



RESEARCH ARTICLE

Heat stress indices of wheat (*Triticum aestivum* L.) varieties as affected by sowing dates and growth regulators under sub-tropical conditions of Jammu

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Abstract

A field experiment was conducted during the rabi season of 2022–23 at the Research Farm, Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, to evaluate the effect of sowing dates, wheat (*Triticum aestivum* L.) varieties and plant growth regulators (PGRs) on yield and heat stress indices under sub-tropical conditions. The study involved three sowing dates, two wheat varieties and three PGR treatments in a split-split plot design. Results showed that sowing on 25 November recorded the highest canopy temperature depression (CTD), while 15 December sowing achieved the highest yield stability index (YSI). The variety DBW 303, particularly when treated with paclobutrazol, performed best in mitigating heat stress and achieving higher yields. Late sowing increased heat stress intensity and susceptibility, especially for variety JAUW 672 and untreated plots. It is concluded that, under the sub-tropical conditions of Jammu, sowing DBW 303 on 25 November with paclobutrazol application can enhance productivity and reduce the negative effects of heat stress.

Keywords: sowing date; DBW 303; heat stress indices; paclobutrazol; yield

Introduction

Wheat (*Triticum aestivum* L.) is most significant cereal crop worldwide (1). It is a self-pollinated annual plant belonging to genus *Triticum* and family Poaceae (grasses) (2). The chromosome number of bread wheat is $2n = 42$ (3). It is second most abundant crop in the world, which is physiologically classified under C_3 plant species. About two billion people (36 % of the world's population) consume it as a staple diet, providing almost 55 % of the carbohydrate and 20 % of the food calories (4) besides generating the income, as cash crop (5).

Globally wheat occupied 220.61 million hectares of cultivated land, with production of 789.49 million tonnes and productivity of 3.58 tonnes ha^{-1} , respectively. In India, wheat is grown as rabi crop on 30.46 million hectares of land with production of 104 million tonnes and productivity of 3.41 tonnes ha^{-1} during 2020–21 (6). Globally wheat occupied 220.61 million hectares of cultivated land, with production of 789.49 million tonnes and productivity of 3.58 tonnes ha^{-1} , respectively. In India, wheat is grown as rabi crop on 30.46 million hectares of land with production of 104 million tonnes and productivity of 3.41 tonnes ha^{-1} . The Jammu and Kashmir Union Territory has 243.93 thousand hectares of wheat cultivated land, with production

of 4883 thousand quintals and productivity 20.02 q ha^{-1} , respectively. The entire area under wheat cultivation in the Jammu region is 242.65 thousand hectares, with a production of 4869 thousand quintals and productivity 20.07 q ha^{-1} during 2020–21 (7). It has been seen that the average production of wheat is declining by 50 % due to abiotic factors like drought (9 %), high temperature (20 %), low temperature (7 %) and salinity (10 %) (8). Sowing date is a basic factor for deciding the crop yield (9). Under sub-tropical condition of Jammu region wheat is sown late (20th November–25th December) and very late (26th December–15th January) due to delayed harvesting of Basmati rice, which decreases the productivity of the crop to the tune of 1–1.5 % per day (10) as late sown crops face heat stress during the flowering and grain filling stages, which results in significant reduction of the final yield due to pollen sterility and lower grain filling (11). An ideal sowing window under sub-tropical condition of Jammu is 1st–25th November that can improve the wheat grain production and baking quality by allowing for better adaptation to physiology, phenology and environmental circumstances. Furthermore, the optimum sowing time governs the crop's exposure to prevailing temperature, soil moisture availability and solar radiation regimes,

which in turn regulate physiological processes, assimilate translocation and nutrient uptake efficiency, ultimately determining crop productivity and yield potential (12).

However, under delayed sowing conditions, the detrimental effects of terminal heat stress can be mitigated through the cultivation of heat-tolerant genotypes, which are adaptable to both late and very early sowing environments, thereby sustaining higher grain yield (13). Early and medium maturity wheat varieties should be identified to escape terminal heat stress. Heat resistant genotypes can be chosen on the basis of heritable, fast growth, reduced grain filling period etc. to protect the plant from damage caused by terminal heat stress (14, 15). The variety taken in to considerations viz., JAUW 672 released by SKUAST-Jammu during 2021 is suitable for restricted irrigation condition of Jammu, thus suitable under stress conditions with an average yield of 57.8 q ha⁻¹ with maturity ranging from 156–170 days and variety DBW 303 released by ICAR-Indian Institute of Wheat and Barley Research, Karnal during 2021 endured lower heat susceptibility index (HSI) (0.9) thus more resilient to terminal heat having medium maturity ranging from 156–165 days (16).

