**Harnessing Heat Susceptibility Index to Screen Bread Wheat Genotypes for Heat Tolerance**

**ABSTRACT**

|  |
| --- |
| Wheat is one of the major cereal crops that is extremely sensitive to heat stress, especially during reproductive stage, which adversely affects grain yield. Screening and evaluation of diverse genotypes using HSI (heat susceptibility index) is one of the effective methods that enable identification of heat-resilient lines for breeding programs. HSI values were estimated for forty-five genotypes including 8 lines, 4 testers, their 32 hybrids and one check for grain yield per plant and other major contributing traits such as biological yield per plant, chlorophyll content at 15 days after anthesis and chlorophyll content at 21 days after anthesis. Results revealed that among 45 genotypes, 14 genotypes, namely AKAW 5104 x DBW 110, MACS 6768, GW 547 x MP 3288, AKAW 5104 x GW 11, DBW 359 x MP 3288, MP 3557 x MP 3288, GW 547, LOK 1, GW 547 x DBW 110, HI 1669 x LOK 1, Check (GW 513), HI 1669 x DBW 110, GW 11 and AKAW 5104 had HIS<0.75 for grain yield per plant and related traits. Hence, these genotypes were considered as heat tolerant and on further evaluation for heterosis and combining ability these genotypes likely provide an opportunity to develop high yielding heat tolerant wheat varieties. |

*Keywords: Heat stress, Heat tolerance, Heat susceptibility index (HSI)*

1. **INTRODUCTION**

Wheat crop is one of the oldest and most extensively cultivated crops in human history. Currently, it is the most important grain crop feeding more than one-third of the world's population and it also occupy more land area than any other commercial food crop. Nutritionally, it is the most vital cereal crop, provides one-fifth of the total calories and proteins required in human diets (Bhutto *et al*., 2016). Owing to its wide cultivation over large area, high production and prominent position in international food grain trade wheat is popularly known as ‘King of the cereals’ (Burdak *et al*., 2023). As a result of its versatile significance, it provides opportunity for achieving food security, poverty alleviation and livelihood improvement.

Wheat belongs to the family Poaceae. India’s varied environmental conditions and dietary preferences economically support the cultivation of three specices viz., Triticum aestivum, Triticum durum and Triticum dicoccum. Among these, T. aestivum (bread wheat) accounts for about 95% to total production of wheat while durum wheat and dicoccum making 4% and 1% respectively (Sharma *et al*., 2013). Bread wheat, a hexaploid species with a chromosome number 2n = 6x = 42, is a highly self-pollinated winter crop grown in tropics and sub tropics regions. Wheat grain contain starch (60 – 68%), fat (1.5 -2.0%), cellulose (2.0 - 2.5%), protein (6.0 – 21.0 %), minerals such as zinc, iron, selenium and magnesium and include vitamins like thiamine and vitamin B (Malav *et al*., 2017). wheat is usually used in preparing diverse food products such as chapatti, bread, biscuits, noodles, cakes, pizzas, doughnuts, semolina etc. which is possible due to its visco elasticity capacity attained due to gluten protein which helps in dough development.

The world population was projected to increase by more than 25% by 2050 (El Hanafi *et al*., 2022). With the ongoing expansion of population in the nation, there will be requirement of more than 140 million tons of wheat grain to be produced by 2050, which is about 40 % increase from our present production scenario (Singh *et al*., 2019). However, to attain this there is a need to overcome challenges posed by climate change because wheat is a cold loving crop and rising temperatures are becoming a constraint in wheat production. In India, it has been predicted that with every 1ºC rise in temperature, wheat production will decrease by 4-6 million tonnes (Venkatesh *et al*., 2022). Among many abiotic and biotic stresses, terminal heat stress is one of the major constraints to the global wheat production

Heat stress significantly affects wheat by impairing its growth, development, and physiological processes, ultimately reducing grain yield. Delayed sowing often exposes wheat to terminal heat, which decreases grain filling period, plant height, tillering, biomass production, chlorophyll content, spike number and overall yield components. (Moshatati *et al*., 2012). High temperatures significantly shorten the grain filling duration, disrupting starch synthesis and deposition, which results in incomplete grain maturation and reduced kernel weight. The reproductive phase, especially from anthesis to maturity, is highly sensitive to heat, during which assimilate availability and translocation are severely hampered. High temperatures also accelerate chlorophyll breakdown and reduce photosynthetic efficiency by deactivating key enzymes like Rubisco (Raines, 2011). This decline in photosynthesis, along with decreased membrane stability, restricts assimilate movement from source to sink, thereby affecting grain formation. biological yield often plays a critical role in supplying assimilates for grain development declines due to reduced photosynthetic efficiency and early senescence. Lower biological yield under stress limits dry matter availability, ultimately reducing grain yield. Genotypes that maintain long grain filling period, higher biological yield and greater chlorophyll content under heat stress conditions demonstrate greater tolerance and perform more efficiently under elevated temperatures compared with other genotypes.

