Vol. 25, No. 1, pp. 108-114 (2025)
Journal of Agricultural Physics
ISSN 0973-032X
https://doi.org/10.56093/JAP.v25i1.11

Research Article

Thermal Response and Heat Use Efficiency of Cotton Genotypes under Various Sowing Environments of Punjab

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ABSTRACT

A study was carried out to examine the thermal response and heat use efficiency of cotton in the hot semi-arid region of south western Punjab, during 2020 and 2021. Four differential sowing environments were created through different sowing dates (April 01, April 20, May 10 and May 30) for two cotton cultivars (non Bt: F 2228 and Bt: RCH 773) in factorial randomized complete block design. Early sown crops accumulated significantly higher growing degree days, helio thermal units, photo thermal units and consequently higher seed cotton yield and heat use efficiency over late sowing environments. Daily meteorological data were recorded to calculate growing degree days (GDD), helio-thermal units (HTU), photothermal units (PTU), phenothermal index (PTI), relative temperature disparity (RTD), and heat use efficiency (HUE). Early sowing (1 April) prolonged crop duration (169.7–173.3 days), enhanced thermal accumulation (GDD: 2438–2482/ °C day; HTU: 17,947–19,544/ °C day hour; PTU: 32,664–33,244/ °C day hour), and resulted in the highest seed cotton yield (2224–2956/ kg/ ha^{-1}) and HUE (0.91–1.20/ kg/ ha^{-1}/ °C day^{-1}). Delayed sowing reduced crop duration, thermal accumulation, yield, and HUE significantly. Among cultivars, F 2228 accumulated higher thermal units, while RCH 773 BGII produced higher yields and superior heat use efficiency, indicating better conversion of thermal energy into economic output. Seed cotton yield showed strong positive associations with GDD (R^2 = 0.72), HTU (R^2 = 0.77), PTU (R^2 = 0.76), PTI (R^2 = 0.62), and RTD (R^2 = 0.60), highlighting the integrated influence of temperature and solar radiation on productivity. Timely sowing coupled with cultivar selection optimized thermal resource use, extended reproductive growth, and maximized cotton yield under semi-arid conditions.

Key words: Cotton, Cultivars, Sowing dates, Seed cotton yield, Thermal units

Introduction

India has emerged as a world leader in cotton production, accounting for nearly one-third of the global cotton area. Around 65% of Indian cotton is rainfed, except in the north-western cotton belt, which comprises the states of Punjab, Haryana, and parts of Rajasthan. In Punjab, cotton is mainly cultivated in the south-western districts, which are characterised by brackish groundwater, less and erratic rainfall, high temperatures at early stages, and changing climatic conditions. High temperatures are a major challenge for sustainable cotton production. The optimum temperature required for cotton growth and development ranges between 28 °C and 37 °C, but in the studied region, the overall average seasonal temperature is higher than the optimum temperature ranges (Rahman *et al.,* 2020). It has a negative impact on morpho-physiological characters and can cause malformation of reproductive organs. Although

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cotton can survive up to 43°C for a shorter period without any significant yield loss. But under heat wave-like conditions for more than a week, crop survival becomes difficult. Sometimes, unusual rainfall, such as heavy rainfall, especially at early stages, leads to problems such as soil crusting, excessive vegetative growth, and an invitation for several insect pests and diseases. These problems lead the farmer's interest towards non-conventional crops, such as paddy, despite crop diversification. Although climatic conditions in south-western Punjab are suitable for cotton production, cotton is grown in areas that are hot and have low to moderate rainfall. To escape from these weather uncertainties, optimum sowing time is a key management decision that determines the rate of several plant processes like phenology, accumulation of assimilates and its conversion into sink structures and finally the economical yield (Bozbek *et al.,* 2006; Ali *et al.,* 2009; Kaur *et al.,* 2022). Besides similar soil types, fertility, climate, and sowing environments, crop cultivars behave differently with respect to growth, phenology, and yield traits. Therefore, another important decision is selecting specific cultivars for different sowing windows. *Bt* cotton cultivars require less time for maturity, having better source sink ratio, heat use efficiency as a resulting in higher seed cotton yield over non-Bt cultivars (Thakur *et al.,* 2017; Singh *et al*., 2023). To look over these optimum conditions, a study was conducted to examine the thermal response of cotton as affected by differential sowing environments and cotton cultivars in the hot semi-arid region of Southwestern Punjab.

