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# Deciphering heat stress tolerance for grain yield in bread wheat genotypes under the semi-arid region of Rajasthan

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## Abstract

Heat stress is a major abiotic constraint limiting wheat (*Triticum aestivum* L.) productivity, particularly in regions experiencing rising temperatures due to climate change. Our breeding program's ultimate goal is to develop thermal stress-tolerant cultivars and the realisation of the potential for yield in hot climates. In light of the above, the study was conducted in three environments, i.e. early, normal and late sown conditions with 18 diverse genotypes and their 45 $F_1$'s to magnify the yield level of wheat in high temperature areas by selecting stress-tolerant parents and cross combinations. Based on the HSI values, the genotypes were classified into four different categories, i.e. highly heat tolerant (HSI <0.50), heat tolerant (HSI: 0.51-0.75), moderately heat tolerant (HSI: 0.76-1.00), and heat susceptible (HSI >1.00). An overall assessment revealed that the parents HD 3086, WH 1081, RAJ 1482, HI 1563; and the crosses HI 1563 x RAJ 4238, RAJ 1482 x RAJ 4238, RAJ 4079 x HTWYT 37, WH 1142 x $F_1$, WH 1081 x $F_1$ and HI 1563 x $F_1$ were identified as desirable for most of the yield associated traits as they displayed maximum tolerance under heat stress conditions.

**Key words**: Wheat, heat susceptibility index, heat tolerance.

## Introduction

Wheat (*Triticum aestivum* L.) is one of the world's most important staple crops, providing a major source of calories and protein for a large portion of the global population. However, wheat production is increasingly threatened by heat stress, especially during critical growth stages such as flowering and grain filling. Heat stress-temperatures above the optimal range for a given period-can significantly impair physiological and biochemical processes in wheat, leading to reduced yield and grain quality (Asseng *et al*., 2015).

Elevated temperatures accelerate phenological development, shorten the grain-filling period, and can disrupt photosynthesis and reproductive processes (Zhao *et al*., 2017). Even brief periods of high temperature (above 30–35°C) during anthesis can cause pollen sterility, leading to significant yield losses (Farooq *et al*., 2011). With climate change models predicting more frequent and intense heatwaves, understanding and mitigating the impacts of heat stress on wheat is critical for global food security.

Our country has witnessed sensational growth in the production and productivity of wheat, which aids in the self-sufficiency regarding food grain production. The area and production of wheat in India were recorded 32.76 million ha and 117.50 million tonnes with an average productivity of 3587 kg ha$^{-1}$ in the year 2024-25, while in Rajasthan, area and production of wheat were recorded 3.16 million ha and 11.38 million tonnes, respectively with an average productivity of 3593 kg ha$^{-1}$ (Anonymous, 2025). The major heat stress-affected (post-anthesis grain filling period) wheat growing areas of Rajasthan include Sriganganagar, Hanumangarh, Bikaner, Churu, Jhunjhunu, Sikar, Jaipur, Alwar and Bharatpur. These areas reported a slight decline in average production during the crop maturity stages, thereby significantly decreasing overall productivity.

The yield potential of any wheat variety is determined by the complex interaction between its genetic makeup and environmental conditions. Rising temperatures have become a critical concern due to the fluctuation of recent climate change driven by global warming. Notably, elevated temperatures during the post-anthesis stages-particularly in late February and March-can accelerate grain development, shorten the grain-filling period, and lead to premature termination of grain growth, ultimately resulting in substantial yield losses. According to Elahmadi (1994), heat stress is a major constraint to wheat production, significantly affecting plant development. It leads to stunted growth, reduced tillering, and hastened phenological progression, resulting in smaller spike size, shrivelled grains, and ultimately lower yields. Acknowledging the above information, the current study was done to assess the heat tolerance of diverse bread wheat genotypes for the semi-arid regions of Rajasthan.

## Materials and Methods

The experimental material was selected based on genetic diversity, thermal tolerance and their stability for different yield traits, comprising 17 diverse wheat varieties, an $F_1$ (derived from a single cross from two varieties among the 17 varieties) and 45 different $F_1$'s (derived from one-way and three-way crosses).

