E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(9): 470-473
Received: 09-06-2025
Accepted: 13-07-2025

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Impact of weather dynamics on radiation use efficiency and biomass accumulation in soybean (*Glycine max* [L.] Merrill) across its growth stage

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DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i9g.3801

Abstract
An experiment was conducted during *Kharif* 2024 at the Research Farm of the Department of Agricultural Meteorology, VNMKV, Parbhani to evaluate the influence of different sowing dates and soybean varieties on growth, yield, phenology and radiation use efficiency (RUE) using a line quantum sensor under rainfed conditions. The study was laid out in a split-plot design with four sowing dates (25th SMW to 28th SMW) and three varieties (MAUS-158, MAUS-162, JS-335). Early sowing (D_1) significantly enhanced growth parameters, including plant height (25.06 cm), leaf area index (2.5) and dry matter accumulation (17.29 g plant^{-1}). Grain yield was highest in D_1 (1969.1 kg ha^{-1}) and decreased with delayed sowing. MAUS-158 outperformed other varieties with maximum yield (1608.8 kg ha^{-1}) and superior RUE (2.40 kg Mj^{-1}) and PAR interception were highest under early sowing and in MAUS-158, indicating efficient use of thermal and radiation resources. Reflected PAR was lowest in MAUS-158, indicating efficient radiation absorption. Results highlight that early sowing in the 25th SMW and selecting MAUS-158 optimize growth, yield, and RUE under semi-arid rainfed conditions. This study emphasizes the importance of strategic sowing time and varietal choice for maximizing soybean productivity through improved radiation and thermal resource management.

Keywords: Soybean, *Glycine max*, radiation use efficiency, RUE

Introduction
The growth and development of the soybean (crop) plants largely influenced directly or indirectly by solar radiation. The intercepted radiation on a (plant) leaf consists of diffused radiation and direct beam radiation from source. The plant canopy and venations is play important factor, which can be influence the interception, transmission and absorption of solar radiation for the function of photosynthesis as well as accumulation of dry matter.
The present investigation was carried out with an objective to determined radiation use efficiency in soybean crop in VNMKV Parbhani, Maharashtra, India. The approach to study this aspect was made with use of the equation used to measured radiation intensity with Line quantum sensor.

Materials and Methods
The values of the accumulated solar radiations were recorded by the Line quantum sensor install in soybean crop at the observatory located adjacent to the experimental site.
During photosynthesis, plants use energy in the region of electromagnetic spectrum from 400-700 nm. The radiation in this range, referred to as PAR (Photosynthetically Active Radiation) can be measured in energy units of quanta (photons) per unit time per unit surface area.
Various component of PAR *i.e*, incoming (PARo), intercepted (IPAR), transmitted (TPAR) and reflected (RPAR) were measured with the help of line quantum sensor, which specially averages radiation over its one meter length and thus minimizes the error, was used. It was connected to the (LI-1000) data logger. The sensor was levelled and always held horizontal during measurements. All measurements were made around solar noon between 1130 to 1300 to

eliminate effects of solar elevation (Siva kumar and Virmani,1984). The measurements were made at phenological stages. PARo was measured by keeping the line quantum sensor facing up above the top of the canopy. Where as TPAR was measured by placing line quantum sensor above the ground across the rows. IPAR was calculated using the equation (Gallo and Daughtry, 1986).

IPAR = PARo - TPAR

Total reflected PAR by canopy and soil (RPARc) was measured by inverting the line quantum sensor and holding it above the canopy across the rows. And that reflected by soil (RPARs) was measured by inverting line quantum sensor and holding it 15 cm above the soil across the rows. RPAR by canopy was determined by using equation.

RPAR = RPARc – RPARs

APAR was worked out by adopting the equation,

APAR= (PARo + RPARs) - (TPAR + RPARc) (Gallo and Daughtry,1986).

