

Deriving PAR use efficiency of wet season rice from bright sunshine hour data and canopy characteristics

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सार – शुद्ध प्राथमिक उत्पादकता की तुलना में फसल विकास दर मुख्य रूप से विकिरण उपयोग दक्षता (RUE) पर निर्भर है। विकिरण उपयोग दक्षता मापने वाले उपकरणों की कमी को देखते हुए महत्वपूर्ण फसलों की विशेषता का निर्धारण करने के लिए अप्रत्यक्ष दृष्टिकोण विकसित किया जाना चाहिए। इस बात को ध्यान में रखते हुए वैश्विक सौर विकिरण (GSR) का निर्धारण अप्रत्यक्ष दृष्टिकोण के माध्यम से किया गया था और वर्ष 2013-2015 के दौरान विधान चन्द्र कृषि विश्वविद्यालय, पश्चिम बंगाल, भारत के विश्वविद्यालय फार्म में प्रकाश विलुप्त गुणांक प्लस का निर्धारण करने हेतु इस क्षेत्र के चावल की दो लोकप्रिय किस्मों की विकिरण उपयोग दक्षता के लिए क्षेत्र-प्रयोग किया गया था। इसके अलग-अलग भूखंड तैयार किए गए, मुख्य भूखंड में रोपाई के लिए चार तिथियाँ निर्धारित की गईं और चावल की दो किस्मों (V₁: स्वर्ण, V₂: शताब्दी) की रोपाई के लिए छोटे-भूखंड तैयार किए गए। सांख्यिकीय परीक्षणों से पुष्टि होती है कि इस क्षेत्र के लिए वैश्विक सौर विकिरण (GSR) का आकलन करने के लिए एंगस्ट्रॉम समीकरण उपयोगी हो सकता है। सभी डेटा सेट के लिए धरातल पर फसल बायोमास रेखिक रूप से इंटरसेप्टेड फोटोसिंथेटिकली एक्टिविटी रेडिएशन (IPAR) से जुड़ा है। किसी वर्ष विशेष की गणना किए बगैर चावल की स्वर्ण प्रजाति ने शताब्दी प्रजाति की तुलना में विकिरण का अधिक कुशलता से उपयोग किया। विकिरण उपयोग दक्षता (RUE) का औसत मान स्वर्ण और शताब्दी प्रजाति के लिए क्रमशः 2.75 और 2.57 gm MJ⁻¹ IPAR थे।

ABSTRACT. The net primary productivity, *vis-à-vis* crop growth rate is mainly dependent on radiation use efficiency (RUE). Considering the scarcity of instruments to measure RUE, the indirect approaches should be evolved to determine this important crop characteristic. Keeping this point in mind, Global Solar Radiation (GSR) was determined through indirect approach and field experiment was conducted during 2013-2015 at University Farm of Bidhan Chandra Krishi Viswavidyalaya, West Bengal, India to determine the light extinction coefficient plus RUE of two popular rice cultivars of the region. In the split-plot design, four dates of transplanting were allotted as main plot treatment and two rice cultivars (V₁: *Swarna*; V₂: *Satabdi*) were considered as sub-plot treatment. Statistical tests confirmed that Angstrom equation can be useful for estimation of GSR for this region. Above ground crop-biomass was linearly related to Intercepted photosynthetically active radiation (IPAR) for all of the data sets. Irrespective of years, *Swarna* cultivar used the radiation more efficiently than the *Satabdi* cultivar. The mean RUE values were 2.75 and 2.57 gm MJ⁻¹ IPAR for *Swarna* and *Satabdi* cultivars respectively.

Key words – Rice, Photosynthetically active radiation, Solar radiation, Light extinction coefficient, Radiation use efficiency.

1. Introduction

Agricultural productivity is influenced mainly by combination of different inputs like seed, soil, water, management etc. and prevailing weather conditions. Rice (*Oryza sativa*) is the staple food crop in eastern India. India contributes 26 percent in world rice production and ranks just after China, the largest producer of rice.

The total cultivated area of rice in India is 43.4 million ha and the country produced 157.2 million tons of rice in 2014. West Bengal is the top-most rice growing state in India. Normally rice is water loving crop and requires a mean temperature range of 17 to 33 °C. Good rice production is associated with exposure to the light of optimum intensity, quality and duration during different phenological stages of the crop. Duration of reproductive

stage and environmental factors [mainly solar radiation (SR) and temperature] prevailing during the stage govern the grain growth process of rice (Bastidas *et al.*, 2008). Shading due to cloud cover during the reproductive and ripening stage have pronounced negative effect on the number of spikelet and its filling procedure. But all portion of incoming solar radiation is not good for crops. UV-B radiation adversely affects the crop yield by reducing leaf areas and crop heights (Liu *et al.*, 2013).