Material and Methods

A field experiment was conducted at Regional Research Station, Bathinda of Punjab Agricultural University, Ludhiana (30°58′N, 74°18′E, 211m amsl) during *Kharif* 2020 and 2021. The experiment was laid out in a factorial randomised complete block design with four sowing dates (April 01, April 20, May 10 and May 30) and two cotton cultivars (F 2228 and RCH 773 BGII) in three replications. The soil of the experimental site was low in available nitrogen (186-197 kg ha^{-1}) and organic carbon (0.33-0.35%), medium in available phosphorus (15-17 kg ha^{-1}), medium to high in available potassium (242-282 kg ha^{-1}), slightly alkaline at pH (8.32-8.35) with a sandy loam texture (Yadav and Pal, 2022). The sowing of cotton was done by dibbling two seeds $hill^{-1}$ in a planting geometry of 67.5×75 cm. All recommended cultural and plant protection measures were followed according to the guidelines of the Punjab Agricultural University (Anonymous, 2020). Daily meteorological observations, such as maximum temperature (Tmax), minimum temperature (Tmin) and duration of bright sunshine hours (BSS), were recorded at an agro-meteorological observatory installed near the experimental area. Thermal units, viz., growing degree days (GDDs), helio thermal units (HTUs), photothermal units (PTUs), pheno-thermal index (PTI), relative temperature disparity (RTD) and heat use efficiency (HUE), accumulated for crop maturity were calculated using a base temperature of 15.5°C (Ban *et al*., 2015). The attainment of a particular phenological phase was visually observed when five out of ten tagged plants were entered into that particular stage. The average boll weight was calculated by randomly selecting 10 bolls per plant and dividing the total weight by 10. Seed cotton yield (SCY) was obtained from the total of two manual pickings on a whole-plot basis. The statistical analysis was performed using Excel and the statistical package CPCS1 designed by the Department of Mathematics and Statistics, PAU, Ludhiana. The following formulae were used to compute different agrometeorological indices (Thavaprakaash *et al*., 2007):

1. Growing Degree Days (GDD): = Σ [(Tmax + Tmin)/2 – Tb]

   Where Tmax = daily maximum temperature (°C), Tmin = daily minimum temperature (°C), Tb = base temperature (°C). If the mean temperature < Tb, GDD is taken as zero.

2. Heliothermal Units (HTU): = Σ (GDD × SSH)

   Where SSH = actual bright sunshine hours (hours).

3. Photothermal Units (PTU): = Σ (GDD × daylength)

4. Phenothermal Index (PTI): = GDD / growing days.

5. Relative Temperature Disparity (RTD): = [(Tmax – Tmin) / Tmax] × 100.

Result and Discussion

Prevailing weather conditions during the study period

The weekly mean weather conditions observed during the crop-growing period are depicted in Fig. 1. During 2020–2021, climatic parameters across sowing dates exhibited clear trends. Mean minimum temperature increased from early to mid-sowings (D_1: 24.0 → D_3 : 24.9/ °C in 2020; D_1 : 23.4 → D_3: 24.4/ °C in 2021) and was lowest for late sowings (D_4 : 23.6/ °C in 2020; 23.3/ °C in 2021). Maximum temperature peaked under mid sowings (D_3: 36.8/ °C in 2020; 36.0/ °C in 2021) and was lowest for late sowings (D_4: 35.8/ °C in 2020; 35.2/ °C in 2021). Bright sunshine hours declined with delayed sowing, from 1362.4/ h (D_1) to 1148.4/ h (D_4) in 2020 and from 1251.5/ h (D_1) to 1146.0/ h (D_4) in 2021. Total rainfall was higher for early sowings in 2020 (D_1: 442/ mm, D_2: 435/ mm) and lower for late sowings (D_3: 410.6/ mm, D_4: 406.6/ mm), whereas in 2021, late sowings received more rainfall (D_3: 473.9/ mm, D_4: 467.3/ mm) than early sowings (D_1: 439.7/ mm, D_2: 433.9/ mm). These variations influenced crop growth, establishment, and yield potential across sowing windows.

