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**Research Article**

# Genetic Analyses of Grain Yield and Yield-attributing Traits in Wheat (*Triticum aestivum* L.) Grown under Terminal Heat Stress

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**ABSTRACT**

Terminal heat stress is a key constraint in wheat cultivation and its impact is anticipated to increase in the current context of climate change. Heat stress poses a serious threat, especially during the reproductive and grain-filling stages in wheat that can causes a significant reduction in yield. The current research was carried out to assess the nature of genetic variability and the relationship between yield and yield attributing traits of 30 different wheat genotypes grown under terminal heat stress and also to isolate the best performing genotypes based on stress tolerance indices. The highest estimates of Phenotypic Coefficient of Variation (PCV) and Genotypic Coefficient of Variation (GCV) were observed for plant height 67 and 65, respectively. Most of the traits showed high heritability, among which days to germination (98.45%), plant height (96.51%), total grain per plant (99.71%) exhibited the highest. The highest genetic advance was estimated in filled spikelet per spike (97.37%). Total grain weight and hundred grain weight had strong positive correlation with yield per plant. The characters viz., plant height, chlorophyll content, no. of tiller per plant, days to 50% flowering, filled grain, hundred grain weight, flag leaf length, days to booting, total grain weight had a positive direct effect on grain yield. In this experiment, SADH-2, DSN-76, NK-5, NE-3, SA-2 had the lowest value of Tolerance Index (TOL) which indicated that they had high tolerance towards heat stress. The highest value of Yield Stability Index (YSI) was observed in DSN-76, NE-3, BAW 1008, NK-5, SADH-22 which indicated that they had lower yield reduction and higher yield stability under heat stress. The optimum sowing date showed better performance for all the examined traits compare to heat stress condition. The identified genotypes hold promise for future breeding programs aimed at developing wheat varieties resilient to terminal heat stress.



## Introduction

Wheat is considered as the most cultivated crop globally with 761 Mt produced in 2021 and essential to worldwide food security and agricultural food systems. Around the world, approximately 17% of grain production is involved in international trade, with individual commodities' shares varying from 9% for rice to 25% for wheat (OECD/FAO, 2021). Wheat holds a pivotal role in human diet, contributing 20% of the daily protein and caloric intake. Wheat consumption in Bangladesh has seen a two-fold increase from 1961 to 2013, reaching 17.5 kg per person, which is approximately one-ninth of the consumption of rice (Mottaleb *et al.*, 2018). Despite the continuous rise in global wheat production over the years, the pace of yield enhancement has either slowed down or decreased in specific wheat-producing regions such as Eastern Europe, Central India, and Western Australia. Furthermore, the anticipated yield increases are not meeting the expected future demand for grain (Ray *et al.*, 2013). Heat stress is one of the major reasons for the low production and a serious threat to the crop production worldwide (Hall, 2001). Since 1880, the global temperature has risen slightly over 1°C (2°F). By the 21st century's end, it's expected to increase by 6°C (De Costa, 2011), affecting the anthesis and grain filling stages of temperate cereal crops. It was predicted that an increase of 1°C temperature cause decline in global wheat production by 6% (Yu *et al.,* 2013). Terminal heat stress, a common occurrence, impacts the anthesis and grain filling stages of wheat. Globally, about seven million hectares of wheat affected by heat stress throughout the life cycle and 40 % crop faces terminal heat stress (Ruwali and Bhawsar, 2000). It affects flowering, pollen viability, and the transfer of photosynthates to the developing kernel. This stress

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also influences starch synthesis and its accumulation within the kernel, leading to a decrease in grain number, weight, and quality due to rising temperatures (Gonzalez-Navarro *et al.,* 2015). According to Poulton and Rawson (2011), Bangladesh has seen a yearly temperature increase of 0.35°C over the last two decades (Mottaleb *et al.*, 2018). If this continues, by 2050, the temperature will be 2.13°C higher than in 1990. This rise in temperature will undoubtedly impact wheat production significantly. Given its large population and limited agricultural land, Bangladesh faces a serious risk of food insecurity. This enables wheat breeders to strategize and lessen the impacts of ongoing global warming. It's well-documented that heat stress plays a major role in diminishing wheat yield and quality (Stone and Nicolas, 1995). Wheat Research Centre tried to develop heat tolerant wheat varieties in Bangladesh but suitable variety of heat-tolerant wheat has yet to be properly identified in the country. A typical approach to selecting plants for heat stress tolerance involves cultivating breeding materials in a high-temperature target environment and identifying individual plants or lines that exhibit higher yield potential (Ehlers and Hall, 1998). Testing promising wheat lines under both optimum and heat stress conditions are crucial, with heat tolerance indices typically used to select heat-resistant wheat cultivars. Therefore, the objective of the research is to isolate the best performing wheat genotypes grown under terminal heat stress conditions based on yield attributes and stress tolerance indices. Importantly, we also assess the nature of genetic variability and the relationship between yield and yield attributing traits.