Plant growth regulators are natural or synthetic substances which can also improve crop yield by rerouting assimilate metabolism and partitioning under heat stress conditions. Exogenously applied plant growth regulators promote plant growth and development in both normal and stressed conditions (17). Under a range of environmental situations, foliar sprays of plant growth regulator have been shown to increase wheat productivity. It has been discovered that plant growth regulator plays an important role in raising the harvest index by increasing photosynthate partitioning towards the reproductive sink (18) or enhance the crop productivity by improving the metabolic imbalances produced in a cell during stress. The use of growth retardant viz., Paclobutrazol a triazole derivative helps in plant stress adoption by preserving relative water content, electrolyte leakage, protecting photosynthetic apparatus which contributes to plant growth and yield (19). The use of growth promoters viz., Kinetin a type of cytokinin, promotes cell division, nucleic acid metabolism which further retard senescence and keep the leaf stay green under heat stress (20). Further, use of plant growth-promoting rhizobacterium (PGPR) *Bacillus subtilis* helps mitigate heat stress in wheat by improving root growth, nutrient and water uptake and enhancing antioxidant enzyme activities (Superoxide dismutase, catalase and peroxidase). It also promotes osmolyte accumulation and heat shock protein synthesis, thereby maintaining photosynthesis, grain filling and reducing yield losses under high temperature conditions.

Therefore, the present investigation was undertaken to evaluate the effect of sowing dates, wheat varieties and plant growth regulators on heat stress tolerance and yield of wheat under sub-tropical conditions of Jammu.

Materials and Methods

The study was conducted at the Research Farm, Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu during rabi, 2022–23 Chatha, Jammu. The soil was sandy clay loam, pH 7.5, low in organic carbon (0.43 %), moderate in available N (245.21 kg ha⁻¹), P (14.84 kg ha⁻¹) and

K (129.03 kg ha⁻¹). The trial was carried out in split-split plot design including of three sowing dates (D₁: 25th November 2022, D₂: 15th December 2022 and D₃: 5th January 2023) in main plots, two varieties (V₁: JAUW 672 and V₂: DBW 303) in sub plots and three plant growth regulator treatments (T₁: Control, T₂: *B. subtilis* at 5 g kg⁻¹ seed + Paclobutrazol at 50 ppm at 30 and 60 days after sowing (DAS) and T₃: *B. subtilis* at 5 g kg⁻¹ seed + Kinetin at 10 ppm at 30 and 60 DAS) in sub-sub plot. The doses of paclobutrazol (50 ppm at 30 and 60 DAS) and kinetin (10 ppm) were selected based on earlier published studies reporting their effectiveness in improving wheat physiological performance, stress tolerance and grain yield under heat stress conditions. Paclobutrazol at 50 ppm has been reported to enhance stress adaptation by improving plant water relations, reducing canopy temperature and protecting the photosynthetic apparatus, while kinetin at 10 ppm effectively delays leaf senescence and enhances assimilate translocation towards developing grains. Therefore, these treatments were selected to evaluate their comparative efficacy under sub-tropical conditions. The fertiliser dose for JAUW 672 was 100 : 50 : 25 kg ha⁻¹ and DBW 303 was 150 : 60 : 40 kg ha⁻¹. The seed rate was 100 kg ha⁻¹ for normal sowing and 125 kg ha⁻¹ for delayed sowing. The gross plot size was 4 × 3 m² and net plot size was 3.2 × 2 m². The 1 m difference between gross and net plot width was maintained to avoid border effects and ensure accurate data recording by minimising the influence of adjacent treatments. The data were analysed by using analysis of variance (ANOVA) (*F*-test). The experimental data were statistically analysed using ANOVA appropriate for the split-split plot design to test the significance of treatment effects. The significance of differences among treatment means was tested at 5 % probability level (*p* = 0.05) using the *F*-test. When significant differences were observed, treatment means were compared using the least significant difference (LSD) test at 5 % level of significance. Statistical analyses were performed using standard statistical software such as OPSTAT.

Heat stress indices viz., canopy temperature depression (CTD), heat intensity index (HII), heat susceptibility index (HSI) and yield stability index (YSI) were calculated using standard formulas to evaluate heat stress tolerance of wheat varieties under sub-tropical conditions. The CTD was calculated to assess heat and drought tolerance of wheat genotypes using the formula CTD = Ta - Tc, where Ta is the air temperature (°C) and Tc is the canopy temperature (°C) (21). Heat intensity index was computed to quantify the severity of heat stress using the formula HII = (Xi - Xs) / Xi, where Xi represents the mean value under non-stress conditions and Xs represents the mean value under stress conditions (22). Heat susceptibility index was estimated to evaluate genotype sensitivity to heat stress using HSI = [1 - (YD / YP)] / D, where YD is the mean performance of genotypes under stress conditions, YP is the mean performance under non-stress conditions and D = 1 - (mean YD / mean YP) (23). The YSI was calculated using YSI = Ys / Yp, where Ys is the yield under stress (late sowing) conditions and Yp is the yield under normal sowing (non-stress) conditions (24). These indices were used to evaluate heat stress tolerance and yield stability of wheat varieties under sub-tropical conditions.

