\omega_s = \cos^{-1}(-\tan(\text{del})\tan(\text{lat})) \quad (3)$$

Table 1 Days on which extraterrestrial radiation is equal to monthly mean value [16]

Month	Day	Day of the year (*N*)
January	17	17
February	16	47
March	16	75
April	15	105
May	15	135
June	11	162
July	17	198
August	16	228
September	15	258
October	15	288
November	14	318
December	10	344

The total daily average extraterrestrial radiation incident on Earth varies seasonally due to the atmospheric transmissivity associated with cloud cover.

$$\mathrm{Hg} = \left(\frac{24\, I_{\mathrm{sc}}}{\pi}\right)\left(1 + 1.033\, \cos\left(\frac{360\, N}{365}\right)\right) \times ((\cos(\mathrm{lat}) \cos(\mathrm{del}) \sin\omega_{\mathrm{s}} - (\omega_{\mathrm{s}} \sin(\mathrm{lat}) \sin(\mathrm{del})))\quad (4)$$

I_{sc} is called as solar constant which is roughly equal to 1,367 W m^{-2}.

Estimation of hourly average of monthly horizontal global radiation

The hourly extraterrestrial radiation on a horizontal surface is obtained from the following expression:

$$\mathrm{I_g} = \left(\frac{3.142\ \mathrm{H_g}}{24}\right)(\mathrm{a} + \mathrm{b}\cos\omega_{\mathrm{s}})\left|\frac{\cos\omega_{\mathrm{s}} - \cos\omega}{\sin\omega_{\mathrm{s}} - \omega_{\mathrm{s}}\cos\omega_{\mathrm{s}}}\right|\quad (5)$$

The empirical constants by regression parameters for a particular location were obtained by the fitting data:

$$a = 0.409 - (0.5016 \sin(\omega_s - 60))\quad (6)$$

$$b = 0.6609 - (0.4767 \sin(\omega_s - 60))\quad (7)$$

Estimation of photosynthetically active global radiation

The PAR (μmol m^{-2} s^{-1}) is a function of various solar angles and the total global solar radiation. The total PAR over a horizontal surface can be determined from the monthly average hourly radiation directly by utilising the following expression [17]:

$$\mathrm{PAR} = \mathrm{Ig} \times 1.83\quad (8)$$

Table 2 The estimation of Hg, Ig and PAR on a horizontal surface estimated for 9° latitude in India

Month	del	Hg kJ m^{-2} day^{-1}	Ig kJ m^{-2} h^{-1}	PAR μmol m^{-2} s^{-1}
Jan	−20.9098	40,914	486.7981	890.84
Feb	−12.9402	51,905	518.3203	948.5262
Mar	−2.399	60,682	578.3328	1,058.3
Apr	9.4335	38,612	366.2531	670.243
May	18.805	16,411	153.1378	280.2423
Jun	23.09	55,774	435.5227	797.008
Jul	21.1729	38,410	330.5119	603.8368
Aug	13.433	6,387	64.789	118.563
Sep	2.1886	9,122.4	101.2441	185.2767
Oct	−9.6267	28,694	309.6061	566.5791
Nov	−18.9306	55,080	604.9113	1,107
Dec	−23.0557	9,738.6	129.2328	236.496

Table 3 The estimation of Hg, Ig and PAR on a horizontal surface estimated for 14° latitude in India

Month	del	Hg kJ m^{-2} day^{-1}	Ig kJ m^{-2} h^{-1}	PAR μmol m^{-2} s^{-1}
Jan	−20.9098	40,579	523.984	958.891
Feb	12.9402	66,806	631.9202	1,156.4
Mar	−2.399	17,258	191.0942	349.7023
Apr	9.4335	12,625	124.5059	227.8458
May	18.805	56,542	403.64	738.6611
Jun	23.09	13,978	114.9241	210.3111
Jul	21.1729	42,435	323.444	591.9024
Aug	13.433	19,069	173.2918	317.1239
Sep	2.1886	46,186	449.6715	882.8988
Oct	−9.6267	51,407	508.4048	930.3808
Nov	−18.9306	15,685	212.6837	389.5406
Dec	−23.0557	48,933	614.4773	1,124.5

Equations 1, 2, 3, 4, 5, 6, 7 and 8 were solved in MATLAB (MathWorks, Inc., Natick, MA, USA) to find the PAR at any given latitude and day. MATLAB program calculates the values of the PAR by substituting values of N ranging from 17 to 344 in Equation 1.