## Materials and Methods

The Genetics and Plant Breeding Department's Farm Laboratory at Bangladesh Agricultural University (BAU), Mymensingh, was the site of the experiment. The field is situated at 24°75′ N latitude and 90°50′ E longitude, 18m above sea level. The farmland is part of the Old Brahmaputra floodplain Agro-ecological Zone and has non-calcareous dark grey floodplain soil. Sandy loam soil with a pH of 6.5 best describes the soil texture. The study was conducted during the Rabi season, from November 2021 to April 2022, using a randomized complete block design (RCBD) with five sowing dates *viz* $21^{st}$ Nov (optimum), $1^{st}$ Dec, $11^{th}$ Dec, $21^{st}$ Dec. and $31^{st}$ Dec. Terminal heat stress was imposed by manipulating sowing dates. Seeds were planted in 4 m x 1.25 m rows, with 25 cm and 5 cm spacings between rows and plants respectively, and 35 cm gaps between plots. Weeding was done on each 30 plots 30 days after sowing. Other agronomic practices were taken in standard dose to give high yield potential. The genotypes included BL-1020, NK-5, KT-1-40, PV-79, KAV-2, DSN-117, SA-2, SA-3, SA-7, SA-8, NE-3, BAW 457, BAW 677, BAW 897 (BARI Gom 19), BAW 898 (BARI Gom 20), BAW 960, BAW 456, BAW 966, BAW 1004, BAW 1008, BAW 1006, BAW 1027, FDS-5, Bijoy, Shatabdi, DSN-76, SADH-12, SADH-14, SADH-22, and SADH-24. Five plants were selected from each plot and data on days to germination, plant height, no. of tiller/plant, flag leaf length, canopy temperature, chlorophyll content, days to booting, days to 50% flowering, pollen viability, spike length, no. of spikelets/spike, filled spikelets/spike, unfilled spikelets/spike, 100-grain weight, total straw weight and yield/plant after harvest were collected in each replication. Statistical analysis was performed using R-software, MS office excel program as done by Tithi and Sagor (2023). Different heat tolerance indices were estimated as Rosielle and Hamblin (1981); Fischer and Maurer (1978); Bouslama and Schapaugh (1984); Ramirez and Kelly (1998); Fernandez (1992). Air temperature and humidity during the experimental period are presented in supplemental Table 1.

## Results and Discussion

### *Analysis of variance for different studied traits*

ANOVA was performed to assess differences in genotypes, treatments and their interactions. Results indicated significant genotype variations at 1% and 5% probability levels for all the studied traits (Table 1). Treatments and genotype × treatment interactions also displayed significance across all characters.

### *Mean, Genetic variability, heritability and genetic advance*

Detailed comparisons of various characters among the optimum and late planting treatments for wheat genotypes are visually presented in Figures 1 and Table 2. For days to germination, SADH-24 and BAW 898 exhibited superior performance, with high heritability and genetic advance (Table 2). Wide variation was found in plant height, with Bijoy as the top performer and BAW 457 the lowest. The average number of tillers per plant was 5.09, ranging from 2.6 to 9.0, with notable genotypic and phenotypic variance. BAW 677 excelled in flag leaf length with high heritability and genetic advance (Table 2). Flag leaf width showed variance, with lower heritability and a modest genetic advance. Canopy temperatures varied, with SA-7 as the top performer, demonstrating high heritability. Chlorophyll content varied significantly, with NE-3 exhibiting the highest, along with high heritability and a substantial genetic advance. Days to booting, days to 50% flowering, pollen viability, and pollen sterility showed significant variance, high heritability and substantial genetic advances. Spike length, spikelets per spike, filled grains per spike, and 100-grain weight displayed considerable variation, with high heritability and genetic advances. The number of unfilled spikelets, straw weight, and yield per plant demonstrated variability, with moderate to high heritability and genetic advances. These results provide brief insights on the genotype performance of several traits in the crop under study.

**Table 1. Mean square (MS) values for 18 morpho-physiological characters in 30 wheat genotypes**

| Characters | Time sowing | Genotype | Genotype × Time sowing | Error |
|---|---|---|---|---|
| Day to germination | 358.2*** | 52.1*** | 2.23*** | 0.27 |
| Plant height | 4242.03*** | 813.12*** | 76.46*** | 9.68 |
| No. of Tiller/plant | 67.57*** | 6.18*** | 12.24*** | 0.59 |
| Flag leaf length | 415.64*** | 45.56** | 8.99*** | 0.98 |
| Canopy temperature | 50.26*** | 25.09*** | 3.27*** | 0.19 |
| Chlorophyll | 1470.39*** | 195.19*** | 35.7*** | 2.17 |
| Days to booting | 378.82*** | 461.28** | 5.76*** | 1.92 |
| Days to 50% flowering | 581.59** | 345.75** | 302.09** | 1.187 |
| Pollen viability (%) | 14669.9** | 210.93** | 234.98** | 6.89 |
| Pollen sterility (%) | 14669.9*** | 210.93*** | 234.98** | 6.89 |
| Spike length | 147.89*** | 37.34*** | 2.78*** | 0.735 |
| No. of spikelets/spike | 2296.31*** | 488.31*** | 156.43*** | 9.42 |
| Filled spikelets/spike | 4619.14*** | 522.231*** | 201.9*** | 8.19 |
| Unfilled spikelets/spike | 402.067** | 16.82** | 62.98** | 2.005 |
| 100-grain weight (g) | 54.02*** | 2.35*** | 0.76*** | 0.06 |
| Total Straw weight per plant (g) | 582.157*** | 11.61*** | 56.34*** | 0.84 |
| Yield/plant | 381.712** | 31.47** | 3.45** | 1.22 |

Note: ** and *** indicate significance at 0.01 and 0.1 probability, respectively.

