# Quantifying the thermal heat requirement of Brassica in assessing biophysical parameters under semi-arid microenvironments

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ORIGINAL PAPER

# Quantifying the thermal heat requirement of *Brassica* in assessing biophysical parameters under semi-arid microenvironments

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**Abstract** Evaluation of the thermal heat requirement of *Brassica* spp. across agro-ecological regions is required in order to understand the further effects of climate change. Spatio-temporal changes in hydrothermal regimes are likely to affect the physiological growth pattern of the crop, which in turn will affect economic yields and crop quality. Such information is helpful in developing crop simulation models to describe the differential thermal regimes that prevail at different phenophases of the crop. Thus, the current lack of quantitative information on the thermal heat requirement of *Brassica* crops under debranched micro-environments prompted the present study, which set out to examine the response of biophysical parameters [leaf area index (LAI), dry biomass production, seed yield and oil content] to modified microenvironments. Following 2 years of field experiments on Typic Ustocrepts soils under semi-arid climatic conditions, it was concluded that the *Brassica* crop is significantly responsive to microenvironment modification. A highly significant and curvilinear relationship was observed between LAI and dry biomass production with accumulated heat units, with thermal accumulation explaining ≥80% of the variation in LAI and dry biomass production. It was further observed that the economic seed yield and oil content, which are a function of the prevailing weather conditions, were significantly responsive to the heat units accumulated from sowing to 50% physiological maturity. Linear regression analysis showed that growing degree days (GDD) could indicate 60–70% variation in seed yield and oil content, probably because of the significant response to differential thermal microenvironments. The present study illustrates the statistically strong and significant response of biophysical parameters of *Brassica* spp. to microenvironment modification in semi-arid regions of northern India.

**Keywords** Microenvironment · Thermal heat requirement · Biophysical parameter · *Brassica juncea*

## Introduction

Understanding within-canopy microenvironment modification can assist in better understanding of plant characteristics, as well as evaluating the effect of such modification on plant processes and biophysical parameters, and should lead to the ability to predict plant response to the microclimatic conditions associated with different management practices.

The physiological and morphological development of *Brassica* spp., which are long-day plants, is influenced markedly by prevailing thermal conditions. Phenological development in this crop is considered to be altered primarily by photoperiod, with a general shortening of phases as day length increases (Thurling 1974a; King and Kondra 1986; Nanda et al. 1995; Rabbani et al. 1997). Calculation of accumulated heat units, or growing degree days (GDD), is the most common and simple method used to quantify the thermal environment. The GDD-based approach is based on the premise that plants need a defined amount of accumu-

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lated heat to fulfill their requirement for phenological development (Gross 1963; Nanda et al. 1996; Worthington and Hutchinson 2005). Unless this requirement is met, differentiation does not take place.

Within the crop growth period of *Brassica* species, biophysical parameters such as leaf area index (LAI) and dry biomass production were found to be significantly and positively correlated with the accumulation of heat units (Patel and Mehta 1987; Merle et al. 1997; Miller et al. 1998). Therefore, changes in thermal regimes would probably affect the physiological growth pattern of the crop, which in turn will effect the economic yield of the crop. Moreover, changing microenvironments under normal field conditions or as modified by management practices, would ultimately affect the balance between source-sink relationships, heat utilisation efficiency as well as the behaviour of pests and diseases (Hodgson 1978; Chakravarty et al. 2008). Crop microenvironment can be modified through removal of lower branches at the flowering and pod filling stages of *Brassica* development so as to increase the flow of photosynthates to the economically valuable parts of the plant. The better performance of mustard crop under debranching microenvironment can probably be attributed to (1) higher radiation penetration to lower parts of the plant canopy (which otherwise must be compensated at low radiation levels), resulting in higher photosynthetically active radiation (PAR) interception; and (2) improved flow of photosynthates to the remaining branches, which became more productive (Inanga et al. 1979; Khader 1983; Ancha and Morgan 1987).

Under field conditions, crops are often exposed to short-term high temperature stress during different growth stages, resulting in significant yield reduction. For *Brassica*, this reduction may amount to ~15% when plants are severely stressed during bud formation, 58% during flowering and 77% during pod development (Gan et al. 2004). Thus, the response of crops under differential thermal regimes along with microenvironment modification will differ, and hence there is a need to quantify thermal responses in general. There is also a need to evaluate the response of the *Brassica* spp. to determine the extent of variability of the thermal response in terms of the GDD concept. The response of biophysical parameters (LAI, biomass, seed yield and oil content) to the prevailing thermal environment (represented by thermal units, GDD) is normally depicted by a linear or polynomial relationship. This statistical relationship within growth stages may serve as an index for predicting biological or economical yield well in advance (Gilmore and Rogers 1958; Wang 1960; Nield and Seeley 1977; Russelle et al. 1984; Perry et al. 1986; Jefferies and Mackerron 1987; Mathan 1989; Ketring and Wheless 1989). Since such quantitative information on the response of biophysical parameters under semi-arid agroecosystems is lacking, this study set out to quantify these aspects.

## Materials and methods

The present study was carried out on the experimental farm of the Indian Agricultural Research Institute (IARI), New

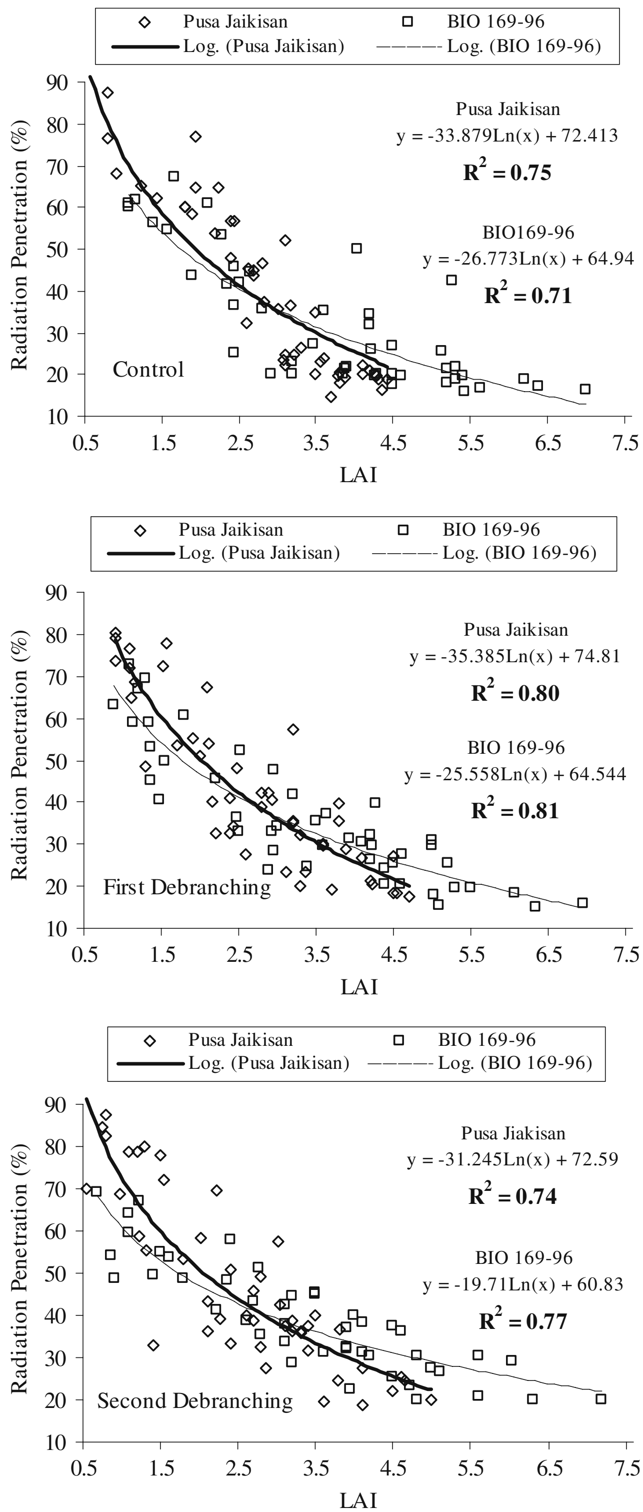


**Fig. 1** Logarithmic relationship of radiation penetration (%) with leaf area index (LAI) within the mustard crop canopy