Results

Variation of daily average of monthly extraterrestrial global solar radiations

The methodology proposed in Equations 1, 2, 3, 4, 5, 6, 7 and 8 has been used to estimate the hourly and daily average of monthly global solar radiation on a horizontal surface as a function of position and location. By knowing the hourly average of monthly global solar radiation

Table 4 The estimation of Hg, Ig and PAR on a horizontal surface estimated for 19° latitude in India

Month	del	Hg kJ m^{-2} day^{-1}	Ig kJ m^{-2} h^{-1}	PAR μmol m^{-2} s^{-1}
Jan	−20.9098	21,924	329.5871	603.1444
Feb	−12.9402	27,172	325.7783	596.1742
Mar	−2.399	5,802	66.9735	122.5614
Apr	9.4335	3,128.3	30.3794	55.5943
May	18.805	63,917	389.353	712.5163
Jun	23.09	22,221	157.0416	287.3862
Jul	21.1729	58,963	370.9429	678.8255
Aug	13.433	6,549	447.2846	818.5308
Sep	2.1886	67,468	591.2964	1,082.1
Oct	−9.6267	61,206	575.3947	1053
Nov	−18.9306	2,790.7	42.9229	78.549
Dec	−23.0557	45,290	629.6278	1,152.2

Table 5 The estimation of Hg, Ig and PAR on a horizontal surface estimated for 24° latitude in India

Month	del	Hg	Ig	PAR
		kJ m^{-2} day^{-1}	kJ m^{-2} h^{-1}	μmol m^{-2} s^{-1}
Jan	−20.9098	3,125	55.4156	101.4106
Feb	−12.9402	10,325	140.9995	258.0291
Mar	−2.399	46,509	451.1772	825.6543
Apr	9.4335	2,321.6	21.5012	39.3471
May	18.805	61,260	330.4533	604.7295
Jun	23.09	40,167	227.2903	415.9413
Jul	21.1729	42,745	255.0006	466.6511
Aug	13.433	13,560	108.7657	199.0412
Sep	2.1886	39,728	361.5716	661.676
Oct	−9.6267	60,757	569.1226	1,040
Nov	−18.9306	2,736.2	45.9098	84.015
Dec	−23.0557	16,963	295.5098	540.7829

data on the horizontal surface, the corresponding average PAR can be determined. Tables 2, 3, 4, 5, 6 and 7 show the estimated declination angle, monthly average of the daily values of global radiation, monthly average of the hourly values of global radiation and the PAR for Indian latitudes. The values obtained for 34° latitude are the lowest and ranged from 16,938 to 4,129.9 kJ m^{-2} day^{-1} as shown in Table 7. The total annual average global solar radiation is highest for 14° latitude (35,958 kJ m^{-2} day^{-1}), and 34° latitude has the lowest value of (18,738 kJ m^{-2} day^{-1}) as shown in Table 8. The results obtained for the studied locations show that irradiance profile is quite similar. The daily global variations for all the latitude are also analogous. It is observed that the estimated

Table 6 The estimation of Hg, Ig and PAR on a horizontal surface estimated for 29° latitude in India