**Table 2. Estimation of genetic parameters for 18 characters studied in wheat**

| Characters | Mean | Range | | Genotypic variance | Phenotypic variance | GCV (%) | PCV (%) | Heritability (%) | GA | GA % |
|---|---|---|---|---|---|---|---|---|---|---|
| Day to germination | 10.83 | 5.000 | 19.0 | 17.28 | 17.55 | 17 | 17 | 98.45 | 8.50 | 33.98 |
| Plant height | 94.85 | 69.42 | 125.73 | 267.81 | 277.49 | 65 | 67 | 96.51 | 33.12 | 77.47 |
| No. of Tiller/plant | 5.094 | 2.6 | 9.0 | 1.86 | 2.46 | 15 | 16 | 75.64 | 2.44 | 9.77 |
| Flag leaf length | 20.24 | 13.0 | 27.0 | 14.86 | 15.84 | 15 | 16 | 93.81 | 7.69 | 30.77 |
| Flag leaf width | 1.35 | 0.03 | 1.7 | 0.14 | 0.18 | 18 | 22 | 76.84 | 0.67 | 2.7 |
| Canopy temperature | 95.88 | 92.0 | 99.6 | 8.30 | 8.49 | 12 | 12 | 97.76 | 5.87 | 23.47 |
| Chlorophyll | 36.39 | 24.56 | 47.8 | 64.34 | 66.51 | 32 | 33 | 96.74 | 16.25 | 65.01 |
| Days to booting | 53.47 | 43.0 | 74.0 | 153.12 | 155.04 | 49 | 50 | 98.76 | 24.33 | 97.33 |
| Days to 50% flowering | 64.35 | 53.0 | 85.0 | 114.85 | 116.04 | 43 | 43 | 98.98 | 21.96 | 87.86 |
| Pollen viability (%) | 79.60 | 48.0 | 95.80 | 68.01 | 74.90 | 33 | 35 | 90.80 | 16.19 | 64.75 |
| Pollen sterility (%) | 19.39 | 4.20 | 52.0 | 70.11 | 77.00 | 33 | 35 | 91.05 | 16.46 | 65.84 |
| Spike length | 14.67 | 11.0 | 21.0 | 12.20 | 12.94 | 14 | 14 | 94.32 | 6.99 | 27.96 |
| No. of spikelets/spike | 48.57 | 31.0 | 72.0 | 159.64 | 169.06 | 51 | 52 | 94.43 | 25.29 | 95.17 |
| Filled spikelets/spike | 42.10 | 24.0 | 68.0 | 171.35 | 179.54 | 52 | 54 | 95.44 | 26.34 | 97.37 |
| Unfilled spikelets/spike | 6.48 | 2.0 | 20.0 | 4.94 | 6.95 | 19 | 21 | 71.13 | 3.86 | 15.45 |
| 100-grain weight (g) | 2.95 | 1.44 | 5.12 | 0.76 | 0.83 | 13 | 14 | 92.49 | 1.73 | 6.92 |
| Straw weight per plant (g) | 5.63 | 2.2 | 14.0 | 3.59 | 4.43 | 18 | 18 | 81.02 | 3.51 | 14.05 |
| Yield/plant(g) | 6.91 | 1.1 | 17.0 | 10.08 | 11.30 | 23 | 33 | 89.21 | 6.18 | 24.71 |

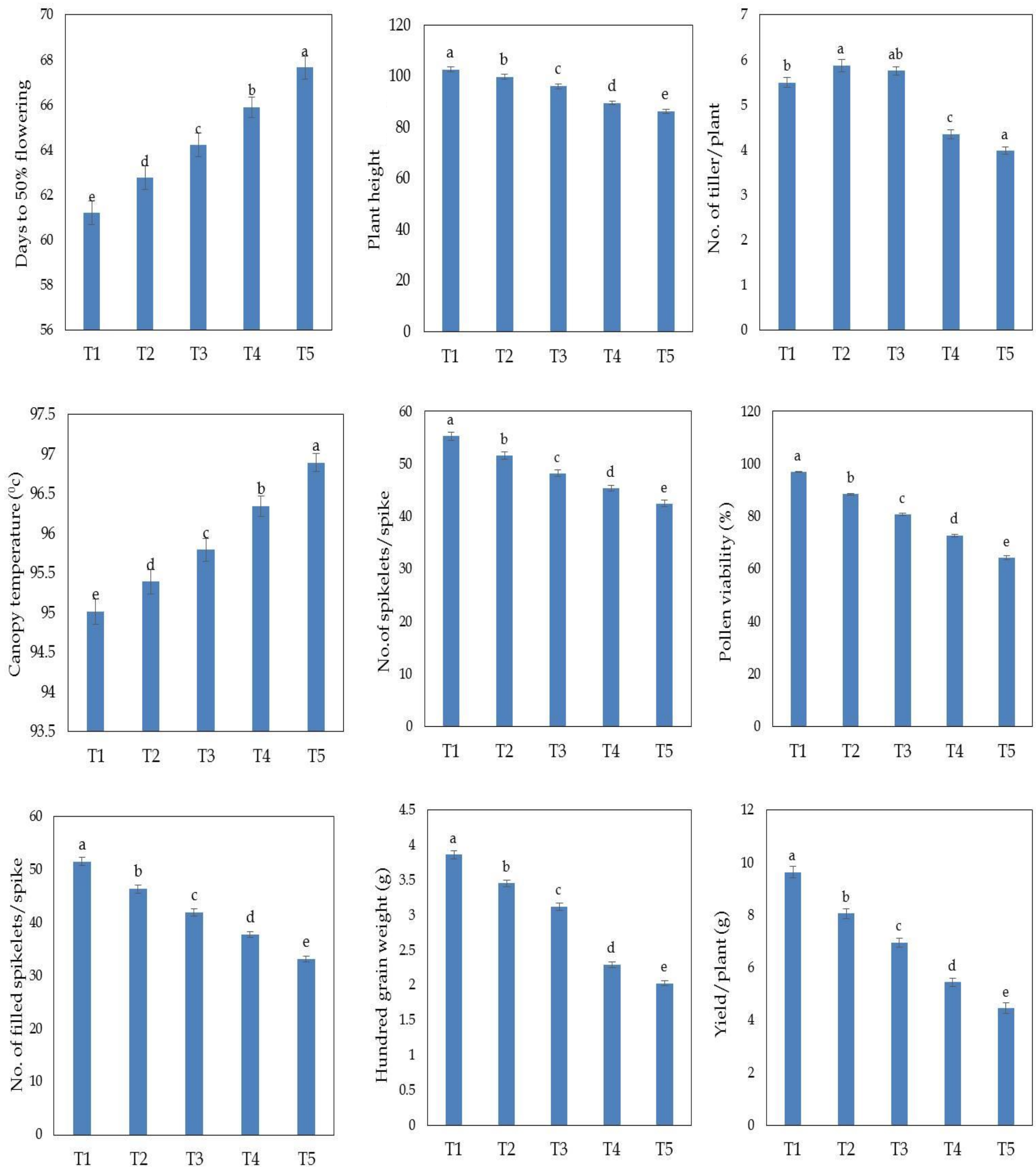


Figure 1. Differences in characters of optimum and late sown treatments of wheat at five sowing days. Mean (±SD) was calculated from three replicates for each treatment. T1= Optimum sowing dates, T2, T3, T4 and T5 = late sowing dates. Bars with different letters indicate significant differences.