Identifying genotypes that thrive under environmental stress is a major goal in developing stress-tolerant cultivars (Khan and Kabir, 2014). While various screening techniques have been suggested, limited methods are available for assessing heat tolerance in wheat. Among many methods, Heat susceptibility index (HSI) developed by Fischer and Maurer (1978) is one of the yield-based stress indices that efficiently evaluate genotypic response under stress versus optimal conditions. HSI effectively distinguishes heat-tolerant genotypes from susceptible ones.

1. **MATERIALS AND METHODS**

**2.1 Plant Materials**

The experimental material consisted of eight lines (GW 547, HI 1669, MP 3557, MACS 6768, AKAW 5104, DBW 359, HD 2864 and GW 556), four testers (DBW 110, LOK 1, GW 11 and MP 3288) along with their 32 crosses developed through line x tester mating design and one check (GW 513). The lines and testers were obtained from Wheat Research Station, Junagadh Agricultural University, Junagadh.

**2.2 Experimental Design**

The experiment was conducted at Wheat Research Station, Junagadh Agricultural University, Junagadh during *Rabi* 2023-24 (crossing) and *Rabi* 2024-25 (evaluation) over three environments created by different dates of sowing. Forty -five genotypes were evaluated in a randomized block design in three replications over three environments viz, early sowing, timely sowing and late sowing for grain yield and its component traits in bread wheat. A single row plot of 3 meters was allotted randomly to each entry. The row-to-row and plant-to-plant distance was kept 22.5 cm and 10 cm, respectively. All the recommended cultural practices and plant protection measures were followed uniformly to grow healthy crop.

Five competitive plants per genotype in each replication in each environment (timely sowing and late sowing) were selected randomly for recording observations on different traits viz., grain filling period (plot basis), grain yield per plant (g), biological yield per plant (g) and chlorophyll content (at 15 and 21 days after anthesis)

**2.3 Statistical Analysis**

The Heat Susceptibility Index (HSI) was estimated for grain yield and its attributes by using following formula suggested by Fisher and Maurer (1978). The mean data of each genotype under timely sown and late sown conditions for each trait were used to obtain HSI of the traits

Where, Y1 andY2 are grain yield per plant of each genotype under normal and heat   
 stress environments, respectively and HI is the Heat Intensity. The heat intensity was   
 calculated using the formula.

Where, Y1 and Y2 are the average of all genotypes for the grain yield per plant under normal and heat stress environments, respectively. Similarly, other traits HSI values were also calculated using same formula. Based on HIS values the genotypes were classified into three distinct categories: heat tolerant (HSI: <0.75), moderately heat tolerant (HSI: 0.75-1.25) and heat susceptible (HSI: > 1.25) (Baranwal *et al*., 2024). In this study, Environment E2 (Timely sowing condition) was taken as normal environment, while E3 (Late sowing condition) was taken as stress environment for the calculation of heat intensity and heatsusceptibility index.

**3. RESULTS AND DISCUSSION**

**3.1 Meteorological data**

In wheat during the anthesis to grain maturity stage, 22–25 °C is optimum temperature for its normal growth and beyond this it causes damage which is irreversible (Farooq *et al*., 2011). Generally, the late sowing of wheat was done during first fort night of December and from meteorological data obtained from weather report collected at Junagadh meteorological station it was observed that mean maximum and minimum temperatures were normal during December (sowing of late sown condition) and from January, temperatures both maximum and minimum were slightly increased initially and later increased to maximum from February to April (Figure 1). During this increased temperature condition, the wheat crop is at vegetative to maturity stage. which mean that profound effect of heat stress is present on wheat crop and reduction in yield was majorly observed in late sown condition compared to normal sown or timely sown condition.

Figure 1. Graphical representation of maximum and minimum temperature during   
 *Rabi* season November 2024-April 2025

**3.2 Heat Susceptibility Indices**

The Heat susceptibility indices (HSI) of grain yield per plant were estimated for all genotypes and ranked based on lower HSI values and provided in Table 1 and Figure 2. All the genotypes were classified into heat tolerant, moderately heat tolerant and heat susceptible based on the HSI values of grain yield per plant and mentioned in Table 2. along with HSI values of related agronomic and physiological traits and their mean values in timely sowing and late sowing condition.

