International Journal of Research in Agronomy 2025; 8(12): 1182-1187

International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(12): 1182-1187
Received: 26-10-2025
Accepted: 29-11-2025

Girish K Prajapati
Ph.D. Research Scholar, Department of Genetics and Plant breeding, N. M. College of Agriculture, Navsari Agriculture University, Navsari, Gujarat, India

Rita R Patel
Assistant Professor, Department of Genetics and Plant Breeding, N. M. College of Agriculture, Navsari Agriculture University, Navsari, Gujarat, India

Kavya K Joshi
Ph.D. Research Scholar, Department of Genetics and Plant breeding, N. M. College of Agriculture, Navsari Agriculture University, Navsari, Gujarat, India

Bhushan H Kale
Associate Professors, Department of Genetics and Plant Breeding, N. M. College of Agriculture, Navsari Agriculture University, Navsari, Gujarat, India

Corresponding Author:
Girish K Prajapati
Ph.D. Research Scholar, Department of Genetics and Plant breeding, N. M. College of Agriculture, Navsari Agriculture University, Navsari, Gujarat, India

Variability studies for yield and its components under heat stress condition in wheat [*Triticum aestivum* (L.)]

Girish K Prajapati, Rita R Patel, Kavya K Joshi, Bhushan H Kale

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i12p.4563

Abstract
The rising global demand for wheat is threatened by climatic challenges such as heat stress, necessitating the identification of key yield-attributing traits for breeding stress-resilient cultivars. The present study evaluated sixty bread wheat (*Triticum aestivum* L.) genotypes during *rabi* 2023-24 at the College Farm, N. M. College of Agriculture, Navsari Agricultural University, Navsari, under late-sown heat stress conditions (December and January) in a randomized block design with two replications. Twenty-three morphological and physiological traits were recorded, including phenological, yield, and stress-related parameters. Analysis of variance revealed highly significant differences among genotypes for all traits, indicating wide genetic variability. Phenotypic coefficients of variation (PCV) were marginally higher than genotypic coefficients of variation (GCV), reflecting environmental influence, with canopy temperature depression (CTD) at anthesis and 15 days after anthesis exhibiting the highest variability and thus strong potential for selection. Grain filling rate, biological yield, and grain yield per plant displayed moderate GCV and PCV, suggesting their suitability as selection targets. High heritability coupled with high genetic advance was observed for grain filling rate (December sowing) and for biological yield and CTD (January sowing), highlighting the predominance of additive gene action and minimal environmental effects. Traits such as effective tillers per plant, harvest index, chlorophyll content, NDVI, and grain yield also showed moderate to high heritability with moderate genetic advance, indicating good scope for improvement. In contrast, plant height, spike length, and grains per spike exhibited low heritability and genetic advance, limiting direct phenotypic selection. Overall, the study identifies CTD, grain filling rate, biological yield, and grain yield as key traits for breeding heat-tolerant wheat genotypes under late-sown stress conditions.

Keywords: Wheat, variability, GCV, PCV, heritability, genetic advance

Introduction

Wheat (*Triticum aestivum* L.) is one of the most extensively cultivated cereal crops worldwide and serves as a primary staple food for a significant portion of the global population. Its adaptability across diverse agro-climatic zones has made it a cornerstone of food security, contributing substantially to caloric and protein intake in both developed and developing nations (Curtis *et al*., 2002; Shiferaw *et al*., 2013) [1, 2]. Beyond its role in human nutrition, wheat also underpins rural livelihoods, agricultural economies, and international trade, making its sustained production a critical priority in the face of increasing global food demand.

The rapid growth of the global population, projected to exceed 9 billion by mid-century, is expected to drive wheat demand to unprecedented levels (Ray *et al*., 2013) [3]. Meeting this demand is challenging, as climate variability increasingly threatens production stability. Among the abiotic stresses affecting wheat, terminal heat stress - characterized by exposure to elevated temperatures during reproductive and grain-filling stages - poses a particularly serious constraint. Even moderate rises in temperature can shorten developmental phases, impair photosynthesis, reduce grain filling duration, and ultimately depress yields (Wardlaw *et al*., 1989; Farooq *et al*., 2011) [4, 5]. Previous estimates suggest that each 1 °C increase during sensitive stages can result in yield losses of 4-6%, highlighting the urgency of developing cultivars capable of maintaining performance under warming environments (Asseng *et al*., 2015) [6].