Delhi (28°35′ N latitude, 77°12′ E longitude and altitude of 228.7 m above mean sea level). The field had a fairly level topography with a 2% slope. The climate is semi-arid, with a dry hot summer and cold winter. May and June are the hottest months, with mean daily maximum temperatures varying from 40 to 46°C, while January is the coldest month with mean daily minimum temperatures ranging from 6 to 8°C. The mean annual rainfall is 710 mm, of which 75% is received during the southwest monsoon from July to September; the rest is received through the 'Western Disturbances' from December to February. Mean daily pan evaporation ranges from 7.1 to 3.5 mm from October to April. The mean wind velocity varies from 3.5 km/h in October to 4.3 km/h in April. The soil of the experimental site belongs to the major group of Indo-Gangetic alluvium with sandy clay loam texture. Taxonomically, the soil is non-acidic mixed hyperthermic Typic Ustocrepts, with a medium-to-weak angular blocky structure, coming under the Holambi Series. The soil is non-calcareous and slightly alkaline in reaction.

Two cultivars of *Brassica juncea* viz., Pusa Jaikisan (most popularly grown in north and north-western parts of the country) and BIO169–96 were grown during two *rabi* seasons (2005–2006 and 2006–2007), following recommended agronomic practices under irrigated conditions. Apart from pre-sowing irrigation, two irrigations of 50 mm each were applied at two critical points, namely the flowering and pod developmental stages. The total amount of rainfall received during the two crop seasons was 26.0 mm (in 3 days) and 18.4 mm (in 6 days), respectively. Although the total amount of rainfall received during the first crop season was marginally higher by 7.6 mm, rain distribution was much more congenial for growth in the second season. The cultivars differed in their phenological behaviour. Pusa Jaikisan is a somaclonal variety—characterised by medium plant height, medium duration (125–135 days), bold seeded,

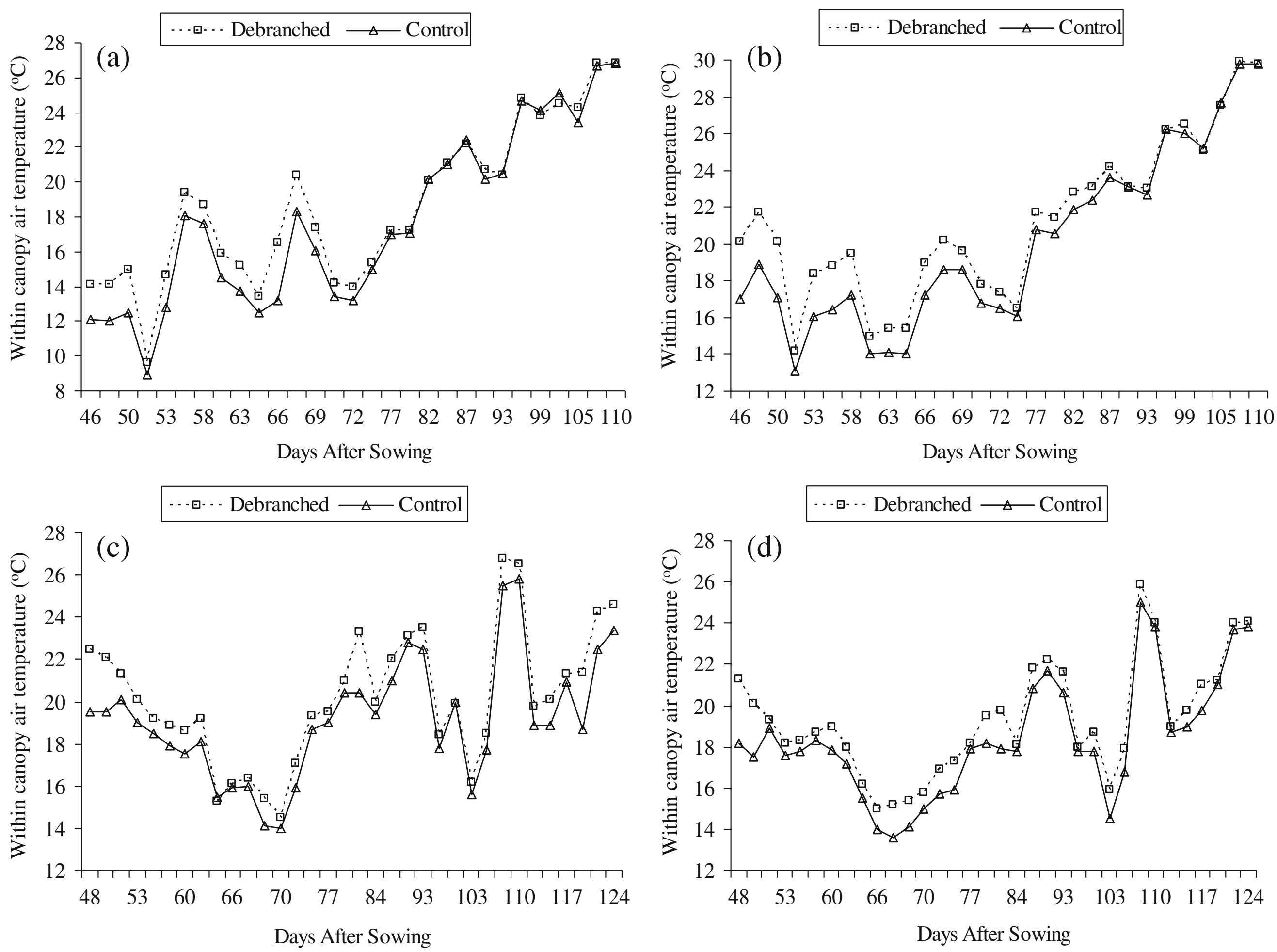


**Fig. 2** Microclimatic trends (air temperature) within the *Brassica* crop canopy. **a**, **b** Within-canopy air temperature at 1130 (**a**) and 1430 (**b**) hours in the first season (2005–2006). **c**, **d** Within-canopy air temperature at 1130 (**c**) and 1430 (**d**) hours in the second season (2006–2007). Standard error for debranched and control plots: 0.69 and 0.87 at 1130 hours and 0.63 and 0.80 at 1430 hours, respectively, in 2005–2006; and 0.28, 0.24 at 1130 hours and 0.22, 0.25 at 1430 hours, respectively, in 2006–2007