Influence of sowing dates and cultivars on cotton phenology, thermal indices, heat use efficiency and seed cotton yield

The pooled results from Tables 1 and 2 clearly indicate that sowing dates and cultivars significantly influenced cotton phenology, thermal unit accumulation, yield and heat use efficiency during both 2020 and 2021. Early sowing on 1 April prolonged crop duration, with maturity taking 169.7–173.3 days, and enabled maximum accumulation of thermal units (GDD: 2481.9–2437.7 °C day; HTU: 19544.5–17946.9 °C day hour; PTU: 33244.3–32663.7 °C day hour). This favourable thermal environment resulted in the highest seed cotton yield (2956.2 and 2223.6 kg ha^{-1}) and superior heat use efficiency (1.20 and 0.91 kg ha^{-1} °C day^{-1}) (Sankaranarayanan *et al.,* 2020). Progressive delay in sowing up to 30 May significantly reduced days to maturity (151.5–156.0 days), thermal accumulation (GDD: 2236.3–2165.7 °C day; HTU:

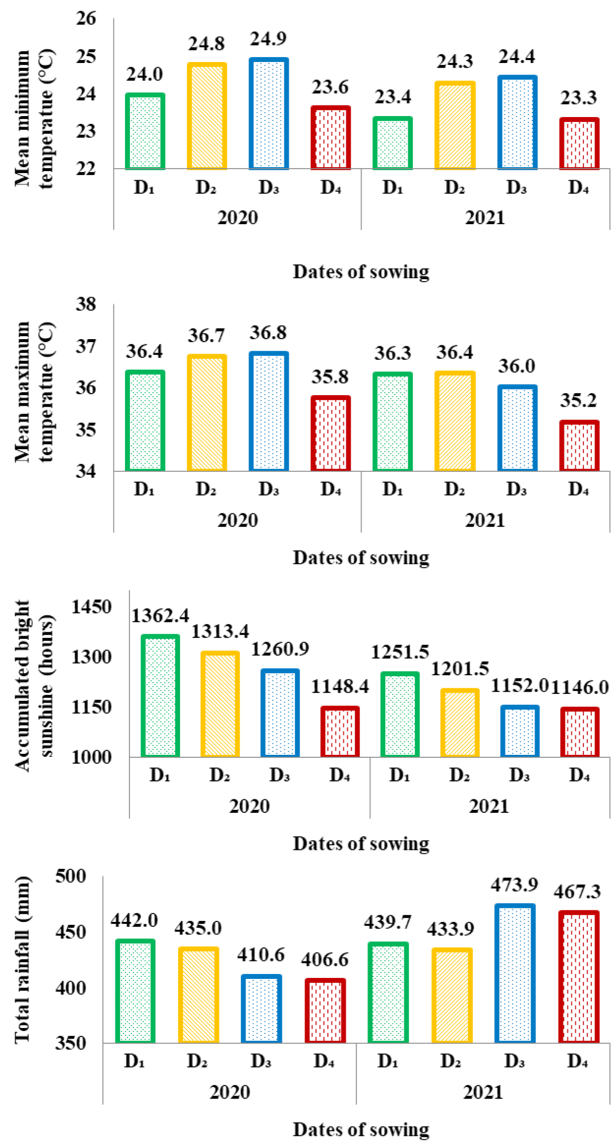

Fig. 1. Inter-annual variability in mean minimum and maximum temperature (°C), accumulated sunshine (hours) and total rainfall (mm) across different sowing windows during 2020–2021