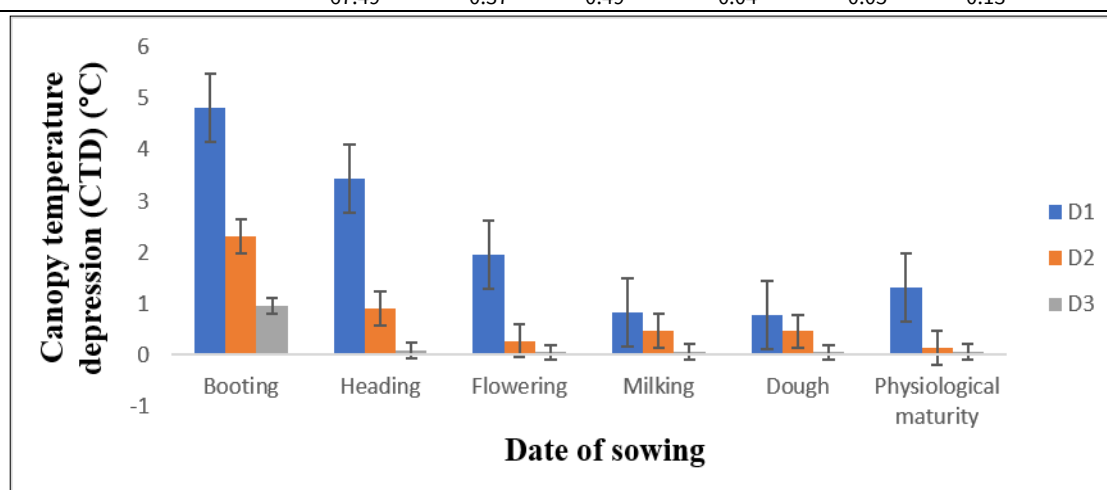
Results

Canopy temperature depression (°C)

Canopy temperature, recognised as a valuable indicator for evaluating

Table 1. Effect of different treatments on grain yield and canopy temperature depression

Treatments	Grain yield (kg ha ⁻¹)	Canopy temperature depression (CTD) (°C)					
		Booting	Heading	Flowering	Milking	Dough	Physiological maturity
Date of sowing							
D ₁ - 5 th November	4793.23	4.83	3.44	1.94	0.81	0.76	1.31
D ₂ - 15 th December	3831.88	2.31	0.89	0.27	0.46	0.45	0.13
D ₃ - 5 th January	2937.30	0.95	0.08	0.04	0.05	0.04	0.05
SEm (±)	23.09	0.23	0.26	0.19	0.18	0.18	0.26
CD (5 %)	69.29	0.69	0.79	0.58	0.26	0.23	0.05
Varieties							
V ₁ - JAUW 672	3574.69	2.39	1.51	0.34	0.08	0.52	0.28
V ₂ - DBW 303	4133.58	2.86	1.61	0.51	0.14	0.12	0.66
SEm (±)	15.86	0.06	0.13	0.25	0.19	0.18	0.09
CD (5 %)	47.59	0.18	0.41	0.76	0.04	0.21	0.02
Plant growth regulator							
T ₁ – Control	3572.84	2.56	1.4	0.36	0.09	0.39	0.35
T ₂ -Paclobutrazol at 50 ppm + <i>Bacillus subtilis</i> at 5 g kg ⁻¹ seed	4177.76	3.13	1.94	0.49	0.25	0.67	0.58
T ₃ - Kinetin at 10 ppm + <i>Bacillus subtilis</i> at 5 g kg ⁻¹ seed	3811.81	2.69	1.26	0.41	0.19	0.44	0.47
SEm (±)	22.49	0.12	0.16	0.16	0.18	0.14	0.18
CD (5 %)	67.49	0.37	0.49	0.04	0.05	0.13	0.05

**Fig. 1.** Effect of sowing dates on canopy temperature depression (CTD) (°C) for different phenophases.

heat and drought tolerance, was assessed through the measurement of CTD. The CTD varied in wheat varieties under different dates of sowing (Table 1 and Fig. 1). Significantly higher CTD was found by 25th November followed by 15th December and 5th January for all phenophases. The corresponding values of CTD for different phenophases under normal sowing, late sowing and very late sowing dates was recorded by crop sown under 25th November viz., 4.83 °C (booting), 3.44 °C (heading), 1.94 °C (flowering), 0.81 °C (milking), 0.76 °C (dough) and 1.31 °C (physiological maturity) followed by 15th December with CTD values at 2.31 °C (booting), 0.89 °C (heading), 0.27 °C (flowering), 0.46 °C (milking), 0.45 °C (dough) and 0.13 °C (physiological maturity) and 5th January with corresponding values of 0.95 °C, 0.08 °C, 0.04 °C, 0.05 °C, 0.04 °C and 0.05 °C, respectively (Fig. 2).

Among the variety the higher CTD was found by variety DBW 303 for different phenophases viz., 2.86 °C (booting), 1.61 °C (heading), 0.51 °C (flowering), 0.14 °C (milking), 0.12 °C (dough) and 0.66 °C (physiological maturity) which was significantly higher than variety JAUW 672 with values of 2.39 °C (booting), 1.51 °C (heading), 0.34 °C (flowering), 0.08 °C (milking), 0.52 °C (dough) and 0.28 °C (physiological maturity), respectively (Fig. 3).

