



RESEARCH ARTICLE

Assessment of soybean yield using thermal indices

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Abstract

A field experiment was conducted at all India coordinated research project on soybean, Dharwad in 2022 to assess the performance of soybean cultivars in terms of thermal indices and yield components. Ten soybean cultivars including three checks were evaluated in a randomized block design. Significant genotypic variation was observed in Growing Degree Days (GDD), with DSb 23 and DSb 39 recorded the highest GDD from Flower Initiation (FI) to Physiological Maturity (PM). Phenothermal Index (PTI) showed a consistent slight increase during crop development, with DSb 39 having the highest PTI at maturity. Heat Use Efficiency (HUE) differed significantly among cultivars, with DLSb 5 recording the highest value. DLSb 5 recorded the highest seed yield (31.21 q/ha), followed by DSb 34. Significantly lowest yield (18.83 q/ha) was recorded in DLSb 1, which also showed the lowest HUE. Significant variation in the number of pods per plant was also found, with DLSb 5 recorded the highest number of pods. Yield was positively associated with the number of pods per plant. The findings highlight the potential of DLSb 5 and DSb 34 as promising cultivars under varied thermal environments. These findings highlight key traits that improve soybean yield.

Keywords: growing degree days; heat use efficiency; phenothermal index; soybean; yield

Introduction

Soybean serves as both a pulse and an oilseed crop and is often referred to as the “king of beans” due to its high seed protein (40%) and oil content (20%). In India, soybean is cultivated on an area of 11.44 million hectares with a total production of 12.04 million tonnes and a productivity of 1052 kg ha⁻¹ (1). Major soybean-growing states include Madhya Pradesh, Maharashtra, Rajasthan, Andhra Pradesh, Karnataka and Gujarat. In Karnataka alone, the area under soybean cultivation is 0.43 million ha with a production of 0.44 million tonnes and a productivity of 1055 kg ha⁻¹ (1).

Despite being a stable and economically viable kharif crop, the lower yield potential of soybean remains a major challenge. Yield in soybean is a complex trait, governed by various genetic, biochemical and temperature related factors. Temperature is crucial for the physiological and morphological development of crops, mainly influencing growth duration. Lower temperatures extend the period crops can intercept radiation. The concept of heat units accounts for temperature's effect on crops, recognizing that each development stage requires a specific temperature accumulation. This approach effectively explains seasonal variations in crops and varieties based on their heat unit needs. Winter crops generally require fewer heat units for all physiological

phases compared to summer crops (2). In the current study, various thermal indices for soybean were calculated using experimental data collected during summer season (3). However, the availability of high-yielding, cultivars suited to diverse agro-climatic conditions is still limited. Moreover, uncertain constraints like lower sink demand contribute to significant yield gap and stagnation in realizing the crop's genetic potential.

Temperature is a fundamental environmental factor governing crop growth through its regulation of key physiological and biochemical activities (4). Each crop requires a definite accumulation of thermal units to initiate and complete successive phenological stages, ultimately leading to Physiological maturity (PM) (5). Crop development is primarily controlled by temperatures ranging between the base temperature, below which growth ceases and the optimum temperature, beyond which growth efficiency declines. Consequently, temperature serves as a reliable indicator of crop growth duration and developmental progress (6). Although temperature increases within the optimal range can enhance photosynthesis and crop growth, exceeding this range (25–30 °C) can lead to significant growth inhibition and yield loss. For soybeans, temperatures above 37 °C during the flowering to maturation period can cause substantial reductions in yield (7).

Materials and Methods

A field experiment was conducted at All India Coordinated Research Project on Soybean, Main Agriculture Research Station, University of Agricultural Sciences, Dharwad. The experimental material comprised of 10 soybean cultivars including three checks. Seven soybean cultivars were DSb 38, DSb 39, DSb 40, DLSb 1, DLSb 3, DLSb 4 and DLSb 5. A field experiment was laid out in randomized block design and replicated thrice. Soybean crop was sown at spacing of 30 × 10 cm.

Phenological characters

The phenological characters like Days to Flower Initiation (DFI), Days to 50 % Flowering (DFF) and Days to Physiological Maturity (DPM) were recorded.

Days to flower initiation

The number of days taken from the date of sowing to the date when flower initiation starts in each cultivar was recorded as DFI.

Days to 50 % flowering

The number of days taken from the day of sowing to the day on which 50 % of plants in the plot exhibited flowering was recorded.