Heat stress significantly reduces wheat grain yield by impacting various aspects of plant development, including crop stand, life cycle duration, tiller number, biomass production, fertilization, grain development, spike size, spike number per m$^2$, grain number per spike, and grain weight (Kumar *et al.,* 2023; Omidi *et al.,* 2013). In this study, grain yield tends to decrease with the increament of terminal ambient temperature by reducing the expression of different yield attributing traits. The detrimental effects on plant morphology highlight the direct relationship between heat stress and these adverse changes in wheat production. Seed germination under constant soil moisture increased with temperature up to the optimum range but decreased supra-optimally (Prasad *et al.,* 2014). Optimum sown treatment displayed the highest tillers per plant which is in accordance with the results of Heffner *et al.*'s (2009) whereas fewer tillers under heat stress were observed. Late sown treatments experienced limited biomass production. Booting time was shorter in lower temperatures (T1 and T2), while late sown treatments demonstrated delayed booting. Canopy temperature and chlorophyll content are important physiological traits directly associated with pollen fertility, grain filling and seed set (Ahmed *et al.,* 2020). Heat stress-induced impacts on mitochondria and protein expression, leading to reduced pollen fertility, were consistent with prior studies (Prasad and Djanaguiraman, 2014; Wheeler *et al.,* 1996). High heritability for chlorophyll content which was previously noted, may contribute to its reduction under heat stress due to disruptions in chloroplast thylakoid structure and function (Shanmugam *et al.,* 2013). Plant height is also a worse victim of heat stress as the high temperature suppress the plant growth through leaf senescence and reduce photosynthesis. The results are similar to the findings of Verma *et al.* (2003) and Pandey *et al.* (2010). Flag leaf is vital for grain filing but the heat stress reduces flag leaf width and length this result is in line with Pask *et al.* (2013). In this experiment, the highest grain yield was found in the optimum sown treatment T1 (Figure 1). After that grain yield started declining in all the late sown treatments of T2, T3, T4 and T5 because of high-temperature stress due to late sowing. Similar results were reported by Kumar *et al.* (2023). Intensity of heat stress was high which eventually lowered the grain yield under late planting conditions.

### *Correlation coefficient of the characters studied*

The correlation coefficients among various morphological and physiological characters related to heat stress tolerance in wheat genotypes were investigated and presented in Table 3. Days to 50% flowering showed non-significant correlations with several parameters, while displaying significant and negative correlations with others, such as pollen sterility and days to germination. Plant height had significant negative correlations with canopy temperature, days to 50% flowering, pollen sterility, and unfilled spikelets, with positive correlations observed elsewhere. No. of tillers per plant displayed significant negative associations with various parameters and positive associations with flag leaf length and width. Flag leaf length demonstrated significant negative correlations with days to germination, canopy temperature, pollen sterility, and unfilled spikelets, with non-significant correlations for days to 50% flowering, tiller count per plant, and yield per plant. Flag leaf width exhibited significant negative correlations with days to germination, pollen sterility, filled spikelets, and canopy temperature, and significant positive associations with other parameters. Chlorophyll content exhibited positive significant correlations with all studied characters, except for negative correlations with canopy temperature, pollen sterility, days to 50% flowering, and days to germination. Canopy temperature showed positive correlations with pollen sterility, unfilled spikelets, and days to germination, with negative correlations with other parameters. Pollen viability exhibited negative and significant correlations with pollen sterility, canopy temperature, and days to germination, while positive correlations were observed elsewhere. Yield per plant had significant negative correlations with days to germination, pollen sterility, unfilled spikelets, and canopy temperature, with positive correlations elsewhere. These findings contribute valuable insights into the intricate relationships among key traits influencing heat stress tolerance in wheat genotypes. Yield per plant had a significant and negative correlation with days to germination, pollen sterility, no. of unfilled spikelets and canopy temperature, while the significantly positive correlation with other parameters were present except total straw weight and flag leaf length. These findings were in partial agreement with Kumar *et al.* 2023; Lopes and Reynolds (2012); Masood *et al.* (2014); Ahmad *et al.* (2010); Akram *et al.* (2008). The growth and development of wheat is negatively correlated with high temperature depending the developmental stage of the plant exposed (Balla *et al.,* 2012). In our study Canopy temperature showed significant negative correlation with yield and yield contributing traits. The higher temperature at flowering stage also induces pollen sterility in wheat (Kumar *et al.,* 2023) very much similar to our findings.