Among the plant growth regulators higher CTD was recorded by paclobutrazol under different phenophases viz., 3.13 °C (booting), 1.94 °C (heading), 0.49 °C (flowering), 0.25 °C (milking),

0.67 °C (dough) and 0.58 °C (physiological maturity) which was significantly higher than kinetin with values of 2.69 °C (booting), 1.26 °C (heading), 0.41 °C (flowering), 0.19 °C (milking), 0.44 °C (dough) and 0.47 °C (physiological maturity) and for control with corresponding values of 2.56 °C, 1.4 °C, 0.36 °C, 0.09 °C, 0.39 °C and 0.35 °C, respectively (Fig. 1–3).

Heat intensity index

To quantify the severity of heat stress at different growth stages on grain yield HII was calculated. It was observed that low to moderate stress was observed by wheat crop during late and very late sowing for different phenophases (Table 2). When mean of late sowing (15th December) was compared to normal sowing (25th November) under different phenophases, the HII was found to be 0.04 for days to booting, days to heading, days to milking and days to flowering whereas 0.09 for days to dough and 0.10 for days to physiological maturity, whereas the increased corresponding value of HII 0.10 for days to booting, 0.11 for days to heading, 0.10 for days to flowering, 0.11 for days to milking, 0.17 for days to dough and 0.18 for days to physiological maturity, were found when mean of very late sowing (5th January) was compared to normal sowing (25th November) under different phenophases (Table 3).

Heat susceptibility index

Among varieties the highest HSI value was recorded by JAUW 672 as

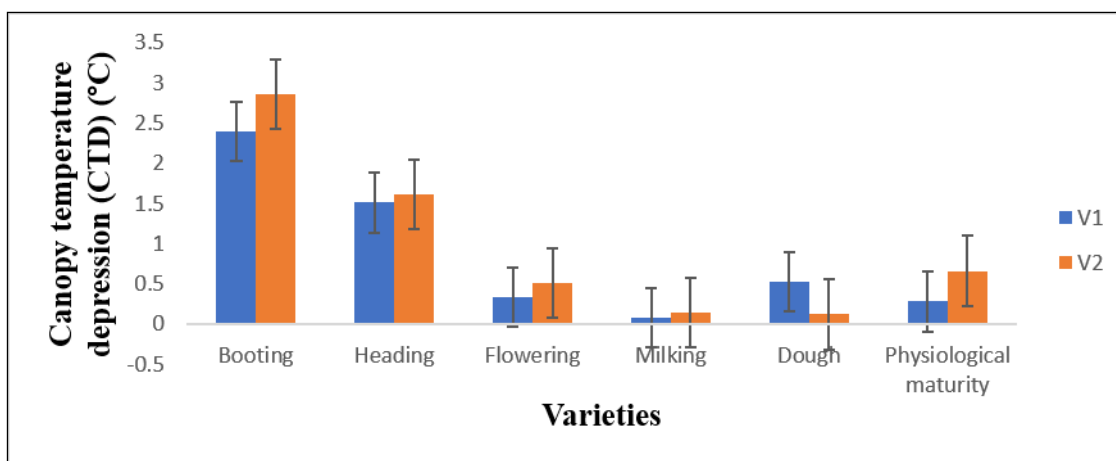


Fig. 2. Effect of varieties on canopy temperature depression (CTD) (°C) for different phenophases.

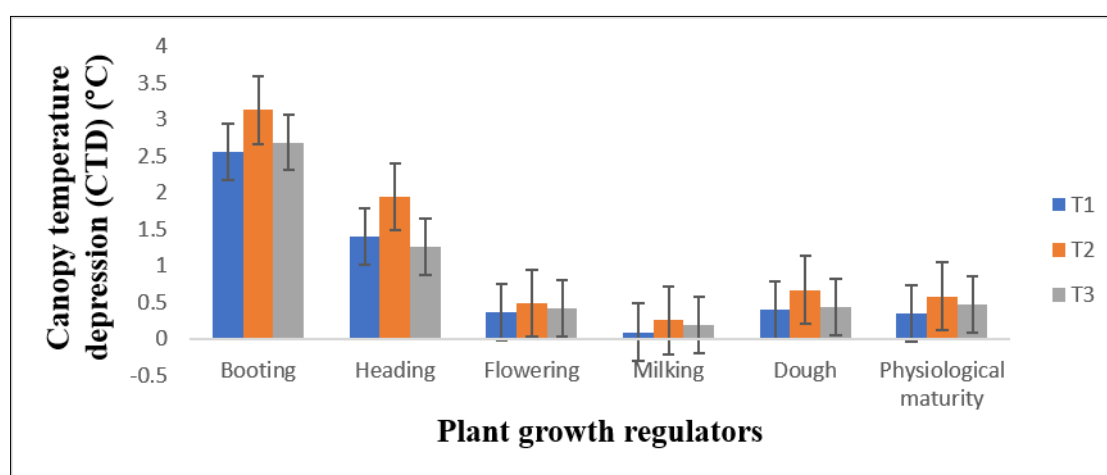


Fig. 3. Effect of plant growth regulators on canopy temperature depression (CTD) (°C) for different phenophases.