Days to physiological maturity

Physiological maturity was recorded as the duration from sowing to the stage when 90 % of the pods were mature and the plants turned yellow.

Thermal indices

Thermal indices viz., GDD, PTI and HUE were recorded.

Growing degree days (°C days)

Growing degree days was calculated at FI, 50 % Flowering (FF) and PM by taking the average of the daily maximum and minimum temperatures compared to a base temperature T_{base} (10 °C) using the following formula (8):

$$GDD = \frac{T_{max} + T_{min}}{2} - T_b \quad (\text{Eqn. 1})$$

Where,

T_b = Base temperature below which crop growth ceases

Phenothermal index (°C day day⁻¹)

Phenothermal index (°C day day⁻¹) is the ratio of GDD to the number of days taken between two phenological stages and is calculated as follows:

$$PTI = \frac{GDD \text{ (day)}}{\text{Number of days taken between the two phenophases}} \quad (\text{Eqn. 2})$$

Heat use efficiency (kg or q ha⁻¹/°C days)

Heat use efficiency is useful for the assessment of yield potential of a treatment in different environment and calculated as follows (9):

$$HUE = \frac{\text{Seed or biomass yield (kg/ha)}}{GDD \text{ (day)}} \quad (\text{Eqn. 3})$$

Results and Discussion

Phenological character

The phenological characters like DFI, DFF and DPM were recorded and presented in Table 1.

Significant differences were observed among cultivars for days to FI. DSb 23 (44.67 days) and DSb 39 (44.33 days) had notably taken more days for FI as compared to other cultivars while, JS 335 (37.33 days) taken less days to FI. The time taken to reach FF varied

Table 1. Mean performance of soybean cultivars for DFI, DFF and DPM

Genotype	DFI (days)	DFF (days)	DPM (days)
DSb 38	42.67 ^{abc}	44.33 ^{abc}	96.35 ^{ef}
DSb 39	44.33 ^{ab}	45.00 ^{ab}	113.08 ^a
DSb 40	42.33 ^{bc}	43.67 ^{abc}	91.94 ^g
DLSb 1	43.33 ^{abc}	45.00 ^{ab}	104.96 ^d
DLSb 3	41.67 ^c	42.00 ^c	92.05 ^g
DLSb 4	42.67 ^{abc}	43.33 ^{bc}	109.05 ^c
DLSb 5	41.33 ^c	42.67 ^{bc}	94.96 ^f
DSb 34 (C)	43.33 ^{abc}	45.00 ^{ab}	96.97 ^e
DSb 23 (C)	44.67 ^a	46.00 ^a	111.00 ^b
JS 335 (C)	37.33 ^d	38.67 ^d	97.98 ^e
Mean	42.37	43.57	100.83
SEm ±	0.71	0.79	0.57
CD (p = 0.05)	2.13	2.36	1.70

DFI: Days to Flower Initiation; DFF: Days to 50 % Flowering and DPM: Days to Physiological Maturity.

significantly among the cultivars (Table 1). DSb 23 took the maximum number of days followed by DSb 39, DLSb 1 and DSb 34, which were all similar with 45 days. JS 335 had the shortest time with 38.67 days. The results showed a significant difference in DPM. DSb 39 and DSb 23 took the maximum time (113.08 days and 111 days, respectively), whereas DSb 40 and DLSb 3 achieved the shortest durations (91.94 days and 92.05 days, respectively).

The significant variation observed among soybean cultivars for DFI, DFF, DPM clearly indicates differential genetic responses to prevailing thermal conditions. In the present experiment, DSb 23 required the maximum number of DFI and DFF, indicating a longer vegetative phase. This prolonged vegetative duration possibly allowed greater biomass accumulation but delayed the transition to reproductive growth. In contrast, JS 335 flowered earliest and attained FF in fewer days, suggesting rapid phenological development and early utilisation of available thermal resources. The results of the present study are consistent with the previous studies (10, 11). Days to physiological maturity differed significantly among the cultivars, with DSb 39 taking the maximum number of days and DSb 40 taking the least number of days. This difference could be attributed to the genetic makeup of the varieties. Importantly, the duration of the reproductive phase, rather than flowering time alone, plays a decisive role in determining yield potential. Cultivars with an extended reproductive period allow greater time for pod development and seed filling, thereby improving yield stability. The variation observed in the present study suggests differential partitioning of assimilates among cultivars, as also reported earlier (10, 11).