Crosses were attempted as per the modified Triple Test Cross method (Ketata *et al*., 1976). Two genetically diverse genotypes, RAJ 4238, HTWYT 37 and their $F_1$ Hybrid (RAJ 4238 x HTWYT-37) were used as testers '$T_1$' (RAJ 4238), '$T_2$' (HTWYT-37) and '$T_3$' ($F_1$), respectively. During *rabi*, 2021-22; these three testers ($T_1$, $T_2$ and $T_3$) were used as male parents for crossing with 15 genotypes (WH 1142, HD 3086, WH 1081, HI 1563, PBW 550, PBW 396, WH 1021, PBW 590, C 306, RAJ 3765, RAJ 1482, RAJ 4120, RAJ 4079, PBW-621-50 and HTWYT 23) as female parents to develop 45 crosses in the form of 30 single crosses and 15 three-way crosses, followed by their evaluation in *rabi*, 2022-23 under three environments $E_1$, $E_2$, $E_3$ (three different dates of sowing 15$^{th}$, 28$^{th}$ Nov, 2022 and 9$^{th}$Dec 2023, respectively) following the 22.5 cm x 10 cm (R x P) crop geometry with a row length of 3 m allocated for each genotype (each genotype was allocated single row), at the Agricultural Research Farm of Rajasthan Agricultural Research Institute, Durgapura, Jaipur, Rajasthan.

Observations were recorded for days to 75% heading, days to maturity, plant height, no. of tillers per plant, grains per spike, spike length, 1000-grain weight, grain yield per plant, biological yield per plant, harvest index, protein content, starch content, chlorophyll content and heat injury on 5 randomly selected plants from each genotype. Mean values over the selected plant were used to analyse the heat susceptibility index.

Heat susceptibility index (HSI) was calculated for yield and other attributes over late sown ($E_3$) and normal sown ($E_2$) environments using the formula suggested by Fischer and Maurer (1978).

HSI = $[1- Y_D/Y_P]/D$

Where, $Y_D$ = mean of the genotypes in stress environment ($E_3$)

$Y_P$ = mean of the genotypes in the non-stress environment ($E_2$)

D = 1- [mean $Y_D$ of all genotypes/mean $Y_P$ of all genotypes].

The HSI values were used to characterize the relative tolerance of genotypes based on minimization of yield losses compared to normal environmental conditions. The differences between genotypes for different characters were tested for significance by using standard variance analysis techniques.

## Results and Discussion

The effects of climate change are increasingly evident through unpredictable weather patterns across various regions of India. Although the North-Western Plain Zone (NWPZ) generally experiences more favourable conditions for wheat cultivation compared to the Central Zone (CZ), wheat yields under late-sown conditions remain comparatively lower even in this key wheat-producing region (Mohan *et al*., 2015). Recognising this challenge, national research programs have prioritised the enhancement of thermal tolerance in wheat. Consequently, breeding for heat-tolerant genotypes has become a critical objective for wheat improvement programs.

The results of the current study indicated a reduction in the mean performance of parents and their crosses under heat stress, late sown conditions ($E_3$), compared to normal sown conditions ($E_2$) for all the traits. Singh *et al*. (2011), Agrawal *et al.* (2014), Abdallah *et al*. (2015), Sial *et al*. (2005), Bhardwaj *et al.* (2017), Sood *et al*. (2017), El-Rawy *et al*. (2018), Kumar *et al*. (2018), Mahdy *et al*. (2022), Kumar *et al.* (2023), and Thakur *et al*. (2020) also reported similar findings. The heat susceptibility index was calculated individually for each character in the stress environment ($E_{3,}$ late sown) against the non-stress environment ($E_1$, normal sown). Based on the HSI, the parents and crosses were classified as highly tolerant, tolerant, moderately tolerant and susceptible to heat stress.

Perusal of Table 1. Revealed that the parents $F_1$ (0.55), HD 3086 (0.35), WH 1081 (0.23), HI 1563 (0.49), RAJ 3765 (0.50), RAJ 1482 (0.45), RAJ 4120 (0.47) and PBW-621-50 (0.45) for days to 75% heading; WH 1081 (0.08), RAJ 3765 (0.10) and RAJ 4120 (0.46) for plant height; HI 1563 (0.15) and PBW-621-50 (0.02) for number of tillers per plant; HI 1563 (0.45) and C 306 (0.23) for grains per spike; HD 3086 (0.70), HI 1563 (0.36), C 306 (0.28) and PBW-621-50 (0.14) for spike length; PBW 396 (0.21) and RAJ 1482 (0.48) for grain yield per plant; RAJ 4079 (0.36) for biological yield per plant; RAJ 1482 (0.38) for harvest index; RAJ 1482 (0.22) for protein content; RAJ 4120 (0.27) for starch content; $F_1$ (0.49), WH 1142 (0.47) and PBW 590 (0.46) for chlorophyll content; HTWYT 37 (0.16), $F_1$ (0.33), PBW 550 (0.29) and PBW-621-50 (0.47) exhibited minimal susceptibility to heat stress in $E_3$ environment.

An overall assessment of parents across all studied traits indicated that HD 3086, WH 1081, RAJ 1482 and HI 1563 were identified as desirable for grain yield and most of their associated traits based on the heat susceptibility index (HSI).