Table 2. Effect of different treatments on heat intensity index (HII) of wheat crop under different phenophases

		(Number of days)																	
Sl. No.	Treatments	Days to booting			Days to heading			Days to flowering			Days to milking			Days to dough			Days to physiological maturity		
		D ₁	D ₂	D ₃	D ₁	D ₂	D ₃	D ₁	D ₂	D ₃	D ₁	D ₂	D ₃	D ₁	D ₂	D ₃	D ₁	D ₂	D ₃
1.	V ₁ T ₁	81.89	78.32	72.25	96.14	92.37	84.89	106.91	102.00	94.74	124.73	115.85	105.33	138.59	125.09	112.54	149.34	134.01	121.30
2.	V ₁ T ₂	84.73	81.40	77.40	99.14	95.65	88.85	109.99	106.63	99.70	127.71	120.31	110.29	141.27	129.28	117.70	151.70	137.63	124.61
3.	V ₁ T ₃	83.91	80.40	75.73	98.19	94.65	87.85	108.97	104.03	97.70	126.40	117.48	109.03	140.25	126.85	116.50	151.01	135.60	123.50
4.	V ₂ T ₁	85.03	80.27	76.60	98.13	94.14	87.76	110.00	104.98	98.00	127.72	118.60	108.59	141.28	127.57	115.80	151.99	137.02	126.02
5.	V ₂ T ₂	88.07	85.94	80.60	102.01	98.69	92.05	113.09	108.95	102.69	130.81	122.31	113.28	144.37	131.28	120.49	155.49	140.81	128.96
6.	V ₂ T ₃	87.03	83.27	79.27	101.58	98.06	91.05	112.69	108.21	101.19	130.61	122.03	111.78	143.97	131.00	118.99	155.01	139.80	128.30

Table 3. Effect of different treatments on heat susceptibility index (HSI) of wheat crop under different phenophases

		Heat susceptibility index (HSI)											
Sl. No.	Treatments	Days to booting		Days to heading		Days to flowering		Days to milking		Days to dough		Days to physiological maturity	
		D ₁ -D ₂	D ₁ -D ₃	D ₁ -D ₂	D ₁ -D ₃	D ₁ -D ₂	D ₁ -D ₃	D ₁ -D ₂	D ₁ -D ₃	D ₁ -D ₂	D ₁ -D ₃	D ₁ -D ₂	D ₁ -D ₃
1.	V ₁ T ₁	1.06	1.23	1.08	1.11	1.13	1.11	1.06	1.09	1.05	1.07	1.05	1.05
2.	V ₁ T ₂	0.95	0.91	0.97	0.98	0.75	0.91	0.87	0.95	0.92	0.96	0.93	1.00
3.	V ₁ T ₃	1.01	1.02	0.99	1.00	1.12	1.01	1.05	0.96	1.03	0.98	0.97	1.02
4.	V ₂ T ₁	1.36	1.04	1.12	1.00	1.12	1.06	1.07	1.05	1.05	1.04	1.05	1.00
5.	V ₂ T ₂	0.59	0.89	0.90	0.93	0.90	0.92	0.97	0.94	0.98	0.95	0.97	0.96
6.	V ₂ T ₃	1.05	0.93	0.96	0.98	0.98	0.99	0.98	1.01	0.97	1.00	1.04	0.97

V₁ and V₂ denote wheat varieties. T₁, T₂ and T₃ denote treatment details. D₁, D₂ and D₃ are dates of sowing.

compared to DBW 303 at all phenophases. The corresponding value of variety JAUW 672 for HSI ranges from 0.91–1.23, 0.97–1.11, 0.75–1.13, 0.87–1.09, 0.92–1.07 and 0.93–1.05 for booting, heading, flowering, milking, dough and physiological maturity, respectively. Whereas, respective values of variety DBW 303 was 0.59–1.36, 0.90–1.12, 0.90–1.12, 0.94–1.07, 0.95–1.05 and 0.96–1.05 for booting, heading, flowering, milking, dough and physiological maturity, respectively (Table 3). Whereas overall HSI value of JAUW 672 was 1.03, 1.02, 1.24, 1.00, 1.00 and 1.00 for booting, heading, flowering, milking, dough and physiological maturity, respectively and the variety DBW 303 has lowest HSI having overall HSI values of 0.97 (booting), 0.98 (heading), 1.22 (flowering), 1.00 (milking), 0.99 (dough) and 0.99 (physiological maturity), respectively (Table 4) (Fig. 4).