Radiation Use Efficiency (RUE) is defined as the amount of biomass (dry matter) produced by a plant per unit of intercepted photosynthetically active radiation (IPAR). RUE was determined by following formula as follows given by (Rani *et al*., 2012) [1].

$$\text{Radiation Use Efficiency (RUE) (kg Mj}^{-1}\text{)} = \frac{\text{Biomass (kg/ha) or Yield (kg/ha)}}{\text{Radiation}}$$

The measurement was recorded at 15 days interval after 15 days of sowing, so that proper canopy developments occur. PAR measurement was made three times in a day between 9.00 12.00 15.00 hrs. The instantaneous PAR values recorded by the instrument were in terms of u mol m^{-2} s^{-1}. The daily average values of all these observations were computed and converted into Mj m^{-2} day^{-1} as per relation.

Results and Discussion

Data collected on photosynthetically active radiation (PARo) (µ mol $m^{-2}s^{-1}$) incident at top of the crop at 12.00 hrs in afternoon at various phenophases are presented in Table 1.

Table 1: Photosynthetically active radiation (PARo) (µ mol $m^{-2}s^{-1}$) incident on soybean under sowing times and varieties 2024

Treatment	Incident Radiation (PAR_i) (µ mol m^{-2} s^{-1})							
	2024							
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
Main Plot: Sowing dates								
D_1 (25thSMW)	1470	1465	1440	1481	1398	1340	1361	1422
D_2 (26thSMW)	1455	1498	1480	1403	1437	1380	1406	1450
D_3 (27thSMW)	1499	1537	1472	1481	1471	1415	1444	1489
D_4 (28thSMW)	1391	1432	1429	1389	1379	1325	1355	1399
Sub Plot: Varieties								
(V_1) MAUS-158	1470	1520	1480	1471	1490	1395	1419	1470
(V_2) MAUS-612	1455	1480	1456	1450	1467	1369	1395	1440
(V_3) JS-335	1416	1465	1435	1425	1435	1340	1369	1420
G. Mean	1447	1488	1457	1448	1464	1368	1394	1443

The data reveals that the incident PAR varied slightly across the different sowing dates and growth stages. Sowing on the 27th SMW (D3) received the highest overall incident PAR, particularly during the middle to later growth stages (P_4-P_8), with values consistently above 1400 and a peak of 1499 at P_1. In contrast, the 28th SMW (D4) had the lowest incident PAR, especially in the P_5 to P_8 periods, with values dropping as low as 1325 at P_6. The D_1 and D_2 dates generally fell between these two extremes, showing relatively similar patterns of incident radiation throughout the growth periods.

Among the soybean varieties, the incident PAR values did not show a clear, consistent trend, as they represent the radiation received by all varieties equally. However, the data confirms that all three varieties—MAUS-158 (V_1), MAUS-612 (V_2), and JS-335 (V_3)—were exposed to similar levels of incoming radiation. The small variations seen in the table's "Sub Plot: Varieties" section are likely due to minor differences in the plot's microenvironment rather than a significant distinction between the varieties themselves, as incident PAR is a measure of the available light rather than the plant's light use. This concept was used by the Purcell, L.C. (2011) [15].

Table 2: Reflected radiation photosynthesis active radiation (PAR) (µ mol $m^{-2}s^{-1}$) (soil + canopy) by soybean phenophases under sowing times and varieties (2024)

Treatment	Reflected radiation (PAR) (µ mol m^{-2} s^{-1})							
	2024							
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
Main Plot: Sowing dates								
D_1 (25thSMW)	521	501	471	419	368	377	467	631
D_2 (26thSMW)	506	472	439	410	335	345	432	588
D_3 (27thSMW)	449	488	465	481	410	410	478	622
D_4 (28thSMW)	601	513	498	562	494	483	533	666
Sub Plot: Varieties								
(V_1)MAUS-158	512	488	453	400	328	342	439	607
(V_2)MAUS-612	548	489	467	484	420	418	484	625
(V_3)JS-335	573	503	485	520	457	451	510	648
G. Mean	530	493	469	468	402	404	478	627