**3.2.1 Heat Tolerant genotypes**

The evaluation of 45 bread wheat genotypes, comprising 12 parents, 32 crosses and one check, during the Rabi 2024–25 season, revealed that fourteen genotypes recorded Heat Susceptibility Index (HSI) values below 0.75 (HSI<0.75), indicating that these genotypes tolerate to terminal heat stress. Among these 14 heat tolerant genotypes, six genotypes AKAW 5104 x DBW 110 (−0.86), MACS 6768 (−0.81), GW 547 x MP 3288 (−0.78), AKAW 5104 x GW 11 (−0.67), DBW 359 x MP 3288 (−0.60) and MP 3557 x MP 3288 (−0.12) recorded negative Heat Susceptibility Index (HSI) values, indicating that the effect of heat stress on grain yields of these genotypes was less than the heat stress experienced under normal sowing conditions. This was evident from their greater mean grain yield in late sown condition than in timely sown condition. These genotypes also recorded mean grain yields higher than the overall mean under stress conditions, suggesting that these genotypes had better adaptation to elevated temperature environments.

Grain yield is a cumulative result of many yield contributing traits. Therefore, genotypes that were found tolerant to heat stress for grain yield were also consistently maintained stable performance in key agronomic and physiological traits, including extended grain filling duration, increased biological yield and elevated chlorophyll content during the grain filling stage (15 and 21 days after anthesis). For instance, among 14 genotypes, all genotypes except LOK 1, check (GW 513) and AKAW 5104 for grain filling period and biological yield per plant, MACS 6768, HI 1669 x DBW 110, LOK 1, check (GW 513) and AKAW 5104 for chlorophyll content at 15 days after anthesis and LOK 1, HI 1669 x LOK 1 and AKAW 5104 for chlorophyll content at 21 days after anthesis had HSI values less than 0.75 and were tolerant to heat stress.

The capacity to maintain yield under heat stress was majorly due to improved photosynthetic efficiency and an optimally controlled source–sink relationships. An extended grain filling period facilitated increased assimilate deposition, which significantly contributed to improved grain mass and overall productivity in stressful conditions. Similarly, elevated chlorophyll content during key grain development stage represents delayed senescence and the continuation of efficient photosynthetic activity, strengthening the plant’s ability to cope with harsh environmental conditions. These outcomes showed that these genotypes can grow well even under high heat and makes them ideal alternatives for breeding programs that aim to develop wheat varieties with better heat tolerance and stable yields in changing weather conditions.

Similarly, other eight heat tolerant genotypes that were identified as the most promising were GW 547 (0.07), LOK 1 (0.17), GW 547 x DBW 110 (0.20), HI 1669 x LOK 1 (0.51), Check (GW 513) (0.51), HI 1669 x DBW 110 (0.52), GW 11 (0.56) and AKAW 5104 (0.71). These genotypes exhibited consistent grain yield performance under elevated temperature conditions, thereby reflecting their resilience and suitability for cultivation in regions prone to terminal heat stress. Similar studies on heat tolerance in wheat were conducted by Thakur *et al*. (2020), Agarwal *et al*. (2021), Devi *et al*. (2022), Baranwal *et al*. (2024), Jainth (2024), Patel *et al*. (2024), Vedi *et al*. (2024), etc. They identified various genotypes tolerant to heat stress with the help of HIS values.

**3.2.2 Moderately Heat Tolerant Genotypes**

Fifteen genotypes, namely AKAW 5104 x MP 3288 (0.75), AKAW 5104 x LOK 1 (0.79), GW 547 x LOK 1 (0.82), DBW 110 (0.84), HD 2864 x DBW 110 (0.86), DBW 359 x DBW 110 (0.88), GW 556 x DBW 110 (0.91), MACS 6768 x LOK 1 (0.94), MP 3557 x GW 11 (0.94), GW 556 x LOK 1 (0.94), GW 556 x GW 11 (0.98), MACS 6768 x GW 11 (1.03), HD 2864 x GW 11 (1.16), DBW 359 x LOK 1 (1.24), DBW 359 x GW 11 (1.25) exhibited moderate tolerance to heat stress, as indicated by their heat susceptibility index (HSI: 0.75–1.25). These genotypes displayed a noticeable reduction in grain yield under elevated temperatures but maintained a reasonable level of adaptation. It was also spotted that the grain filling period was moderately affected by heat stress for these genotypes as evident from mean values and HSI values. Among above mentioned genotypes none of the genotypes were found stable and adapted to late sowing condition for grain yield per plant indicating effect from heat stress. These discrepancies in performance under elevated temperatures underscore the need specialized breeding strategies to improve their resilience to heat stress**.**