### *Path coefficient analysis for grain yield*

The investigation of factors influencing grain yield in wheat genotypes under heat stress employed a Path Coefficient Analysis involving 15 independent characters shown in Table 4. The study revealed intricate direct and indirect relationships among these characters, shedding light on their contributions to grain yield. Days to germination exhibited a negative direct effect on grain yield, with positive indirect effects through various parameters such as chlorophyll content, days to 50% flowering, and 100-grain weight. Days to 50% flowering demonstrated a positive direct effect on grain yield, with negative indirect effects observed with plant height and canopy temperature. Plant height displayed a positive direct association with grain yield, while other characters exhibited positive indirect associations, except for canopy temperature, chlorophyll content, and total grain weight. Number of tillers per plant had a positive direct effect on grain yield, with positive indirect associations with other characters, except for canopy temperature, number of spikes per plant, and total straw weight. Flag leaf length showed positive direct effects on grain yield, with negative indirect effects observed in canopy temperature and days to 50% flowering. Canopy temperature had a negative direct effect on grain yield, with positive indirect effects via no. of unfilled spikelets and spike length. Chlorophyll content exhibited a positive direct effect on grain yield, with negative indirect effects through plant height, canopy temperature, and 100-grain weight. Pollen viability had a negative direct effect on grain yield, with both positive and negative indirect effects via various parameters. The detailed Path Coefficient Analysis provides valuable insights into the direct and indirect influences of different traits on grain yield under heat stress, offering crucial information for targeted breeding efforts aimed at developing heat-tolerant wheat varieties. The characters viz, plant height, chlorophyll content, no. of tiller per plant, days to 50% flowering, filled grain, 100-grain weight, flag leaf length, days to booting, total grain weight had a positive direct effect on grain yield. Positive direct effects of these characters suggest that direct selection for these characters for high grain yield would be effective. These results are found to be similar with the findings of Narwal *et al.* (1999); Bhutta *et al.* (2006); Mohsin *et al.* (2009); Uddin *et al.* (1997). Highly positive direct effects suggest that these characters are important components of grain yield, hence merits special attention in the selection strategies. These correlates with the reports of Zeeshan *et al.* (2014); Khan *et al.* (2014).

**Table 3. Interrelation between different studied characters associated with heat tolerance in wheat**

| | CT | CH | DTF | PV | PS | NOTPP | NOSPS | FS | NUFS | HGW | TGW | TSW | DTG | FLL | FLW | SL | YPP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PH | -0.23* | 0.32** | -0.17** | 0.63* | -0.63** | 0.45** | 0.27ns | 0.38ns | -0.49* | 0.56** | 0.63* | 0.23** | 0.69* | 0.53** | 0.29* | 0.66* | 0.46* |
| CT | | -0.31* | 0.075ns | -0.44** | 0.44** | -0.24* | -0.47* | -0.57* | 0.427* | -0.45* | -0.37* | -0.27* | 0.25*** | -0.52* | -0.24* | -0.28ns | -0.41* |
| CH | | | 0.12* | 0.55** | -0.55** | 0.36** | 0.37* | 0.49** | -0.44ns | 0.44* | 0.59* | 0.19* | -0.41* | 0.48** | 0.17** | 0.16** | 0.43** |
| DTF | | | | 0.47ns | 0.47** | -0.17* | -0.16** | -0.26* | 0.42** | -0.43** | -0.37ns | -0.17** | 0.78** | -0.09ns | -0.01ns | -0.04ns | 0.47* |
| PV | | | | | -1.0* | 0.51* | 0.62** | 0.76* | -0.76ns | 0.76* | 0.83* | 0.03* | -0.6* | 0.67** | 0.43** | 0.41* | 0.75** |
| PS | | | | | | -0.56* | -0.62* | -0.76* | 0.76* | -0.76* | -0.83* | -0.03* | 0.6** | -0.67* | -0.43* | -0.41* | -0.75* |
| NOTPP | | | | | | | 0.23** | 0.26* | -0.36* | 0.37* | 0.57** | 0.27** | -0.32** | 0.35ns | 0.09ns | 0.23** | 0.40** |
| NOSPS | | | | | | | | 0.94** | -0.37* | 0.47** | 0.53* | 0.13* | -0.25** | 0.46** | 0.17* | 0.28** | 0.67** |
| FS | | | | | | | | | -0.63* | 0.64* | 0.65** | 0.25* | -0.38** | 0.54* | 0.19* | 0.32*** | 0.74* |
| NUFS | | | | | | | | | | -0.64* | -0.63* | -0.33* | 0.55*** | -0.51* | -0.14* | -0.35* | -0.69** |
| HGW | | | | | | | | | | | 0.66* | 0.06** | -0.51** | 0.67* | 0.45* | 0.48* | 0.72*** |
| TGW | | | | | | | | | | | | 0.23ns | -0.53* | 0.51*** | 0.18* | 0.52* | 0.67** |
| TSW | | | | | | | | | | | | | -0.53* | 0.51* | 0.18* | 0.52* | 0.67ns |
| DTG | | | | | | | | | | | | | | 0.3*** | -0.48* | -0.27* | -0.47* |
| FLL | | | | | | | | | | | | | | | 0.12* | 0.59** | 0.55ns |
| FLW | | | | | | | | | | | | | | | | 0.19* | 0.29* |
| SL | | | | | | | | | | | | | | | | | 0.39* |

*** indicate 0.1%, ** indicates 1%, * indicates 5% level of significance and ns indicates non-significant

**Legend:**

DTG = Days to germination, DTF= Days to 50% Flowering, CT= Canopy temperature, CH= Chlorophyll content, PH= Plant height, PV=Pollen viability, PS=Pollen sterility, NOTPP=No. of tillers per plant, FS= No. of filled spikelets, NUFS= No. of unfilled spikelets, HGW= 100-grain weight, TGW= Total grain weight, TSW= Total straw weight, FLL= Flag leaf length, FLW= Flag leaf width, SL= Spike length, YPP= Yield per plant, NOSPS= No. of spikelets per spike