Thermal indices

Thermal indices considered in this study were GDD, PTI and HUE.

The data on GDD is presented in Table 2 for soybean cultivars, while Fig. 1 is the graphical visualization of these results. Notably, a significant variability in GDD was observed across

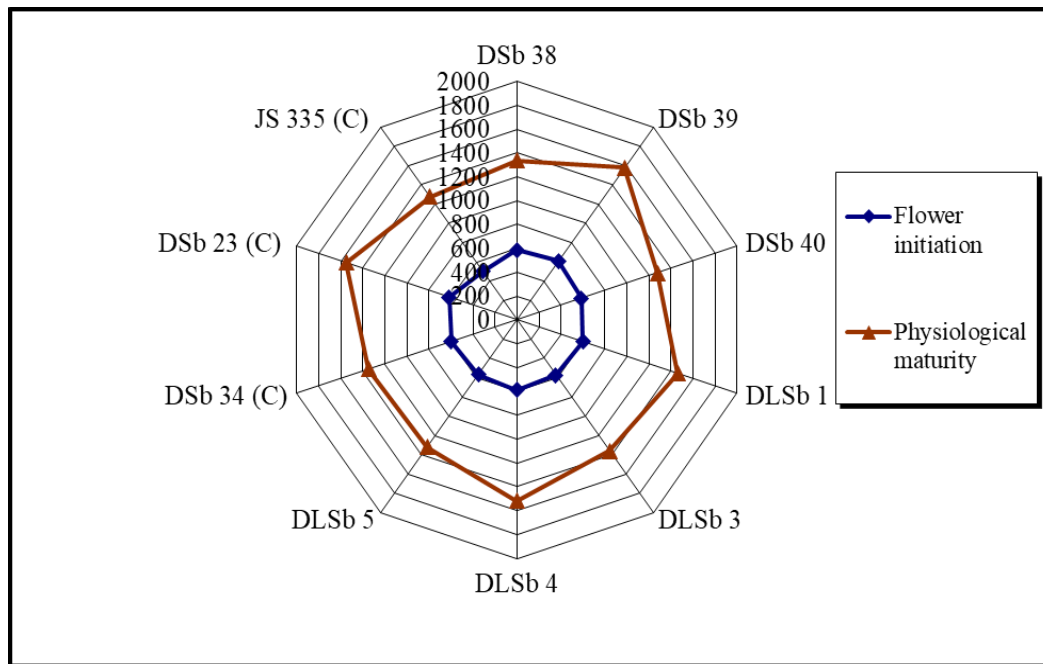


Fig. 1. Mean performance of soybean cultivars for GDD at FI and PM.

Table 2. Mean performance of soybean cultivars GDD at FI, FF, PM

Genotype	GDD (°C days)		
	FI	FF	PM
DSb 38	586 ^{abc}	610 ^{abc}	1336 ^{ef}
DSb 39	612 ^{ab}	621 ^{ab}	1577 ^a
DSb 40	583 ^{bc}	602 ^{abc}	1276 ^g
DLSb 1	598 ^{abc}	621 ^{ab}	1462 ^d
DLSb 3	573 ^c	578 ^c	1361 ^e
DLSb 4	588 ^{abc}	597 ^{bc}	1519 ^c
DLSb 5	568 ^c	588 ^{bc}	1317 ^f
DSb 34 (C)	598 ^{abc}	621 ^{ab}	1345 ^e
DSb 23 (C)	616 ^a	634 ^a	1548 ^b
JS 335 (C)	504 ^d	525 ^d	1276 ^g
Mean	582	599	1401
SEm ±	10.83	11.45	8.39
CD (p = 0.05)	32.17	34.03	24.95

soybean cultivars, from FI to PM. The trend indicated a consistent increase in GDD values as the plants progressed from FI to PM. During the stages of FI and 50% flowering, DSb 23 recorded highest GDD values (616, 634 °C days), which was closely followed by DSb 39. On the other hand, JS 335 recorded the lowest GDD values (504, 525 °C days) during these particular growth stages. During the PM stage, the highest GDD was recorded in DSb 39 (1577 °C days), followed by DSb 23 (1548 °C days). On the other hand, DSb 40 (1276 °C days) and JS 335 (1276 °C days) recorded the lowest GDD values which were on par with each other.