Month	del	Hg	Ig	PAR
		kJ m^{-2} day^{-1}	kJ m^{-2} h^{-1}	μmol m^{-2} s^{-1}
Jan	−20.9098	56,579	871.1424	1,590
Feb	−12.9402	57,924	595.6629	1,090.1
Mar	−2.399	59,268	523.9165	958.7672
Apr	9.4335	3,097.5	27.0581	49.5164
May	18.805	49,033	246.9362	451.8933
Jun	23.09	53,528	237.00	433.3325
Jul	21.1729	13,957	84.1	153.7891
Aug	13.433	50,563	302.5928	553.7448
Sep	2.1886	2,856.5	30.4309	55.6882
Oct	−9.6267	50,511	505.964	925.9142
Nov	−18.9306	22,507	378.2182	692.1392
Dec	−23.0557	7,722.9	158.0091	289.1566

Table 7 The estimation of Hg, Ig and PAR on a horizontal surface estimated for 34° latitude in India

Month	del	Hg	Ig	PAR
		kJ m^{-2} day^{-1}	kJ m^{-2} h^{-1}	μmol m^{-2} s^{-1}
Jan	−20.9098	16,938	354.4352	648.6163
Feb	−12.9402	15,198	223.4562	408.9248
Mar	−2.399	11,756	132.4627	242.4067
Apr	9.4335	19,738	148.7651	272.2402
May	18.805	2,601.4	15.3687	28.1247
Jun	23.09	52,384	191.0395	349.6022
Jul	21.1729	6,846.5	37.1997	68.0754
Aug	13.433	2,432.7	17.4003	31.8426
Sep	2.1886	27,305	255.5551	467.6658
Oct	−9.6267	18,757	240.8388	440.735
Nov	−18.9306	46,777	742.5132	1,358.8
Dec	−23.0557	4,129.9	98.8037	180.8108

daily global radiation results are in close agreement with the other literature data [16].

Variation of the PAR

The observed values of the PAR across the six locations have means of 621.9093, 656.5131, 604.1243, 436.4398, 557.8364 and 377.8203 μmol m^{-2} s^{-1}, respectively. The annual average values of PAR, Hg, Ig and irradiance are shown in Table 8. It is observed that 34° latitude has the lowest value of irradiance and PAR. The seasonal and location-specific variation of the PAR is clearly evident from the data presented in Tables 2, 3, 4, 5, 6 and 7. These data show the availability of PAR at a specific latitude that is highly useful for locating an open pond algae cultivation system that transmits sufficient PAR to produce a higher biomass yield. However, low disperse irradiance level results in higher photosynthetic efficiency of plants and microorganisms when their cells are growing under irradiance level far from saturation. The analysis of solar radiation performed in this paper suggests that 34° latitude is the best option for large-scale microalgal cultivation because of the fact that microalgae requires

Table 8 Annual average of PAR and irradiance

Latitude	H_g	I_g	PAR	Irradiance
	kJ m^{-2} day^{-1}	kJ m^{-2} h^{-1}	μmol m^{-2} s^{-1}	W m^{-2}
9	34,310	627.4	621.9093	397.996
14	35,958	356	656.5131	417.113
19	32,202	329.7	604.1243	373.54
24	28,349	440.41	436.4398	328.85
29	35,628	609.37	557.8364	413.28
34	18,738	204.8	377.8203	217.36

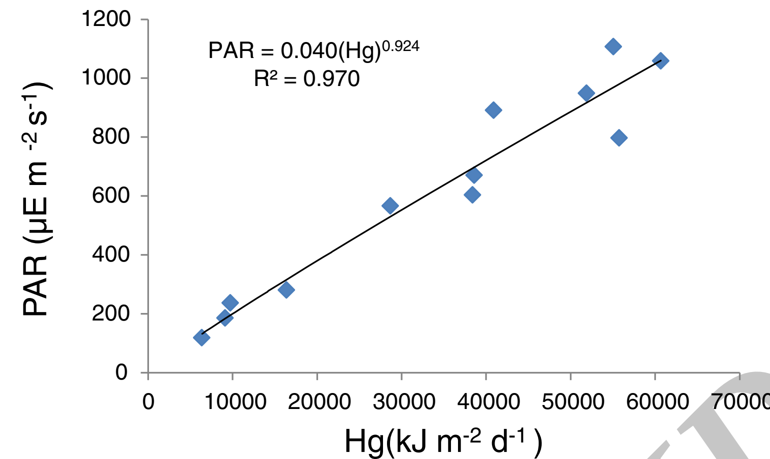

Figure 2 Estimated PAR vs Hg (Φ = 9°).

light intensity below 400 μmol m^{-2} s^{-1} for optimum growth [17].

