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RESEARCH ARTICLE

Agrometeorological assessment of *Bt* -Cotton yield with varietal interactions response under varying growing environments under semi-arid region of Hisar

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Abstract

The present investigation was conducted during *Kharif* 2023 and 2024 at University Research Farm, CCS HAU, Hisar, Haryana, India to evaluate the influence of weather variability on *Bt* cotton yield across different growing environments. The study spanned 21 to 44 Standard Meteorological Weeks (SMWs), encompassing key weather parameters such as rainfall, temperature, humidity, wind speed, evaporation and sunshine hours. Four *Bt* cotton varieties were sown on 3 different dates with 3 replications of each to assess their phenological response and yield performance. Agrometeorological indices as Growing degree days (GDD), Heliothermal Units (HTU) and Photothermal Units (PTU) were computed to quantified thermal utilized by Bt cotton through life cycle completion. Results revealed variation of seed cotton yield under different growing environment. Maximum value of yield attributes (like No. of sympodial branches/ plant, No. of bolls/plant and Avg. boll weight/boll (g) and yield (yield/plant and yield/ha) was observed in crop sown earlier on 3rd week of May with maximum accumulation of thermal units (GDD, HTU and PTU). From present study it was concluded that variety V_4: ACH 177 performed best under prevalent weather conditions. For late sown crop 3rd week of May is suitable further delay in sowing leads to yield reduction. Future research should focus on developing user-oriented agrometeorological advisory systems that provide farmers with timely, location-specific guidance on optimum sowing dates and suitable *Bt* cotton varieties for prevailing weather conditions. Such initiatives would support sustainable *Bt* cotton production and enhance resilience to increasing climatic variability and uncertainty in semi-arid regions.

Keywords: agrometeorological indices; *Bt* cotton; growing environments; seed cotton yield; SMWs; thermal units; weather variability

Introduction

Cotton (*Gossypium hirsutum* L.) a member of the genus *Gossypium* and family Malvaceae also known as "White gold" and "King of fibres". It is an important fiber and oilseed crop cultivated worldwide (1) providing 35 % of the total fiber produced worldwide (2). Cotton, a climate-sensitive crop, is profoundly influenced by temporal variations in weather parameters. In India, the *Kharif* season coincides with the monsoon (June to September), making cotton cultivation vulnerable to rainfall variability, temperature extremes, and humidity fluctuations (morning & evening), cloudiness. Cotton is very sensitive to its climatic requirements and responds negatively to any deviation from optimum weather conditions (3, 4). Late planting caused late flowering which pushed boll development into the cooler temperatures, which decreased production (5). Both short-term meteorological events (the weather) and long-term meteorological factors (the climate) have an impact on crop growth, development, and yield (6). The optimal planting period creates favourable conditions for sufficient crop growth and leads to the realization of the crop's production potential (7). Bt cotton, with its genetic advantage, offers yield stability with determinate type of nature, yet its performance is modulated by growing environments (sowing time) and environmental conditions. The slightly variation in the sowing windows in different agroclimatic region of the country due variability in the prevailing weather conditions. Understanding the interaction between growing environments (varietal traits) and agrometeorological indices is crucial for optimizing productivity. Improved knowledge of weather resources can contribute to higher crop productivity (8). Under the present study aims to quantify the impact of weather elements and thermal indices on *Bt* cotton yield under different growing environments during SMWs 21 to 44.

Vegetative and reproductive growth occurs simultaneously which makes interpretation of the crop's response to climate and management difficult. When cotton is grown under optimum management practices (of water and fertilizer conditions), the temperature experienced between flowering and boll opening becomes the most important factor influencing fiber quality which is dependent on the planting date for a certain site and cultivar (9). The rate at which *Bt* cotton crop develops from planting to maturity depends on temperature, GDD, HTU, and sun radiation (10). The optimum temperature range for biochemical and metabolic activities of plants is known as the thermal kinetic window (TKW) (11). Plant temperatures above or below it results in stress that limits growth and yield. The TKW for cotton growth is 23.5-32 °C, with an optimum temperature of 28 °C. Genotype selection and the appropriate time of sowing are very crucial elements that significantly affects the crop production (12). Variation in the weather parameters, exacerbated by climate change, pose significant challenges to cotton growers, leading to yield losses, increased pest and disease incidence, and reduced fiber quality (13).