**Table 4. Direct and indirect effects of yield contributing and heat tolerant related traits on yield**

| | PH | CT | CH | DTF | NOTPP | NOSPS | FS | NUFS | HGW | TGW | TSW | DTG | FLL | DTB | SL | YPP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PH | **0.002** | 0.005 | -0.001 | -0.002 | 0.019 | -0.058 | -0.078 | -0.009 | 0.152 | -0.00082 | -0.002 | 0.004 | 0.003 | -0.04 | -0.006 | 0.161 |
| CT | -0.003 | **-0.006** | -0.008 | -0.029 | -0.078 | -0.064 | -0.125 | 0.031 | -0.026 | -0.00076 | 0.004 | -0.002 | -0.008 | 0.006 | -0.007 | -0.168 |
| CH | -0.005 | 0.006 | **0.059** | 0.004 | 0.003 | 0.063 | 0.029 | 0.004 | 0.068 | 0.00039 | 0.002 | 0.003 | 0.008 | 0.067 | -0.003 | 0.043 |
| DTF | 0.009 | 0.008 | 0.063 | **0.182** | 0.0154 | -0.208 | 0.054 | -0.054 | -0.183 | -0.01425 | -0.004 | 0.025 | -0.001 | 0.005 | -0.006 | 0.082 |
| NOTPP | 0.004 | 0.071 | 0.071 | 0.374 | **0.192** | 0.0165 | 0.038 | -0.021 | 0.034 | 0.00568 | 0.004 | 0.018 | 0.078 | 0.008 | -0.007 | 0.312 |
| NOSS | -0.004 | 0.008 | 0.081 | 0.041 | -0.003 | **-0.765** | 0.81 | -0.003 | 0.064 | -0.00217 | -0.007 | -0.009 | 0.002 | 0.081 | 0.004 | 0.045 |
| FS | -0.003 | 0.018 | 0.002 | 0.013 | 0.006 | 0.567 | **0.923** | -0.189 | 0.0341 | 0.00321 | -0.001 | -0.012 | 0.013 | 0.006 | 0.002 | 0.168 |
| NUFS | 0 | -0.009 | 0.007 | 0.045 | -0.01 | 0.014 | -0.543 | **-0.321** | -0.0567 | -0.00893 | 0 | 0.005 | -0.012 | -0.0125 | -0.002 | -0.243 |
| HGW | 0.001 | 0.003 | -0.004 | -0.069 | -0.012 | 0.098 | -0.043 | -0.034 | **0.533** | 0.01458 | 0.004 | 0.009 | 0.009 | -0.015 | 0.003 | 0.459 |
| TGW | -0.001 | 0.002 | 0.001 | -0.098 | 0.011 | 0.045 | 0.086 | -0.053 | 0.178 | **0.039** | 0.002 | -0.004 | 0.003 | 0.043 | 0.006 | 0.329 |
| TSW | 0.00002 | 0.004 | -0.002 | 0.008 | -0.023 | -0.067 | 0.056 | -0.002 | -0.045 | -0.00106 | **-0.078** | -0.007 | 0.012 | 0 | 0.0001 | -0.209 |
| DTG | 0.0001 | 0.002 | 0.009 | 0.032 | 0.053 | -0.065 | -0.121 | 0.0147 | -0.003 | -0.00253 | 0.008 | **-0.089** | 0.0003 | 0.01278 | 0.0001 | 0.136 |
| FLL | 0.00006 | 0.005 | 0.002 | -0.003 | 0.001 | 0.012 | 0.147 | -0.023 | 0.006 | 0.00274 | -0.009 | 0.00001 | **0.085** | -0.011 | -0.007 | 0.091 |
| DTB | 0.00004 | 0.003 | -0.001 | -0.005 | -0.004 | 0.003 | -0.025 | -0.031 | 0.022 | -0.00733 | 0 | -0.005 | 0.004 | **0.192** | 0.007 | -0.181 |
| SL | 0.00008 | -0.011 | 0.003 | 0.032 | 0.031 | 0.067 | -0.082 | -0.0060 | 0.03861 | -0.0057 | 0.002 | -0.001 | 0.015 | 0.006 | **0.043** | -0.052 |

Residuals: 0.064; Bold indicate direct effect, Rest are indirect effect

**Legend:** DTG = Days to germination, DTF= Days to 50% Flowering, CT= Canopy temperature, CH= Chlorophyll, PH= plant height, PV=Pollen viability, PS=Pollen sterility, NOTPP=No. of tillers per plant, FS= No.of filled spikelets, NUFS= No.of unfilled spikelets, HGW= 100-grain weight, TSW= Total straw weight, TGW= Total grain weight, FLL= Flag leaf length, DTB= Days to booting, SL= Spike length, YPP= Yield per plant, NOSPS= No. of spikelets per spike.

*Heat stress tolerance indices*

Stress tolerance indices are calculated using the yield performance of different genotypes under both normal and stress condition which were used to find or screen out the stress tolerant genotypes by many researchers previously (Tithi and Sagor, 2023; Singh *et al.*, 2011; Sharma *et al.,* 2013). The six different indices namely tolerance index (TOL), stress susceptibility index (SSI), yield stability index (YSI), mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI)—for five different sowing dates (T1= 21st November 2021 is considered as the optimum sowing and T2 = 1st December 2021, T3 = 11th December 2021, T4 = 22th December 2021, T5 = 2nd January 2022) considering a magnitude of terminal heat stress condition are shown in Figure 2, 3, 4, 5, 6, and 7 respectively. BL-1020, SADH-12, DSN-76, NK-5, NE-3, SA-2 exhibited high heat stress tolerance, as indicated by their low TOL values, suggesting their resilience to heat-induced yield reduction, aligning with the preference for genotypes with lower TOL for high-yield selection under stress conditions, supported by Tithi and Sagor, (2023). The lowest value of SSI belonged to the genotype DSN- 76, NK-5, BL-1020, NE-3, SADH-22 which indicated that they had low susceptibility and high tolerance under heat stress. As a result, they had a high grain yield under both normal and heat stress conditions. Selection based on SSI helps to determine high yielding genotypes under both stressed and non-stressed conditions (Kamrani *et al.,* 2018). The highest value of YSI was observed in DSN-76, NE-3, BAW 1008, NK-5, SADH-22 which indicated that they had lower yield reduction and higher yield stability under heat stress conditions. SA-8 and SADH-14 varieties consistently exhibited high productivity in various heat stress conditions across different sowing dates, followed by SADH-12, BAW 1027, and BAW 960, while DSN-76 and BAW 898 showed lower performance according to mean productivity (MP) study. As found in GMP study, SA-8, followed by SADH-14, SADH-12, BAW 1006, BAW 1027, BAW 1008, and BAW 966, consistently exhibited high geometric mean productivity across various heat stress conditions. A similar result was presented by Kamrani *et al.* (2018), who suggested selection based on MP, GMP, and STI would identify higher-yielding and heat tolerant genotypes. In terms of high yield under moderate to high stress conditions SADH-12, SADH-22 and BAW 1008 produced a high grain yield under T4 and T5 sowing date, heat stress conditions among all the other genotypes. But in this study, it was found that the SA-8, SADH-12, SADH-14, BAW 1008 had higher STI.