The impact of heat stress on wheat is multifaceted. Physiological processes such as chlorophyll stability, canopy temperature regulation, and efficiency of photosystem II are adversely affected, which translates into reduced biomass accumulation and lower grain weight (Reynolds *et al*., 2009; Wahid *et al*., 2007) [7, 8]. At the morphological level, traits including plant height, spike length, tiller number, and grain number per spike may also be compromised. Importantly, the extent of yield reduction is not uniform across genotypes, indicating the presence of exploitable genetic variability for stress tolerance (Joshi *et al*., 2007) [9]. Identifying and utilizing such variability is essential for developing cultivars that can sustain productivity under late-sown or high-temperature conditions.

Genetic improvement of wheat for heat tolerance relies on understanding the heritable variation in both yield-attributing traits and stress-responsive physiological characteristics. Traits such as canopy temperature depression, chlorophyll content, normalized difference vegetation index (NDVI), and chlorophyll fluorescence have proven useful as indirect selection criteria because they provide insight into the plant's ability to withstand heat while maintaining productivity (Pinto & Reynolds, 2015) [10]. Similarly, grain filling rate and duration are critical determinants of final yield under stress, as they directly influence grain weight and biomass partitioning (Dias & Lidon, 2009) [11]. The effectiveness of selection for these traits depends on their variability, heritability, and the nature of gene action involved. High heritability coupled with high genetic advance is particularly desirable, as it reflects additive genetic effects that can be directly exploited in breeding programs (Falconer & Mackay, 1996) [12].

Despite considerable progress in wheat breeding, the pace of yield gain is insufficient to counterbalance the negative impacts of climate change (Ray *et al*., 2013) [3]. Strengthening breeding strategies with a focus on stress-adaptive traits offers a sustainable pathway for enhancing resilience. Therefore, assessing genetic variability and identifying reliable selection indices under heat-stressed environments remain essential steps toward breeding high-yielding and climate-resilient wheat cultivars.

Materials and Methods

Experimental material

Sixty diverse genotypes of wheat were used in this experiment. The genotypes 1 to 57 were procured from Borlaug Institute for South Asia (BISA), Ludhiana, India. The check variety HD 2931 and DBW 222 procured from IARI, New Delhi and the check variety LOK 1 was procured from Wheat Research Station, Bardoli, Navsari Agricultural University, Gujarat, India and, India. The sixty genotypes studied in this investigation are listed in Table 1.

Experimental location

The study was conducted at the College Farm of N. M. College of Agriculture, Navsari Agricultural University, Navsari. The experimental site is located at 20°37′ N latitude and 72°54′ E longitude, with an elevation of about 11.98 m above mean sea level. This location falls within the "South Gujarat Heavy Rainfall Zone (AEZ III)." The soil of the site is characterized as medium black cotton soil and is classified under the order *Inceptisols* according to soil taxonomy. It has medium to poor drainage conditions, with a pH ranging from 7.5 to 7.8, and is considered fairly suitable for wheat cultivation.

Experimental detail

The field trial was conducted with two different sowing dates: 17 December 2024 (E1) and 5 January 2024 (E2). In both cases, the crop was exposed to heat stress, with the later sowing experiencing comparatively stronger terminal heat stress. The climatic conditions during the crop growth period were typical of the respective sowing months. The experiment was laid out in a Randomized Block Design (RBD) with two replications. A total of sixty genotypes were planted in paired rows of 3 m length, maintaining a row spacing of 20 cm in both sowings. Recommended agronomic practices were followed uniformly across treatments.