The researchers from all over the world have to rely on different indirect approaches for estimation of global radiation, *i.e.*, estimation of GSR from other meteorological parameters. It is observed that SR data calculated from sunshine duration achieves highest degree of precision for agricultural and hydrological studies (Trnka *et al.*, 2005; Sahin, 2007). Angstrom (1924), one of the pioneers, proposed a linear statistical formula using Bright Sunshine Hour (BSS) and GSR. This empirical equation is then modified by Prescott (1940) and Page (1961).

Availability of visible portion (0.4 to 0.7 μm wavelength), popularly known as photosynthetically active radiation (PAR), of the spectrum controls the photosynthesis process in green leaf. This portion of the radiation spectrum is extremely important as it serves as the sole energy source for photosynthesis in plant to provide the living organisms food, fibres, etc. Degree of exposure to PAR determines the capacity of plant to produce biomass and its partitioning within the plant consequently determines the crop yield. Thus plant growth and productivity under field conditions are primarily dependent on the potential of the canopy architecture (*i.e.*, how much leaf area index (LAI) is effectively exposed to light) to intercept incoming PAR and to convert it into biomass. The amount of biomass produced per unit of intercepted light is called radiation use efficiency (RUE) and largely determines the growth and biomass in plants. There often exists a relationship between intercepted PAR and biomass. The ability of the canopy to intercept incoming PAR and conversion efficiency of this radiation into biomass determines the plant biomass and its growth.

Hence, the accurate determination and clear understanding of the PAR components are required for many applications specially for different crop simulation models. Due to the non-availability of PAR measurement facilities, this parameter is often calculated indirectly based on its relationship with SR. Monteith (1973) suggested that the PAR can be taken as half of the total SR in the tropics as well in temperate latitude. According to McCree (1966), PAR value reaches its peak (48% of SR) when sky is covered with cloud. As PAR percentage vary according to location, season, sky clearness, sky

brightness and atmospheric depth for the solar beam, relative BSS duration and water vapour pressure, altitude, day length etc. The PAR-SR relationship needs to be calibrated according to the local climatic conditions.

Leaf is the principal photosynthetic functional unit, therefore, its efficiency on the capture and use of solar energy determine the vegetable productivity. The area and arrangement of foliage or canopy architecture, determine the interception of solar radiation by a crop and the distribution of irradiance among individual leaves (Loomis and Connor, 2002).

The efficiency of interception of PAR depends on the leaf area of the plant population as well as on the shape and inclination angle of the leaf or canopy. Reduction in LAI is typically associated with concomitant decrease in IPAR (Kiniry *et al.*, 2004). Values for LAI of rice have been reported as high as 6 to 10. The light extinction coefficient (K) describes the capacity of the canopy of light interception. K value is mainly crop specific but can differ on the basis of cultivated varieties and on the orientation of the leaves, planting pattern and the values may vary from 0.3 to 1.5 (Zarea *et al.*, 2005). K values also changes diurnally with changing sun's azimuth angle. Higher K values determine strong light absorption while reduced K values (more upright leaves) are important for allowing better light penetration into leaf canopies (Kiniry *et al.*, 2001).

Under no stressed conditions (*i.e.*, with adequate water and nutrient supply), cumulative dry matter is linearly related to the amount of solar radiation or PAR intercepted by the crop canopy and the slope of this regression is known as radiation use efficiency (Soltani *et al.*, 2006). According to O'Connell *et al.* (2004), RUE levels vary with plant species, climatic conditions, measuring method and plant characteristics. But, despite these differences, many species sustain very consistent RUE values throughout the duration of the cropping season (Park *et al.*, 2005). Due to the variation in RUE observed in different rice cultivars, they have different growth rates and yields.

Keeping these views in mind, the objectives set for the study are:

- (i) Validating the Angstrom equation for calculation of GSR
- (ii) Estimation of extinction coefficient for popular rice cultivars
- (iii) Study of PAR interception pattern and its use efficiency

2. Materials and method

2.1. Study site

The present study was conducted in the 'C' Block Farm of Bidhan Chandra Krishi Viswavidyalaya, Kalyani (Latitude 22°59'13" N, Longitude 88°27'20" E and altitude 10.8 m above sea level), West Bengal, India. This study area is characterized by tropical sub-humid climate with hot and humid summer followed by wet monsoon. Analysing long term (1960-2015) data shows that May is the hottest month of the year as the mercury touches the 36.0 °C average. January is the coolest month as the cold wind blows from North-Eastern Himalayan range to lower down the mean monthly temperature in the time of 11.0 °C. Average sunshine duration during the month of April is at the highest magnitude (9.00 hrs) followed by March. Whereas, during monsoon months, BSS values are at the lowest level due to cloud cover. Relative humidity levels at morning and noon are at the highest level during monsoon. The mean annual rainfall of this region is 1443.5 mm and the area receives 1046.0 mm rainfall (73% of annual) during monsoon season.