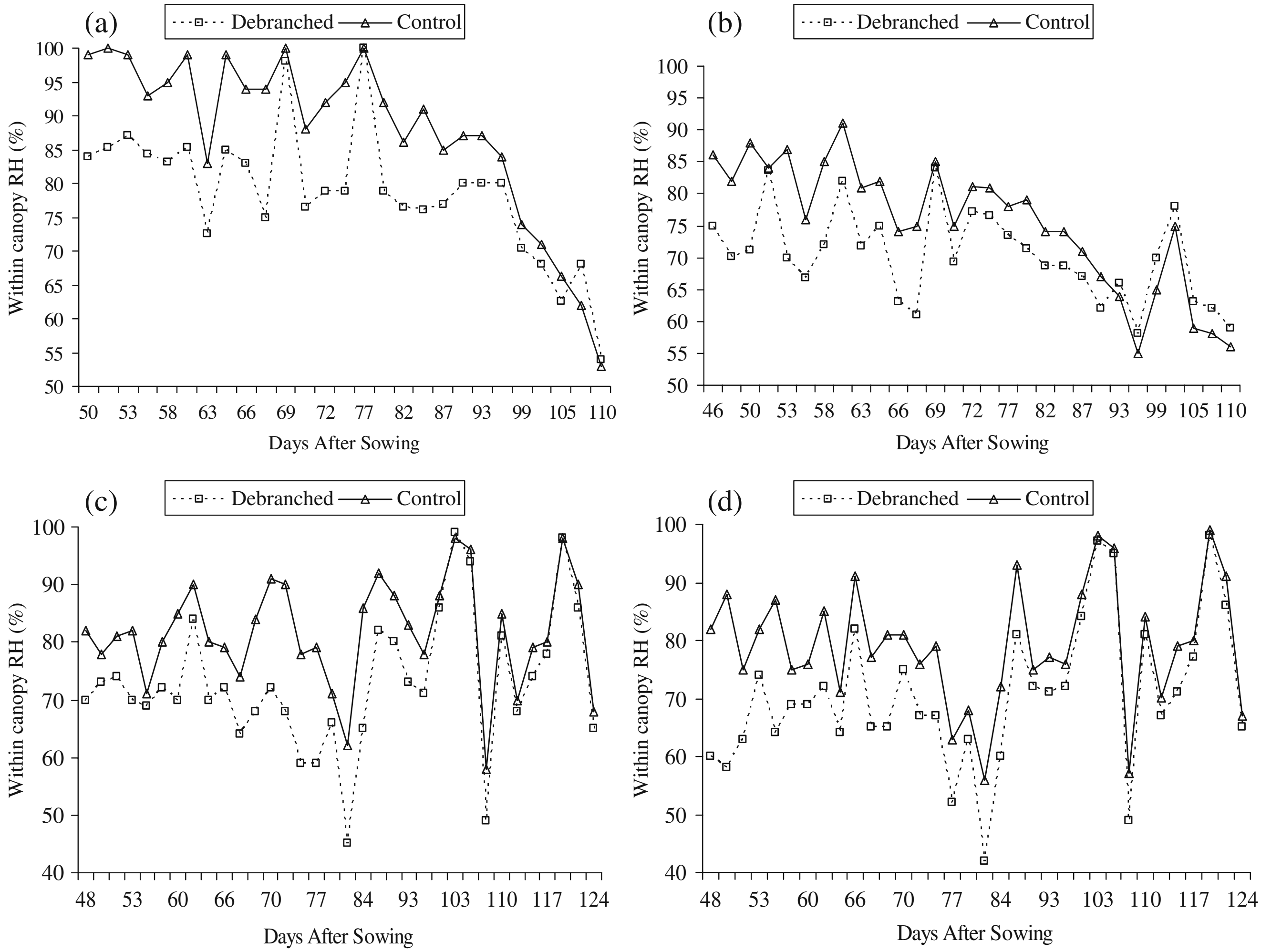


**Fig. 3** Microclimatic trends [relative humidity (RH)] within the *Brassica* crop canopy. **a**, **b** Within-canopy RH at 1130 (**a**) and 1430 (**b**) hours in the first season (2005–2006). **c**, **d** Within-canopy RH at 1130 (**c**) and 1430 (**d**) hours in the second season (2006–2007). Standard error for debranched and control plots: 3.4 and 5.8 at 1130 hours and 1.7 and 3.5 at 1430 hours, respectively, in 2005–2006; and 4.1, 2.6 at 1130 hours and 4.7, 3.3 at 1430 hours, respectively, in 2006–2007

lodging resistant and high yielding with average oil content of 40%—while BIO169-96 is a pipeline variety undergoing multi-location trials characterised as a late maturing cultivar (140–150 days) and high yielding, particularly in terms of LAI, dry biomass and seed yield production.

Both varieties were sown on 15 and 30 October, in keeping with current farming practice prevailing in north and north-western parts of the country, i.e. normal, advanced /delayed by 2 weeks or so due to delay in harvesting of the previous crop. This change in sowing time is expected to cause variations in hydrothermal regimes that would form a basis for a changed microenvironment within the crop canopy. Microenvironment modification was further created by removing three to four lower branches at 40 days after sowing (DAS) (D1: first debranching) and 50 DAS (D2: second debranching) in both the cultivars of plots sown on 15 October, while in plots sown on 30 October, debranching was at 50 DAS and 60 DAS due to lower plant growth. This branch removal coincides with the two important critical stages, i.e. the flowering and pod filling stages. One control plot (D0) was also maintained without removing branches. The experiment was laid out in a randomised block design with three replications in a 5 m×5 m plot. The number of days required to attain different phenological stages such as emergence, beginning of flowering, 50% flowering, 50% podding, maturity and harvesting, were recorded.

Digital thermo-hygro clocks (MEXTECH, model J412CTH) were installed within the debranched and non-debranched plots at different canopy heights (5, 35, 85 and 135 cm). These instruments continuously and simultaneously recorded within-canopy air temperature and relative humidity (RH). Pooled data were analysed and reported on a weekly basis. Radiation penetration was also recorded. Both incoming and outgoing photosynthetically active radiation (PAR) was measured at three heights, viz., top, middle (50% canopy

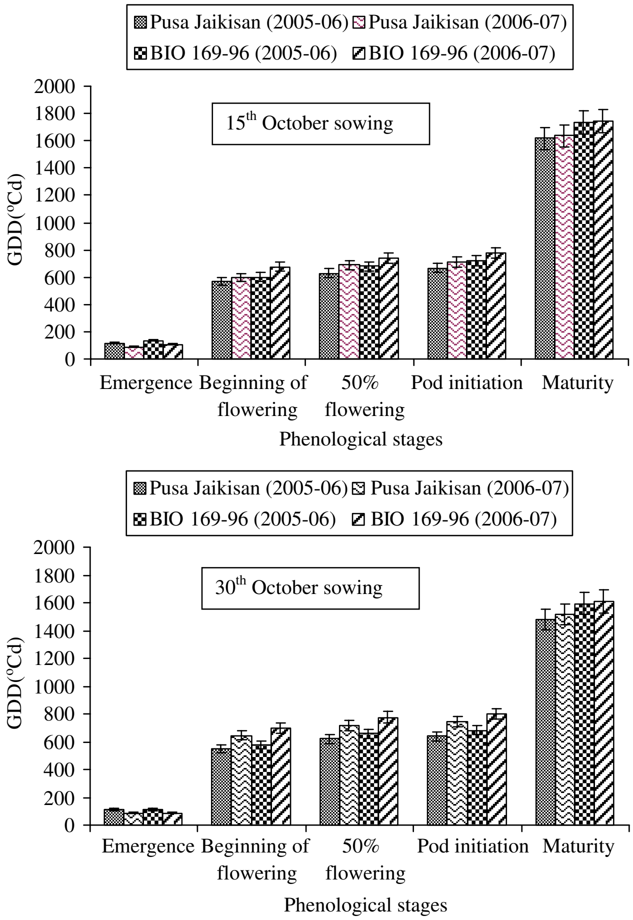


**Fig. 4** Growing degree days (°Cd) accumulation at different phenological stages in *Brassica* varieties

height) and bottom of the crop canopy throughout the growing season using a line quantum sensor (LICOR-3000, Li-Cor, Lincoln, NE). To measure reflected radiation from top, middle and bottom ground, the sensor was held in an inverted position and the radiation penetration was calculated as radiation penetration from top to bottom = [(incoming − outgoing) PAR at bottom *100]/ (incoming PAR at top) and radiation penetration from mid to bottom = [(incoming − outgoing) PAR at bottom*100]/ (incoming PAR at middle). All these measurements were made on a weekly basis on cloud-free days between 1100 and 1300 hours IST at solar zenith angles ranging between 40 and 50° in order to minimise disturbances from the atmosphere, changes in solar angle and elevation, leaf shading and leaf curling. To assess biophysical parameters such as leaf area index (LAI), three randomly selected plant samples (above ground) were taken and the leaf area was measured using a leaf area meter (model LICOR- 3100). LAI was calculated using the formula: LAI = measured leaf area per plant ($cm^2$)/ground area covered by the plant ($cm^2$). Samples collected for estimating LAI were utilised for assessing biomass production. Plant samples were oven-dried at 80°C for 48 h to constant weight in order to estimate