Table 1: List of genotypes

Sr. No.	Genotype	Sr. No.	Genotype
1.	GS\2022-23\8031	31.	ESWYT\2022-23\ 104
2.	GS\2022-23\8035	32.	ESWYT\2022-23\ 109
3.	GS\2022-23\8036	33.	ESWYT\2022-23\ 123
4.	GS\2022-23\8040	34.	ESWYT\2022-23\ 124
5.	GS\2022-23\8045	35.	ESWYT\2022-23\ 128
6.	GS\2022-23\8046	36.	ESWYT\2022-23\ 142
7.	GS\2022-23\8057	37.	ESWYT\2022-23\ 145
8.	GS\2022-23\8060	38.	ESWYT\2022-23\ 146
9.	GS\2022-23\9001	39.	ESWYT\2022-23\ 147
10.	GS\2022-23\ 9014	40.	13HZW\2022-23\ 403
11.	GS\2022-23\ 9031	41.	13HZW\2022-23\ 407
12.	GS\2022-23\ 9042	42.	13HZW\2022-23\ 409
13.	GS\2022-23\9043	43.	13HZW\2022-23\ 412
14.	GS\2022-23\9046	44.	13HZW\2022-23\ 429
15.	GS\2022-23\9048	45.	13HZW\2022-23\ 433
16.	SATYN\2022-23\ 9404	46.	13HZW\2022-23\ 436
17.	SATYN\2022-23\ 9405	47.	2nd HZW \2022-23\ 510
18.	SATYN\2022-23\ 9406	48.	2nd HZW \2022-23\ 527
19.	SATYN\2022-23\ 9412	49.	2nd HZW \2022-23\ 531
20.	SATYN\2022-23\ 9413	50.	2nd HZW \2022-23\ 544
21.	SATYN\2022-23\ 9415	51.	2nd HZW \2022-23\ 545
22.	SATYN\2022-23\ 9419	52.	2nd HZW \2022-23\ 548
23.	SATYN\2022-23\ 9424	53.	HTWYT \2A022-23\ 13
24.	SATYN\2022-23\ 9425	54.	HTWYT \2022-23\ 16
25.	HTW\ 2022-23\ 2	55.	HTWYT \2022-23\ 17
26.	HTW\ 2022-23\ 3	56.	HTWYT \2022-23\ 18
27.	HTW\ 2022-23\ 7	57.	HTWYT \2022-23\ 45
28.	HTW\ 2022-23\ 10	58.	DBW -222 ©
29.	HTW\ 2022-23\ 11	59.	HD 2931 ©
30.	ESWYT\2022-23\ 102	60.	LOK 1 ©

Parameters studies

Observations were recorded for traits such as days to heading, days to anthesis, days to maturity, plant height (cm), number of effective tillers per plant, spike length (cm), grains per spike, 1000-grain weight (g), grain yield per plant (g), biological yield per plant (g), harvest index (%), grain filling duration, and grain filling rate across both seasons. In the second sowing date (E2), additional physiological parameters were measured, which included canopy temperature depression (°C) at anthesis and 15 days after anthesis, chlorophyll content index at anthesis and 15 days after anthesis, chlorophyll fluorescence index at anthesis and 15 days after anthesis, as well as normalized difference vegetation index (NDVI) at anthesis and 15 days after anthesis. The collected data were subjected to analysis of variance (ANOVA) and further used to assess mean performance and estimate genetic variability parameters such as PCV, GCV, heritability, and genetic advance.

Results and Discussion

Mean performance under December and January sown condition

Analysis of variance (ANOVA) showed significant differences among genotypes for most of the studied traits under both sowing environments, indicating the presence of substantial genetic variability. Such variability forms the basis for selection and improvement under heat stress conditions. Sixty wheat genotypes were evaluated under two late-sowing environments: December (E1) and January (E2). Significant variation was observed among genotypes for phenological, morphological, yield, and physiological traits, indicating substantial genetic diversity.

In wheat breeding programs aimed at developing heat-tolerant varieties with higher yield potential, understanding genotypic performance under stress conditions is essential. The present study highlighted the impact of terminal heat stress on phenology, growth, yield, and physiological traits across sixty wheat genotypes under two late-sown environments: December (E1) and January (E2). The analysis revealed a clear reduction in most traits under heat stress, reflecting the severity of high temperatures during critical growth stages.

Mean performance of the genotypes demonstrated that days to heading (DH), days to anthesis (DA), days to maturity (DM), plant height (PH), spike length (SL), grains per spike (GS), 1000-grain weight (TGW), grain yield per plant (GY), biological yield per plant (BY), harvest index (HI), grain filling duration (GFD), and grain filling rate (GFR) decreased under terminal heat stress in January compared to December sowing. For instance, DH ranged from 42 (GS\2022-23\8060) to 67 days (ESWYT\2022-23\142) in E1, whereas in E2 it was shortened to 45.5 to 56.5 days. Similarly, DA decreased from 49 -72.5 days in E1 to 50.5 - 66.5 days in E2, and DM shortened from 81-105 days in E1 to 82-100.5 days in E2, indicating accelerated crop development under heat stress. Plant height decreased from 71.1-91.2 cm (mean 79.7 cm) in E1 to 61.8-76.1 cm (mean 68.62 cm) in E2, while spike length and grains per spike were also reduced, reflecting restricted vegetative and reproductive growth.