2.2. Experimental design and cultivation management

Field experiment was conducted during wet seasons (popularly known as *Kharif* season in local language). The rice growth period generally started from June and continued up to early November. The experiment was conducted in consecutive three years (2013 to 2015). The experimental design was split plot with three replications. Following local farmers practice, rice varieties were transplanted in the middle of June. The net plot size was 20 m² (5 m × 4 m). The soil moisture of the nursery bed was maintained before the 3 leaf stage and shallow water was kept stagnant after the 3-leaf stage. 21-days old seedlings were transplanted at a spacing 20 cm (row to row) by 15 cm (plant to plant). Main plots and sub-plots were divided by a 1.25 m irrigation channel and 0.75 m bund respectively acting as a buffer. *Swarna* (IET 5656) and *Satabdi* (IET 4786) are the popular and widely used cultivars in this region. They are high yielding inbred variety. The crop duration for *Swarna* variety is around 135 days, whereas, that of *Satabdi* is around 110 days. The recommended dose of fertilizer was applied through urea (46% N), single superphosphate (16% P₂O₅) and muriate of potash (60% K₂O). The full dose of P₂O₅ and K₂O were applied as basal dose. But urea was applied in three splits. Half of the urea was applied before transplanting and the rest was equally divided and applied as top dressing after 21 days after transplanting (DAT) (*i.e.*, maximum tillering stage) and 45 DAT (*i.e.*, panicle initiation stage).

2.3. Sampling and observations

In every year, data collection was started at 20 DAT and continued upto maturity with 15 days interval. In each sampling day, three hills were selected randomly but always a distance was maintained from previously sampled area to avoid edge effects. Six plants from each plot were randomly chosen and tagged for recording observations on growth parameter. The plant height, phenological stages, biomass, yield and yield attributes were recorded throughout the growing period.

2.4. Meteorological data collection

In order to obtain the set of equations necessary for this research, daily maximum and minimum temperature, sunshine hour, relative humidity, rainfall, wind speed, rainy day, pan evaporation and cloud cover were recorded at Kalyani Meteorological Observatory under AICRP on Agrometeorology for the study period. The GSR values (Wm⁻² Sec⁻¹) with a wavelength of 0.3 - 3.0 μm on a horizontal surface were recorded from August, 2013 to December, 2015 using a Pyranometer sensor (Kipp & Zones CMP6 model) mounted at 1.5 m height.

In this study, GSR is calculated from different empirical equations using temperature, BSS, rainfall, cloud cover etc. Angstrom (1924) first proposed the relationship based on linear statistical equation and then modified by Prescott (1940) and Page (1961) to its present form and presented as:

$$H/H_0 = a + b(n/N) \quad (1)$$

where, H = Incoming daily global solar radiation (MJ m⁻² day⁻¹),

H₀ = Daily extra-terrestrial radiation (MJ m⁻² day⁻¹),

a and b = Empirical constants,

n = Bright sunshine hours per day (hr),

N = Astronomical day length (hr).

where, the Astronomical day length N is calculated by the following formula:

$$N = \frac{2}{15} \cos^{-1} [- \tan(\Phi) \times \tan(\delta)] \quad (2)$$

where, Φ = latitude in degree,

δ = Solar declination angle in degree,

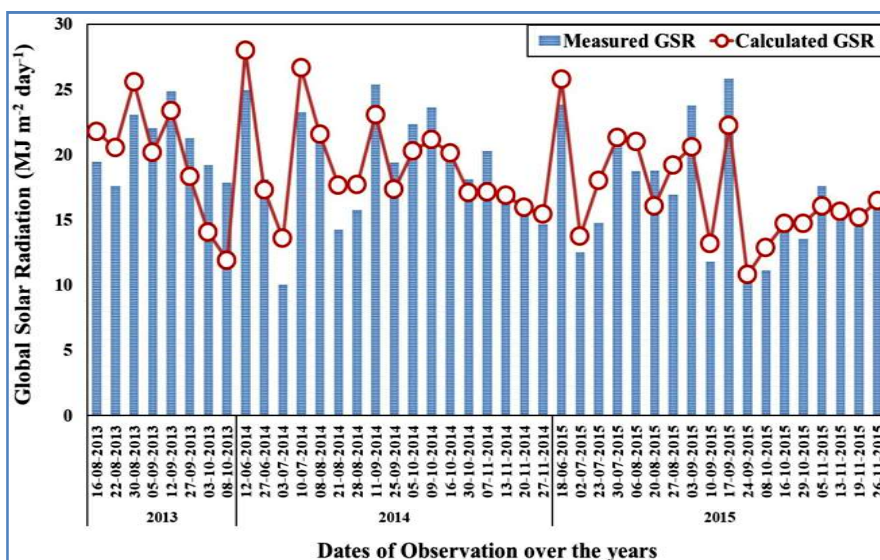


Fig. 1. Comparison between measured and calculated GSR during the wet seasons of three years