Contemplating the heat susceptibility index (HSI) in $F_1$'s, Table 1.; the crosses PBW 396 x RAJ 4238 (0.46), WH 1021 x RAJ 4238 (0.11), PBW 590 x RAJ 4238 (0.35), RAJ 3765 x RAJ 4238 (0.36), RAJ 1482 x RAJ 4238 (0.46), C 306 x HTWYT 37 (0.32), RAJ 1482 x HTWYT 37 (0.43) and PBW 550 x $F_1$ (0.33) for days to 75% heading; WH 1021 x RAJ 4238 (0.15), RAJ 4120 x RAJ 4238 (0.18), HD 3086 x $F_1$ (0.29), WH 1081 x $F_1$ (0.01), HI 1563 x $F_1$ (0.48), PBW 396 x $F_1$ (0.04), PBW 590x $F_1$ (0.35), C 306 x $F_1$ (0.46), RAJ 3765 x $F_1$ (0.33) and RAJ 4120 x $F_1$ (0.37) for plant height; HI 1563 x RAJ 4238 (0.31), RAJ 3765 x RAJ 4238 (0.33), WH 1142 x HTWYT 37 (0.09), WH 1142 x $F_1$ (0.24), PBW 396 x $F_1$ (0.26), RAJ 1482 x $F_1$ (0.41) and RAJ 4120 x $F_1$ (0.50) for number of tillers per plant; RAJ 1482 x RAJ 4238 (0.41), RAJ 4079 x HTWYT 37 (0.26), WH 1142 x $F_1$ (0.39), WH 1081 x $F_1$ (0.37), HI 15163 x $F_1$ (0.28) and PBW 396 x $F_1$ (0.50) for grains per spike; WH 1142 x RAJ 4238 (0.11), HTWYT 23 x RAJ 4238 (0.31), WH 1081 x $F_1$ (0.49) and PBW 396 x $F_1$ (0.45) for spike length; WH 1142 x $F_1$ (0.50), PBW 396 x $F_1$ (0.48) and RAJ 4120 x $F_1$ (0.28) for biological yield per plant; HD 3086 x RAJ 4238 (0.49) for harvest index; WH 1081 x RAJ 4238 (0.30), PBW 550 x HTWYT 37 (0.47) and HTWYT 23 x $F_1$ (0.12) for protein content; PBW 550 x RAJ 4238 (0.16), WH 1021 x HTWYT 37 (0.42), PBW 590 x HTWYT 37 (0.38), RAJ 4120 x HTWYT 37 (0.47) and RAJ 4120 x $F_1$ (0.36) for starch content;WH 1081 x RAJ 4238 (0.10), RAJ 4079 x RAJ 4238 (0.37), WH 1021 x HTWYT 37 (0.22), PBW 550 x $F_1$ (0.17) and WH 1021 x $F_1$ (0.03), RAJ 4079 x $F_1$ (0.25) and HTWYT 23 x $F_1$ (0.18) for chlorophyll content; WH 1021 x RAJ 4238 (0.06), PBW 590 x RAJ 4238 (0.45), RAJ 3765 x RAJ 4238 (0.26), PBW-621-50 x RAJ 4238 (0.20), HD 3086 x HTWYT 37 (0.16), WH 1021 x HTWYT 37 (0.27), RAJ 3765 x HTWYT 37 (0.22) and HD 3086 x $F_1$ (0.35) for heat injury exhibited relatively higher tolerance among 45 crosses under heat stress conditions ($E_3$).

An overall assessment of crosses across all studied traits revealed that HI 1563 x RAJ 4238, RAJ 1482 x RAJ 4238, RAJ 4079 x HTWYT 37, WH 1142 x $F_1$, WH 1081 x $F_1$ and HI 1563 x $F_1$ were identified as desirable for most of the yield associated traits based on the heat susceptibility index (HSI).

Given that grain yield is a fundamental goal in all breeding programs, the crosses HD 3086 x RAJ 4238, PBW 550 x RAJ 4238, WH 1142 x $F_1$, HD 3086 x $F_1$, WH 1081 x $F_1$, WH 1021 x $F_1$ and C