**3.2.3 Heat Susceptible Genotypes**

In contrast, a significant number of genotypes displayed high HSI values (>1.25), indicating considerable susceptibility to heat stress. A total of sixteen genotypes MACS 6768 x MP 3288 (1.40), GW 547 x GW 11 (1.42), HD 2864 (1.45), MP 3288 (1.46), DBW 359 (1.48), GW 556 x MP 3288 (1.55), HI 1669 x MP 3288 (1.57), HD 2864 x LOK 1 (1.62), HI 1669 x GW 11 (1.75), MACS 6768 x DBW 110 (1.91), HD 2864 x MP 3288 (1.95), MP 3557 x DBW 110 (1.98), GW 556 (2.19), MP 3557 x LOK 1 (2.23), HI 1669 (2.26) and MP 3557 (2.32) were categorized as heat susceptible. The notable decrease in grain yield under heat stress conditions highlights their restricted adaptation to high-temperature environments, making them less suitable for cultivation in regions that are liable to terminal heat stress. These genotypes were more severely affected by heat stress, experiencing short grain filling period, reduced chlorophyll content and lesser total biomass production. The inefficient allocation of resources during grain formation led to decrease in grain yield. Additionally, early degradation of chlorophyll under stress conditions resulted in diminished photosynthetic activity, limiting carbohydrate accumulation that is needed for grain filling. The stress-induced shortening of the grain filling period further accounted for lesser grain weight and overall yield loss under heat stress conditions.

**Table 1. Heat susceptibility index for grain yield per plant (g) in wheat**

|  |  |  |  |
| --- | --- | --- | --- |
| **Sr. No** | **Genotype** | **HSI** | **Rank** |
| 1 | GW 547 | 0.07 | 07 |
| 2 | HI 1669 | 2.26 | 44 |
| 3 | MP 3557 | 2.32 | 45 |
| 4 | MACS 6768 | -0.81 | 02 |
| 5 | AKAW 5104 | 0.71 | 14 |
| 6 | DBW 359 | 1.48 | 34 |
| 7 | HD 2864 | 1.45 | 32 |
| 8 | GW 556 | 2.19 | 42 |
| 9 | DBW 110 | 0.84 | 18 |
| 10 | LOK 1 | 0.17 | 08 |
| 11 | GW 11 | 0.56 | 13 |
| 12 | MP 3288 | 1.46 | 33 |
| 13 | GW 547 x DBW 110 | 0.20 | 09 |
| 14 | HI 1669 x DBW 110 | 0.52 | 12 |
| 15 | MP 3557 x DBW 110 | 1.98 | 41 |
| 16 | MACS 6768 x DBW 110 | 1.91 | 39 |
| 17 | AKAW 5104 x DBW 110 | -0.86 | 01 |
| 18 | DBW 359 x DBW 110 | 0.88 | 20 |
| 19 | HD 2864 x DBW 110 | 0.86 | 19 |
| 20 | GW 556 x DBW 110 | 0.91 | 21 |
| 21 | GW 547 x LOK 1 | 0.82 | 17 |
| 22 | HI 1669 x LOK 1 | 0.51 | 10 |
| 23 | MP 3557 x LOK 1 | 2.23 | 43 |
| 24 | MACS 6768 x LOK 1 | 0.94 | 22 |
| 25 | AKAW 5104 x LOK 1 | 0.79 | 16 |
| 26 | DBW 359 x LOK 1 | 1.24 | 28 |
| 27 | HD 2864 x LOK 1 | 1.62 | 37 |
| 28 | GW 556 x LOK 1 | 0.94 | 24 |
| 29 | GW 547 x GW 11 | 1.42 | 31 |
| 30 | HI 1669 x GW 11 | 1.75 | 38 |
| 31 | MP 3557 x GW 11 | 0.94 | 23 |
| 32 | MACS 6768 x GW 11 | 1.03 | 26 |
| 33 | AKAW 5104 x GW 11 | -0.67 | 04 |
| 34 | DBW 359 x GW 11 | 1.25 | 29 |
| 35 | HD 2864 x GW 11 | 1.16 | 27 |
| 36 | GW 556 x GW 11 | 0.98 | 25 |
| 37 | GW 547 x MP 3288 | -0.78 | 03 |
| 38 | HI 1669 x MP 3288 | 1.57 | 36 |
| 39 | MP 3557 x MP 3288 | -0.12 | 06 |
| 40 | MACS 6768 x MP 3288 | 1.40 | 30 |
| 41 | AKAW 5104 x MP 3288 | 0.75 | 15 |
| 42 | DBW 359 x MP 3288 | -0.60 | 05 |
| 43 | HD 2864 x MP 3288 | 1.95 | 40 |
| 44 | GW 556 x MP 3288 | 1.55 | 35 |
| 45 | Check (GW 513) | 0.51 | 11 |