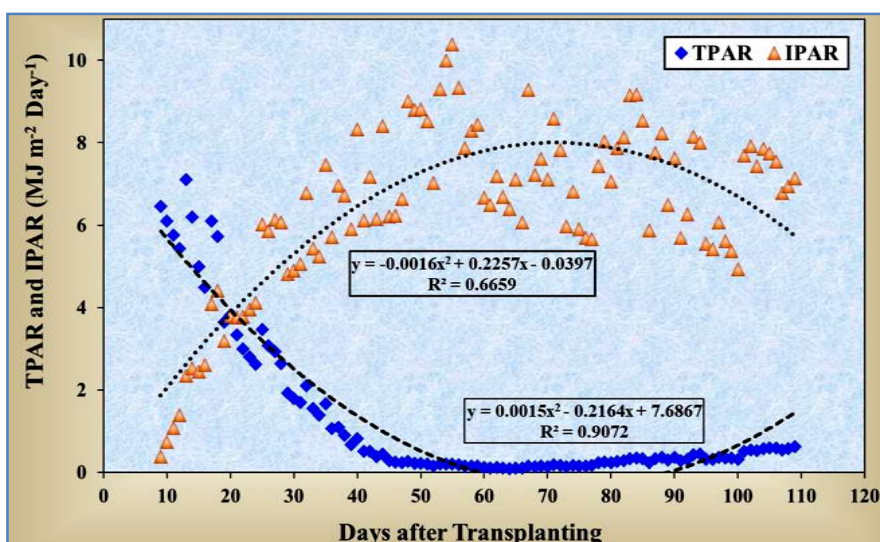


Fig. 2. Comparison between incident and transmitted PAR throughout the growing season of *Swarna* variety under D₁ treatment

In the present study, H_0 ($\text{MJ m}^{-2} \text{ day}^{-1}$) is calculated by using the following equation utilized by Castellvi (2001).

$$H_0 = 37.6[1 + 0.33 \cos(0.0172k)] [\omega \sin(\phi) \sin(\delta) + \sin(\omega) \cos(\phi) \cos(\delta)] \quad (3)$$

Here, k = Julian day and

ω = sunset hour angle in radian which can be calculated by following formula:

$$\omega = \arccos[-\tan(\phi) \tan(\delta)] \quad (4)$$

During the crop growth period, diurnal variation of incident and transmitted PAR were measured at weekly interval starting from 8 am to 4 pm with a gap of one hour. A line quantum sensor was used manually to capture the radiation in and above the canopy. To maintain the parity, PAR along with GSR and R_n are expressed in energy flux ($\text{W m}^{-2} \text{ Sec}^{-1}$). For comparison of different radiation parameters [GSR, net radiation (R_n) and PAR], PAR data was converted into its energy flux using the constant conversion factor of 1.08.

NASA POWER also provides solar radiation data along with other meteorological parameters for $1/2^\circ \times 1/2^\circ$

TABLE 1

Comparison of mean monthly measured and calculated GSR over the study period with statistical testing

Year of experiment		Month-wise variation of GSR (MJ m ⁻² day ⁻¹)						Mean	
		June	July	August	September	October	November		
2013	Measured	-	-	20.0	22.7	18.5	-	20.4	
	Calculated	-	-	22.6	20.6	13.0	-	18.7	
	NASA POWER	-	-	18.6	18.1	10.0	-	15.6	
2014	Measured	21.5	16.6	17.2	22.4	21.1	16.7	19.3	
	Calculated	22.7	20.1	19.0	20.2	19.6	16.3	19.6	
	NASA POWER	15.9	12.7	12.7	17.2	18.1	15.8	15.4	
2015	Measured	23.8	16.4	18.1	18.2	13.0	16.7	17.7	
	Calculated	25.8	17.7	18.8	16.7	14.1	15.8	18.1	
	NASA POWER	18.6	11.1	16.6	12.8	14.0	15.6	14.8	
<i>Statistical tests</i>									
		r	R ²	MBE	MAE	RMSE	MPE	MAPE	NSE
	Calculated	0.83	0.69	-0.12	2.01	2.39	-0.67	11.15	0.68
	NASA POWER	0.77	0.59	-2.18	3.06	3.80	9.57	17.01	0.39

TABLE 2

Stage wise RUE, light extinction coefficient and maximum LAI value achieved under different DOTs of *Swarna* and *Satabdi* variety

Variety	DOT	Maximum LAI value			Light extinction coefficient (K)	RUE (gm MJ ⁻¹)			
		2013	2014	2015		Vegetative	Reproductive	Grain filling	Total / Overall
Swarna	D1	9.7	7.8	9.5	0.448	3.12	2.41	3.43	2.97
	D2	6.6	5.3	9.1	0.490	2.78	2.35	2.88	2.54
	D3	7.1	5.6	8.5	0.418	2.99	2.70	2.97	2.89
	D4	6.2	7.5	7.3	0.422	3.30	2.33	3.95	2.74
	Mean	7.4	6.6	8.6	0.445	3.05	2.44	3.31	2.79
Satabdi	D1	8.3	5.6	7	0.422	2.83	2.13	2.25	2.18
	D2	7.4	6.1	6.7	0.505	2.62	3.14	1.77	2.71
	D3	7.6	4.2	8.4	0.517	2.56	2.34	2.41	2.5
	D4	5.1	5.5	3.5	0.519	2.37	2.97	2.71	2.90
	Mean	7.1	5.4	6.4	0.491	2.60	2.65	2.29	2.57

(i.e., ~55 km × ~55 km) resolution across the world. In the present study the daily global solar irradiance was collected from the NASA POWER website (NASA POWER, 2016) and GSR values collected from NASA POWER was compared with the observed GSR data for the study period. The comparison was done to find out the possibility of using the NASA Power in the study region.