Regression model

Regression analyses between the PAR and the monthly average of daily global solar radiation are carried out for each latitude. A power regression in the form $y = C(x)^n$ was chosen. The graphs of the PAR against daily average global irradiance are plotted for various locations (Figures 2, 3, 4, 5, 6 and 7). The statistic performance of power regression equation to calculate the PAR for each latitude is shown in Table 9.

The power regression model provides estimates with some degree of correlation between the PAR and Hg. The estimated results are correlated for various latitudes in the following manner: 9° (R^2 = 0.931), 14° (R^2 = 0.829), 19° (R^2 = 0.721), 24° (R^2 = 0.766), 29° (R^2 = 0.830) and 34° (R^2 = 0.768). The power regression analysis between the estimated PAR and the Hg values shows a strong correlation for 9° latitude. A weaker correlation is observed for the rest of the latitudes. On the other hand, the spreading of these differences is higher at higher latitudes. The results for the PAR model suggest that the PAR could be estimated with an average level of confidence using global irradiance as a parameter .This suggests that the PAR values obtained from the analysis present a greater local dependency of climatic conditions and show marked differences. The proposed estimation scheme tries to highlight the necessity of local and seasonal calibration of the PAR/Hg ratio. Nevertheless, considering the differences in climatic conditions, it is possible that some differences exist in the correlation applicable to these different latitudes. This proves that there are marked tendencies to overestimate or underestimate the range of the PAR for other latitudes.

Discussion

PAR must be determined for applications related to microalgae growth, biomass yield, natural lighting and

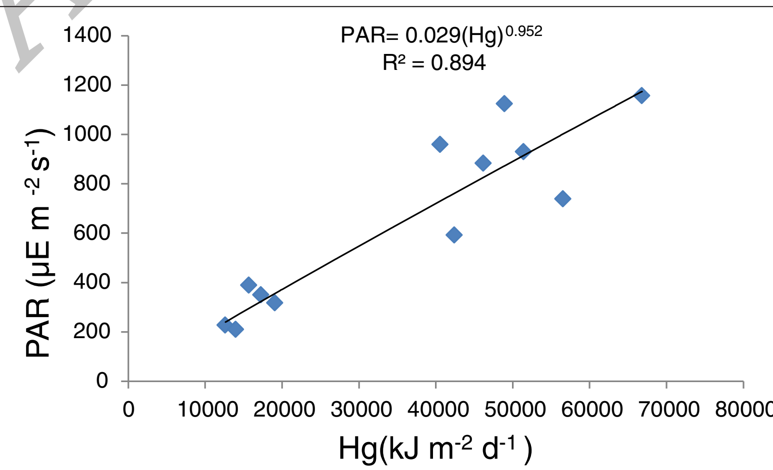

Figure 3 Estimated PAR vs Hg (Φ = 14°).