**Table 1** Pooled second order regression equations in assessing leaf area index (LAI) as a function of growing degree days (GDD) in *Brassica* spp.

| | | Sown on 15 October | Sown on 30 October | Pooled for sowing dates |
|---|---|---|---|---|
| Pusa Jaikisan | | | | |
| Pooled for seasons[a] | D0 | $y = -1E-05x^2 + 0.0267x - 12.303 (R^2 = 0.90)$[b] | $y = -3E-06x^2 + 0.0116x - 4.6356 (R^2 = 0.94)$ | $y = -2E-06x^2 + 0.0099x - 4.1583 (R^2 = 0.86)$ |
| | D1 | $y = -7E-06x^2 + 0.0211x - 10.105 (R^2 = 0.91)$ | $y = -2E-06x^2 + 0.0102x - 4.1878 (R^2 = 0.94)$ | $y = -2E-06x^2 + 0.0102x - 4.3049 (R^2 = 0.86)$ |
| | D2 | $y = 1E-06x^2 + 0.0073x - 4.9073 (R^2 = 0.94)$ | $y = 3E-06x^2 + 0.0042x - 2.3009 (R^2 = 0.95)$ | $y = 4E-06x^2 + 0.0014x - 1.3306 (R^2 = 0.87)$ |
| BIO 169-96 | | | | |
| Pooled for seasons | D0 | $y = 5E-06x^2 + 0.0031x - 3.126 (R^2 = 0.96)$ | $y = -8E-06x^2 + 0.0214x - 7.986 (R^2 = 0.96)$ | $y = 1E-06x^2 + 0.007x - 3.2255 (R^2 = 0.90)$ |
| | D1 | $y = 4E-06x^2 + 0.0039x - 3.2715 (R^2 = 0.92)$ | $y = -6E-06x^2 + 0.0193x - 7.5132 (R^2 = 0.93)$ | $y = 8E-07x^2 + 0.0081x - 3.7206 (R^2 = 0.87)$ |
| | D2 | $y = 5E-06x^2 + 0.0024x - 2.7795 (R^2 = 0.95)$ | $y = -7E-06x^2 + 0.0195x - 7.4466 (R^2 = 0.90)$ | $y = 1E-06x^2 + 0.0066x - 3.1196 (R^2 = 0.86)$ |
| Pooled for two sowing dates, two seasons and two varieties | | | | |
| | D0 | $y = -8E-07x^2 + 0.009x - 3.8509$ | | $R^2$=0.80 |
| | D1 | $y = -2E-06x^2 + 0.0117x - 4.9807$ | | $R^2$=0.75 |
| | D2 | $y = 3E-06x^2 + 0.0033x - 1.9643$ | | $R^2$=0.81 |

[a] D0: Control, D1: first debranching, D2: second debranching

[b] Y = LAI; X = GDD

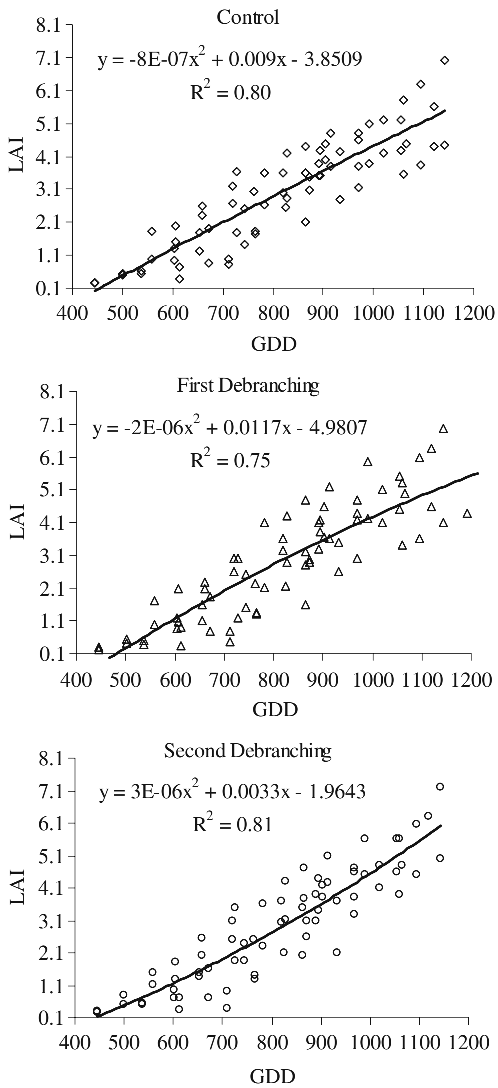


**Fig. 5** Assessing LAI using thermal time in *Brassica* (pooled sowing dates, seasons and varieties)

the accumulation of dry matter in different parts (leaves and stems). All these observations were made on a weekly basis. Plants from areas of 1 $m^2$ each were cut above ground from three randomly selected places in each plot. After sufficient air drying, these samples were weighed. Threshing was done separately and average seed weight was recorded. Oil content (%) of the seeds for each plot was measured using low resolution pulsed H1 NMR ( frequency 20 MHz; model no. PC20, Bruker, http://www.bruker-biospin.com/) in the Nuclear Research Laboratory, IARI, New Delhi. Finally, oil content (%) was determined using the following calibration curves.

1. For 2005–2006: $Y = 1.502 \times X - 0.0767\left(R^2 = 0.99\right)$
2. For 2006–2007: $Y = 1.3156 \times X - 0.0727\ \left(R^2 = 0.99\right)$

Where, Y = oil content (%) and X = signal

Daily weather data of temperature (maximum and minimum), RH (morning and evening), rainfall, wind speed, bright sunshine hours and evaporation rates were recorded for both growing seasons. These data were used to calculate accumulated heat units/GDD $\left({}^{0}D\right) = \left(T_{Max} + T_{Min}\right)/2 - \left(T_{Base}\right)$ Where, $T_{Max}$ and $T_{Min}$ are the maximum and minimum temperatures (°C) of a day and $T_{Base}$ is the base temperature. For *Brassica*, this is taken as 5°C (Morrison et al. 1989). GDD were computed on daily basis and cumulated up to maximum LAI and biomass. To evaluate the responses of biophysical parameters (LAI, biomass, seed yield and oil content) to the prevailing thermal environment, biophysical parameters were analysed statistically and correlated with GDD. The best fit polynomial (curvilinear thermal response curves) second order regression equations were developed relating GDD with LAI, and best-fit third-order sigmoid graphs were developed from which third-order regression equations were drawn between biomass and thermal time. Linear regression equations were developed among seed yield and oil content with GDD. Heat use efficiency, the efficiency of any crop to produce dry matter in terms of accumulated heat unit was also assessed and evaluated using the formula HUE (seed yield/biomass) = seed yield or biomass/ GDD. Statistical analysis, viz. computation of Pearson's correlation coefficients, regression equations, ANOVA, multiple correlation coefficients were carried out using MS Excel and SPSS packages (version 10.0). Graphs were drawn using MS Excel/Power Point software packages.