2.5. Calculation of different indices

Based on the measured values of LAI and PAR data (incident PAR above the canopy and incident PAR transmitted through the canopy) amount of light extinction coefficient of the crop was determined using the Beer-Lambert equation (Thornley and France, 2007)

$$I_t/I_0 = e^{-K*LAI} \quad (5)$$

where, I_t = transmitted PAR, I_0 = incident PAR and K = light extinction coefficient.

From this equation, we can calculate Intercepted PAR (IPAR) as:

$$IPAR = I_0(1 - e^{-K*LAI}) \quad (6)$$

Radiation use efficiency was calculated from the slope of the linear regression of cumulative IPAR on cumulative dry biomass obtained from the sequential samplings (Kiniry *et al.*, 2001).

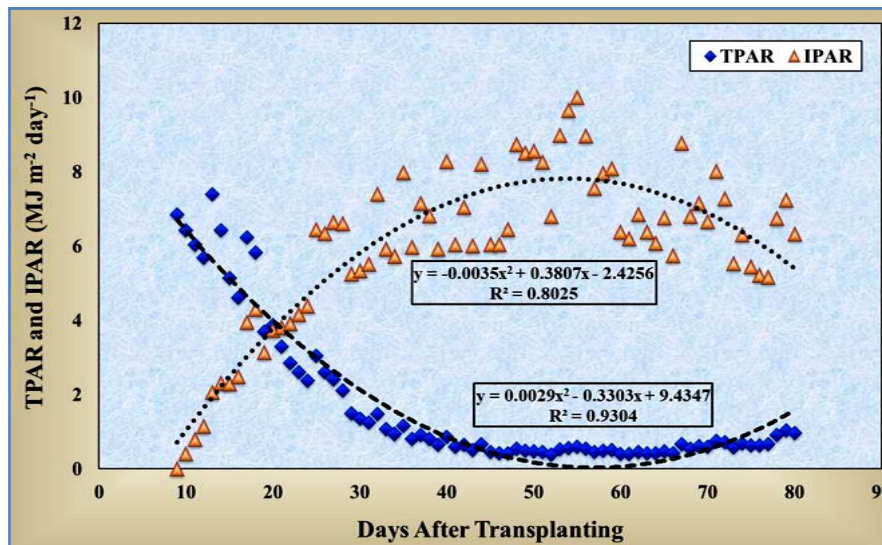


Fig. 3. Comparison between incident and transmitted PAR throughout the growing season of *Satabdi* variety under D₁ treatment

2.6. Statistical analysis

Performance of the Angstrom equation for this region is tested by using some statistical indicators, namely, mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), coefficient of determination (R^2), mean percentage error (MPE), Nash-Sutcliffe efficiency (NSE), etc. These parameters are most commonly used to compare the model output value with the observed value (Sabziparvar *et al.*, 2007; Banerjee *et al.*, 2016). The linearity between observed and calculated values is measured through R^2 whereas the RMSE is the indicator of mean absolute deviation between them. The values of MBE represent the systematic error or bias. A positive value of MBE shows an over-estimation while a negative value represents under-estimation by the equation. Accuracy of calculated GSR value is some measures to identify how close the prediction or output is with the actual value (*i.e.*, the measured GSR). The accuracy of simulation is characterized by lower RMSE and lower SE. MPE is a test of long term performance of the examined regression equation and its positive and negative value represents similar trends like MBE. For a better model performance, a low value of MPE is desirable and the percentage error between -10% and +10% is considered acceptable (Menges *et al.*, 2006). NSE is a simple measure to determine the model precision by plotting observed values against simulated data in a 1:1 line. Generally, NSE ranges between $-\infty$ and 1.0 and the model is more efficient when NSE is closer to 1. The following statistical tools is used in the present study.

(i) Mean bias error is simply the average of the predicted value minus the average observed value.

$$MBE = \frac{1}{N} \sum_{i=1}^N (f_i - O_i)$$

Here, f_i is the calculated GSR, O_i is the observed GSR and N is the number of observation.