16967.9–15994.5 °C day hour; PTU: 29130.5–28247.3 °C day hour), seed cotton yield (1902.2 and 1192.9 kg ha^{-1}) and heat use efficiency (0.85 and 0.55 kg ha^{-1} °C day^{-1}), indicating sub-optimal utilization of thermal resources under delayed planting. Phenothermal index showed significant variation across sowing dates, attaining relatively higher values under 10 May sowing (15.46 and 14.37 °C), while relative temperature disparity was highest under early sowing (42.26–44.69%) and declined with delayed sowing. The higher PTI observed for the May 10

Table 1. Crop phenology and thermal unit accumulation of cotton as affected by different treatments

Treatments	Days taken for crop maturity		Growing degree days(°C day)		Helio thermal units (°C day hour)		Photo thermal units (°C day hour)	
	2020	2021	2020	2021	2020	2021	2020	2021
Sowing dates								
April 01	169.7[a]	173.3[a]	2481.9[a]	2437.7[a]	19544.5[a]	17946.9[a]	33244.3[a]	32663.7[a]
April 20	163.2[b]	166.3[b]	2434.7[b]	2387.8[b]	19252.6[b]	17590.5[b]	32580.2[b]	31963.5[b]
May 10	157.0[c]	162.0[c]	2427.2[b]	2327.3[c]	19258.1[b]	17120.8[c]	32087.6[c]	30782.7[c]
May 30	151.5[d]	156.0[d]	2236.3[c]	2165.7[d]	16967.9[c]	15994.5[d]	29130.5[d]	28247.3[d]
CD (5%)	1.01	2.26	14.40	12.26	117.37	69.98	175.73	144.43
Cultivars								
F 2228	164.7[a]	169.4[a]	2469.3[a]	2391.7[a]	19367.9[a]	17611.0[a]	32628.7[a]	31633.8[a]
RCH 773 BGII	156.0[b]	159.4[b]	2320.7[b]	2267.5[b]	18143.6[b]	16715.4[b]	30892.6[b]	30194.7[b]
CD (5%)	0.72	1.59	10.18	8.67	82.99	49.48	124.26	102.13

Table 2. Phenothermal index, heat use efficiency, relative temperature disparity and seed cotton yield as affected by different treatments

Treatments	Seed cotton yield (kg/ha)		Phenothermal index (°C)		Relative temperature disparity (%)		Heat use efficiency (kg/ha/°C day)	
	2020	2021	2020	2021	2020	2021	2020	2021
Sowing dates								
April 01	2956.2[a]	2223.6[a]	14.63[d]	14.07[b]	42.26[a]	44.69[a]	1.20[a]	0.91[a]
April 20	2820.8[a]	2131.2[b]	14.91[b]	14.36[a]	41.04[b]	42.81[b]	1.17[a]	0.90[a]
May 10	2467.0[b]	1834.2[c]	15.46[a]	14.37[a]	38.01[d]	37.76[d]	1.02[b]	0.79[b]
May 30	1902.2[c]	1192.9[d]	14.76[c]	13.88[c]	39.81[c]	39.26[c]	0.85[c]	0.55[c]
CD (5%)	149.89	70.40	0.06	0.14	0.23	0.16	0.06	0.03
Cultivars								
F 2228	2345.8[b]	1777.1[b]	15.00[a]	14.12[b]	40.13[b]	40.48[b]	0.94[b]	0.74[b]
RCH 773 BGII	2727.3[a]	1913.9[a]	14.88[b]	14.22[a]	40.43[a]	41.78[a]	1.17[a]	0.84[a]
CD (5%)	105.99	49.78	0.04	0.10	0.16	0.11	0.04	0.02

sowing is due to the crop completing its growth in a shorter duration (157 days) while accumulating nearly the same GDD (2427.2) as earlier sowings. This indicates more efficient use of thermal energy, as the crop developed faster per unit of heat received.