## Results and discussion

### Weather parameters during the crop growth periods

Although the maximum temperature remained almost constant in the early crop growth stage during both the seasons, it was in the optimum range (for crop growth) of 20–24°C during the pod-filling stage in the second season. The maximum temperature was lower by 0.7 to 7.4°C during the 16th to 22nd week after sowing in the second season as compared to the first season. In contrast, the weekly minimum temperature in the second season was higher in the initial crop growth stages (1–12 weeks after sowing) by about 0.3°C to 7°C as compared to first season, facilitating rapid crop growth. During the pod-filling stage, the minimum temperature was initially high but later decreased.

### Assessment of radiation penetration

Assessing the radiation penetration, it was observed that lower LAI facilitated more radiation penetration at the initial stages of crop growth. With the steady development of LAI, the magnitude of PAR penetration decreased; at later stages of the crop, higher penetration was again

**Table 2** Third order regression equations in assessing biomass as a function of GDD in *Brassica* spp.

| | | Sown on 15 October | Sown on 30 October | Pooled for two sowing dates |
|---|---|---|---|---|
| Pusa Jaikisan | | | | |
| Pooled for two seasons[a] | D0 | $y = -5E - 06x^3 + 0.0165x^2 - 15.254x + 4422.2 (R^2 = 0.96)$[b] | $y = -2E - 06x^3 + 0.0064x^2 - 3.5269x + 461.03 (R^2 = 0.98)$ | $y = -3E - 06x^3 + 0.0098x^2 - 7.7647x + 1928.6 (R^2 = 0.91)$ |
| | D1 | $y = -4E - 06x^3 + 0.016x^2 - 15.875x + 4891.1 (R^2 = 0.96)$ | $y = -4E - 06x^3 + 0.0106x^2 - 7.4135x + 1561.7 (R^2 = 0.98)$ | $y = -4E - 06x^3 + 0.0116x^2 - 9.8025x + 2582.2 (R^2 = 0.92)$ |
| | D2 | $y = -7E - 06x^3 + 0.0231x^2 - 22.578x + 6950.5 (R^2 = 0.93)$ | $y = -5E - 06x^3 + 0.0132x^2 - 9.7852x + 2221.1 (R^2 = 0.98)$ | $y = -4E - 06x^3 + 0.0131x^2 - 11.08x + 2928.5 (R^2 = 0.91)$ |
| BIO 169-96 | | | | |
| Pooled for two seasons | D0 | $y = -4E - 06x^3 + 0.0138x^2 - 11.988x + 3216 (R^2 = 0.95)$ | $y = -4E - 06x^3 + 0.0118x^2 - 8.044x + 1620.1 (R^2 = 0.97)$ | $y = -3E - 06x^3 + 0.0094x^2 - 6.8948x + 1544.2 (R^2 = 0.92)$ |
| | D1 | $y = -4E - 06x^3 + 0.0141x^2 - 12.421x + 3377.7 (R^2 = 0.93)$ | $y = -4E - 06x^3 + 0.01x^2 - 6.5358x + 1228.3 (R^2 = 0.98)$ | $y = -3E - 06x^3 + 0.0091x^2 - 6.5107x + 1393.1 (R^2 = 0.87)$ |
| | D2 | $y = -6E - 06x^3 + 0.0166x^2 - 13.603x + 3407.7 (R^2 = 0.98)$ | $y = -4E - 06x^3 + 0.009x^2 - 4.5525x + 436.62 (R^2 = 0.94)$ | $y = -3E - 06x^3 + 0.0097x^2 - 6.7015x + 1327.8 (R^2 = 0.95)$ |
| Pooled for two sowing dates, two seasons and two varieties | | | | |
| | D0 | $y = -3E - 06x^3 + 0.0096x^2 - 7.3297x + 1736.4$ | | $R^2$=0.91 |
| | D1 | $y = -3E - 06x^3 + 0.0104x^2 - 8.1566x + 1987.7$ | | $R^2$=0.88 |
| | D2 | $y = -4E - 06x^3 + 0.0114x^2 - 8.8907x + 2128.2$ | | $R^2$=0.91 |

[a] D0: Control, D1: first debranching, D2: second debranching

[b] Y = Biomass; X = GDD

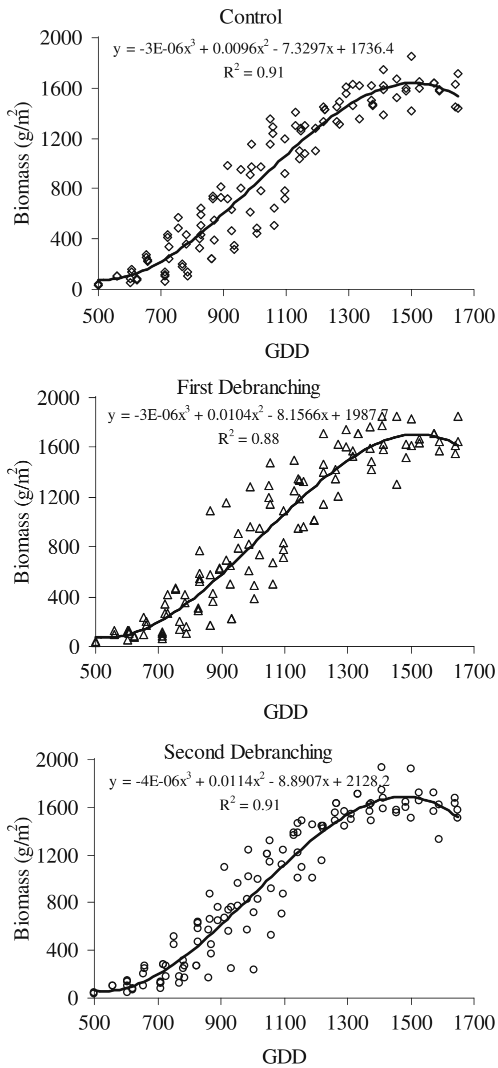


**Fig. 6** Quantifying dry biomass production in *Brassica* through thermal time concepts

observed due to leaf senescence. The magnitude of radiation penetration (%) from middle to the bottom of the crop was higher than that from the top to the bottom of the canopy. Higher radiation interception may have caused lower radiation penetration from top to bottom of the canopy. Furthermore, higher penetration was observed in debranched plots compared to the non-debranched plot. During the first season, radiation penetration from middle to bottom of Pusa Jaikisan varied from 20 to 76%, 30 to 74% and 38 to 88% in control, first and second debranching samples, respectively, in plots sown on 15 October, while the corresponding values for the next season were 18–68%, 17–76% and 18–82%, respectively. Similarly, in the 30 October sowing, radiation penetration from middle to bottom varied from14 to 76%, 20 to 48% and 18 to 54% in control, first and second debranching treatments, respectively, for the first season, while in the second season the corresponding values were 16–76%, 18–80% and 18–78%, respectively. The lower degree of radiation penetration in late-sown crops is due to lower sunshine hours. Analysis of radiation penetration in BIO169-96 revealed that, during the first season, radiation penetration varied from 20 to 67%, 15 to 69% and 20 to 59% in control, first and second debranching, respectively, in the 15 October sowing, while the corresponding values for the next season were 17–60%, 15–64% and 20–69%, respectively. Similarly, in late-sown plants (30th October), radiation penetration varied from 20 to 56%, 25 to 72% and 18 to 50% in control, first and second debranching treatments, respectively, in the first season, with corresponding values of 16–62%, 15–66% and 20–67%, respectively, for the second season. Higher LAI in both sowing dates of the second season coupled with lower sunshine duration reduced radiation penetration from middle to bottom as compared to the first season. Furthermore, a statistically significant logarithmic relationship was revealed when radiation penetration was studied