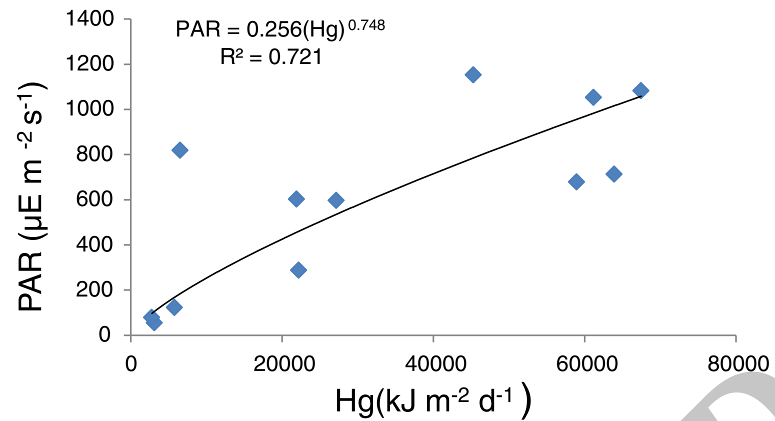

Figure 4 Estimated PAR vs Hg (Φ = 19°).

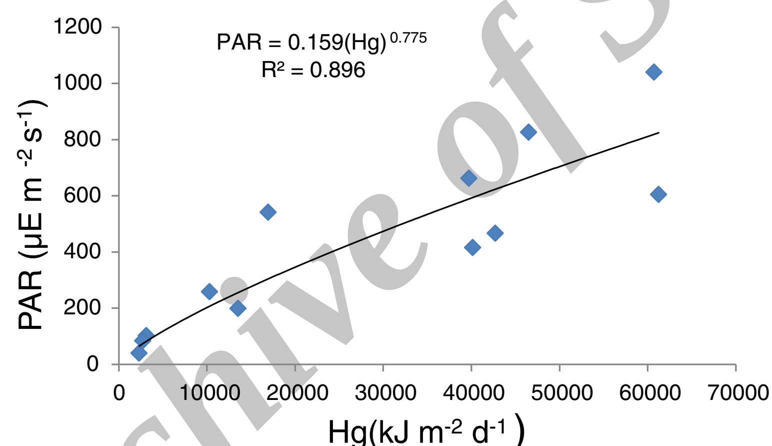

Figure 5 Estimated PAR vs Hg (Φ = 24°).

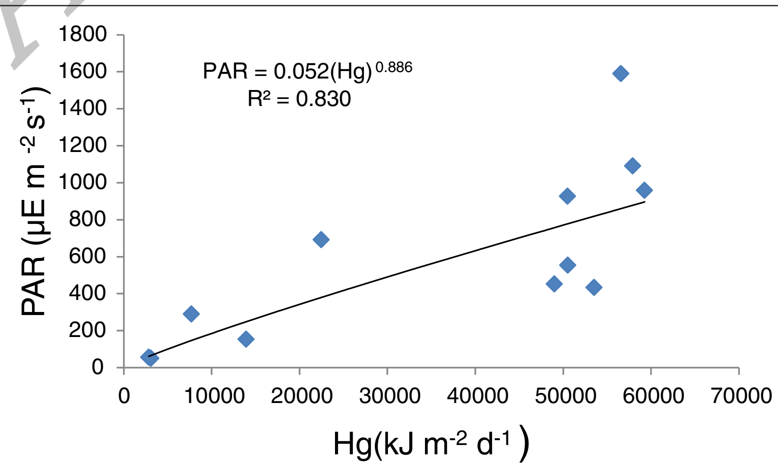

Figure 6 Estimated PAR vs Hg (Φ = 29°).

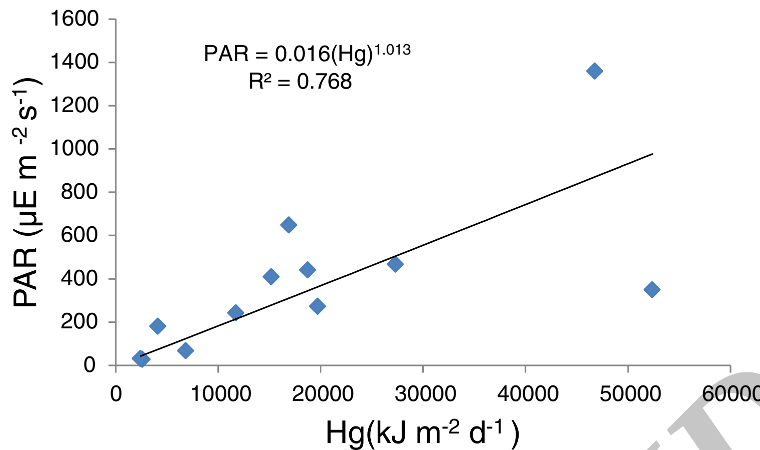

Figure 7 Estimated PAR vs Hg (Φ = 34°).