High humidity during boll opening can negatively impact lint quality, leading to reduced lint index (14). Continuous rain during flowering impairs pollination, leading to poor boll setting. Excessive moisture during boll opening can cause boll rot, lint discoloration, and reduce fiber quality. Co-occurrence of heat and drought stress, exacerbated by climate change, is predicted to become more frequent which is often more severe than individual stresses, leading to greater yield and fiber quality losses (15). Uncertain and erratic rainfall patterns, including delayed monsoons and intense rainfall during critical stages, negatively impact cotton productivity. As in Surat, Gujarat, delayed monsoon and high rainfall during squaring and flowering in 2011-12 significantly disturbed crop physiology and reduced yield (16).

The objective of present investigation was to assess the weather entities, heat units and response cultivation of *Bt*-cotton. It underscores the importance of optimizing prevailing weather based growing environments and varietal selection responses for climate-resilient cotton production under the semi-arid region of Hisar, Haryana.

Materials and methods

Experimental site

The present study was conducted under field condition at Research farm, Chaudhary Charan Singh Haryana Agricultural University, Hisar (Haryana), India, during *Kharif* season of the year 2023 and 2024. The experimental site is situated in trans-genetic agro-climatic zone of India at 75° 46' E, latitude 29° 10' N with an altitude of 215.2 m above mean sea level.

Experimental design

The experiment was conducted in Split Plot Design (SPD) with three dates of sowing i.e. D_1-3rd week of May, D_2-4th week of May and D_3-1st week of June, with four varieties *viz.*, V_1- RCH 773, V_2- NCS 9013, V_3-US51, V_4-ACH 177 replicated thrice.

Parameters to be observed

Observation recorded at crop field includes plant parameters (yield attributes, yield) and Agrometeorological indices (GDD, HTU, PTU). Daily meteorological data of Agrometeorological observatory was used to compute the agrometeorological indices.

Yield parameters

No. of sympodial branches/plant and No. of bolls/plant Their number were counted on three tagged plants at maturity and then average was taken to calculate number of sympodial branches and No. of bolls/plant. Average boll weight (g) or (g/boll): Three plants were randomly selected and five bolls were randomly harvested from each of these plants. Weight of each boll was measured, and then average boll weight for one boll was calculated.

Yield

Seed cotton yield per plant (g) The seed cotton was picked from 3 tagged plants of each plot and their average was calculated to find out yield per plant. Seed cotton yield (kg/ha) The seed cotton was picked from each plot separately and weighted. This weight is divided by the area of plot and then multiplied by 10000 to calculate yield in kg/ha.

Agrometeorological indices

Growing degree days (GDD)

GDD expressed in ˚C day, it is the sum of daily mean temperature above base temperature. The following formula was used for calculating the GDD:

$$\text{GDD (°C day)} = \sum_a^b \left(\frac{Tmax+Tmin}{2} - Tb\right)$$

Where, a = date of start of a phenophase, b = date of end of a phenophase, $T_{max.}$ =daily maximum temperature (˚C), $T_{min.}$ =daily minimum temperature (˚C) and T_b = base temperature (10 °C)

Heliothermal units (HTU)

HTU is the product of GDD and bright sunshine hours for that particular day and are expressed in °C day hours. The total HTU for a particular phenophase were calculated according to the formula:

HTU (˚C day hours) = ∑ (GDD x BSS)

Where, BSS = Bright sunshine hours/ actual sunshine hours

Photothermal units (PTU)

PTU is the product of GDD and maximum possible sunshine hours and are expressed in ˚C day hours. PTU was calculated using the following formula:

PTU (˚C day hours) = Σ (GDD x N)

Where, N = Maximum possible sunshine hours or day length

Statistical analysis

Data used in the interpretation were the mean values of the replicated observations. All the data of research field was statistically analysed using the online computer programme OPSTAT.

C D = (√2*EMS/n)* t value at 5 %

Where, C D stands for critical difference, EMS stands for error mean sum of squares, n stands for the number of observations and t is the value of t-distribution at 5 % level of significance and error degree of freedom.

Analysis of variance

Analysis of variance of the observations recorded on different characters was carried out as per the standard procedure suggested by Fisher (17).