**Table 3** Pearson's correlation coefficients of LAI and biomass (up to maximum) with GDD

| | | PUSA JAIKISAN | | | | BIO 169-96 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 15th October sowing | | 30th October sowing | | 15th October sowing | | 30th October sowing | |
| | | 2005–2006 | 2006–2007 | 2005–2006 | 2006–2007 | 2005–2006 | 2006–2007 | 2005–2006 | 2006–2007 |
| LAI[a] | D0 | 0.95* | 0.99* | 0.99* | 0.98* | 0.98* | 0.99* | 0.98* | 0.97* |
| | D1 | 0.96* | 0.99* | 0.98* | 0.99* | 0.95* | 0.99* | 0.98* | 0.98* |
| | D2 | 0.97* | 0.98* | 0.99* | 0.99* | 0.97* | 0.99* | 0.97* | 0.97* |
| Biomass (g/m$^2$) | D0 | 0.98* | 0.97* | 0.98* | 0.99* | 0.98* | 0.96* | 0.98* | 0.97* |
| | D1 | 0.99* | 0.96* | 0.98* | 0.99* | 0.97* | 0.95* | 0.95* | 0.97* |
| | D2 | 0.99* | 0.95* | 0.98* | 0.97* | 0.96* | 0.98* | 0.96* | 0.96* |

* Correlation significant at the 0.01 level (2-tailed)

[a] D0: Control, D1: first debranching, D2: second debranching

as a function of LAI. LAI could explain around 70–80% variation in radiation penetration in control and debranched plots with higher magnitude in the debranched plot (Fig. 1). Thus, it can be inferred from the results of this study that the debranched plots were more sensitive to radiation penetration and had the capability to regain its growth pattern within the prevailing thermal environment.

## Assessment of within-canopy air temperature and relative humidity

Assessing the within-canopy air temperature and RH profiles (Figs. 2, 3) revealed that air temperature and RH variations were greater near the ground (within 5 cm canopy height) and decreased with increasing height within the crop canopy (i.e. 35, 85 and 135 cm). In the debranched plot, air temperatures were higher (2–3°C) compared to the control plot at 5 cm within the canopy, decreased at 35 cm and remained almost same with further increase in height at 1130 hours, while at 1430 hours the magnitude of temperature variations was relatively higher. In contrast to air temperature, RH in the debranched plot was less than that in the control plot. At 5 cm height, RH in the control plot was more than 10% higher compared to that in the debranched plot at both 1130 hours and 1430 hours in both seasons. Likewise, at 35 cm, about 10% higher RH variation was observed in the control plot compared to the debranched plot in both seasons. The higher temperature in debranched plots was attributed mainly to removal of the lower three to four branches leading to better radiation penetration as compared to the non-debranched plot. The difference in temperature, particularly near the ground (at 5 cm height) could probably also be attributed to this reason. With the rapid development of leaf area, the per cent radiation penetration decreased within the canopy, which further justifies the lower temperature difference at the higher canopy height.

## Assessing thermal heat requirement at different phenological stages

To determine the effect of thermal time accumulation at various phenological stages, GDD values were cumulated from sowing to different phenological stages in both varieties for both sowing dates and seasons. It was observed that the second-sown crop (30 October) accumulated fewer thermal units compared to the early sown crop (15 October) in both varieties in both seasons. The variety BIO169-96 accumulated a relatively higher degree of GDD as compared to Pusa Jaikisan in both seasons and sowing dates (Fig. 4). This thermal heat accumulation actually indicates the stage-wise heat requirement of the *Brassica* crop and is critically important for prediction of harvest stages as well as planning of planting times (Ramesh and Gopalaswamy 1990; Perry et al. 1993; Roy et al. 2005).

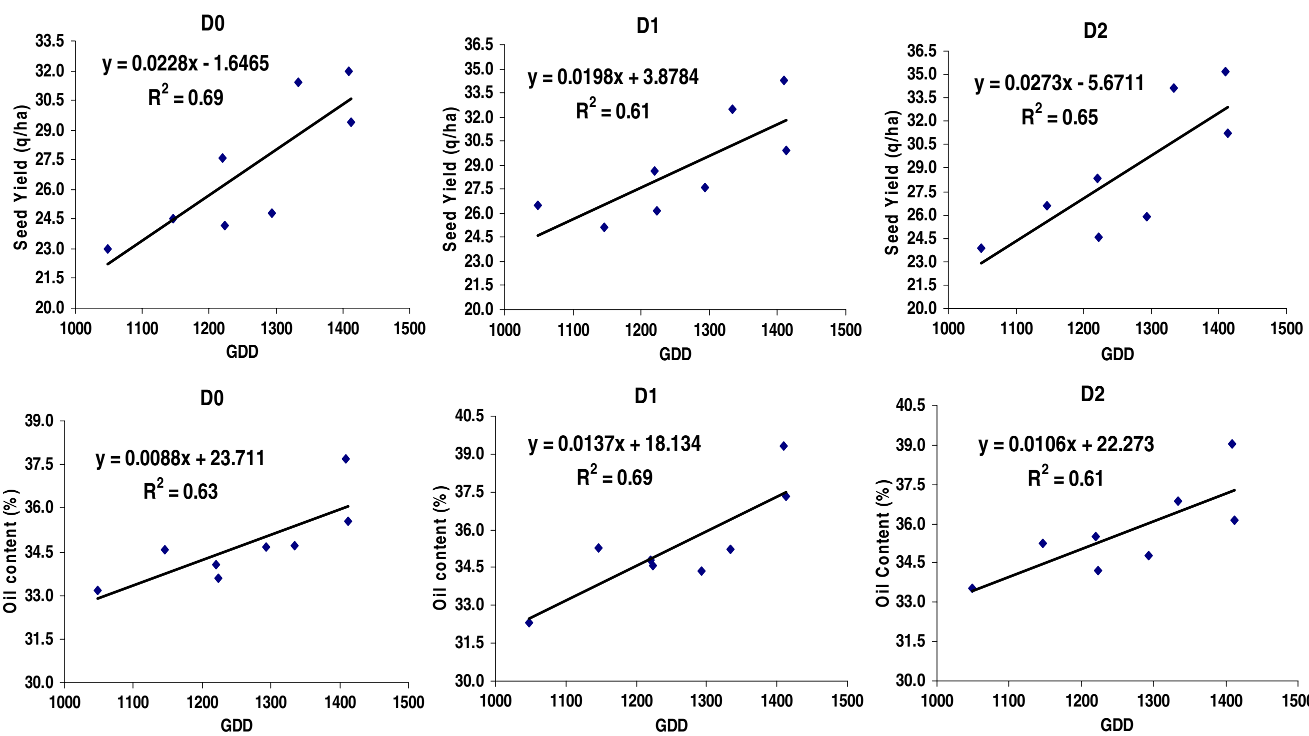


**Fig. 7** Functional relationship (linear analysis) among seed yield and oil content in *Brassica* with thermal time. *D0* Control, *D1* first debranching, *D2* second debranching