Grain yield per plant showed a substantial decline under heat stress. In E1, genotypes HTWYT\2022-23\17 and 13HZW\2022-23\436 produced the highest grain yield per plant (3.77 g), whereas 13HZW\2022-23\407 yielded the lowest (1.83 g). Under E2, the highest grain yield per plant was observed in GS\2022-23\8040 (2.74 g) and the lowest in SATYN\2022-23\9405 (1.36 g). Biological yield per plant followed a similar pattern, declining from 4.41-9.58 g in E1 to 3.10-5.16 g in E2. Harvest index also decreased slightly, suggesting reduced efficiency in partitioning assimilates to grains under high temperature conditions.

Grain filling duration and rate were notably affected by terminal heat stress. In E1, GFD ranged from 29 to 37 days (mean 32.83 days) and GFR from 0.0572 to 0.1223 g/day (mean 0.0893 g/day), whereas in E2, GFD shortened to 28-34.5 days (mean 31.51 days) and GFR reduced to 0.0393-0.0918 g/day (mean 0.066 g/day), demonstrating accelerated maturation and reduced assimilate accumulation under high temperatures.

Physiological traits measured in E2 indicated stress adaptation mechanisms in certain genotypes. Canopy temperature depression (CTD) ranged from 2.13-7.63 °C at anthesis and 0.76-6.32 °C 15 days after anthesis, showing the variation in heat dissipation capacity among genotypes. Chlorophyll content index (CCI) ranged from 46.98-59.59 at anthesis and 41.22-57.29 at 15 days post-anthesis, suggesting genotypic differences in photosynthetic efficiency under stress. NDVI decreased from 0.73-0.87 at anthesis to 0.50-0.78 at 15 days after anthesis, indicating reduced plant greenness under heat stress.

Notably, some genotypes maintained relatively higher yield and physiological performance under stress. GS\2022-23\8040, HTWYT\2022-23\45, and 13HZW\2022-23\433 showed superior grain yield, extended grain filling duration, and higher NDVI and CCI under E2, indicating better heat tolerance. These genotypes completed photosynthetic activity efficiently during grain filling, allowing better assimilate accumulation despite heat stress.

Genetic Variability

The analysis of genetic variability among sixty wheat genotypes under late-sown heat stress conditions revealed significant differences in the extent of genotypic (GCV) and phenotypic (PCV) variation for various traits. Both sowing environments (E1 and E2) exhibited a reduction in the magnitude of genetic variability under higher terminal heat stress, reflecting the environmental influence on trait expression.

Phenological traits such as days to heading, days to anthesis, and days to maturity exhibited relatively low GCV and PCV across both environments, indicating that these traits are largely influenced by genetic makeup with minimal environmental interference. For example, DH in E1 showed a GCV of 8.08% and PCV of 8.55%, while in E2 it reduced further to 3.98% and 4.47%, respectively. Similarly, DA and DM had low GCV (4-7%) and PCV (4-7%) under E2, demonstrating that terminal heat stress compresses the phenological period uniformly across genotypes, leaving limited scope for selection based on these traits. The results were in agreement with (Azimi *et al.* 2017, Sapi *et al*. 2017, Neeru *et al*. 2017, Bhanu *et al*. 2018 and Chandramaniya *et al.* 2025) [13, 14. 15, 16, 17].

Morphological traits including plant height, spike length, and effective tillers per plant displayed low to moderate variability. Plant height recorded GCV of 3.01% and PCV of 6.39% in E1, which slightly increased to 3.69% and 6.73% in E2. Spike length showed a GCV of 4.24% (E1) and 4.57% (E2), while effective tillers per plant exhibited moderate variation with GCV ranging from 7.63% to 8.95% and PCV from 11.15% to 12.86%. This suggests that while heat stress reduces overall plant stature, there remains some genotypic differentiation that can be exploited for breeding. Similar finding were observed by (Kumar *et al.* 2017[, Meles *et al.* 2017, Raaj *et al.* 2018, Tomar *et al.* 2019, Kanwar *et al.* 2020, Poudel *et al.* 2021 and Poonia *et al.* 2023) [18, 19, 20, 21, 22, 23, 24].