**Table 1. Heat susceptibility index (HSI) determined as $E_2$ vs $E_3$ for different traits**

| Genotype | Days to 75 % heading | Days to maturity | Plant height | No. of tillers per plant | Grains per spike | Spike length | 1000-grain weight | Grain yield per plant | Biological yield per plant | Harvest index | Protein content | Starch content | Chlorophyll content (SPAD) | Heat injury |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Testers | | | | | | | | | | | | | | |
| RAJ-4238 | 1.20 | 0.96 | 0.70 | 0.55 | 1.19 | 1.05 | 1.51 | 1.13 | 1.28 | 1.13 | -0.22 | 0.98 | 0.51 | 0.89 |
| HTWYT-37 | 1.05 | 0.93 | -1.97 | 2.01 | 1.26 | -0.10 | 0.92 | 0.68 | 0.91 | 0.62 | 1.56 | 0.74 | 5.53 | 0.16 |
| $F_1$ | 0.55 | 0.95 | -1.01 | 1.23 | 1.50 | -1.41 | 0.91 | 0.74 | 1.28 | 0.61 | 0.31 | 0.92 | 0.49 | 0.33 |
| Lines | | | | | | | | | | | | | | |
| WH-1142 | 0.89 | 0.90 | -0.43 | -0.02 | 1.18 | -1.25 | 1.20 | 1.08 | 1.47 | 1.02 | -0.53 | 0.90 | 0.47 | 1.14 |
| HD-3086 | 0.35 | 0.81 | 0.74 | 0.76 | 1.55 | 0.70 | 0.84 | 0.75 | 1.24 | 0.64 | 0.86 | 1.04 | 3.62 | 0.58 |
| WH-1081 | 0.23 | 0.86 | 0.08 | 0.95 | 1.21 | -0.82 | 0.71 | 0.52 | 2.74 | -0.12 | 1.51 | 1.07 | 4.30 | 0.83 |
| HI-1563 | 0.49 | 0.96 | -0.79 | 0.15 | 0.45 | 0.36 | 0.73 | 0.83 | 1.73 | 0.65 | 0.80 | 1.35 | 1.55 | 0.97 |
| PBW-550 | 1.81 | 0.97 | -2.60 | 0.90 | 0.88 | 0.67 | 0.87 | 0.62 | 0.82 | 0.54 | 1.70 | 1.27 | 2.90 | 0.29 |
| PBW-396 | 1.10 | 0.91 | 0.55 | 1.61 | 0.53 | 1.32 | 0.93 | 0.21 | 1.41 | -0.09 | 1.08 | 0.63 | 0.87 | 0.91 |
| WH-1021 | 0.69 | 0.96 | -1.28 | -0.20 | 1.34 | -0.13 | 0.93 | 1.07 | 1.12 | 1.07 | 1.57 | 0.75 | 1.36 | 0.96 |
| PBW-590 | 0.74 | 0.95 | 0.67 | -0.09 | 1.06 | 1.25 | 1.00 | 0.92 | 1.63 | 0.80 | 1.17 | 0.62 | 0.46 | 1.97 |
| C-306 | 1.89 | 1.14 | 1.40 | 0.98 | 0.23 | 0.28 | 0.91 | 0.69 | 0.92 | 0.65 | -1.07 | 0.85 | 4.32 | 1.06 |
| RAJ-3765 | 0.50 | 0.93 | 0.10 | 1.26 | 0.63 | -1.08 | 0.94 | 0.82 | 0.88 | 0.80 | 1.62 | 0.90 | 2.21 | 0.63 |
| RAJ-1482 | 0.45 | 1.00 | -1.68 | 1.46 | 0.72 | 1.50 | 1.24 | 0.48 | 0.86 | 0.38 | 0.22 | 2.19 | 4.22 | 1.54 |
| RAJ-4120 | 0.47 | 0.83 | 0.46 | -1.08 | 0.74 | -0.58 | 0.79 | 1.00 | 1.16 | 0.95 | 2.13 | 0.27 | 2.18 | 1.19 |
| RAJ-4079 | 0.60 | 0.95 | -1.65 | -0.27 | 1.45 | -0.60 | 0.88 | 0.72 | 0.36 | 0.78 | 1.27 | 1.55 | 1.02 | 1.02 |