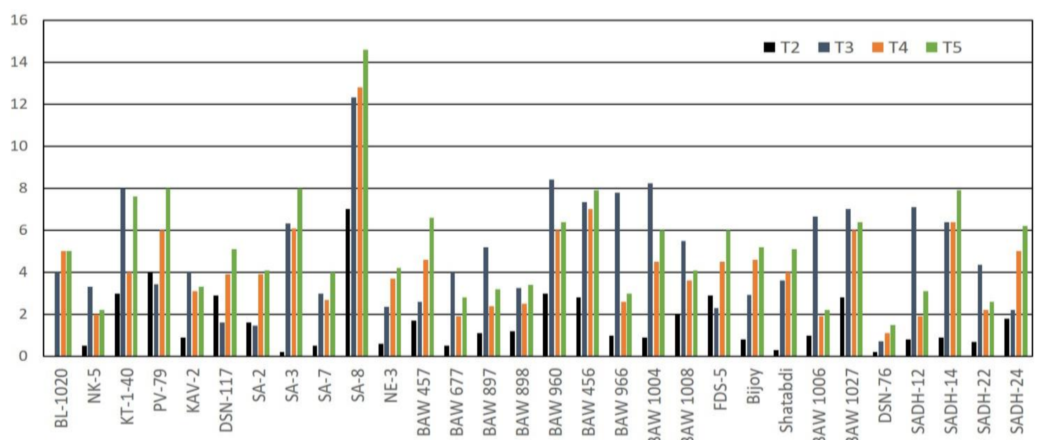


Figure 2. Tolerance index (TOL) of 30 wheat genotypes under four late planting heat stress condition

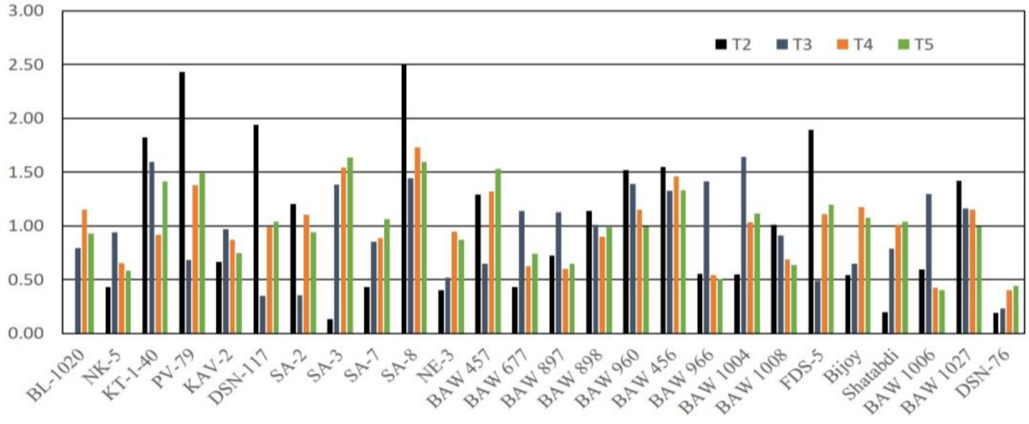


Figure 3. Stress susceptibility index (SSI) of 30 wheat genotypes under four late planting heat stress condition

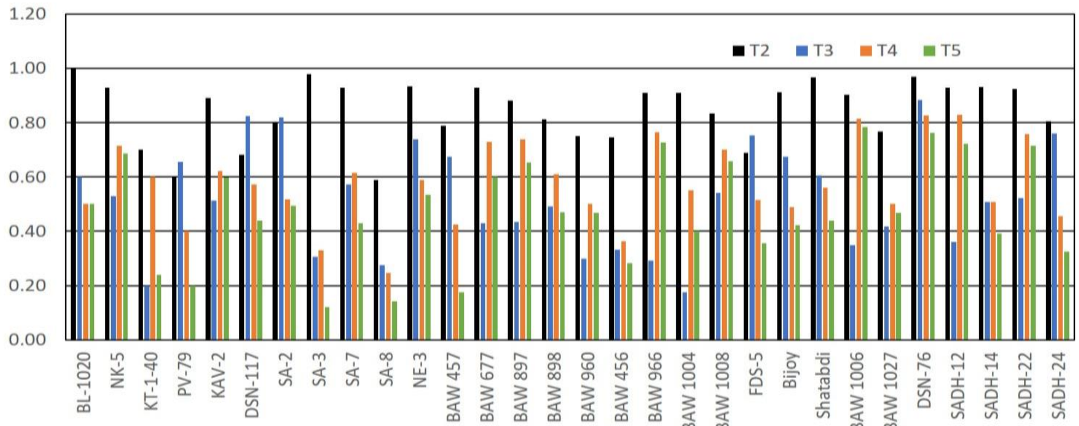


Figure 4. Yield Stability Index (YSI) of 30 wheat genotypes under four late planting heat stress condition