Yield and yield-related traits such as grains per spike, 1000-grain weight, grain yield per plant, and biological yield demonstrated moderate genetic variability. For instance, grain yield per plant had a GCV of 13.26-13.81% and PCV of 17.41-19.57% under heat stress environments, indicating that selection for high-yielding genotypes under terminal heat stress is feasible. Biological yield showed slightly higher variability with GCV of 12.90-19.38% and PCV of 18.57-20.70%, reflecting greater environmental influence on total biomass accumulation. Similarly, grains per spike and 1000-grain weight exhibited low to moderate GCV (3.98-8.17%) and PCV (7.28-10.22%), suggesting a more stable genetic control over these components compared to total yield. Same result was founded by (Islam *et al.* 2017, Tomar *et al.* 2019, Shehrawat *et al.* 2021 and Singh *et al.* 2024) [25, 21, 26, 27].

Physiological traits measured under the more stressful E2 environment revealed relatively higher variability, highlighting the adaptive potential among genotypes. Canopy temperature depression (CTD) showed a GCV of 20.87-38.81% and PCV of 21.25-39.20%, indicating substantial genotypic differences in heat avoidance or tolerance. Chlorophyll content index (CCI) and normalized difference vegetation index (NDVI) exhibited low to moderate variation with GCV ranging from 3.76-9.27%

and PCV from 5.78-10.12%, suggesting that while stress reduces photosynthetic activity uniformly, certain genotypes maintain higher greenness and chlorophyll retention. Chlorophyll fluorescence showed minimal variability (GCV 2.71-2.82%, PCV 4.97-5.00%), indicating strong genetic stability for photosystem II efficiency even under heat stress.

Heritability and genetic advance

Under late-sown heat stress (December), days to heading (DH) and days to anthesis (DA) exhibited very high heritability (89.48% and 89.56%, respectively) with moderate GAM (15.75% and 14.28%), suggesting predominant non-additive gene action and limited scope for direct phenotypic selection. Comparable finding shown by Zewdu *et al.* (2024) [28] for days to heading and by Patel *et al.* (2022) [29] for day to anthesis. Similarly, days to maturity (DM) showed high heritability (83.68%) but low GAM (9.1%), indicating environmental influence. These findings are confirmed with the result of Bhatt *et al.* (2023) [30]. In January, DH, DA, and DM showed slightly lower heritability (79.09%, 76.31%, and 57.52%, respectively) and low GAM (7.29%, 7.26%, and 3.93%), reflecting moderate environmental impact, which limits selection efficiency for these traits.

Plant height (PH) was strongly influenced by the environment, with low heritability (22.09%) and low GAM (2.91%) in December, and moderate heritability (30.01%) with low GAM (4.16%) in January, indicating limited response to selection. Effective tillers per plant (ET) showed moderate heritability (48.42% in December and 46.79% in January) and moderate GAM (12.83% and 10.75%), suggesting potential for improvement through selection. Tomar *et al* (2019) [21], Shehrawat *et al.* (2021) [26] and Sharadhi *et al.* (2023) [31] obtained similar results. Spike length (SL) had moderate to low heritability (33.20% in December and 29.81% in January) with low GAM (5.03% and 5.14%), reflecting limited scope for selection. Grains per spike (GS) exhibited high heritability (63.86%) and moderate GAM (13.45%) in December is confirmed with the findings of Azimi *et al.* (2017) [13], while low heritability (29.85%) and low GAM (4.47%) in January, highlighting strong environmental effects under severe heat stress.