Although the GDD concept assumes a relatively constant thermal requirement for crop development, the present study revealed significant genotypic variation in accumulated GDD for all phenophases. The variation in GDD required to reach first flowering, FF and PM indicates differences in thermal efficiency among cultivars. DSb 40 and JS 335 required fewer thermal units to reach PM, reflecting faster development per unit of heat received. This efficient utilization of heat resulted in shorter crop duration, making these cultivars more suitable for late sowing or environments with limited growing periods. Conversely, DSb 39 accumulated the highest GDD to reach maturity, suggesting a longer thermal duration and slower developmental rate. This

prolonged exposure to heat units may be advantageous under longer growing seasons but may increase vulnerability to terminal stress under delayed sowing conditions. Thus, the significant variation in GDD among cultivars justifies their differential suitability across sowing windows and agro-climatic conditions. Thus, all varieties that reached PM with fewer thermal units are likely to have

Table 3. Mean performance of soybean cultivars for PTI at FI, FF, PM

Genotype	PTI (°C day day ⁻¹)		
	FI	FF	PM
DSb 38	13.73 ^a	13.77 ^a	13.87 ^b
DSb 39	13.80 ^a	13.80 ^a	13.95 ^a
DSb 40	13.77 ^a	13.79 ^a	13.88 ^b
DLSb 1	13.79 ^a	13.80 ^a	13.93 ^a
DLSb 3	13.75 ^a	13.76 ^a	13.89 ^b
DLSb 4	13.77 ^a	13.78 ^a	13.93 ^a
DLSb 5	13.74 ^a	13.77 ^a	13.87 ^b
DSb 34 (C)	13.79 ^a	13.80 ^a	13.87 ^b
DSb 23 (C)	13.79 ^a	13.80 ^a	13.95 ^a
JS 335 (C)	13.51 ^b	13.59 ^b	13.86 ^b
Mean	13.74	13.76	13.89
SEm ±	0.02	0.02	0.009
CD (p = 0.05)	0.07	0.06	0.02

a shorter crop duration (12–14).

The data on PTI for soybean cultivars are presented in Table 3. Non-significant results were obtained among cultivars from FI to PM. However, the trend showed a slight but consistent increase in PTI values as the plants advanced through these growth stages. During FI and 50% flowering, all cultivars performed similarly, except for JS 335. Among cultivars, DSb 39 recorded the highest PTI value (13.80 °C day day⁻¹), while JS 335 recorded lowest (13.59 °C day day⁻¹) at these particular stages. During the PM stage, the highest PTI was recorded in DSb 39 (13.95 °C day day⁻¹) which was at par with DSb 23 (13.95 °C day day⁻¹).

The PTI gives an idea about the rate of development of the various phenological events with reference to heat units, which will eventually help in evaluating relative performance of different varieties. PTI for soybean was estimated using accumulated GDD

for different phenophases and the number of days required for completing the corresponding phenophase (12–15). However, the accumulated PTI to reach first flower appearance, 50 % flowering and PM varied among the soybean varieties in this study. The total PTI accumulated for attaining first flower ranged from 13.51–13.80 °C day day⁻¹ for FF it ranged from 13.59–13.80 °C day

Table 4. Mean performance of soybean cultivars for HUE at harvest

Genotype	HUE (q ha ⁻¹ /°C days)
	At harvest
DSb 38	1.65 ^c
DSb 39	1.69 ^c
DSb 40	2.17 ^{ab}
DLSb 1	1.29 ^d
DLSb 3	2.25 ^a
DLSb 4	1.56 ^{cd}
DLSb 5	2.37 ^a
DSb 34 (C)	2.18 ^{ab}
DSb 23 (C)	1.73 ^c
JS 335 (C)	1.85 ^{bc}
Mean	1.87
SEm ±	0.12
CD (p = 0.05)	0.36

day⁻¹ and for PM ranged from 13.86–13.95 °C day day⁻¹. Among the soybean cultivars, JS 335 consumed the lowest amount of PTI to reach PM while DSb 23 and DSb 39 consumed the highest. This variation clearly justified the observed differences in phenological duration and maturity behaviour among cultivars.

The data on HUE is displayed in Table 4 for soybean cultivars. There was significant variability in HUE across the studied soybean cultivars at harvest. DLSb 5 exhibited the highest HUE value (2.37 q ha⁻¹/°C days) which was at par with DLSb 3 (2.25 q ha⁻¹/°C days). On the other hand, DLSb 1 displayed the lowest HUE (1.29 q ha⁻¹/°C days) at harvest.