The reflected PAR values varied notably across different sowing dates. Sowing on the 28th SMW (D_4) generally showed the highest reflected radiation, particularly in the later growth stages (P_6-P_8), culminating in a peak of 666 at P_8. In contrast, the 26th SMW (D_2) consistently had some of the lowest reflected PAR values, indicating a higher absorption of light by the canopy. For all sowing dates, reflected PAR values were lowest during the middle growth stages (P4-P6) and highest at the beginning (P_1) and end (P), which suggests less canopy cover early on and senescence-related changes later. Among the soybean varieties, JS-335 (V_3) reflected the most PAR, especially from P_4 onwards, peaking at 648 at P8. This suggests that this variety's canopy was less efficient at absorbing light compared to the others. MAUS-612 (V_2) and MAUS-158 (V_1) had similar reflection patterns, with MAUS-612 showing slightly higher values. Overall, MAUS-158 generally had the lowest reflected PAR, particularly in the P_4-P_6 range, suggesting it had the most efficient canopy for absorbing radiation during the key growth period. This concept was used by the Purcell, L.C. (2011) [15].

Table 3: Absorb Photosynthetically active radiation (APAR) (µ mol $m^{-2}s^{-1}$) on soybean under sowing dates and varieties during 2024

Treatment	Absorption PAR (µ mol m^{-2} s^{-1})							
	2024							
	P1	P2	P3	P_4	P_5	P_6	P7	P8
Main Plot: Sowing dates								
D1 (25thSMW)	589	655	630	750	820	665	601	679
D2 (26th-SMW)	512	630	714	785	800	655	588	630
D3 (27thSMW)	600	656	695	730	755	630	575	645
D4 (28thSMW)	623	665	698	690	730	675	600	659
Sub Plot: Varieties								
(V1)MAUS-158	560	820	822	761	815	770	730	648
(V2)MAUS-612	522	794	790	722	790	745	695	600
(V3) JS-335	500	700	736	624	700	721	601	555
G. Mean	527	771	782	702	768	745	690	601

The data shows that the APAR values varied significantly across different sowing dates. Sowing on the 25th SMW (D_1) generally showed higher APAR values compared to the other dates, with a peak of 820 observed at P5. In contrast, the 26th SMW (D_2) and 27th SMW (D_3) had slightly lower overall APAR values, with D_2 peaking at 800 and D_3 at 755, both at P_5. The 28th SMW (D_4) had values that were more consistently in the middle range. Overall, the P_4 and P_5 periods showed the highest APAR for all sowing dates, indicating peak light absorption during those growth stages. Looking at the different soybean varieties, MAUS-158 (V_1) consistently demonstrated the highest APAR values, with a peak of 822 at P_3, making it the most photosynthetically efficient variety among those tested. MAUS-612 (V_2) and JS-335 (V_3) had lower APAR values in comparison, with V_2 peaking at 794 and V_3 at 736. The overall mean values reinforce this finding, showing that MAUS-158 absorbed more radiation on average. This concept was used by the Purcell, L.C. (2011) [15].

Table 4: Transmitted Photosynthetically active radiation (µ mol $m^{-2}s^{-1}$) as influenced by different cultivar on soybean

Treatment	Transmitted PAR (µ mol m^{-2} s^{-1})							
	2024							
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
Main Plot: Sowing dates								
D_1 (25th SMW)	1232	1208	1135	1033	909	945	964	1028
D_2 (26th SMW)	1198	1174	1103	1004	883	919	937	993
D_3 (27th SMW)	1181	1158	1088	990	871	909	924	980
D_4 (28thSMW)	1262	1237	1162	1058	944	977	1003	1098
Sub Plot: Varieties								
(V_1) MAUS-158	1237	1213	1140	1037	923	956	975	1044
(V_2) MAUS-612	1221	1197	1125	1023	901	937	961	1024
(V_3) JS-335	1196	1172	1102	1003	882	918	936	1007
G. Mean	1218	1194	1122	1021	902	937	957	1025