Among the plant growth regulators, the highest HSI value was recorded by control ranges from 1.04–1.36, 1.00–1.12, 1.06–1.13, 1.05–1.09, 1.04–1.07 and 1.00–1.05 for booting, heading, flowering, milking, dough and physiological maturity trend followed by kinetin with range of respective values were 0.93–1.05, 0.96–1.00, 0.98–1.12, 0.96–1.05, 0.97–1.03 and 0.97–1.04 and lower HSI was recorded by paclobutrazol having range of value 0.59–0.95 (booting), 0.90–0.98 (heading), 0.75–0.92 (flowering), 0.87–0.97 (milking), 0.92–0.98

(dough) and 0.93–1.00 (physiological maturity), respectively (Table 3). Whereas overall HSI of wheat crop at various phenophase showed that highest HSI was found in control with corresponding values of 1.77, 1.63, 1.33, 1.60, 1.58 and 1.56 for booting, heading, flowering, milking, dough and physiological maturity followed by kinetin having values of 0.49, 0.49, 1.23, 0.49, 0.49 and 0.49, respectively. Whereas, HSI was observed by paclobutrazol having values of 0.45 (booting), 0.47 (heading), 1.12 (flowering), 0.47 (milking), 0.48 (dough) and 0.48 (physiological maturity), respectively (Table 4 and Fig. 5).

Yield stability index

The value of YSI ranges from 0.53 to 0.85 with the general mean value of 0.87 when the YSI was calculated in late sown (15th December) condition against normal sown (25th November) and 0.74 when the YSI was calculated in very late sown (5th January) condition against normal sown (25th November) (Table 5). Among the sowing dates the highest overall YSI was recorded in crop sown under 15th December (0.87) as compare to 5th January (0.74) (Table 6).

Among the varieties the highest overall YSI was recorded by DBW 303 (0.81) as compared to JAUW 672 (0.80) (Table 6).

Table 4. Effect of different treatments on overall heat susceptibility index (HSI) of wheat crop under different phenophases

Treatments	Days to booting	Days to heading	Days to flowering	Days to milking	Days to dough	Days to physiological maturity
Date of sowing						
D ₁ - 25 th November	-	-	-	-	-	-
D ₂ -15 December	-	-	-	-	-	-
D ₃ -05 January	-	-	-	-	-	-
Varieties						
V ₁ - JAUW 672	1.03	1.02	1.24	1.00	1.00	1.00
V ₂ - DBW 303	0.97	0.98	1.22	1.00	0.99	0.99
Plant growth regulator						
T ₁ - Control	1.77	1.63	1.33	1.60	1.58	1.56
T ₂ -Paclobutrazol at 50 ppm + <i>Bacillus subtilis</i> at 5 g kg ⁻¹ seed	0.45	0.47	1.12	0.47	0.48	0.48
T ₃ - Kinetin at 10 ppm + <i>Bacillus subtilis</i> at 5 g kg ⁻¹ seed	0.49	0.49	1.23	0.49	0.49	

V₁ and V₂ denote wheat varieties. T₁, T₂ and T₃ denote treatment details. D₁, D₂ and D₃ are dates of sowing.

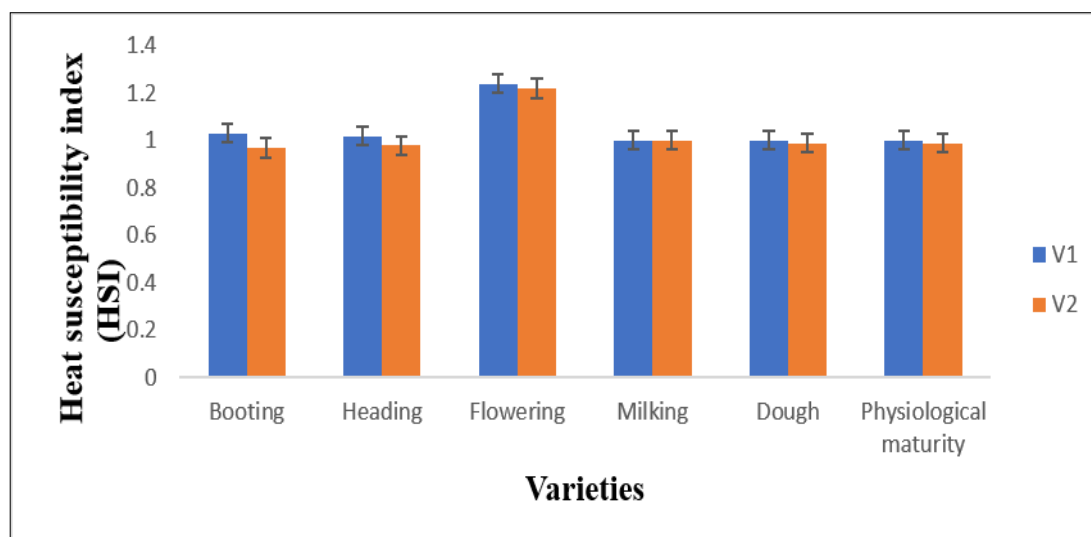


Fig. 4. Effect of varieties on overall heat susceptibility index (HSI) of wheat crop under different phenophases.