**Table 2 List of the genotypes classified based on heat susceptibility index (HSI) and its mean performance for other related traits.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **HSI**  **rank** | **Genotypes** | **Grain yield (g)** | | **HSI** | **Grain filling period** | | **HSI** | **Biological yield (g)** | | **HSI** | **Chlorophyll content (15 DAA)** | | **HSI** | **Chlorophyll content (21 DAA)** | | **HSI** |
| **E2** | **E3** | **E2** | **E3** | **E2** | **E3** | **E2** | **E3** | **E2** | **E3** |
| **Heat tolerant genotypes (HSI < 0.75)** | | | | | | | | | | | | | | | | |
| 1 | AKAW 5104 x DBW 110 | 11.33 | 13.17 | -0.86 | 38.00 | 35.00 | 0.41 | 28.33 | 27.50 | 0.16 | 30.47 | 31.04 | -0.12 | 23.47 | 25.04 | -0.32 |
| 2 | MACS 6768 | 11.00 | 12.67 | -0.81 | 35.00 | 33.00 | 0.30 | 31.83 | 33.50 | -0.29 | 35.75 | 31.01 | 0.85 | 28.75 | 25.01 | 0.63 |
| 3 | GW 547 x MP 3288 | 17.00 | 19.50 | -0.78 | 38.67 | 36.39 | 0.31 | 41.50 | 45.83 | -0.59 | 39.98 | 40.82 | -0.14 | 32.98 | 34.82 | -0.27 |
| 4 | AKAW 5104 x GW 11 | 13.17 | 14.83 | -0.67 | 31.58 | 28.27 | 0.55 | 35.00 | 37.83 | -0.45 | 32.31 | 32.61 | -0.06 | 25.31 | 24.61 | 0.13 |
| 5 | DBW 359 x MP 3288 | 11.83 | 13.17 | -0.60 | 36.33 | 32.67 | 0.53 | 27.50 | 28.33 | -0.17 | 43.58 | 40.00 | 0.53 | 36.58 | 39.00 | -0.32 |
| 6 | MP 3557 x MP 3288 | 14.83 | 15.17 | -0.12 | 39.67 | 37.00 | 0.35 | 33.33 | 38.33 | -0.84 | 33.67 | 31.01 | 0.51 | 26.67 | 24.01 | 0.48 |
| 7 | GW 547 | 18.33 | 18.10 | 0.07 | 45.10 | 42.48 | 0.30 | 47.67 | 45.83 | 0.22 | 39.32 | 36.32 | 0.49 | 32.32 | 30.32 | 0.30 |
| 8 | LOK 1 | 18.00 | 17.41 | 0.17 | 37.67 | 32.25 | 0.75 | 46.67 | 27.50 | 2.31 | 37.74 | 32.90 | 0.83 | 30.74 | 23.90 | 1.07 |
| 9 | GW 547 x DBW 110 | 21.58 | 20.78 | 0.20 | 40.33 | 36.50 | 0.50 | 35.80 | 39.47 | -0.58 | 41.31 | 39.44 | 0.29 | 34.31 | 33.11 | 0.17 |
| 10 | HI 1669 x LOK 1 | 17.50 | 15.83 | 0.51 | 36.21 | 34.50 | 0.25 | 47.00 | 44.00 | 0.36 | 36.96 | 33.25 | 0.65 | 29.96 | 24.25 | 0.92 |
| 11 | Check (GW 513) | 16.97 | 15.33 | 0.51 | 40.33 | 31.67 | 1.12 | 46.00 | 34.50 | 1.40 | 37.12 | 30.83 | 1.09 | 30.12 | 25.83 | 0.69 |
| 12 | HI 1669 x DBW 110 | 11.83 | 10.67 | 0.52 | 35.33 | 31.57 | 0.56 | 25.17 | 22.67 | 0.56 | 35.17 | 30.92 | 0.78 | 28.17 | 24.92 | 0.56 |
| 13 | GW 11 | 17.76 | 15.90 | 0.56 | 38.00 | 34.68 | 0.46 | 42.70 | 39.83 | 0.38 | 36.77 | 32.61 | 0.73 | 29.77 | 25.94 | 0.62 |
| 14 | AKAW 5104 | 15.59 | 13.50 | 0.71 | 36.33 | 30.00 | 0.91 | 41.17 | 30.33 | 1.48 | 32.68 | 26.06 | 1.30 | 25.68 | 17.06 | 1.62 |