Results and Discussions

Weather conditions prevailed during *Kharif* season 2023 and 2024

The mean weekly meteorological data prevailed during both crop seasons *Kharif* 2023 and 2024 are shown below in Fig. 1 and 2 which was calculated using daily meteorological data from Agromet observatory. *Kharif* 2023 experienced erratic rainfall even less than half of normal rainfall for D_2 (4th week of May) and D_3 (1st week of June) sowing dates and half for D_1 (3rd week of May) sowing date, while in *Kharif* 2024 rainfall was above normal and T_{max} and T_{min} were also higher during *Kharif* 2024 while relative humidity was lesser.

Yield parameters and yield of cotton varieties in different growing environment

The experimental results for yield parameters are presented in Table 1. Maximum number of sympodial branches/plant during *Kharif* 2023 was observed in D_1:3rd week of May with value 17.5 and during *Kharif* 2024 was 22.1 which was significantly higher than other dates of sowing while among varieties maximum number of branches was observed in V_4: ACH 177 during both the years with value 16.2 in *Kharif* 2023 and 23.3 in *Kharif* 2024 which was

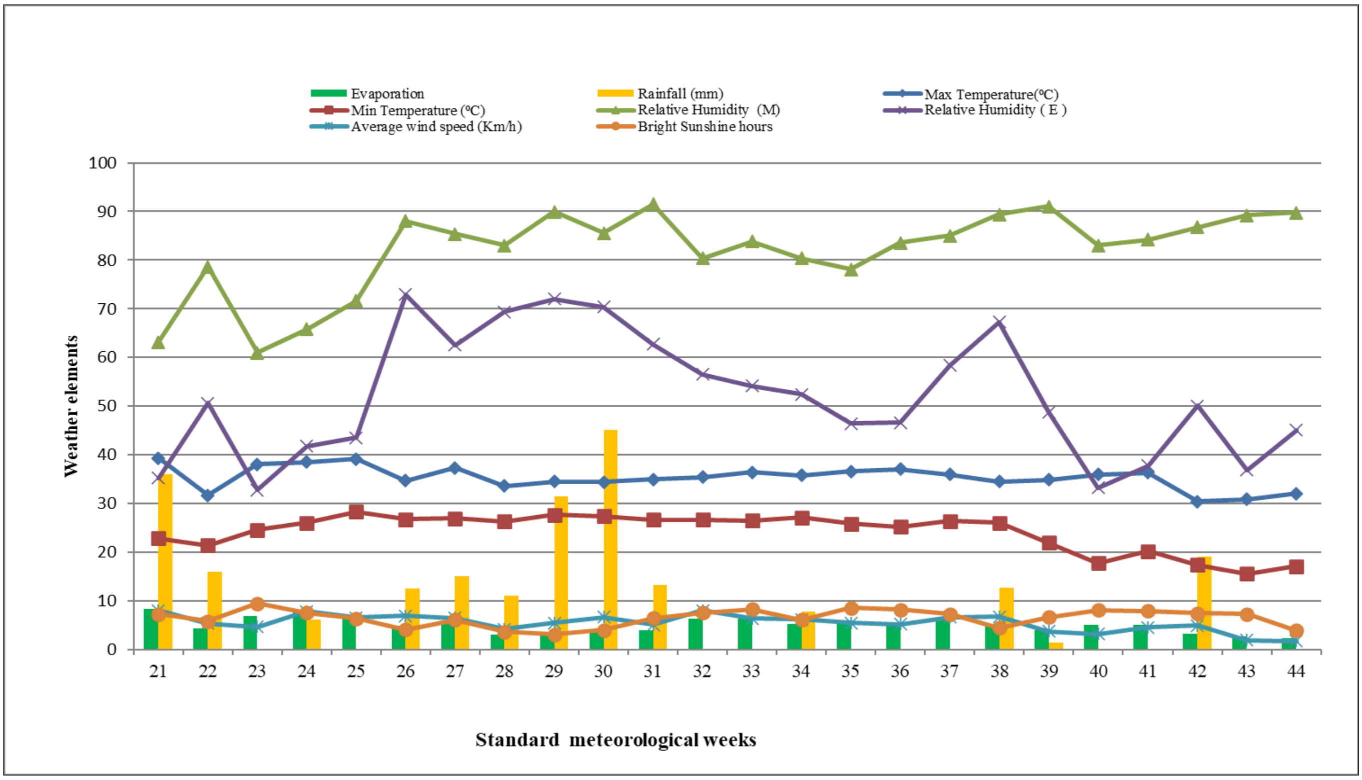

Fig. 1. The mean weekly meteorological data recorded during *Kharif* season 2023.