| PBW-621-50 | 0.45 | 0.85 | 0.55 | 0.02 | 1.13 | 0.14 | 0.76 | 1.32 | 1.19 | 1.38 | -0.44 | 0.99 | 1.98 | 0.47 |
| HTWYT-23 | 1.83 | 1.05 | -2.07 | -0.98 | 1.42 | -0.36 | 0.52 | 0.76 | 1.20 | 0.67 | -0.12 | 1.20 | 4.10 | 1.92 |
| Crosses | | | | | | | | | | | | | | |
| WH-1142 X RAJ-4238 | 1.12 | 0.93 | 2.06 | 1.01 | 0.71 | 0.11 | 1.53 | 1.19 | 0.77 | 1.29 | 1.02 | 0.65 | -0.88 | 2.17 |
| HD-3086 X RAJ-4238 | 0.57 | 0.85 | 0.54 | 1.18 | 1.56 | 1.02 | 1.33 | 0.56 | 0.94 | 0.49 | 1.37 | 0.96 | 1.00 | 0.89 |
| WH-1081 X RAJ-4238 | 0.80 | 0.93 | 2.51 | 1.82 | 0.89 | 2.57 | 1.17 | 0.94 | 0.87 | 0.96 | 0.30 | 1.01 | 0.10 | 1.69 |
| HI-1563 X RAJ-4238 | 2.04 | 1.05 | 1.09 | 0.31 | 2.01 | 1.78 | 1.19 | 1.09 | 0.92 | 1.13 | -0.69 | 1.73 | 2.17 | 0.82 |
| PBW-550 X RAJ-4238 | 2.48 | 1.05 | 2.23 | 0.53 | 1.21 | 0.85 | 0.57 | 0.73 | 0.89 | 0.68 | 1.93 | 0.16 | 2.96 | 1.44 |
| PBW-396 X RAJ-4238 | 0.46 | 1.06 | 1.75 | 0.74 | 1.03 | 1.00 | 1.07 | 0.92 | 0.77 | 0.93 | 1.17 | 1.42 | 0.37 | 1.51 |
| WH-1021 X RAJ-4238 | 0.11 | 1.09 | 0.15 | 1.03 | 1.08 | 1.83 | 1.34 | 1.33 | 0.98 | 1.41 | -0.31 | 0.66 | -3.21 | 0.06 |
| PBW-590 X RAJ-4238 | 0.35 | 1.03 | 1.51 | 1.65 | 1.21 | 1.09 | 0.91 | 1.01 | 0.60 | 1.08 | 1.01 | 0.98 | 0.76 | 0.45 |
| C-306 X RAJ-4238 | 1.82 | 1.26 | 2.08 | 0.95 | 1.55 | 1.50 | 1.16 | 1.35 | 0.85 | 1.45 | 1.42 | 1.02 | -1.97 | 2.14 |
| RAJ-3765 X RAJ-4238 | 0.36 | 1.00 | 2.82 | 0.33 | 0.81 | 2.21 | 1.21 | 1.02 | 1.30 | 1.00 | 0.89 | 1.87 | -0.17 | 0.26 |
| RAJ-1482 X RAJ-4238 | 0.46 | 1.01 | 0.63 | 1.86 | 0.41 | 2.82 | 1.11 | 1.42 | 0.92 | 1.55 | 2.57 | 0.92 | -0.39 | 0.55 |
| RAJ-4120 X RAJ-4238 | 1.19 | 1.00 | 0.18 | 1.51 | 1.17 | 0.28 | 1.07 | 0.98 | 1.55 | 0.87 | 1.22 | 0.82 | 3.66 | 0.79 |
| RAJ-4079 X RAJ-4238 | 0.86 | 1.01 | 1.67 | 0.90 | 0.73 | 0.85 | 0.96 | 1.39 | 1.37 | 1.46 | 1.80 | 0.83 | 0.37 | 0.66 |
| PBW-621-50 X RAJ-4238 | 1.63 | 0.84 | 1.78 | 1.90 | 1.86 | 2.48 | 0.85 | 1.02 | 0.82 | 1.08 | 1.01 | 0.77 | 1.93 | 0.20 |
| HTWYT-23 X RAJ-4238 | 2.17 | 0.95 | 0.83 | 0.88 | 1.63 | 0.31 | 0.86 | 1.09 | 0.61 | 1.18 | 1.17 | 1.22 | 2.14 | 0.54 |
| WH-1142 X HTWYT-37 | 1.53 | 0.92 | 0.71 | 0.09 | 1.18 | 0.73 | 1.26 | 0.88 | 1.14 | 0.85 | 1.09 | 1.32 | 1.78 | 0.74 |