The data shows that the amount of PAR transmitted through the canopy to the ground varied depending on the sowing date. The 26th SMW (D_2) consistently had the lowest transmitted PAR values across most growth stages, with a minimum of 883 at P_5. This suggests that the canopy of the D_2 crop was the most efficient at intercepting and absorbing light. Conversely, the 28th SMW (D_4) had the highest transmitted PAR, indicating less efficient light interception, especially at the beginning and end of the season. For all sowing dates, the lowest transmission values were recorded during the P_5 and P_6 stages, which is expected as the plant canopy would be at its densest, maximizing light absorption. Among the soybean varieties, JS-335 (V_3) transmitted the lowest amount of PAR, with a minimum value of 882 at P_5. This indicates that this variety developed the densest canopy, which was the most effective at absorbing incoming radiation for photosynthesis. The other two varieties, MAUS-612 (V_2) and MAUS-158 (V_1), showed slightly higher transmitted PAR values, with V_1 consistently having the highest transmission among the three. This suggests that the canopy of MAUS-158 was less efficient at intercepting light compared to the other two varieties. This concept was used by the Purcell, L.C. (2011) [15].

Radiation use efficiency (kg ha^{-1} Mj^{-1}) as influenced by different cultivar on soybean

The data on soybean cultivars MAUS-158, MAUS-162 and JS-335 for Phenological stages between emergences to harvesting of soybean of different treatment are presented in the Table 5 Nautiyal *et al.*, (2002) [4]. The concept of the use of radiation use efficiency (RUE) has great potential for the predictions of crop productivity. The incoming solar radiation and PAR are practically easy to measure. The relation between IPAR or solar radiation and dry matter production is useful for the estimation of the dry matter production. This concept was used by the Sinclair *et al.*, (1999) [3].

The relation between IPAR and the accumulated average dry matter production of Four dates of sowing D_1 D_2, D_3 and D_4 are presented in the Table 1 and Fig. 1(a) and 2(b). The radiation use efficiency (RUE) that was greatly impacted by the various planting dates is shown in Table 1 and Fig. 1(a) and 2(b). Overall, D_1 (25th SMW) had the highest radiation use efficiency (RUE) (2.80 kg ha^{-1} Mj^{-1}), followed by D_2 (26th SMW) (2.58 kg ha^{-1} M J^{-1}), D_3 (27th SMW) (2.24 kg ha^{-1} Mj^{-1}) and D_4 (28th SMW) with the lowest seed (RUE) (1.44 kg ha^{-1} Mj^{-1}). In terms of photosynthetically active radiation interception (PAR_I), canopy temperature, yield, and yield components, it was discovered that D_1 (25th SMW) (2.80 kg ha^{-1} Mj^{-1}) produced noteworthy outcomes. Similar results given by K. Anil *et al.*, (2008).

The Radiation use efficiency (RUE) influenced significantly on different varieties. The highest Radiation use efficiency (RUE) was found V_1 (MAUS-158) (2.40 kg ha^{-1} Mj^{-1}) overall all other Varieties V_2 (MAUS-162) (2.22 kg ha^{-1} Mj^{-1}), V_3 (JS-335) (2.21 kg ha^{-1} Mj^{-1}) was almost similar results have been reported by Ali *et al.*, (2009) [5]. The lowest seed (RUE) was seen in V_3 (JS-335) (2.21 kg ha^{-1} Mj^{-1}). It was found that V_1 (MAUS-158) (2.40 kg ha^{-1} Mj^{-1}). gave significant results in photosynthetically active radiation interception (PAR_I), canopy temperature, yield and yield components. Similar results given by K. Anil *et al.*

The dry matter production was also regressed on the corresponding cumulated values of the solar radiation. The results revealed that the V_1 varietie had highest value of RUE as compared to the V_2 and D_3 varieties Zaki *et al.*, (2013) [6]. The RUE value decreased due to delay in sowing. Similar results have been reported by Abdel-Wahab *et al.*, (2016) [7].