**Table 2 cont.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **HSI**  **rank** | **Genotypes** | **Grain yield (g)** | | **HSI** | **Grain filling period** | | **HSI** | **Biological yield (g)** | | **HSI** | **Chlorophyll content (15 DAA)** | | **HSI** | **Chlorophyll content (21 DAA)** | | **HSI** |
| **E2** | **E3** | **E2** | **E3** |  | **E2** | **E3** | **E2** | **E3** | **E2** | **E3** |
| **Moderately heat tolerant genotypes (HSI: 0.75-1.25)** | | | | | | | | | | | | | | | | |
| 15 | AKAW 5104 x MP 3288 | 14.36 | 12.33 | 0.75 | 37.33 | 31.01 | 0.88 | 54.17 | 49.17 | 0.52 | 31.19 | 25.99 | 1.07 | 24.19 | 26.99 | -0.56 |
| 16 | AKAW 5104 x LOK 1 | 14.52 | 12.37 | 0.79 | 33.00 | 27.28 | 0.91 | 51.67 | 49.67 | 0.22 | 31.53 | 28.58 | 0.60 | 24.53 | 20.58 | 0.78 |
| 17 | GW 547 x LOK 1 | 23.25 | 19.67 | 0.82 | 42.33 | 30.17 | 1.50 | 55.67 | 44.67 | 1.11 | 40.09 | 32.46 | 1.22 | 33.09 | 26.46 | 0.97 |
| 18 | DBW 110 | 15.83 | 13.33 | 0.84 | 40.42 | 35.17 | 0.68 | 36.77 | 35.67 | 0.17 | 33.7 | 24.46 | 1.76 | 26.70 | 25.46 | 0.22 |
| 19 | HD 2864 x DBW 110 | 15.12 | 12.67 | 0.86 | 37.27 | 30.00 | 1.02 | 47.30 | 39.00 | 0.99 | 32.36 | 26.57 | 1.15 | 25.36 | 20.57 | 0.91 |
| 20 | DBW 359 x DBW 110 | 23.92 | 19.98 | 0.88 | 34.00 | 27.16 | 1.05 | 34.33 | 36.17 | -0.30 | 43.18 | 38.44 | 0.71 | 36.18 | 32.44 | 0.50 |
| 21 | GW 556 x DBW 110 | 21.70 | 18.00 | 0.91 | 41.67 | 31.98 | 1.22 | 41.83 | 37.7 | 0.55 | 40.12 | 36.78 | 0.54 | 33.12 | 27.78 | 0.78 |
| 22 | MACS 6768 x LOK 1 | 19.84 | 16.33 | 0.94 | 35.87 | 29.00 | 1.00 | 47.80 | 38.33 | 1.11 | 27.77 | 22.71 | 1.17 | 20.77 | 13.71 | 1.64 |
| 23 | MP 3557 x GW 11 | 16.00 | 13.17 | 0.94 | 37.67 | 27.50 | 1.41 | 40.00 | 31.00 | 1.26 | 35.72 | 29.24 | 1.17 | 28.72 | 20.24 | 1.42 |
| 24 | GW 556 x LOK 1 | 21.45 | 17.67 | 0.94 | 37.54 | 29.50 | 1.12 | 40.20 | 40.33 | -0.02 | 42.32 | 34.69 | 1.16 | 35.32 | 27.69 | 1.04 |
| 25 | GW 556 x GW 11 | 22.78 | 18.58 | 0.98 | 42.00 | 29.50 | 1.56 | 41.00 | 27.00 | 1.92 | 43.11 | 35.53 | 1.13 | 36.11 | 26.53 | 1.28 |
| 26 | MACS 6768 x GW 11 | 14.67 | 11.83 | 1.03 | 34.64 | 29.50 | 0.78 | 27.00 | 26.33 | 0.14 | 34.96 | 31.29 | 0.68 | 27.96 | 22.29 | 0.98 |
| 27 | HD 2864 x GW 11 | 15.34 | 12.00 | 1.16 | 33.8 | 27.17 | 1.02 | 43.50 | 38.00 | 0.71 | 31.18 | 24.65 | 1.35 | 24.18 | 18.65 | 1.10 |
| 28 | DBW 359 x LOK 1 | 22.17 | 17.00 | 1.24 | 40.00 | 27.00 | 1.70 | 66.00 | 45.83 | 1.72 | 44.18 | 34.22 | 1.45 | 37.18 | 25.22 | 1.55 |
| 29 | DBW 359 x GW 11 | 22.00 | 16.83 | 1.25 | 36.67 | 28.50 | 1.16 | 38.50 | 36.67 | 0.27 | 46.45 | 34.46 | 1.66 | 39.45 | 25.46 | 1.71 |