**Table 1.** ***Continued ...***

| Genotype | Days to 75 % heading | Days to maturity | Plant height | No. of tillers per plant | Grains per spike | Spike length | 1000-grain weight | Grain yield per plant | Biological yield per plant | Harvest index | Protein content | Starch content | Chlorophyll content (SPAD) | Heat injury |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HD-3086 X HTWYT-37 | 0.91 | 0.98 | 0.99 | 1.51 | 1.30 | 2.13 | 1.15 | 0.97 | 1.00 | 0.97 | 1.37 | 1.86 | 1.71 | 0.16 |
| WH-1081 X HTWYT-37 | 0.99 | 0.99 | 1.75 | 1.00 | 0.85 | 1.83 | 1.13 | 0.91 | 0.85 | 0.91 | 1.33 | 1.64 | -1.55 | 1.70 |
| HI-1563 X HTWYT-37 | 0.66 | 0.92 | 2.31 | 0.92 | 1.12 | 1.86 | 1.25 | 0.87 | 1.02 | 0.87 | 1.28 | 1.57 | 1.49 | 0.58 |
| PBW-550 X HTWYT-37 | 0.78 | 0.95 | 2.22 | 0.68 | 1.46 | 2.76 | 0.88 | 1.07 | 0.70 | 1.13 | 0.47 | 1.06 | 3.48 | 0.92 |
| PBW-396 X HTWYT-37 | 1.73 | 0.99 | 2.37 | 1.80 | 0.73 | 1.71 | 0.98 | 1.28 | 0.43 | 1.42 | 1.27 | 1.36 | -0.35 | 2.13 |
| WH-1021 X HTWYT-37 | 1.43 | 0.99 | 0.82 | 0.53 | 0.74 | 2.58 | 1.18 | 0.98 | 0.43 | 1.10 | -0.52 | 0.42 | 0.22 | 0.27 |
| PBW-590 X HTWYT-37 | 1.33 | 0.99 | 1.24 | 0.81 | 1.73 | 2.62 | 1.07 | 1.15 | 0.81 | 1.24 | -1.45 | 0.38 | 2.74 | 1.25 |
| C-306 X HTWYT-37 | 0.32 | 1.23 | 0.95 | 0.78 | 1.39 | 1.67 | 0.95 | 1.28 | 0.61 | 1.38 | -0.89 | 1.26 | 0.54 | 1.31 |
| RAJ-3765 X HTWYT-37 | 1.65 | 1.00 | 0.16 | 0.97 | 0.97 | -0.35 | 1.11 | 1.13 | 0.70 | 1.22 | 1.14 | 0.67 | -0.48 | 0.22 |
| RAJ-1482 X HTWYT-37 | 0.43 | 1.08 | -0.26 | 1.81 | 1.82 | 3.05 | 1.27 | 1.17 | 0.89 | 1.23 | 2.39 | 0.61 | -2.46 | 0.61 |
| RAJ-4120 X HTWYT-37 | 0.66 | 1.07 | 1.48 | 0.94 | 0.83 | 0.90 | 1.05 | 1.09 | 1.10 | 1.13 | 1.67 | 0.47 | 2.60 | 0.77 |
| RAJ-4079 X HTWYT-37 | 0.76 | 1.04 | 0.92 | 1.87 | 0.26 | 1.72 | 0.93 | 1.24 | 0.97 | 1.35 | 1.84 | 1.39 | 1.14 | 1.32 |
| PBW-621-50 X HTWYT-37 | 1.21 | 0.96 | 1.82 | 1.56 | 1.21 | 0.57 | 0.99 | 1.07 | 0.74 | 1.14 | 1.42 | 1.11 | -3.17 | 0.63 |
| HTWYT-23 X HTWYT-37 | 0.98 | 0.91 | 0.84 | 0.66 | 0.79 | 2.78 | 0.86 | 1.26 | 1.23 | 1.33 | 0.54 | 0.85 | -2.99 | 1.53 |
| WH-1142 X $F_1$ | 1.64 | 1.10 | 0.89 | 0.24 | 0.39 | -0.05 | 1.05 | 0.52 | 0.50 | 0.51 | 1.65 | 1.40 | -0.82 | 0.96 |
| HD-3086 X $F_1$ | 0.67 | 1.00 | 0.29 | 1.02 | 0.87 | -0.30 | 0.70 | 0.70 | 0.96 | 0.65 | 2.14 | 1.27 | -0.18 | 0.35 |
| WH-1081 X $F_1$ | 0.66 | 0.99 | 0.01 | 1.30 | 0.37 | 0.49 | 0.56 | 0.72 | 1.22 | 0.61 | -0.90 | 1.11 | -1.23 | 1.07 |
| HI-1563 X $F_1$ | 0.91 | 1.14 | 0.48 | 0.65 | 0.28 | 2.29 | 1.16 | 0.91 | 0.78 | 0.93 | -0.44 | 1.09 | 3.57 | 0.90 |
| PBW-550 X $F_1$ | 0.33 | 0.97 | 2.74 | 1.84 | 0.69 | 2.33 | 0.77 | 1.22 | 0.83 | 1.30 | 1.48 | 1.74 | 0.17 | 1.82 |
| PBW-396 X $F_1$ | 1.86 | 1.09 | 0.04 | 0.26 | 0.50 | 0.45 | 0.91 | 1.01 | 0.48 | 1.11 | 0.98 | 1.22 | -1.61 | 0.55 |
| WH-1021 X $F_1$ | 0.89 | 1.02 | -0.98 | 1.67 | 0.80 | -0.34 | 1.15 | 0.74 | 0.85 | 0.68 | 1.83 | 0.52 | 0.03 | 0.59 |
| PBW-590 X $F_1$ | 0.87 | 1.09 | 0.35 | 1.81 | 1.04 | 0.60 | 1.06 | 1.20 | 0.78 | 1.31 | 3.42 | 1.03 | -0.59 | 1.04 |
| C-306 X $F_1$ | 0.87 | 1.01 | 0.46 | 1.05 | 0.86 | 1.77 | 1.02 | 0.71 | 1.00 | 0.68 | 1.43 | 1.41 | -0.45 | 0.71 |
| RAJ-3765 X $F_1$ | 1.30 | 1.10 | 0.33 | 0.82 | 0.73 | 0.54 | 0.99 | 0.84 | 0.74 | 0.85 | 1.68 | 0.72 | -0.55 | 0.56 |
| RAJ-1482 X $F_1$ | 1.75 | 1.16 | 1.81 | 0.41 | 0.94 | 1.86 | 1.24 | 1.34 | 1.24 | 1.40 | 1.64 | 0.54 | 2.69 | 0.87 |
| RAJ-4120 X $F_1$ | 1.00 | 1.10 | 0.37 | 0.50 | 0.78 | 0.63 | 1.02 | 1.08 | 0.28 | 1.22 | -0.21 | 0.36 | 2.28 | 1.62 |
| RAJ-4079 X $F_1$ | 0.75 | 0.97 | 1.61 | 0.55 | 0.82 | 2.29 | 0.75 | 1.21 | 0.55 | 1.33 | 0.98 | 1.29 | 0.25 | 1.10 |
| PBW-621-50 X $F_1$ | 0.97 | 1.05 | 0.60 | 0.79 | 1.16 | 0.79 | 1.11 | 1.30 | 0.66 | 1.44 | 2.13 | 0.80 | 1.70 | 1.63 |
| HTWYT-23 X $F_1$ | 1.65 | 1.01 | -0.14 | 1.28 | 0.74 | -0.12 | 0.98 | 1.19 | 1.17 | 1.20 | 0.12 | 1.08 | 0.18 | 1.38 |