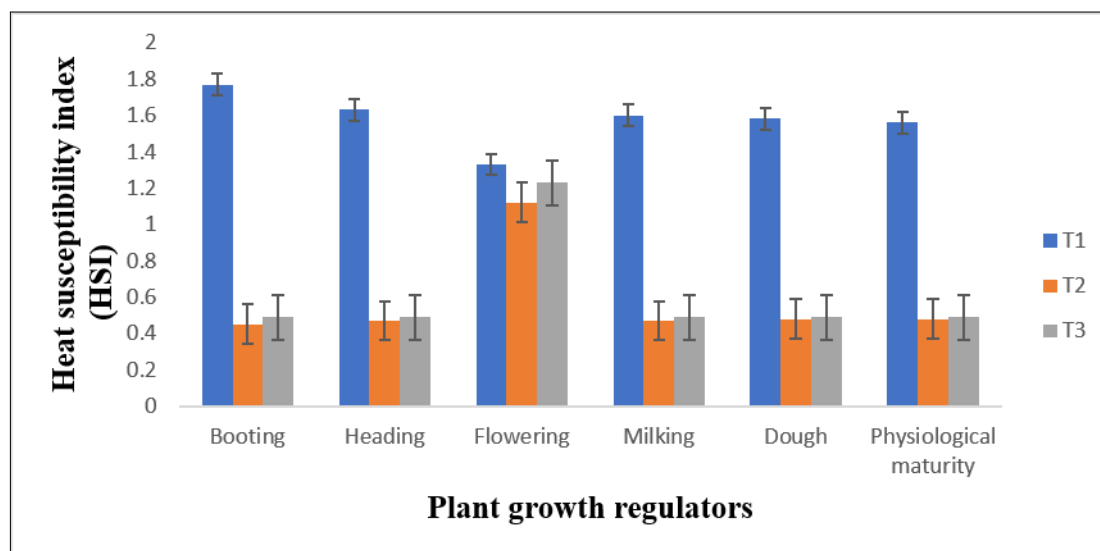


Fig. 5. Effect of plant growth regulators on overall heat susceptibility index (HSI) of wheat crop under different phenophases.

Table 5. Effect of different treatments on yield stability index (YSI) of wheat crop

Treatments	Yield stability index
Date of sowing	
D ₁ - 25 th November	-
D ₂ -15 December	0.87
D ₃ -5 January	0.74
Varieties	
V ₁ - JAUW 672	0.80
V ₂ - DBW 303	0.81
Plant growth regulator	
T ₁ - Control	1.20
T ₂ - Paclobutrazol at 50 ppm + <i>Bacillus subtilis</i> at 5 g kg ⁻¹ seed	1.29
T ₃ - Kinetin at 10 ppm + <i>Bacillus subtilis</i> at 5 g kg ⁻¹ seed	1.22

V₁ and V₂ denote wheat varieties. T₁, T₂ and T₃ denote treatment details. D₁, D₂ and D₃ are dates of sowing.

Table 6. Effect of different treatments on overall yield stability index (YSI) of wheat crop

Yield stability index (YSI)			
Sl. No.	Treatments	D1-D2	D1-D3
1	V ₁ T ₁	0.81	0.68
2	V ₁ T ₂	0.84	0.70
3	V ₁ T ₃	0.85	0.71
4	V ₂ T ₁	0.75	0.53
5	V ₂ T ₂	0.78	0.56
6	V ₂ T ₃	0.78	0.55
7	Mean	0.87	0.74

Among the plant growth regulators, the highest overall YSI recorded by paclobutrazol (1.29) followed by kinetin (1.22) and control (1.20).

Discussion

Canopy temperature depression

The CTD is an important physiological indicator of heat tolerance in wheat, reflecting the plant's ability to maintain cooler canopy temperatures through efficient transpiration and stomatal regulation. In the present study, early sowing on 25th November recorded the highest CTD values, indicating better plant water status and reduced heat stress compared to late and very late sowing dates. As timely sowing helps maintain better phenological development and reduces temperature-induced stress in wheat (25). Further, cooler canopy temperature is associated with better grain growth and yield performance under favourable sowing environments (26).

Among varieties, DBW 303 showed higher CTD values than JAUW 672, indicating superior physiological and heat stress adaptability. This might be due to the heat-tolerant wheat genotypes that maintain higher CTD values under stress conditions due to better water extraction and physiological stability (27).

Among plant growth regulators, paclobutrazol recorded higher CTD values than kinetin and control treatments, which may be due to improved chlorophyll stability, reduced canopy temperature and enhanced photosynthetic efficiency. These growth regulators improve photosynthetic performance and plant stress tolerance by improving physiological and antioxidant activities (28).