For yield-related traits, 1000-grain weight (TGW) showed moderate heritability (50.45%) and low GAM (7.03%) in December, while in January heritability was high (70.67%) with low GAM (8.64%), indicating predominance of non-additive gene action with limited selection potential. Biological yield (BY) exhibited moderate heritability (48.2%) and moderate GAM (18.44%) in December, whereas in January both heritability (79.92%) and GAM (34.09%) were high, suggesting additive gene action and significant scope for improvement. Harvest index (HI) had moderate heritability in both periods (31.97% in December and 38.74% in January) with low to moderate GAM (9.41% and 15.81%), indicating partial environmental influence. Grain yield (GY) showed moderate heritability (49.78% in December and 57.97% in January) coupled with high GAM (20.07% and 20.79%), demonstrating substantial potential for genetic improvement even under heat stress. These results are in agreement with (Sapi *et al.* 2017 and Lamara *et al.* 2022) [14, 32].

Physiological traits reflected varying responses. Grain filling duration (GFD) had moderate heritability (30.02% in December and 30.66% in January) with low GAM (4.13% and 3.51%), indicating non-additive control. The result was match up with the findings of Jain *et al.* (2017) [33] and Alemu *et al.* (2020) [34].

In contrast, grain filling rate (GFR) displayed high heritability (64.15%) and high GAM (25.96%) in December, and moderate heritability (55.39%) with high GAM (20.64%) in January, highlighting additive gene action and good selection response. Similar findings for this character were also reported by Islam *et al.* (2017)[25]. Canopy temperature depression (CTD) showed very high heritability both at anthesis (96.47%) and 15 days after anthesis (98.04%) with high GAM (42.23% and 79.17%), reflecting strong genetic control and minimal environmental influence. The present results are in agreement with Patel *et al.* (2022) [29].

Chlorophyll content (CCI) at anthesis and 15 days after anthesis showed moderate heritability (42.18% and 78.79%) with low to moderate GAM (5.02% and 12.29%), indicating combined additive and non-additive effects. Chlorophyll fluorescence (CFI) at anthesis and 15 days after anthesis had low to moderate heritability (29.73% and 31.81%) with low GAM (3.04% and 3.27%), reflecting limited scope for selection. NDVI at anthesis showed moderate heritability (31.76%) and low GAM (3.46%), whereas NDVI at 15 days after anthesis exhibited high heritability (83.91%) with moderate GAM (17.5%), indicating higher potential for selection during grain filling.

Overall, traits such as GFR, CTD, late-stage CCI, and NDVI at 15 days after anthesis are largely governed by additive gene action and are suitable targets for selection under heat stress. In contrast, PH, SL, early-stage CCI, and CFI are strongly influenced by the environment, limiting direct selection efficiency. These results provide valuable insights into the genetic architecture of wheat under terminal heat stress and will guide breeders in identifying superior genotypes for heat-tolerant wheat improvement programs.

Table 2: Variability, heritability (broad sense) and genetic advance percentage means estimate studied morphological traits across two environments

Character		Min	Max	Mean	GCV (%)	PCV (%)	h^2_{bs}(%)	GAM
Days to heading	E1	42.00	67.00	53.68	8.08	8.55	89.48	15.75
	E2	45.50	56.50	50.25	3.98	4.47	79.09	7.29
Days to anthesis	E1	49.00	72.50	59.21	7.33	7.74	89.56	14.28
	E2	50.50	66.50	55.42	4.04	4.62	76.31	7.26
Days to maturity	E1	81.00	105.00	92.01	4.83	5.28	83.68	9.10
	E2	82.00	100.50	86.94	2.52	3.32	57.52	3.93
Plant height (cm)	E1	71.10	91.20	79.70	3.01	6.39	22.09	2.91
	E2	61.80	76.10	68.62	3.69	6.73	30.01	4.16
Effective tillers/plant	E1	4.80	8.30	6.69	8.95	12.86	48.42	12.83
	E2	3.60	5.80	4.63	7.63	11.15	46.79	10.75
Spike length (cm)	E1	7.92	10.58	8.86	4.24	7.36	33.20	5.03
	E2	7.22	9.45	8.37	4.57	8.37	29.81	5.14
Grains/spike	E1	32.90	61.20	47.12	8.17	10.22	63.86	13.45
	E2	35.30	45.10	40.08	3.98	7.28	29.85	4.47
1000 grain weight (g)	E1	36.85	48.30	42.14	4.80	6.76	50.45	7.03
	E2	35.50	44.60	39.48	4.99	5.94	70.67	8.64
Biological yield (g/plant)	E1	4.41	9.58	7.01	12.90	18.57	48.20	18.44
	E2	3.21	9.10	5.16	19.38	20.70	79.92	34.09
Harvest index	E1	30.56	65.72	42.12	8.08	14.29	31.97	9.41
	E2	23.63	64.57	41.59	12.33	19.81	38.74	15.81
Grain yield/plant (g/plant)	E1	1.83	3.77	2.92	13.81	19.57	49.78	20.07
	E2	1.36	2.74	2.09	13.26	17.41	57.97	20.79
Grain filling duration (days)	E1	29.00	37.00	32.83	3.66	6.69	30.02	4.13
	E2	28.00	34.5	31.51	20.87	21.25	96.47	42.23
Grain filling rate (g/days)	E1	0.0572	0.1223	0.0893	15.74	19.65	64.15	25.96
	E2	0.0393	0.0918	0.066	38.81	39.20	98.04	79.17