**Table 2 cont.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **HSI**  **rank** | **Genotypes** | **Grain yield (g)** | | **HSI** | **Grain filling period** | | **HSI** | **Biological yield (g)** | | **HSI** | **Chlorophyll content (15 DAA)** | | **HSI** | **Chlorophyll content (21 DAA)** | | **HSI** |
| **E2** | **E3** | **E2** | **E3** | **E2** | **E3** | **E2** | **E3** | **E2** | **E3** |
| **Heat susceptible genotypes (HSI > 1.25)** | | | | | | | | | | | | | | | | |
| 30 | MACS 6768 x MP 3288 | 15.17 | 11.17 | 1.40 | 35.24 | 27.58 | 1.14 | 36.67 | 22.00 | 2.25 | 35.21 | 25.08 | 1.85 | 28.21 | 16.08 | 2.07 |
| 31 | GW 547 x GW 11 | 22.14 | 16.23 | 1.42 | 33.24 | 25.50 | 1.22 | 43.50 | 33.83 | 1.25 | 43.81 | 33.14 | 1.57 | 36.81 | 24.14 | 1.66 |
| 32 | HD 2864 | 13.28 | 9.67 | 1.45 | 34.00 | 26.34 | 1.18 | 31.67 | 24.83 | 1.21 | 30.76 | 24.89 | 1.23 | 23.76 | 15.89 | 1.60 |
| 33 | MP 3288 | 14.25 | 10.33 | 1.46 | 43.00 | 38.27 | 0.57 | 34.10 | 23.33 | 1.77 | 30.6 | 23.32 | 1.53 | 23.60 | 14.32 | 1.90 |
| 34 | DBW 359 | 21.00 | 15.17 | 1.48 | 38.00 | 25.50 | 1.72 | 37.17 | 30.83 | 0.96 | 36.68 | 27.11 | 1.68 | 29.68 | 18.11 | 1.88 |
| 35 | GW 556 x MP 3288 | 17.67 | 12.50 | 1.55 | 39.67 | 28.00 | 1.54 | 44.17 | 26.83 | 2.21 | 40.18 | 30.92 | 1.48 | 33.18 | 21.92 | 1.64 |
| 36 | HI 1669 x MP 3288 | 18.83 | 13.28 | 1.57 | 44.74 | 28.14 | 1.94 | 41.67 | 30.00 | 1.57 | 42.57 | 32.88 | 1.47 | 35.57 | 23.88 | 1.59 |
| 37 | HD 2864 x LOK 1 | 13.17 | 9.17 | 1.62 | 35.33 | 25.52 | 1.45 | 29.83 | 23.50 | 1.19 | 30.48 | 24.94 | 1.17 | 23.48 | 15.94 | 1.55 |
| 38 | HI 1669 x GW 11 | 17.17 | 11.51 | 1.75 | 34.67 | 24.17 | 1.58 | 48.50 | 35.50 | 1.51 | 37.28 | 32.67 | 0.80 | 30.28 | 23.67 | 1.05 |
| 39 | MACS 6768 x DBW 110 | 17.67 | 11.33 | 1.91 | 40.33 | 30.50 | 1.27 | 41.17 | 25.00 | 2.21 | 35.98 | 28.5 | 1.34 | 28.98 | 19.50 | 1.58 |
| 40 | HD 2864 x MP 3288 | 15.26 | 9.67 | 1.95 | 31.24 | 24.40 | 1.14 | 45.67 | 20.50 | 3.10 | 31.03 | 22.69 | 1.73 | 24.03 | 13.69 | 2.08 |
| 41 | MP 3557 x DBW 110 | 19.67 | 12.33 | 1.98 | 36.33 | 27.00 | 1.34 | 48.33 | 29.17 | 2.23 | 34.28 | 29.86 | 0.83 | 27.28 | 20.86 | 1.14 |
| 42 | GW 556 | 19.33 | 11.36 | 2.19 | 41.67 | 31.24 | 1.31 | 35.30 | 25.83 | 1.51 | 40.69 | 33.32 | 1.17 | 33.69 | 24.32 | 1.34 |
| 43 | MP 3557 x LOK 1 | 20.67 | 12.00 | 2.23 | 32.14 | 29.50 | 0.43 | 47.80 | 22.33 | 2.99 | 33.03 | 27.33 | 1.11 | 26.03 | 18.33 | 1.43 |
| 44 | HI 1669 | 16.18 | 9.30 | 2.26 | 38.66 | 29.12 | 1.29 | 27.50 | 24.17 | 0.68 | 34.58 | 30.85 | 0.69 | 27.58 | 21.85 | 1.00 |
| 45 | MP 3557 | 19.50 | 11.00 | 2.32 | 38.66 | 29.12 | 1.29 | 27.50 | 24.17 | 0.68 | 34.58 | 30.85 | 0.69 | 27.58 | 21.85 | 1.00 |

HSI: heat sensitivity index; E2: Timely sowing condition (normal environment); E3: Late sowing condition (stress environment)



**Figure 2. Heat susceptibility index of forty-five genotypes of bread wheat**

**CONCLUSION**

Heat Susceptibility Index (HSI) has emerged as a valuable quantitative tool to assess the tolerance of wheat genotypes to heat stress. HSI measures the extent of grain yield reduction under high-temperature conditions and helps identify genotypes with better adaptability and yield stability under heat stress. Among all the genotypes AKAW 5104 x DBW 110, MACS 6768, GW 547 x MP 3288, AKAW 5104 x GW 11, DBW 359 x MP 3288, MP 3557 x MP 3288, GW 547, LOK 1, GW 547 x DBW 110, HI 1669 x LOK 1, Check (GW 513), HI 1669 x DBW 110, GW 11 and AKAW 5104 were found heat tolerant for grain yield per as well as yield related traits such as grain filling period, biological yield and chlorophyll content at 15 and 21 days after anthesis that cumulatively contribute to grain yield. A lower HSI value indicates higher heat tolerance and the genotype experiences minimal yield loss despite high temperatures. This stability in yield and related traits suggests that the plant can maintain key physiological and biochemical processes under stress, making it suitable for cultivation in heat-prone environments. Thus, genotypes with low HSI values are considered more resilient and efficient under heat stress conditions. Heat tolerant genotypes on further evaluation for heterosis and combining ability for grain yield and yield related traits likely provide an opportunity to select productive parents that that combine well with other genotypes and superior crosses that produce transgressive segregants for specific character along with resilience to heat stress.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declares that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text to image generators have been used during writing or editing of manuscript.