Among different varieties, the HUE varied from 1.29 to 2.37 q ha⁻¹/°C days. The higher HUE recorded in DLSb 5 followed by DLSb 3 and least was recorded in DLSb 1 followed by DLSb 4. The lower HUE of DLSb 1 and DLSb 4 was associated with their lower seed yield. This suggests that the HUE index can be used to assess seed yield in a relative sense. Higher HUE in DLSb 5 and DLSb 3 suggests a more efficient utilization of thermal energy for biomass production and its subsequent partitioning towards seed yield. Cultivars with higher HUE are known to possess better photosynthetic efficiency, longer effective reproductive periods and improved assimilate translocation to developing seeds. Similar observations were reported by earlier researchers (12–15), who demonstrated a strong positive relationship between HUE and seed yield. Conversely, the lower HUE observed in DLSb 1 and DLSb 4 was associated with their comparatively lower seed yield, indicating inefficient utilization of available heat units. This may be attributed to sub optimal phenological synchronisation, reduced photosynthetic activity or shortened seed filling duration, as reported in previous studies (12–15). These findings suggest that cultivars with poor heat utilization capacity fail to translate accumulated GDD into yield advantage. The consistent association between higher HUE and increased seed yield observed in the present study, in agreement with earlier reports (12–15), highlights the usefulness of HUE as a reliable agro-physiological index for evaluating varietal performance and identifying heat-efficient, high-yielding soybean cultivars under varying thermal environments.

Table 5. Mean performance of soybean cultivars for yield components

Genotype	Pods/Plant	Yield (q/ha)
DSb 38	47.07	22.08
DSb 39	47.93	26.69
DSb 40	55.20	27.68
DLSb 1	44.07	18.83
DLSb 3	55.33	28.68
DLSb 4	45.47	23.76
DLSb 5	63.20	31.21
DSb 34 (C)	57.27	29.34
DSb 23 (C)	52.40	26.78
JS 335 (C)	51.67	25.12
Mean	51.96	26.01
SEm ±	3.14	1.68
CD p = (0.05)	9.35	4.99

Performance of soybean cultivars for yield components

The data on seed yield of the soybean cultivars is presented in Table 5. It has shown that the seed yield among the cultivars varied significantly. The highest seed yield was (31.21 q/ha) recorded by DLSb 5 followed by DSb 34 (29.34 q/ha) and the lowest seed yield (18.83 q/ha) was obtained with DLSb 1. The data on number of pods per plant is presented in Table 5, which revealed a variation among soybean cultivars. Cultivar DLSb 5 recorded the highest number of pods per plant (63.20), which was at par (45.47) with DLSb 4. Soybean cultivars recorded significant differences in the number of pods per plant. DLSb 5 recorded highest number of pods per plant which led to significant enhancement in seed yield, followed by DSb 34.

The significant differences in seed yield among soybean cultivars were primarily governed by variation in yield components, particularly the number of pods per plant and seeds per pod. DLSb 5 recorded the highest number of pods per plant, which directly contributed to its superior seed yield. This indicates that enhanced sink capacity through increased pod formation played a major role in yield improvement. DSb 34 also performed well due to a relatively higher number of pods per plant. In contrast, DLSb 1 and DLSb 4 produced significantly fewer pods per plant and seeds per pod, resulting in reduced seed yield. The lower yield in these cultivars can be attributed to limited assimilate partitioning towards reproductive structures. The strong association between pod number, seed number and final yield observed in the present experiment justifies the significant yield differences among cultivars (16, 17). The superior performance of DLSb 5 can be attributed to its higher dry matter production, greater number of pods per plant and more seeds per pod. In contrast, DLSb 1 had the lowest number of pods per plant and seeds per pod, resulting in lower yield. These traits-pods per plant and seeds per pod are known to be positively correlated with seed yield (16–20).

Conclusion

The study demonstrated that soybean cultivars differed significantly in their thermal requirements and yield performance. Early maturing cultivars with lower GDD and PTI were better suited to short growing seasons, while higher HUE was closely associated with superior seed yield. Hence, thermal indices can be effectively used for selecting suitable soybean cultivars for different sowing windows and climatic conditions.

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Authors' contributions

S carried out the field research and prepared the manuscript. S and AVH conceptualized and designed the experiment. S, AVH, KBO and GKN analyzed the data and interpreted the results. S, AVH, KBO and GKN critically revised and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

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