greenhouse design. The feasibility of microalgal cultivation system at a given location is greatly dependent on the availability of photosynthetically active component of natural sunlight. The models developed for this study were able to estimate PAR for a given day, latitude, surface and atmospheric conditions using MATLAB. This study is done to develop a simpler approach for estimating and validating the PAR . This can be used to provide rough estimates of hourly, daily, monthly and yearly global solar radiation. It is also evident that the annual average PAR can lie between 621 and 377 μmol m^{-2} s^{-1} which is close to established literature values [7–12]. With the relationships among irradiance, the PAR was examined using regression model. The results are used to determine if regression relationships differed significantly. For the 9° latitude data set, it is found that the power regression models provide better estimates. The estimates of PAR obtained through this method could be improved through actual ground measurements. The results of this model can be easily connected to biological process models for plant growth modelling and feasible design of algae cultivation system.

Conclusions

This study is a step towards modelling and estimation of PAR for a geographic location and day of the year. It takes into account the various solar angles, cloudiness, weather conditions and relates them to the global irradiance. The variation in the PAR during the whole year for various latitudes ranging from 9° to 34° geographical locations is quantified. The paper is the first attempt to quantify the PAR for various Indian latitudes; thus, the results can be used to obtain the important PAR values for similar conditions where Hg data are available. The performance of this method to estimate monthly average of hourly and daily global solar radiation is verified and validated with the other literature models. This approach represents a new opportunity to estimate the PAR for any location inside the study area. This could be particularly useful for designing algae cultivation system for optimising the PAR energy utilisation for maximum yield.

Table 9 Power regression equations obtained to estimate the PAR

Latitude (°)	R^2	Regression model
9	0.970	PAR = 0.040 $(Hg)^{0.924}$
14	0.894	PAR = 0.029 $(Hg)^{0.952}$
19	0.721	PAR = 0.256 $(Hg)^{0.748}$
24	0.896	PAR = 0.159 $(Hg)^{0.775}$
29	0.830	PAR = 0.052 $(Hg)^{0.886}$
34	0.768	PAR = 0.016 $(Hg)^{1.013}$

Abbreviations

a,*b*: empirical constants by regression parameters for a particular location, obtained by fitting data; del: declination angle (degrees); Hg: monthly average of daily global radiations on a horizontal surface (kJ m^{-2} day^{-1}); Ig: monthly average of hourly global radiations on a horizontal surface (kJ m^{-2} h^{-1}); I_{sc}: solar constant (W m^{-2}); lat: latitude (degrees); L_{ST}: local solar time (minutes); *N*: day number of the year; PAR: photosynthetically active radiation (μmol m^{-2} s^{-1}); ω_s: solar angle (degrees); ω: solar hour angle (degrees).

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MP gave guidance to KS who carried out the PAR modelling and drafted the manuscript. TS compiled them into a journal format. GS went through the text of the paper and critically checked the correlation for correctness. All authors read and approved the final manuscript.

Authors' information

KS is an assistant professor in the Department of Energy at Maulana National Institute of Technology, Bhopal. His research interests are algae photosynthesis, biofuels, solar thermal and PV, solar energy modelling, climate change and carbon sequestration. MP is an associate professor in Centre for Energy and Environmental Science and Technology at the National Institute of Technology, Tiruchirappalli. Her research interests are energy conservation, carbon sequestration treatment, energy modelling and simulation. TS and GS are M. Tech. scholars at the Energy Centre, Maulana National Institute of Technology, Bhopal.