Heat-intensity index

The HII was used to quantify the degree of stress imposed by heat across different sowing dates. In this study, the HII increased progressively with delayed sowing, with crops sown on 5th January showing the highest values for key phenophases such as booting, heading, flowering, milking, dough and physiological maturity. This demonstrates the increasing severity of heat stress with very late sowing. The index effectively revealed the influence of sowing dates on phenological development under elevated temperature conditions. Such analyses emphasise the importance of choosing optimal sowing dates to avoid higher HII values and minimise heat stress impacts on wheat phenology. The results are supported by studies such as those by previous researchers, who used heat indices to screen wheat genotypes under temperature stress conditions (29,30).

Heat-susceptibility index

The HSI is widely used to quantify the relative performance stability of genotypes under contrasting thermal environments by

integrating yield and physiological responses to heat stress. In the present study, higher HSI values recorded in JAUW 672 indicate its greater vulnerability to terminal heat stress, particularly under delayed and very late sowing conditions. The higher susceptibility of JAUW 672 may be attributed to poor maintenance of cellular homeostasis under high temperature stress, resulting in reduced photosynthetic carbon assimilation, accelerated leaf senescence and impaired pollen viability and grain filling processes. High temperature stress during reproductive stages adversely affects spike fertility, assimilate partitioning and starch biosynthesis, thereby reducing yield potential and increasing stress susceptibility. In contrast, DBW 303 exhibited lower HSI values, reflecting superior thermotolerance mechanisms such as better stomatal regulation, higher water use efficiency and improved antioxidant defence systems, which collectively help maintain reproductive success under heat stress environments. These findings are consistent with earlier reports, which documented substantial genetic variability in heat stress adaptation due to differences in physiological efficiency and stress-responsive gene expression (31).

Among plant growth regulators, paclobutrazol recorded the lowest HSI values, followed by kinetin, whereas control treatments exhibited the highest susceptibility to heat stress. The superior performance of paclobutrazol may be attributed to its triazole-mediated growth regulation, which enhances stress tolerance by reducing excessive vegetative growth, improving source-sink balance, maintaining membrane integrity and enhancing the activity of antioxidant enzymes such as superoxide dismutase and catalase under thermal stress. Paclobutrazol also improves chlorophyll stability and reduces canopy temperature, thereby enhancing photosynthetic efficiency and assimilate transport to developing grains. Kinetin application also improved heat tolerance compared to control treatments by delaying leaf senescence, enhancing nucleic acid metabolism and sustaining cellular division and metabolic activity under stress conditions. These physiological adjustments improve grain setting efficiency and yield stability under sub-tropical heat stress environments. These observations are in accordance with previous studies, which emphasised the importance of stress susceptibility indices in identifying stress-resilient wheat genotypes and management practices for climate-resilient wheat production systems (32–34).

Yield stability index

The YSI is an important indicator of yield performance stability under stress and non-stress environments. In the present study, higher YSI values were recorded under 15th December sowing compared to 5th January sowing, indicating better yield stability under moderate heat stress. This may be attributed to favourable temperature conditions during reproductive stages that supported better grain formation, while very late sowing exposed crops to terminal heat stress, reducing grain filling duration and yield stability (35, 36).

Among varieties, DBW 303 showed higher YSI values than JAUW 672, indicating better physiological adaptability and heat stress tolerance due to superior assimilate partitioning and stress tolerance mechanisms (35, 36).

Among plant growth regulators, paclobutrazol recorded the highest YSI, followed by kinetin and control treatments. This improvement may be due to enhanced root growth, improved photosynthetic efficiency, better source-sink balance and delayed senescence under stress conditions (37). These findings are

consistent with previous studies (35–37), which reported YSI as a reliable parameter for identifying heat-tolerant and stable-yielding genotypes under stress-prone environments.

Conclusion

Based on the study findings, it can be concluded that the wheat crop sown on 25th November exhibited superiority over those sown on 15th December and 5th January across various parameters, including yield, canopy temperature depression (CTD) and yield stability index (YSI). Normal sowing on 25th November resulted in 25.08 % and 63.18 % higher grain yield compared to late (15th December) and very late (5th January) sowing dates, respectively. Among the wheat varieties, DBW 303, when cultivated under irrigated conditions in Jammu, emerged as a promising variety, showcasing favourable attributes related to yield and CTD, heat susceptibility index (HSI) and YSI under normal (25th November) and late (15th December) sowing dates. However, under very late (5th January) sowing conditions, both varieties (JAUW 672 and DBW 303) exhibited improved performance.

Among growth regulators paclobutrazol proved most effective in enhancing heat tolerance and yield stability across sowing environments, particularly under delayed planting conditions, followed by kinetin, while control treatments were most susceptible to heat stress. Overall, timely sowing on 25th November combined with variety DBW 303 and paclobutrazol application under irrigated conditions proved most effective in maximising yield, enhancing CTD, reducing heat susceptibility and improving yield stability under subtropical heat stress conditions of Jammu.

Authors' contributions

SS carried out an experimental trial on wheat crop and tabulated the results. MK conceived the experimental study, compiled the results and edited the manuscript. HSB and VT prepared the graphs. RS, MS and BKS assisted with the methodology and experimental procedures. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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