**Table 2. Mean of all genotypes under normal ($E_2$) and heat stress ($E_3$) environments, per cent reduction in the mean performance of different characters under heat stress environment ($E_3$) as compared to normal environment ($E_2$) and heat stress intensity (D-value) for different characters**

| Characters | Mean of all genotypes in | | % Reduction | D-Value |
|---|---|---|---|---|
| | $E_2$ | $E_3$ | | |
| Days to 75% heading | 83.19 | 80.16 | 3.64 | 0.03 |
| Days to maturity | 116.59 | 95.63 | 17.97 | 0.18 |
| Plant height (cm) | 83.35 | 75.42 | 9.51 | 0.10 |
| No. of tillers per plant | 14.84 | 10.80 | 27.22 | 0.27 |
| Grains per spike | 60.67 | 52.65 | 13.21 | 0.13 |
| Spike length (cm) | 11.68 | 10.37 | 11.21 | 0.11 |
| 1000-grain weight (g) | 35.40 | 24.67 | 30.31 | 0.30 |
| Grain yield per plant (g) | 15.98 | 9.26 | 42.05 | 0.42 |
| Biological yield per plant (g) | 46.58 | 42.51 | 8.73 | 0.09 |
| Harvest index (%) | 34.95 | 22.38 | 35.96 | 0.36 |
| Protein content (%) | 10.75 | 11.06 | -2.88 | -0.03 |
| Starch content (%) | 61.52 | 55.10 | 10.43 | 0.10 |
| Chlorophyll content (SPAD) | 50.77 | 49.29 | 2.91 | 0.03 |
| Heat injury (%) | 35.20 | 37.85 | -7.52 | -0.08 |

(-) indicates a slight increase in the mean values of the traits.

306 x $F_1$ which demonstrated greater tolerance for grain yield per plant, were identified as desirable for thermal stress tolerance in $E_3$.

Traits with a low heat stress intensity (D-value) less than 0.20 indicated greater tolerance under heat stress/late sown environment ($E_3$), Table 2. Specifically, days to 75% heading (0.03), days to maturity (0.18), plant height (0.10), grains per spike (0.13), spike length (0.11), biological yield per plant (0.09), protein content (0.03), starch content (0.10), chlorophyll content (0.03) and heat injury (0.08) showed more tolerance. Conversely, traits such as number of tillers per plant (0.27), 1000-grain weight (0.30), grain yield per plant (0.42) and harvest index (0.36) exhibited higher heat stress intensity (D-value) ranging from 0.27 to 0.42, indicating they suffered more under heat stress/late sown conditions ($E_3$). Singh *et al*. (2011), Bhardwaj *et al.* (2017), Sood *et al.* (2017), Kumar *et al*. (2018), and Mahdy *et al.* (2022) also reported consistent findings regarding heat stress intensity.

## Conclusion

Based on the heat susceptibility index, the parents HD 3086, WH 1081, RAJ 1482 and HI 1563 and crosses HD 3086 x RAJ 4238, PBW 550 x RAJ 4238, WH 1142 x $F_1$, HD 3086 x $F_1$, WH 1081 x $F_1$, WH 1021 x $F_1$ and C 306 x $F_1$ were considered promising for heat tolerance under stress environment. Consequently, these genotypes are proposed as promising donors for heat tolerance and should be further exploited to enhance grain yield under late sowing conditions. Moreover, the Heat Susceptibility Index (HSI) should be emphasized as a critical selection parameter in breeding wheat for such environments.