(ii) Mean absolute error is the average of the absolute difference between predicted and observed value.

$$MAE = \frac{1}{N} \sum_{i=1}^N (|f_i - O_i|)$$

(iii) Standard error (SE) is calculated with the help of comparing actual value (O_i) & model output value (f_i). The equation of standard error of the predicted value is as follows:

$$SE = \sqrt{\frac{1}{(N-2)} \sum (O_i - O'_i)^2 - \frac{[\sum (f_i - f'_i)(f_i - f'_i)]^2}{\sum (O_i - O'_i)^2}}$$

(iv) The root mean squared error is simply the root of the MSE value. It is usually best to report the RMSE rather than MSE, because the RMSE is measured in the same units as the data, rather than in squared units.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (f_i - O_i)^2}$$

(v) The mean percentage error can be defined as the percentage deviation of the monthly average daily radiation values estimated by the model used from the measured values.

$$MPE = \frac{1}{N} \sum 100 \times \frac{(O_i - f_i)}{O_i}$$

(vi) Mean absolute percentage error (MAPE)

$$MAPE = \frac{1}{N} \sum 100 \times \left| \frac{(O_i - f_i)}{O_i} \right|$$

(vii) The NSE equation is presented as follows:

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O}_i)^2}$$

3. Results and discussion

3.1. Comparison of measured and estimated GSR

The accuracy of the estimated GSR through Angstrom equation in the study region has been tested by comparing the GSR data measured by pyranometer. The relationship between measured and estimated incoming daily GSR ($MJ\ m^{-2}\ day^{-1}$), received at the horizontal surface, during the wet season of three consecutive years are presented in Fig. 1. Calculation of Bias, MPE, MAPE, SE, RMSE and R^2 values indicates the accuracy of GSR estimation using Angstrom equation. The results have been summarized in Table 1. From the table it has been observed that, irrespective of month, measured mean daily GSR value is slightly higher than the calculated value. Hence, the Angstrom equation under-estimated the GSR values marginally. Negative MPE value indicated the under estimation of calculated GSR and as the value of MPE was within acceptable range (-10% to +10%), the Angstrom equation can be used in the study region for estimation of GSR. High R^2 value (62%), low RMSE and SE indicated that the Angstrom equation can be used safely. Acceptable MPE indicated long term performance of the examined regression equation, whereas low RMSE confirmed the short term performance of Angstrom equation.

Testing of the applicability of NASA POWER in this region revealed that in all the experimental months (except October, 2015), the website underestimated the GSR data by a big margin (Table 1). Statistical parameters such as, low R^2 value (59%) along with high negative MBE and very high MPE indicated that the accuracy level of the above-mentioned website is very poor for this region. Very low values of NSE (0.39) also confirmed the poor fitting of NASA POWER data.

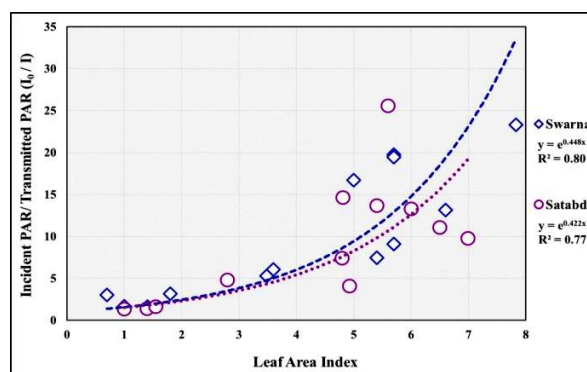


Fig. 4. Estimation of light extinction coefficient of two rice cultivars under 1st date of transplanting

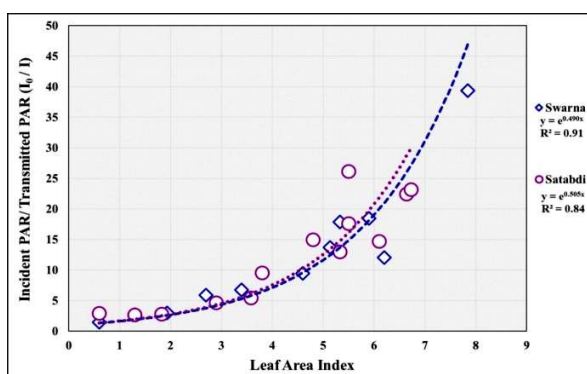


Fig. 5. Estimation of light extinction coefficient of two rice cultivars under 2nd date of transplanting

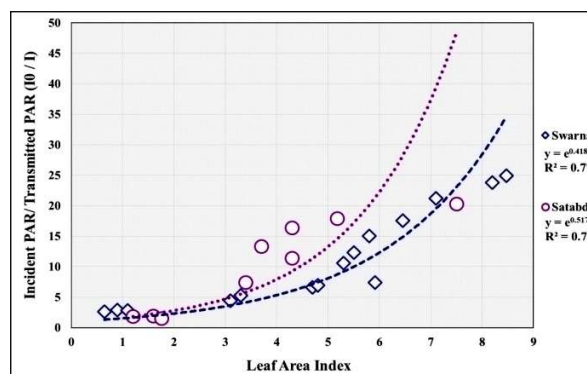


Fig. 6. Estimation of light extinction coefficient of two rice cultivars under 3rd date of transplanting