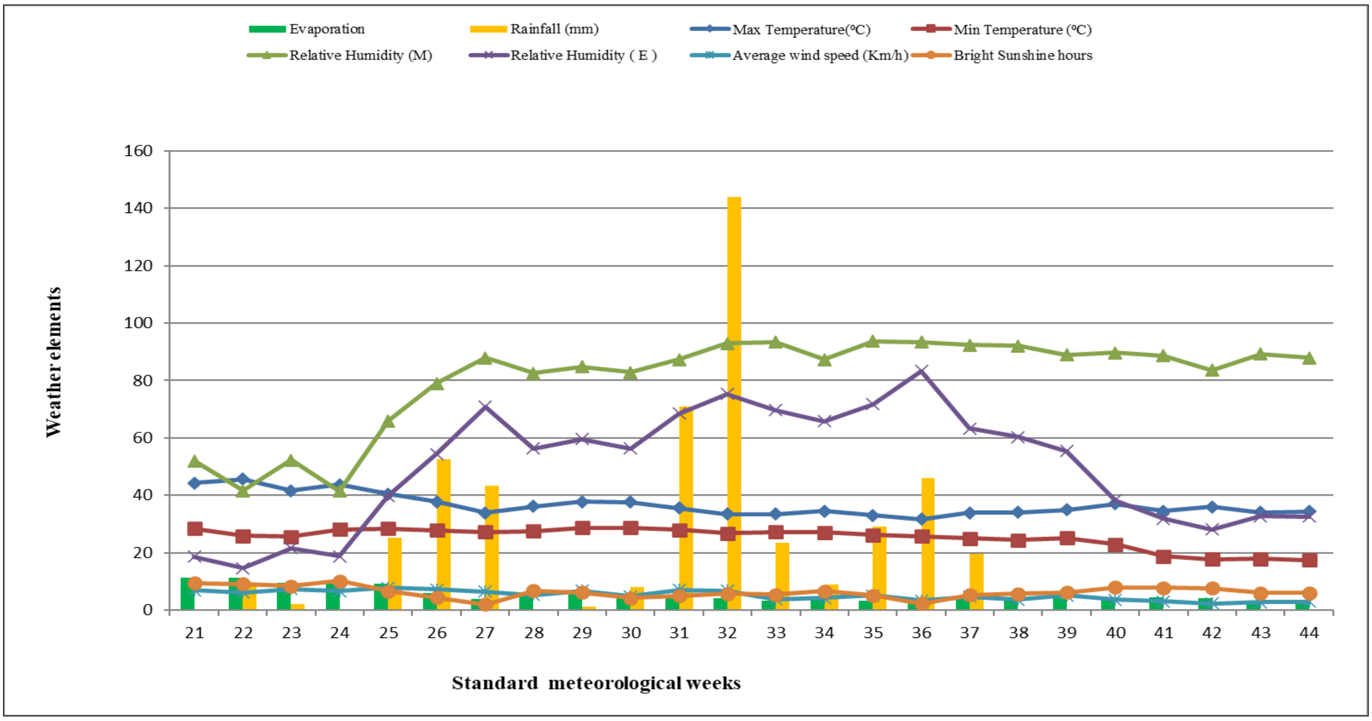

Fig. 2. The mean weekly meteorological data recorded during *Kharif* season 2024.

Table 1. Effect of different growing environment on yield parameters in various *Bt* cotton varieties.

Treatments	Different yield parameters					
	Kharif 2023			*Kharif* 2024		
Dates of sowing	No. of sympodial branches/ plant	No. of bolls/plant	Avg. boll weight / boll (gm)	No. of sympodial branches/ plant	No. of bolls/plant	Avg. boll weight/boll (gm)
D_1:3rd week of May	17.5	40.9	3.5	22.1	45.3	4.0
D_2:4th week of May	14.6	35.9	3.1	21.6	41.8	3.6
D_3:1st week of June	13.9	30.3	2.8	20.3	37.4	3.1
SE(m)	0.22	0.35	0.05	0.06	0.37	0.02
C D at 5 %	0.89	1.40	0.18	0.25	1.48	0.06
Varieties						
V_1: RCH 773	14.1	31.3	2.9	18.4	36.6	3.4
V_2: NCS 9013	15.7	38.5	3.1	20.3	43.6	3.5
V_3: US51	15.3	32.2	3.1	23.1	40.6	3.5
V_4: ACH 177	16.2	40.8	3.4	23.3	45.3	3.8
SE(m)	0.12	0.29	0.04	0.12	0.35	0.04
C D at 5 %	0.37	0.86	0.11	0.36	1.04	0.13