Acknowledgements
The authors are grateful to the Director of the Maulana National Institute of Technology Bhopal, MP and to the director of the National Institute of Technology Tiruchirappalli, Tamilnadu.

Author details
[1]Energy Centre, Maulana Azad National Institute of Technology Bhopal, Madhya Pradesh 462 051, India. [2]CEESAT, National Institute of Technology Tiruchirappalli, Tamil Nadu 642051, India.

Received: 14 November 2012 Accepted: 8 April 2013
Published: 30 April 2013

References

1. Iqbal, M: An Introduction to Solar Radiation. Academic Press, Toronto (1983)
2. Siddiqui, R, Bajpai, U: Correlation between thicknesses of dust collected on photovoltaic module and difference in efficiencies in composite climate. Int. J. Energy Env. Eng. **3**(26), 1–7 (2013)
3. Sharma, P, Harinarayana, T: Enhancement of energy generation from two layer solar panels. Int. J. Energy Env. Eng. **3**(12), 1–9 (2012)
4. Kandasamy, S, Vellingiri, M, Sengottain, S, Balasundaram, J: Performance correlation for single-basin double-slope solar still. Int. J. Energy Env. Eng. **4**(4), 1–6 (2013)
5. Panchal, H, Shah, PK: Investigation on solar stills having floating plates. Int. J. Energy Env. Eng. **3**(8), 1–5 (2012)
6. Oyedepo, S: Efficient energy utilization as a tool for sustainable development in Nigeria. Int. J. Energy Env. Eng. **3**, 11–22 (2012)
7. Papaioannou, G, Papanikolaou, N, Retails, D: Relationships of photosynthetically active radiation and shortwave irradiance. Theor. Appl. Climatol. **48**, 23–27 (1993)
8. Alados, I, Foyo-Moreno, I, Alados-Arboledas, L: Photosynthetically active radiation: measurements and modelling. Agric. For. Meteorol. **78**, 121–131 (1996)
9. Zhou, Y, Xiang, Y, Luan, L: Climatological estimation of photosynthetically active quantum flux. Acta meteorologica sinica **54**, 447–454 (1996)
10. Nojd, P, Hari, P: Instantaneous PAR estimated using long records of daily temperature and rainfall. Agric. For. Meteorol. **109**, 47–59 (2001). doi:10.1016/S0168-1923(01)00258-1
11. Tsubo, M, Walker, S: A model of radiation interception and use by a maize-bean intercrop canopy. Agric. For. Meteorol. **110**, 203–215 (2002). doi:10.1016/S0168-1923(01)00287-8
12. Jacovides, CP, Timvios, FS, Papaioannou, G, Asimakopoulos, DN, Theofilou, CM: Ratio of PAR to broadband solar radiation measured in Cyprus. Agric. For. Meteorol. **121**, 135–140 (2004). doi:10.1016/j.agrformet.2003.10.001
13. Ritchie, RJ: Modelling photosynthetic photon flux density and maximum potential gross photosynthesis. Photosynthetica **48**, 596–609 (2010)
14. Duffie, JA, Beckman, WA: Solar engineering of thermal processes. Wiley, New York (1980)
15. Liu, BYH, Jordan, RC: The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Sol. Energy **7**, 53–65 (1968)
16. Klein, SA: Calculation of monthly average insolation on titled surfaces. Sol. Energy **19**, 325 (1997)
17. Molina Grima, E, Fernandez, FGA, Camacho, FG, Chisti, Y: Photobioreactors: light regime, mass transfer, and scale up. J. Biotechnol. **70**, 231–247 (1999)

doi:10.1186/2251-6832-4-21
Cite this article as: Sudhakar *et al.*: **Modelling and estimation of photosynthetically active incident radiation based on global irradiance in Indian latitudes.** *International Journal of Energy and Environmental Engineering* 2013 **4**:21.