3.2. Relationship between transmitted and intercepted PAR

At the initial stage, when the LAI was low, the most of the incident PAR was transmitted through crop canopy. Upto 20 DAT, the transmitted portion of PAR (TPAR) was more than incident PAR. With advent of time the IPAR value gradually increased with time upto 70 DAT

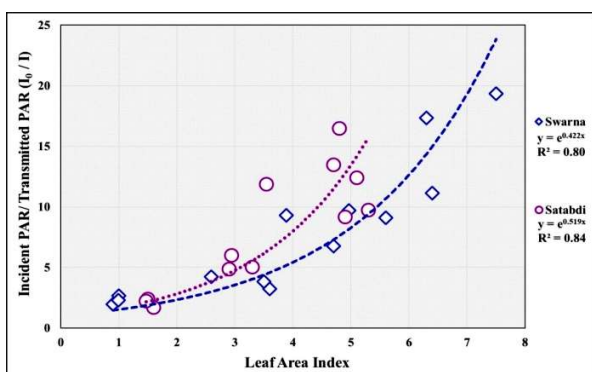


Fig. 7. Estimation of light extinction coefficient of two rice cultivars under 4th date of transplanting

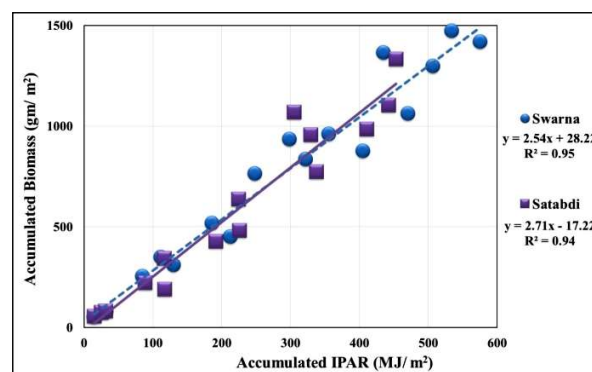


Fig. 9. Regression analysis between accrued biomass and relative cumulated APAR of two rice cultivars under 2nd date of transplanting

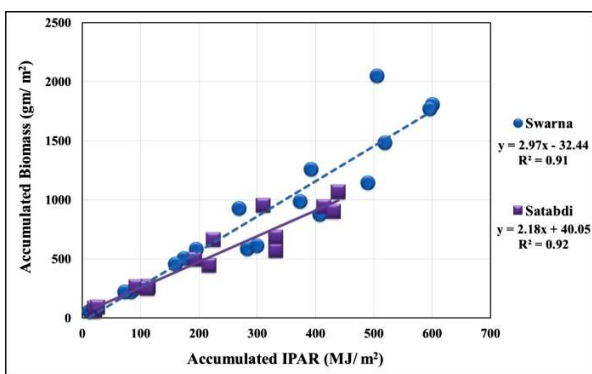


Fig. 8. Regression analysis between accrued biomass and relative cumulated APAR of two rice cultivars under 1st date of transplanting

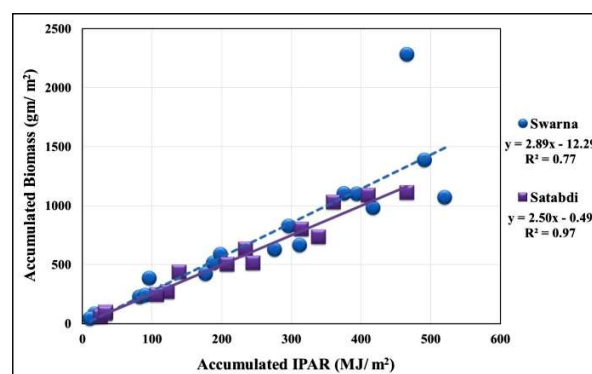


Fig. 10. Regression analysis between accrued biomass and relative cumulated APAR of two rice cultivars under 3rd date of transplanting

for *Swarna* variety (Fig. 2). Afterwards due to gradual drying of leaves, the IPAR decreased slowly, but never became less than TPAR value as observed during initial phase. The variation of IPAR and TPAR followed the similar pattern in case of *Satabdi* variety (Fig. 3). In this case, the peak of IPAR was observed around 55 DAT. The change of values of IPAR and TPAR were well fitted with crop age through second order polynomial equation. The equations for both the varieties were observed significant at 1% level and confirmed the pattern of PAR components change over time.

3.3. Derivation of light extinction coefficient (K)

The LAI values measured throughout the growing period of rice is very much close to reported values in the literature (Ying *et al.*, 1998; Kiniry *et al.*, 2001). On an average, LAI increased upto 80 days after transplanting to reach its peak value and after that a decreasing trend upto maturity was observed. In the year 2014, observed maximum LAI value was 5.7, whereas the same was 7.8 during 2015 for *Swarna* variety. In general, the LAI of *Satabdi* variety was lower than *Swarna* variety (Table 2).