## References

Abdallah, E., Ali, M. M. A., Yasin, M. A. T. and Salem, A. H. 2015. Combining ability and mode of gene action for earliness, yield and some yield attributes of bread wheat (*Triticum aestivum* L.) genotypes grown on different sowing dates. *Zagazig Journal of Agricultural Research*, **42**(2):215-235.

Anonymous, 2024-25. 3rd Advance estimates. Ministry of Agriculture & Farmers Welfare, Department of Agriculture & Farmers Welfare, India.

Agrawal, A.P., Pandey, D. and Pandey, D. 2014. Variation parameters for the heat tolerance index of wheat. *Journal of Wheat Research*, **6**(1): 37-40.

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D. and Zhu, Y. 2015. Rising temperatures reduce global wheat production. *Nature Climate Change*, **5**(2):143-147.

Bhardwaj, R., Sharma, A., Singh, H. and Sharma, B.K. 2017. Determination of heat susceptibility indices for some quantitative traits in bread wheat (*Triticum aestivum* L. em. Thell.). *International Journal of Pure and Applied Bioscience*, **5**(2): 230-239.

Elahmadi, A. B. 1994. Development of wheat germplasm tolerant to heat stress in Sudan. In: Saunders DA, Hettel GP (Eds.), Wheat in heat–stressed environment: Irrigated, Dry Areas and Rice–Wheat Farming System, Mexico, DF: CIMMYT, 48-54.

El-Rawy, M. A., Hassan, M. I., Omran, M. F. and El-defrawy, M. M. 2018. Gene action and combining ability of cellular thermotolerance in bread wheat (*Triticum aestivum* L.). *Plant Breeding and Biotechnology*, **6**(3): 206-220.

Farooq, M., Bramley, H., Palta, J. A., and Siddique, K. H. 2011. Heat stress in wheat during reproductive and grain-filling phases. *Critical Reviews in Plant Sciences*, **30**(6):491-507.

Fischer, R.A. and Maurer, R. 1978. Drought resistance in spring wheat cultivars I. grain yield responses. *Australia Journal of Agriculture Research*, **29**(5): 897- 912.

Ketata, H., E.L. Smith, L.K. Edwards and R.W. McNew. 1976. Detection of epistasis, additive and dominance variation in winter wheat. *Crop Science*, **16**: 1-4.

Kumar, P., Singh, H., Singh, J. and Choudhary, R.N. 2018. Estimation of heat stress tolerance for yield and its contributing attributes in bread wheat. *International Journal of Current Microbiology and Applied Sciences,* **7**(7): 3817-3825.

Kumar, H., Chugh, V., Kumar, M., Gupta, V., Prasad, S., Kumar, S. and Kumar, M. 2023. Investigating the impact of terminal heat stress on contrasting wheat cultivars: a comprehensive analysis of phenological, physiological, and biochemical traits. *Frontiers in Plant Science*, **14**:01-17.

Mahdy, A. G. M., Abdel-Haleem, S. H. M., Haridy, M. H. and Mohi, M. M. 2022. Combining ability and heterosis estimates for yield and its components in bread wheat (*Triticum aestivum* L.) under different sowing dates. *Archives of Agriculture Sciences Journal*, **5**(2):191-212.

Mohan, D., Mamrutha, H. M., Tyagi, B. S. and Sharma, Y. 2015. Weather conditions favouring high wheat productivity at some sites of Madhya Pradesh under late-sown conditions. *Wheat and Barley Newsletter*, ICAR-IIWBR, Karnal, 9 (1& 2).

Sial, M. A., Dahot, M. U., Arain, M. A., Mangrio, S. M., Naqvi, M. H. and Nizamani, N. A. 2005. Effect of time of planting and heat stresses on wheat advanced genotypes. *Pakistan Journal of Biotechnology*, **2**(1-2): 13-23.

Singh, K., Sharma, S. N. and Sharma, Y. 2011. Effect of high temperature on yield attributing traits in bread wheat. *Bangladesh Journal of Agricultural Research*, **36**(3): 415-426.

Sood, N., Mavi, G. S., Malhotra, A., Jhinjer, R. K., Singh, B., Kaur, B. and Sohu, V. S. 2017. Evaluating the performance of bread wheat (*Triticum aestivum* L.) genotypes for terminal heat tolerance. *International Journal of Agriculture, Environment and Biotechnology*, **10**(3): 295-302.

Thakur, P., Prasad, L.C., Prasad, R., Chandra, K. and Rashmi, K. 2020. Estimation of genetic variability, heat susceptibility index and tolerance efficiency of wheat (*Triticum aestivum* L.) for timely and late sown environments. *Electronic Journal of Plant Breeding*, **11**(3): 769-775.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y. and Asseng, S. 2017. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, **114**(35): 9326-9331.