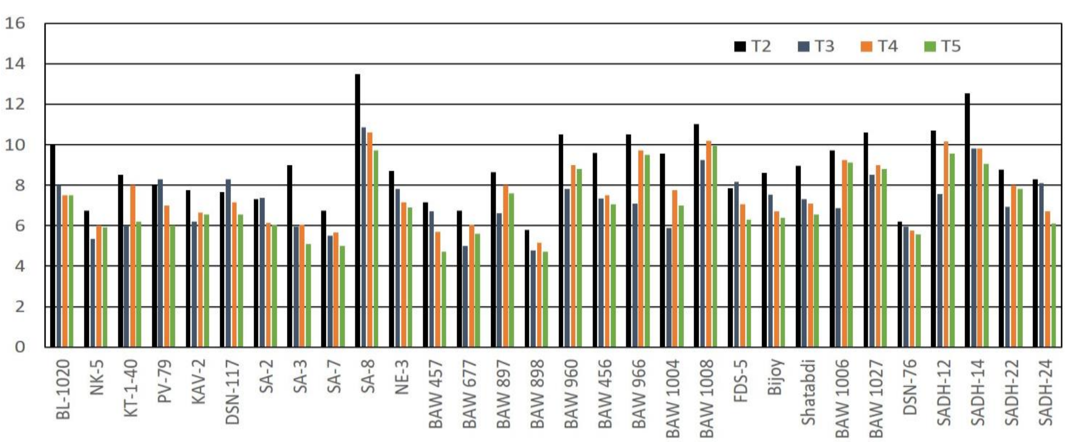


Figure 5. Mean Productivity of 30 wheat genotypes under four late planting heat stress condition

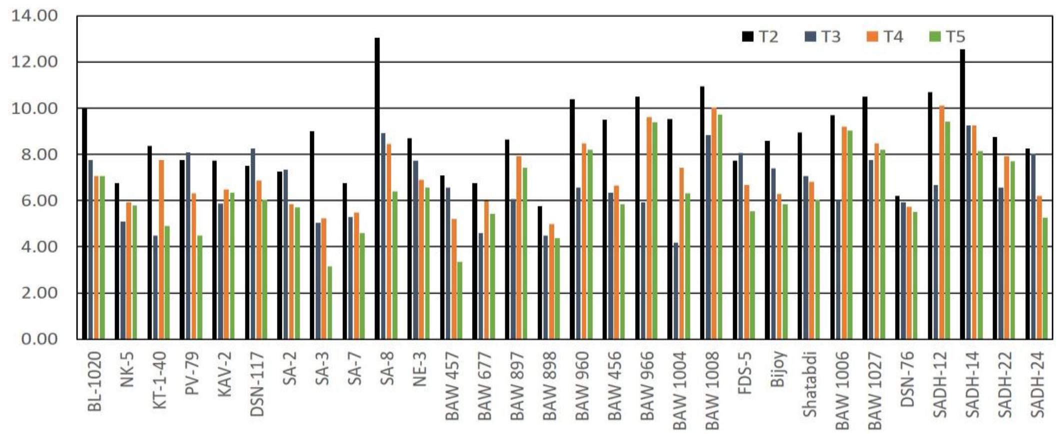


Figure 6. Geometric Mean Productivity (GMP) of 30 wheat genotypes under four late planting heat stress condition

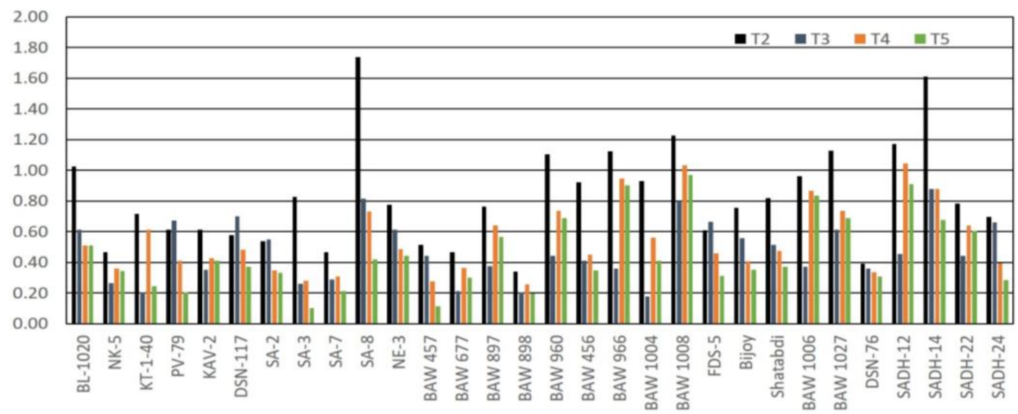


Figure 7. Stress Tolerance Index of 30 wheat genotypes under four late planting heat stress condition

## Conclusion

In this study, 30 wheat genotypes were evaluated, grown under terminal heat stress as imposed by different sowing dates to assess the impact of varying heat stress conditions on yield attributing traits and to identify potential candidates for breeding programs. Significant insights were gained into the morpho-physiological responses of wheat varieties to late planting conditions. Genotypes such as SA-8 and SADH-14 consistently displayed high productivity across different heat stress conditions and sowing dates. In contrast, DSN-76 and BAW 898 exhibited lower performance, emphasizing their susceptibility to heat stress. Key traits contributing to superior performance included plant height, no. of tillers per plant, flag leaf length, and canopy temperature. Overall, the study concludes that considerable genetic variation exists in terminal heat stress tolerance among wheat genotypes. The identified heat-tolerant genotypes, particularly those demonstrating consistency in performance and stability, hold promise for future breeding programs aimed at developing wheat varieties resilient to terminal heat stress.

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**Supplementary Table 1. Air Temperature and humidity data during the experiment period**

| Date | Air Temperature (°C) | Humidity (%) |
|---|---|---|
| 10th November | 24.7 | 81 |
| 20h November | 23.3 | 83 |
| 30th November | 21.9 | 79 |
| 10th December | 23.1 | 77 |
| 20th December | 19 | 78 |
| 30th December | 19.3 | 84 |
| 10th January | 20.6 | 84 |
| 20th January | 17.7 | 85 |
| 30th January | 16.7 | 78 |
| 10th February | 17.3 | 91 |
| 20th February | 20.8 | 70 |
| 28th February | 23.8 | 79 |
| 10th March | 26.3 | 69 |
| 20th March | 27 | 69 |
| 30th March | 26.9 | 84 |