Light extinction coefficient was calculated by plotting LAI against the ratio of incident to transmitted PAR through exponential relation and the power of the equation was taken as K value as per Beer's law [Figs. (4-7)]. Table 2 also represents the K values of different transplanting treatments of both the varieties. Irrespective of dates of transplanting (DOT), highest average K value (0.491) was observed for *Satabdi* variety. Whereas, 1st July transplanted crops exhibits highest mean light extinction coefficient value compare to the other DOT's.

3.4. Radiation use efficiency

The linear relationship between accumulated biomass and accumulated IPAR, for both the varieties under all four DOT's, are graphically presented in Figs. (8-11). Phenological stagewise values of RUE were also estimated and presented in Table 2 along with the overall RUE values. From the Table 2 it can be explained that the *Swarna* variety used the PAR most efficiently than the *Satabdi* cultivar. In case of our study, the highest overall RUE value (2.97 gm MJ^{-1}) was higher than the findings of Kiniry *et al.* (1989), who observed that RUE

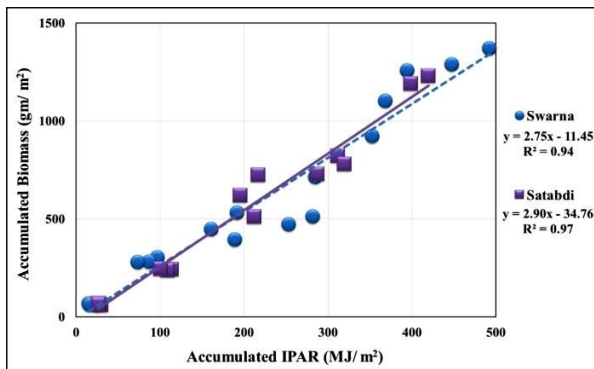


Fig. 11. Regression analysis between accrued biomass and relative cumulated APAR of two rice cultivars under 4th date of transplanting

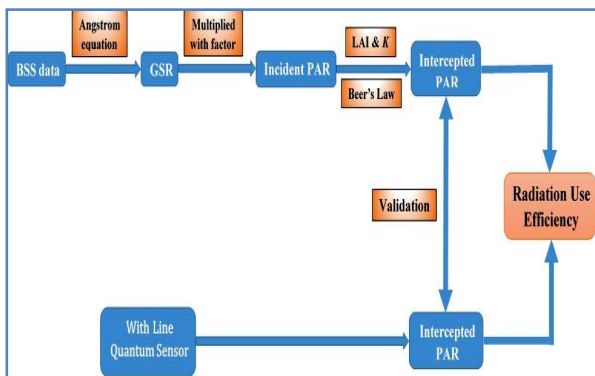


Fig. 12. Suggested protocol for determination of radiation use efficiency

of rice ranged from 2.2 to 2.4 gm MJ⁻¹. A study carried out in Philippines also showed that the RUE value was 2.34 gm MJ⁻¹ (Mitchell *et al.*, 1998). Higher biomass throughout the growing season for all the three years may be the reason for higher RUE. However, Horie *et al.* (1997) calculated the RUE value for rice in Japan and Australia closer to RUE values observed in the present study. From the Table 2, we can also observe that grain filling stage is the most important phase for *Swarna* cultivar. Whereas, vegetative and reproductive stages are more important for production of biomass for *Satabdi* variety.

If one considers the steps of calculation of RUE from the beginning, it can be divided into following steps:

(i) Calculation of GSR from BSS data (the Sunshine Recorder is readily available in Class A Meteorological Observatory, but the Pyranometer is not so widely available).

(ii) Converting GSR data to incident PAR over the crop canopy

(iii) Calculation of Intercepted PAR through Beer's Law using measured LAI and K value (the K value of different crops and varieties is constant and can be collected from secondary source.)

(iv) Calculation of RUE from biomass and Intercepted PAR data.

So, determination of RUE is possible without sophisticated radiation instruments through the given steps (Fig. 12). Such protocol can be used for determining RUE of various crops and will be helpful for forecasting biomass accumulation from BSS data.

4. Conclusions

The Angstrom equation can be used reliably to determine the GSR in the study region. All the statistical indicators pointed out close relationship between estimated and measured values of GSR and it can be concluded the BSS data can be converted to GSR data with reliable accuracy. The PAR interception pattern with advancement of crop growth period has been studied thoroughly. Measurement of PAR interception pattern and LAI at different growth stages throughout growing season can provide average value of light extinction coefficient (K values) for a particular variety and transplanting-treatment. Thus, it is possible to convert BSS data into GSR, GSR data to incident PAR and incident PAR to intercepted PAR with the help of LAI and K values. It will enable scientists and researchers to calculate and monitor the radiation use efficiency without sophisticated PAR sensors.

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