significantly higher than other varieties. Maximum No. of boll/plant during *Kharif* 2023 was observed in D_1:3rd week of May with value 40.9 and during *Kharif* 2024 was 45.3 which was significantly higher than other dates of sowing while maximum number of bolls was observed in V_4: ACH 177 during both the years with value 40.8 in *Kharif* 2023 and 45.3 in *Kharif* 2024 which was significantly higher than other varieties. Maximum avg. boll weight during *Kharif* 2023 was observed in D_1:3rd week of May with value 3.5 g and during *Kharif* 2024 was 4.0 g which was significantly higher than other dates of sowing while maximum avg. boll weight was observed in V_4: ACH 177 during both the years with value 40.8 in *Kharif* 2023 and 45.3 in *Kharif* 2024 which was significantly higher than other varieties. Whereas among both the years value of these parameters was higher in *Kharif* 2024.

The experimental result for yield is presented in Table 2. Maximum yield/plant and yield/ha was observed in crop sown on 3rd week of May during *Kharif* 2024. Maximum yield /plant during *Kharif* 2023 was observed in D_1:3rd week of May with value 89.8 g and during *Kharif* 2024 was 92.7 g which was significantly higher than other dates of sowing. In early sown crop there was more PAR interception and more efficient utilization of Heat units that leads to higher value of yield and yield attributes. While among varieties maximum yield/plant was observed in V_4: ACH 177 during both the years with value 90.2 in *Kharif* 2023 and 90.4 in *Kharif* 2024 which was significantly higher than other varieties. Maximum yield /ha during *Kharif* 2023 was observed in D_1:3rd week of May with value 2010 Kg/ha and during *Kharif* 2024 was 2178 Kg/ha which was significantly higher than other dates of sowing while among varieties maximum yield/ha was observed in V_4: ACH 177 during both the years with value 1980 Kg/ha in *Kharif* 2023 and 2159 Kg/ha in *Kharif* 2024 which was significantly higher than other varieties. V_4: ACH 177 had superior thermal use efficiency and yield stability across different environments. In interaction Table 3 it was observed that maximum yield was recorded in early sown V_4: ACH 177 crops with value 2010 Kg/ha in *Kharif* 2023 and 2178 Kg/ha in *Kharif* 2024. Interaction between sowing date × variety × environment, indicating the need for location -specific recommendations for sowing dates and varieties. Whereas among both the years seed cotton yield/plant and seed cotton yield/ha were higher in *Kharif* 2024 which was due to higher temperature during *Kharif* 2024 which was positively correlated to seed cotton yield.

Early works found that late sowing of crop leads to yield reduction (18-20). The higher value of yield attributes is obtained in early sown crop as compared to late sown (21). Previous works also given findings similar to ours that no of sympodial branches are higher in early sown crop as in late sown crop plenty of squares did not develop into bolls (22). Early sown crops achieve full vegetative growth earlier which maximizes PAR (Photosynthetically active radiation) interception which ultimately increases crop production. Each crop has an optimal weather conditions, early sowing often

Table 2. Effect of different growing environment on yield in various *Bt* cotton varieties

Treatments	Yield			
	Kharif 2023		*Kharif* 2024	
Dates of sowing	Yield/plant (gm)	Yield/ha (Kg/ha)	Yield/plant (gm)	Yield/ha (Kg/ha)
D_1:3rd week of May	89.8	2010	92.7	2178
D_2:4th week of May	84.6	1826	85.0	2092
D_3:1st week of June	81.9	1742	82.2	1904
SE(m)	0.26	43.5	0.17	39.8
C D at 5 %	1.03	175.6	0.68	160.7
Varieties				
V_1: RCH 773	80.8	1733	83.9	1962
V_2: NCS 9013	83.1	1845	85.6	2063
V_3: US51	87.8	1880	86.5	2049
V_4: ACH 177	90.2	1980	90.4	2159
SE(m)	0.54	38.3	0.35	42.5
C D at 5 %	1.63	114.7	1.04	127.2

Table 3. Interaction of date of sowing with varieties for yield/ha (D X V)