**Table 4** Heat use efficiency (HUE; g $m^{-2}$ °$Cd^{-1}$) for biomass in *Brassica* varieties duringfirst and second crop seasons. DAS Days after sowing, SE standard error of individual treatments, Sd standard deviations among all the treatments

| | PUSA JAIKISAN | | | BIO 169-96 | | |
|---|---|---|---|---|---|---|
| DAS[a] | D0 | D1 | D2 | D0 | D1 | D2 |
| First crop season (*rabi*, 2005–2006) | | | | | | |
| 15 October sowing | | | | | | |
| 39 | 0.12 | 0.14 | 0.11 | 0.14 | 0.13 | 0.13 |
| 46 | 0.16 | 0.13 | 0.17 | 0.20 | 0.15 | 0.17 |
| 53 | 0.23 | 0.18 | 0.17 | 0.26 | 0.26 | 0.23 |
| 60 | 0.40 | 0.35 | 0.33 | 0.49 | 0.37 | 0.33 |
| 67 | 0.45 | 0.41 | 0.42 | 0.63 | 0.49 | 0.51 |
| 74 | 0.51 | 0.54 | 0.60 | 0.68 | 0.70 | 0.80 |
| 81 | 0.62 | 0.62 | 0.58 | 0.92 | 0.83 | 0.83 |
| 88 | 0.77 | 0.72 | 0.81 | 0.96 | 0.94 | 0.98 |
| 95 | 0.84 | 0.76 | 0.80 | 1.09 | 0.99 | 1.13 |
| 102 | 0.93 | 0.83 | 0.95 | 1.13 | 1.14 | 1.24 |
| 109 | 1.09 | 0.94 | 0.94 | 1.19 | 1.20 | 1.22 |
| 116 | 1.11 | 1.16 | 1.14 | 1.24 | 1.19 | 1.17 |
| 123 | 1.12 | 1.16 | 1.12 | 1.15 | 1.15 | 1.12 |
| 130 | 1.05 | 1.06 | 1.08 | 1.14 | 1.09 | 1.13 |
| 137 | 0.88 | 0.95 | 0.99 | 0.99 | 0.98 | 1.02 |
| SE | 0.008 | 0.009 | 0.009 | 0.010 | 0.010 | 0.011 |
| Sd | 0.37 | | | | | |
| 30 October sowing | | | | | | |
| 38 | 0.07 | 0.07 | 0.08 | 0.08 | 0.09 | 0.08 |
| 45 | 0.20 | 0.23 | 0.19 | 0.19 | 0.16 | 0.17 |
| 52 | 0.23 | 0.21 | 0.23 | 0.26 | 0.17 | 0.22 |
| 59 | 0.36 | 0.31 | 0.41 | 0.34 | 0.26 | 0.37 |
| 66 | 0.58 | 0.37 | 0.38 | 0.60 | 0.47 | 0.38 |
| 73 | 0.64 | 0.61 | 0.68 | 0.75 | 0.62 | 0.60 |
| 80 | 0.71 | 0.65 | 0.70 | 0.78 | 0.71 | 0.76 |
| 87 | 0.82 | 0.70 | 0.72 | 0.91 | 0.70 | 0.85 |
| 94 | 0.84 | 0.83 | 0.81 | 1.00 | 0.96 | 1.01 |
| 101 | 1.10 | 1.14 | 1.15 | 1.29 | 1.23 | 1.10 |
| 108 | 1.12 | 1.04 | 1.21 | 1.10 | 1.17 | 1.10 |
| 115 | 1.06 | 1.06 | 1.18 | 1.15 | 1.13 | 1.03 |
| 122 | 1.06 | 0.97 | 1.08 | 1.19 | 1.04 | 0.95 |
| 129 | 1.06 | 1.07 | 1.10 | 1.08 | 0.96 | 0.90 |
| 136 | 1.00 | 0.99 | 1.02 | 1.00 | 0.92 | 0.84 |
| SE | 0.009 | 0.009 | 0.010 | 0.010 | 0.010 | 0.009 |
| Sd | 0.37 | | | | | |
| Second crop season (*rabi*, 2006–2007) | | | | | | |
| 15 October sowing | | | | | | |
| 41 | 0.09 | 0.10 | 0.11 | 0.15 | 0.17 | 0.19 |
| 48 | 0.14 | 0.14 | 0.21 | 0.17 | 0.20 | 0.34 |
| 54 | 0.29 | 0.20 | 0.19 | 0.28 | 0.20 | 0.66 |
| 61 | 0.34 | 0.25 | 0.26 | 0.37 | 0.24 | 0.82 |
| 68 | 0.44 | 0.38 | 0.24 | 0.49 | 0.49 | 0.71 |
| 75 | 0.48 | 0.47 | 0.50 | 0.61 | 0.63 | 0.87 |
| 82 | 0.66 | 0.66 | 0.64 | 0.72 | 0.72 | 1.02 |
| 89 | 0.91 | 0.83 | 0.88 | 0.96 | 1.18 | 1.07 |
| 96 | 0.92 | 0.85 | 0.84 | 1.07 | 0.85 | 1.22 |
| 104 | 1.03 | 1.28 | 1.28 | 1.18 | 0.95 | 1.29 |
| 109 | 1.02 | 1.28 | 1.28 | 1.22 | 1.29 | 1.28 |
| 115 | 0.99 | 1.26 | 1.30 | 1.24 | 1.31 | 1.24 |
| 124 | 0.95 | 1.28 | 1.01 | 1.23 | 1.07 | 1.00 |
| 130 | 1.04 | 1.09 | 0.99 | 1.05 | 1.09 | 1.10 |
| 136 | 0.87 | 1.00 | 0.91 | 1.16 | 1.17 | 0.95 |
| SE | 0.008 | 0.014 | 0.012 | 0.011 | 0.012 | 0.007 |
| Sd | 0.40 | | | | | |
| 30 October sowing | | | | | | |
| 41 | 0.09 | 0.09 | 0.08 | 0.14 | 0.17 | 0.21 |
| 46 | 0.42 | 0.15 | 0.15 | 0.29 | 0.31 | 0.36 |
| 53 | 0.47 | 0.37 | 0.24 | 0.38 | 0.37 | 0.57 |
| 60 | 0.55 | 0.53 | 0.40 | 0.39 | 0.32 | 0.85 |
| 67 | 0.52 | 0.63 | 0.56 | 0.62 | 0.63 | 1.06 |
| 74 | 0.86 | 0.66 | 0.77 | 0.87 | 0.83 | 1.26 |
| 81 | 0.79 | 0.76 | 0.74 | 0.96 | 0.96 | 1.26 |
| 89 | 0.98 | 0.97 | 1.02 | 1.25 | 1.09 | 1.30 |
| 94 | 1.17 | 1.08 | 1.08 | 1.24 | 1.17 | 1.34 |
| 100 | 1.15 | 1.11 | 1.23 | 1.26 | 1.32 | 1.29 |
| 109 | 1.16 | 1.14 | 1.18 | 1.24 | 1.39 | 1.27 |
| 115 | 1.20 | 1.24 | 1.21 | 1.24 | 1.36 | 1.26 |
| 121 | 1.10 | 1.16 | 1.14 | 1.35 | 1.18 | 1.27 |
| 128 | 1.04 | 0.89 | 1.08 | 1.27 | 1.15 | 1.07 |
| SE | 0.008 | 0.010 | 0.012 | 0.015 | 0.010 | 0.010 |
| Sd | 0.40 | | | | | |

[a] D0: Control, D1 first debranching, D2: second debranching

## Assessing thermal time as an indicator of LAI

Leaf area index is an important parameter for crop growth studies since it is useful in interpreting the capacity of a crop for producing dry matter in terms of the interception of radiation and amount of photosynthates synthesised. Since the heat requirement of a particular cultivar is correlated linearly within a growth stage, a statistical correlation between GDD and LAI up to its maximum value/peak was developed. Highly significant and best-fit quadratic second-order regression equations were developed between LAI and GDD for each cultivar, considering LAI as a dependent variable with GDD as an independent variable. The pooled regression equations are presented in Table 1. From the pooled thermal response curves, it was observed that GDD could explain <94% variation in LAI in the case of 15-October sown Pusa