**REFERENCES**

Agarwal, V. P., Gupta, N. K., Gupta, S. and Singh, G. (2021). Screening of wheat germplasm for terminal heat tolerance under hyper-arid conditions. *Cereal Research Communications*, **49(3)**: 375-383.

Baranwal, D., Kumar, R., Azad, C. and Munjal, R. (2024). Assessment of terminal heat tolerance among wheat (*Triticum aestivum*) genotypes based on multivariate analysis and selection indices. *The Indian Journal of Agricultural Sciences*, **94(9)**:923-928

Bhutto, A. H., Rajpar, A. A., Kalhoro, S. A., Ali, A., Kalhoro, F. A. and Ahmed, M. (2016). Correlation and regression analysis for yield traits in wheat (*Triticum aestivum* L.) genotypes. *Natural Science*, **8**: 96-104.

Burdak, A., Prakash, V., Kakralya, B. L., Gupta, D. and Choudhary, R. (2023). Heterotic performance and inbreeding depression for yield and component traits in bread wheat (*Triticum aestivum* L. em. Thell.). *International Journal of Environment and Climate Change*, **13(3)**: 56-64.

Devi, K., Chahal, S., Pandey, G.C., Rinki. and Tiwari, R. (2022). Utilization of heat susceptibility index for comparative evaluation of consistent yield performance in wheat under heat stress. *National Academy Science Letters*, **45(4)**: 291-295.

El Hanafi, S., Cherkaoui, S., Kehel, Z., Sanchez-Garcia, M., Sarazin, J. B., Baenziger, S. and Tadesse, W. (2022). Hybrid seed set in relation with male floral traits, estimation of heterosis and combining abilities for yield and its components in wheat (*Triticum aestivum* L.). *Plants*, **11(4)**: 508.

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

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

Jainth, H. (2024). Elucidating the morpho-physiological and biochemical changes in wheat genotypes (*Triticum aestivum* L.) under terminal heat stress condition. M. Sc. (Agri.), Banda University of Agriculture and Technology, Banda, UP, Krishikosh Repository. <https://krishikosh.egranth.ac.in/items/> 2ca6d10f-0e26-43e7-aafb-23e56a22fe25.

Khan, A.A. and Kabir, M.R. (2014). Evaluation of spring wheat genotypes (*Triticum aestivum* L.) for heat stress tolerance using different stress tolerance indices*. Cercetari Agronomice în Moldova*, **160(4)**: 49-63.

Malav, A. K., Monpara, B. A., Gaur, A. and Bhati, S. S. (2017). Character association analysis in yield and yield components in bread wheat (*Triticum aestivum* L.) genotypes. *Journal of Plant Development Sciences*, **9(2)**:77-83.

Moshatati, A., Siadat, S.A., Alami Saeid, K., Bakhshandeh, A.M. and Jalal Kamali, M.R. (2012). Effect of terminal heat stress on yield and yield components of spring bread wheat cultivars in ahwaz, Iran. *International Journal of Agriculture: Research and Review*, **2(6)**: 844-49.

Patel, N. S., Patel, J. B. and Tomar, R. S. (2024). Identification of heat tolerant bread wheat (*Triticum aestivum* L.) genotypes through heat susceptibility index (HSI) and SSR markers. *Cereal Research Communications*, **52(2)**:465-474.

Raines, C. A. (2011) Increasing photosynthetic carbon assimilation in C3 plants to improve crop yield: Current and future strategies. *Plant Physiology*, **155 (1)**: 36 - 42

Sharma, I., Singh, G. and Gupta, R.K. (2013). Wheat Improvement in India. In: *Improving Wheat Productivity in Asia*, 81p.

Singh, G. P., Sendhil, R. and Jasrotia, P. (2019). AICRP on wheat and barley salient achievements and future directions. *Indian Journal of Fertilizers*, **15(4)**: 80-90.

Thakur, P., Prasad, L.C., Prasad, R. and Chandra, 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(03)**: 769-775.

Vedi, A., Raghuvanshi, D., Tripathi, A. and Pandey, G. C. (2024). Characterization of traits associated with grain yield under terminal heat stress in bread wheat (*Triticum aestivum* L.) on the basis of heat susceptibility index. *National Academy Science Letters*, **47(2)**:173-175

Venkatesh, K., Senthilkumar, K. M., Mamrutha, H. M., Singh, G. and Singh, G. P. (2022). High temperature stress in wheat under climate change scenario, effects and mitigation strategies. In: *Climate change and crop stress.* Academic Press, pp. 209-229.