genotypic coefficient of variation (GCV%); phenotypic coefficient of variance (PCV%); broad sense heritability (h^2_{bs}(%)); genetic advance per percent means (GAM).

Table 3: Variability, heritability (broad sense) and genetic advance percentage means estimate studied morphological traits for environment 2 (E2- January sowing)

Character		Min	Max	Mean	GCV (%)	PCV (%)	h^2_{bs}(%)	GAM
CTD 1 (ºC)	E2	2.13	7.63	5.31	3.76	5.78	42.18	5.02
CTD 2 (ºC)	E2	-0.76	6.32	3.34	6.72	7.57	78.79	12.29
CC 1	E2	46.98	59.59	54.38	2.71	4.97	29.73	3.04
CC 2	E2	41.22	57.29	49.82	2.82	5.00	31.81	3.27
CF 1	E2	0.68	0.82	0.75	2.98	5.29	31.76	3.46
CF 2	E2	0.65	0.83	0.75	9.27	10.12	83.91	17.50
NDVI 1	E2	0.73	0.87	0.80	3.08	5.56	30.66	3.51
NDVI 2	E2	0.78	0.87	0.639	13.46	18.08	55.39	20.64

Genotypic coefficient of variation (GCV%); phenotypic coefficient of variance (PCV%); broad sense heritability (h^2_{bs}(%)); genetic advance per percent means (GAM).

GFD= Grain filling duration (days), GFR= Grain filling rate (g/days), CTD 1: Canopy temperature depression at anthesis (ºC), CTD 2: Canopy temperature depression at anthesis (ºC), CC 1: Chlorophyll content at anthesis, CC 2: Chlorophyll content 15 days after anthesis, CF 1: Chlorophyll fluorescence at anthesis, CF 2: Chlorophyll fluorescence 15 days after anthesis, NDVI 1: Normalized differential vegetative index at anthesis, NDVI 2: Normalized differential vegetative index 15 days after anthesis.

Conclusion

The present study revealed substantial genetic variability among sixty wheat genotypes under late-sown heat stress conditions, with significant reductions observed in most phenological, morphological, yield, and physiological traits under higher temperature stress. Traits such as days to heading, anthesis, maturity, plant height, spike length, grains per spike, 1000-grain weight, grain yield, and biological yield were notably affected, reflecting accelerated crop development and restricted assimilate accumulation under terminal heat. Despite this, certain genotypes maintained higher yield and physiological performance, indicating inherent heat tolerance. Analysis of heritability and genetic advance showed that traits including grain filling rate, canopy temperature depression, biological yield, and NDVI at 15 days after anthesis exhibited high heritability coupled with moderate to high genetic advance, suggesting predominant additive gene action and considerable potential for direct selection. In contrast, plant height, spike length, early-stage chlorophyll content, and chlorophyll fluorescence were strongly influenced by the environment, limiting the effectiveness of phenotypic selection. Overall, the study identifies key traits and promising genotypes that can be exploited in wheat breeding programs aimed at enhancing heat tolerance, yield stability, and physiological resilience under terminal heat stress conditions**.**

Acknowledgements

The authors acknowledge NAU, Navsari for providing experimental land and other necessary facilities for conducting the experiment. We appreciate the facilities, resources, and research assistance provided by the Department of Genetics and Plant Breeding, N.M. College of Agriculture, NMCA, NAU, Navsari. We extend our gratitude to all parties who supported this study and contributed to the preparation of this article.

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