	Kharif 2023					*Kharif* 2024				
	V_1: RCH 773	V_2: NCS 9013	V_3: US51	V_4: ACH 177	Mean	V_1: RCH 773	V_2: NCS 9013	V_3: US51	V_4: ACH 177	Mean
D_1: 3rd week of May	1881	1996	2000	2161	2010	2044	2255	2101	2314	2178
D_2: 4th week of May	1726	1821	1836	1920	1826	2074	2084	2078	2134	2092
D_3: 1st week of June	1591	1719	1802	1858	1742	1767	1851	1969	2029	1904
Mean	1733	1845	1880	1980		1962	2063	2049	2159	
SE(m) V at same level of D	87.1					79.7				
C D at 5 % V at same level of D	NS					NS				
SE(m) D at same level of V	72.1					75.2				
C D at 5 % D at same level of V	NS					NS				

ensures that the critical development stages coincide with these optimum weather conditions that is also favourable for higher crop production.

Effect of different growing environment on Agrometeorological indices attained in different *Bt* cotton varieties

GDD (°C day), HTU (°C day hour), PTU (°C day hour) required to attain different phenophases by various cotton varieties sown on different dates have been worked out and presented in Table 4, 5 and 6 respectively. During P_1 phenophase in 2023 maximum value of GDD, HTU, PTU was attained in 1st week of June sown crop while at all other phenophases maximum GDD, HTU, PTU was accumulated by crop sown on 3rd week of May at P_2, P_3, P_4, P_5 respectively which was significantly higher than other dates of sowing whereas in 2024 maximum GDD, HTU, PTU was accumulated by crop sown on 3rd week of May at all phases. While among varieties during both the years all the varieties accumulated same amount of GDD, HTU, PTU at P_1 phenophases while at all other phenophases during both the years maximum GDD, HTU, PTU was accumulated by V_4: ACH 177. Among both the years maximum GDD, HTU, PTU was accumulated in *Kharif* 2024 due to prevailing higher temperature.

Agrometeorological indices (GDD, HTU, PTU) attained were higher in crop sown earlier in 3rd week of May (D1) during both crop years than the crop sown late, this could be due to more number of days to attain a particular phase in crop sown earlier which enhances boll development and seed cotton yield. Among different *Bt* cotton varieties V_4-ACH 177 had attained higher value of these indices with superior thermal use efficiency and yield stability across different environments. Previous works found that early sown crop accumulates more value of Agrometeorological indices than late sown (23-26). Cotton is a warm season crop with a strong positive correlation with temperature. Temperature also governs the development in cotton, with specific heat units' thresholds for each development stage. Early sown crop has more time to accumulate higher heat units which ultimately increases crop production.

Conclusion

The study highlights, weather elements and critical role of agrometeorological indices in *Bt* cotton performance under variable weather. Early grown environment enhances thermal use efficiency and yield. Strategic alignment of growing windows with favourable SMWs. Maximum value of yield attributes and yield was observed in crop grown on 3rd week of May during both the years while among varieties it was observed in V_4- ACH 177. Maximum yield was obtained when variety V_4- ACH 177 was sown on 3rd week of May. Maximum GDD, HTU, PTU was observed in crop sown on 3rd week of May at phenophases vegetative stage, 50 % square formation, 50 % flowering, 50 % boll formation, 50 % boll opening except at vegetative stage in *Kharif* 2023 maximum value of these indices were observed in crop sown on 1st week of June. *Bt* cotton yield is highly influenced by sowing date, variety, and weather conditions. Agrometeorological indices as GDD, HTU and PTU effectively quantified crop-weather interactions. Early sowing enhances more thermal accumulation and cotton seed yield. The findings underscore the importance of integrating agrometeorological parameters into crop management decisions to improve productivity and resource use efficiency. The study provides a basis for modelling yield prediction and developing dynamic weather-based advisories for cotton growers. These insights can guide adaptive strategies to mitigate the impacts of climate variability and ensure sustainable cotton production in semi-arid regions.