Among cultivars, F 2228 required a longer duration to mature (164.7–169.4 days) and accumulated higher thermal units (GDD: 2469.3–2391.7 °C day; HTU: 19367.9–17611.0 °C day hour; PTU: 32628.7–31633.8 °C day hour), whereas RCH 773 BGII matured earlier (156.0–159.4 days) and accumulated comparatively lower thermal units. Despite lower thermal accumulation, RCH 773 BGII recorded significantly higher seed cotton yield (2727.3 and 1913.9 kg ha^{-1}) and heat use efficiency (1.17 and 0.84 kg ha^{-1} °C day^{-1}) than F 2228, reflecting better conversion of available thermal energy into economic yield. The critical difference values at 5% probability confirm that the effects of sowing dates and cultivars on phenology, thermal indices, yield and heat use efficiency were statistically significant (Tables 1 & 2). Singh *et al.* (2023) also found significantly higher seed cotton yield of Bt cultivars in contrast to non-Bt cultivars due to an improved number of bolls per plant. Kaur *et al.* (2022) also documented the outperformance *Bt* genotypes with 9% more biomass in fruiting structures over the non-*Bt* cultivars.

Interrelationship between seed cotton and thermal units' accumulation

Figure 2 demonstrates an interconnected response of seed cotton yield (kg ha^{-1}) to cumulative thermal and photothermal indices. Seed cotton yield increased linearly with growing degree days (GDD), indicating that greater thermal accumulation creates a favourable baseline for crop growth and yield (R^2 = 0.72). This fundamental temperature–yield relationship is further strengthened when thermal duration is integrated with diurnal temperature effects, as reflected by the strong positive association between yield and accumulated helio-thermal units (HTU) (R^2 = 0.77).

Building on thermal accumulation alone, the inclusion of radiative energy via photothermal units (PTU) showed a similarly strong linear increase in seed cotton yield (R^2 = 0.76), highlighting that yield enhancement is not only temperature-driven but also dependent on the combined availability of heat and solar radiation. This integrated effect is further refined by the phenothermal index (PTI), which normalises phenothermal accumulation over time; the positive relationship between PTI and yield (R^2 = 0.62) suggests more efficient utilisation of thermal and radiative resources under higher-yielding conditions. Finally, variations in the thermal regime, represented by relative temperature disparity (RTD), also exhibited a positive association with seed cotton yield (R^2 = 0.60). This indicates that yield gains achieved under higher thermal and photothermal accumulation are accompanied by greater temperature variability, collectively shaping the crop's growth environment.

Overall, the sequential strengthening from GDD to HTU, PTU, PTI, and RTD demonstrates that seed cotton productivity is governed by a continuum of thermal accumulation, heat–radiation interactions and temperature variability rather than by a single climatic factor (Fig. 2). Sarlach and Brar (2020)