Table 5: Total Biological yield Kg ha^{-1} Mean (PARo), (μ mol m^{-2}s^{-1}) incident radiation, Mean RUE (kg ha^{-1} M j^{-1}) of soybean in *kharif* season of different sowing of dates

Sowing Date	Total Biological yield Kg ha^{-1}	Mean (PARo) (μ mol m^{-2}s^{-1}) incident on soybean crop	Mean RUE (kg ha^{-1} M j^{-1})
D_1 (25th SMW)	3915	1422	2.80
D_2 (26th SMW)	3750	1438	2.58
D_3 (27th SMW)	3306	1476	2.24
D_4 (28th SMW)	2002	1387	1.44
Variety	TOTAL Biological yield Kg ha^{-1}	Mean (PARo) (μ mol m^{-2}s^{-1}) incident on soybean crop	Mean RUE kg ha^{-1} M j^{-1}
MAUS-158 (V_1)	3447	1464	2.40
MAUS-612 (V_2)	3190	1439	2.22
JS-335 (V_3)	3092	1412	2.21

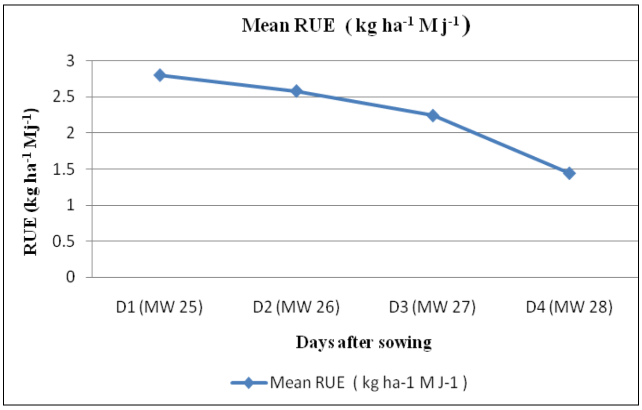

Fig 1 (a): Radiation use efficiency (kg ha^{-1} Mj^{-1}) as influenced by different cultivar on soybean

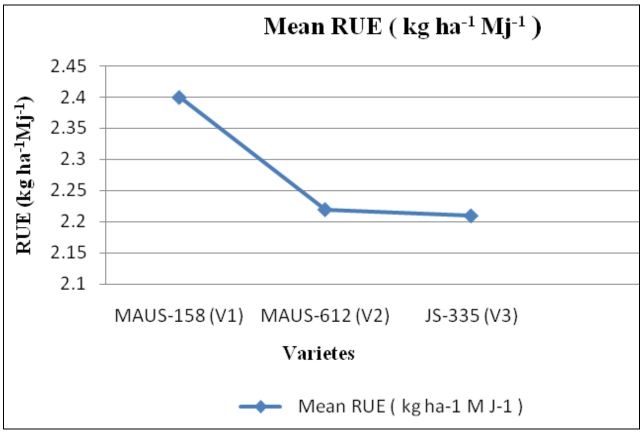

Fig 1 (b): Radiation use efficiency (kg ha^{-1} Mj^{-1}) as influenced by different cultivar on soybean

Conclusion

The RUE conversion efficiency of IPAR and dry matter accumulation remained very narrow range in days of sowing D_1 recorded 2.80 kg h^{-1} MJ^{-1} and V_1 recorded 2.40 kg h^{-1} MJ^{-1} in the case of seed yields, it did not show any consistent trend in the RUE use efficiency with respect of date of sowing and varieties in the soybean.

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