Table 4. Effect of different growing environment on Growing degree days (°C day) attained in different *Bt* cotton varieties

Treatments	GDD (°C day)									
	Kharif 2023					*Kharif* 2024				
Dates of sowing	P_1- Vegetative stage	P_2- 50 % square formation	P_3- 50 % flowering	P_4- 50 % boll formation	P_5- 50 % boll opening	P_1- Vegetative Stage	P_2- 50% square formation	P_3- 50 % flowering	P_4- 50 % boll formation	P_5- 50 % boll opening
D_1:3rd week of May	613	1110	1533	2032	2489	764	1284	1749	2227	2650
D_2:4th week of May	638	1043	1465	1915	2393	749	1173	1624	2035	2495
D_3:1st week of June	671	1042	1469	1901	2331	719	1110	1559	1963	2359
SE(m)	NS	6.4	6.3	5.0	4.3	NS	10.2	6.3	4.6	3.8
C D at 5 %	NS	25.8	25.4	20.0	17.1	NS	41.1	25.5	18.7	15.5
Varieties										
V_1: RCH 773	641	1049	1466	1919	2404	744	1179	1621	2045	2501
V_2: NCS 9013	641	1054	1478	1927	2391	744	1174	1632	2052	2492
V_3: US51	641	1068	1494	1959	2390	744	1190	1653	2086	2486
V_4: ACH 177	641	1089	1518	1992	2432	744	1212	1671	2117	2527
SE(m)	NS	9.2	7.8	5.9	7.8	NS	9.2	7.3	5.7	7.7
C D at 5 %	NS	27.6	23.4	17.8	23.5	NS	27.4	21.7	17.0	23.2

Table 5. Effect of different growing environment on Accumulated heliothermal units (°C day hour) in different *Bt* cotton varieties

Treatments	HTU (°C day hour)									
	Kharif 2023					*Kharif* 2024				
Dates of sowing	**P_1- Vegetative stage**	**P_2- 50 % square formation**	**P_3- 50 % flowering**	**P_4- 50 % boll formation**	**P_5- 50 % boll opening**	**P_1- Vegetative Stage**	**P_2- 50 % square formation**	**P_3- 50 % flowering**	**P_4- 50 % boll formation**	**P_5- 50 % boll opening**
D_1:3rd week of May	4458	6986	8989	12680	16145	7119	9460	12187	14812	16756
D_2 :4th week of May	4406	6458	8698	11143	15574	6360	8240	10735	13026	15263
D_3:1st week of June	4712	6015	8734	12073	14962	4885	7153	9502	11817	13620
SE(m)	NS	37	41	495	23	NS	72	17	35	30
C D at 5 %	NS	149	166	NS	92	NS	292	71	144	121
Varieties										
V_1: RCH 773	4525	6446	8634	12016	15557	6122	8215	10716	13013	15205
V_2: NCS 9013	4525	6449	8737	12081	15511	6122	8179	10748	13064	15147
V_3: US51	4525	6484	8849	11133	15491	6122	8300	10845	13271	15100
V_4: ACH 177	4525	6566	9007	12631	15682	6122	8442	10921	13525	15399
SE(m)	NS	50	58	615	39	NS	72	35	44	55
C D at 5 %	NS	NS	174	NS	118	NS	NS	104	132	164

Table 6. Effect of different growing environment on Accumulated photothermal units (°C day hour) in different *Bt* cotton varieties

Treatments	PTU (°C day hour)									
	Kharif 2023					*Kharif* 2024				
Dates of sowing	**P_1- Vegetati ve stage**	**P_2- 50 % square formation**	**P_3- 50 % flowering**	**P_4- 50 % boll formation**	**P_5- 50 % boll opening**	**P_1- Vegetati ve stage**	**P_2- 50 % square formation**	**P_3- 50 % flowering**	**P_4- 50 % boll formation**	**P_5- 50 % boll opening**
D_1:3rd week of May	8174	14928	20466	26881	32563	10163	17106	22306	29361	34584
D_2 :4th week of May	8525	13849	19262	24758	30965	9988	15646	20666	26804	32510
D_3:1st week of June	8975	13846	19442	24890	30178	9606	14794	20606	25756	30590
SE(m)	NS	122	82	65	49	NS	135	784	59	45
C D at 5 %	NS	493	331	261	197	NS	545	NS	238	182
Varieties										
V_1: RCH 773	8558	14093	19426	25131	31228	9919	15722	21519	26938	32556
V_2: NCS 9013	8558	14035	19579	25223	31115	9919	15658	20457	27024	32450
V_3: US51	8558	14211	19791	25641	31028	9919	15859	20634	27429	32371
V_4: ACH 177	8558	14491	20096	26044	31569	9919	16156	22160	27837	32867
SE(m)	NS	110	102	77	103	NS	120	847	74	93
C D at 5 %	NS	329	304	232	310	NS	361	NS	223	280

Disclaimers

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Authors' contributions

All authors contributed equally. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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