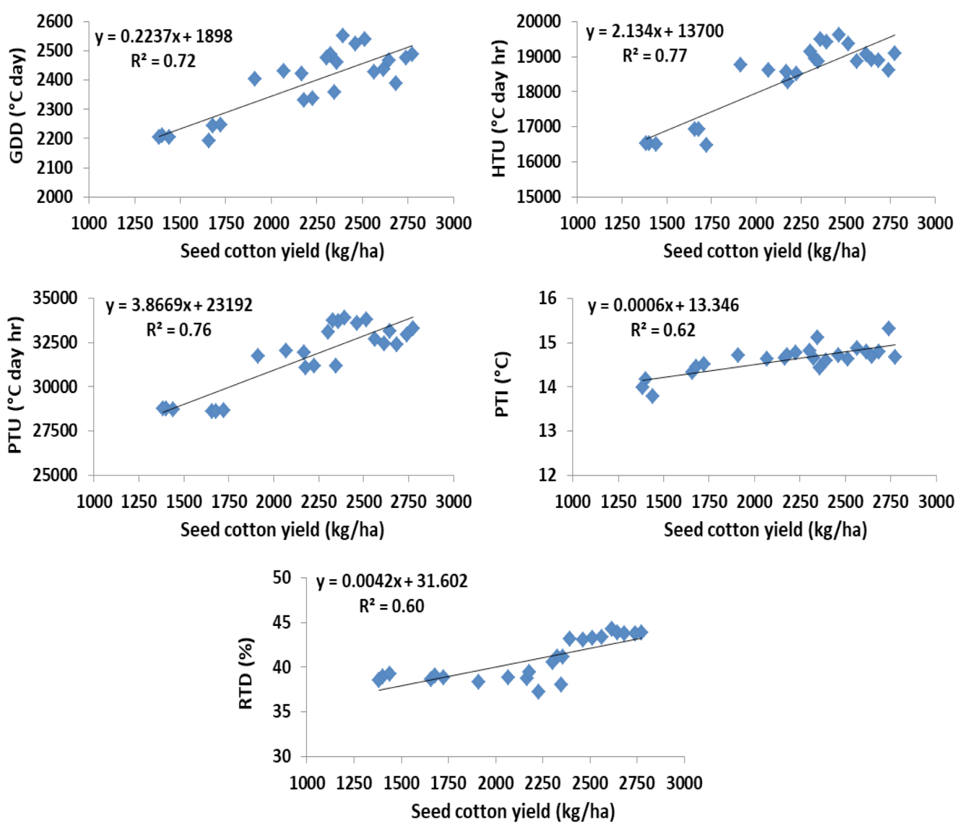

Fig. 2. Relationship between seed cotton yield and accumulated growing degree days (GDD), helio-thermal unit (HTU), photo-thermal unit (PTU), pheno-thermal index (PTI) and relative temperature disparity (RTD) in cotton (pooled data of 2020-2021)

found that higher accumulation of thermal units was the main reason for improved seed cotton yield under timely sown conditions.

The thermal regime strongly regulated cotton phenology and yield across sowing environments and cultivars. Early sowing (April 01) accumulated 15–20% higher growing degree days than late sowing, which prolonged the reproductive phase and enhanced assimilate partitioning to bolls. Consequently, seed cotton yield declined progressively by 4–5%, 17–18%, and 36–46% under April 20, May 10, and May 30 sowings, respectively. Growing degree days explained 65–76% of yield variability, while helio- and photo-thermal units accounted for >68–70%, highlighting the dominance of thermal–radiative controls. The Bt hybrid RCH 773 required fewer thermal units yet produced a higher yield due to superior heat use efficiency. Maximum heat use efficiency under early sowing (0.92–1.19 kg ha^{-1} °C day^{-1}) underscores the advantage of timely sowing in optimizing thermal resource use and cotton productivity.

Conclusion

The study demonstrates that cotton phenology, thermal unit accumulation, heat use efficiency, and seed cotton yield are strongly influenced by sowing date–cultivar interactions and the thermal environment. Early sowing (1 April) extended crop duration and enhanced accumulation of GDD, HTU, and PTU, promoting boll development, assimilate partitioning, and higher yield. Delayed sowing shortened growth, reduced thermal accumulation, lowered heat use efficiency, and caused significant yield losses. Among cultivars, the Bt hybrid RCH 773 BGII outperformed F 2228, achieving higher yield and efficiency with fewer thermal units, indicating superior conversion of thermal energy into economic yield. Strong correlations between yield and thermal indices highlight the combined effect of temperature, radiation, and thermal dynamics. Timely sowing with thermally efficient cultivars optimizes cotton productivity across agro-climatic conditions.

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Received: 15 February 2025; Accepted: 29 April 2025