**Table 5** Heat use efficiency (kg m$^{-2}$ °Cd$^{-1}$) for seed yield in *Brassica* spp. *SEm* Standard error of mean, *CD* critical difference at 5% level of significance

| Variety | Season | 15 October sowing | | | 30 October sowing | | |
|---|---|---|---|---|---|---|---|
| | | D0[a] | D1 | D2 | D0 | D1 | D2 |
| Pusa Jaikisan | 2005-2006 | 1.71 | 1.77 | 1.75 | 1.55 | 1.79 | 1.61 |
| | 2006-2007 | 1.92 | 2.00 | 2.10 | 1.60 | 1.67 | 1.62 |
| | Mean | 1.82 | 1.89 | 1.93 | 1.58 | 1.73 | 1.62 |
| BIO169-96 | 2005-2006 | 1.70 | 1.71 | 1.80 | 1.54 | 1.67 | 1.57 |
| | 2006-2007 | 1.83 | 1.96 | 2.01 | 1.54 | 1.71 | 1.72 |
| | Mean | 1.77 | 1.83 | 1.90 | 1.54 | 1.69 | 1.64 |
| | | | Pusa Jaikisan | | | BIO169-96 | |
| | | | SEm ± | CD (0.05) | | SEm ± | CD (0.05) |
| Season | | | 0.02 | 0.04 | | 0.02 | 0.04 |
| Treatment | | | 0.02 | 0.04 | | 0.03 | 0.06 |
| Sowing date | | | 0.02 | 0.04 | | 0.02 | 0.04 |
| Season × sowing date | | | 0.03 | 0.06 | | 0.03 | 0.06 |
| Season × treatment | | | 0.03 | 0.06 | | 0.04 | 0.07 |
| Sowing date × treatment | | | 0.03 | 0.06 | | 0.04 | 0.07 |
| Season × sowing date × treatment | | | 0.05 | 0.09 | | 0.05 | 0.11 |

[a] D0: Control, D1: first debranching, D2: second debranching

Jaikisan, and >94% in the 30th October sowing. This is also true for BIO 169–96, wherein >94% variation could be explained. Further pooling the sowing dates and seasons, 83–86% variation may be explained by GDD in different treatments in Pusa Jaikisan, while the corresponding values in BIO169–96 was slightly higher (87–89%). However, using the overall pooled response curves (pooling the seasons, sowing dates and varieties) it was inferred that thermal accumulation could explain variation in LAI by 80, 75 and 81% in control, early debranching and late debranching plots, respectively (Fig. 5).

## Assessing dry biomass production through thermal heat accumulation

The statistical analysis revealed that dry biomass production was correlated significantly with GDD. However, unlike LAI, biomass was best modelled by a sigmoid curve wherein the third order polynomial regression equations were best suited (Table 2). Thus, it was inferred that around 91% variation in biomass was due to differential thermal heat accumulation in both cultivars**.** From the overall pooled effect, around 90% variation in debranched and non-debranched plots that could be well explained by GDD (Fig. 6). Thus, the mathematical relationship indicated that dry biomass increased with increase in accumulated heat units up to around 1400 GDD; thereafter it tended to decline significantly. This result clearly indicated that any further increase in seasonal degree days beyond the above-mentioned value is not desirable for enhancing dry biomass production. The same was also true for seed yield and oil content production.

Pearson's correlation coefficients were determined using SPSS (version 10.0) to evaluate the statistical significance of LAI and biomass with GDD; they were found to be statistically significant at the 1% level (Table 3). The present results assessing biomass production by thermal response are supported by the findings of Nagarajan et al. (1994); Singh et al. (1996); Kar and Chakravarty (1999).

## Functional relationships among seed yield, oil content and thermal time

Although seed yield is a function of soil-crop-climatic factors, under a given set of conditions and in a particular place, seed yield may be assessed/predicted from the heat units accumulated from sowing to 50% physiological maturity. Since it was observed that accumulated thermal heat was significantly related to biomass production up to around 1400 GDD, seed yield and oil content were also correlated up to above said range (incorporating from sowing to 50% maturity). Linear regression relationships were developed among seed yield and oil content with GDD (Fig. 7). It was found that thermal time could indicate 60–70% variation in seed yield and oil content. This highlights the importance of thermal time in quantifying differential thermal microenvironments in determining the strong relationship of variations in yield and oil content in mustard crops under semiarid agroecosystems. Thus, the present study envisages using thermal time in assessing yield as well as oil content of *Brassica* spp. The results of the present investigation underline the need for quantifying the thermal heat requirements of *Brassica* for economic yield assessment and evaluation of the yield gap between potential and actual yields that exists due to differential hydrothermal regime variations within crop growth periods (Thurling 1974b; Richards and Thurling 1978; Mendham et al. 1984, 1990; Neog et al. 2005).

### Assessment of heat use efficiency

The efficiency with which *Brassica* crops produce biomass in terms of accumulated heat units was studied; heat use efficiency (HUE) is tabulated in Table 4. HUE was marginally higher in the debranched plot as compared to the control plot. Furthermore, higher HUE was found in BIO169-96 than in Pusa Jaikisan. HUE ranged from 1.1 to 1.3 g m$^{-2}$ °Cd$^{-1}$ in different treatments in first (15 October) and second (30 October) sown crop in both seasons. HUE was also studied in terms of seed yield (Table 5). The HUE varied from 1.77 to 1.93 kg m$^{-2}$ °Cd$^{-1}$ in the first sown crop, while in the second sown crop the values were 1.54 to 1.73. Therefore, it was concluded that delaying sowing by 2 weeks decreased HUE (seed yield) significantly. This kind of variation was due particularly to the lower GDD accumulation and lower yield with delayed sowing. Again, it was observed that HUE was significantly higher in debranched plot (at 50 DAS) as compared to the control, whereas the debranched plot was statistically at par. The results presented indicate a strong effect of delayed sowing, not only on dry matter or yield production but also on the HUE of the crop. The reduction in HUE with delayed sowing was attributable either to the reduction in dry matter production and partitioning into pods or to a decline in the ability of the plants to initiate enough pods to utilise the carbon assimilates available. Higher HUE in the debranched treatments indicated a strong response of the plants to enhance energy utilisation efficiency by way of higher photosynthate translocation to pods.

## Conclusion

The success or failure of farming, as well as its quantitative and qualitative improvement, are intimately related to the prevailing weather conditions of any agro-ecological region. Since the phenological development of *Brassica* spp. is governed primarily by the environmental conditions of the soil and climate, it is useful to quantify the response of crops under changing thermal regimes under field conditions. Furthermore, microenvironments are continuously changing in the field owing to changes in temperature, rainfall, radiation and humidity patterns, thus the physiological behaviour pattern of *Brassica* crops requires special attention so as to better adapt management practices to avoid any detrimental effect of a sudden rise in temperature, particularly during the reproductive phase, that might cause forced maturity. Therefore, in our study we evaluated the thermal heat requirement of *B. juncea* at each phenological stage, and evaluated its efficiency to quantify/indicate biophysical characters. It was inferred that accumulated thermal heat would explain around 80% of the variation in LAI, 90% of biomass, and 60–70% of seed yield and oil content variation of *B. juncea* under the semi-arid climates of northern India. These results could further form the basis for planning suitable planting, as well as harvesting, time of the crop. Moreover, thermal response patterns may also be incorporated into developing dynamic crop simulation models that aim to understand ever-changing hydrothermal regimes.

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