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Effects of Terminal Heat Stress on Wheat Yield and Morpho-Physiological Traits in Ongole, Andhra Pradesh

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ABSTRACT

Terminal heat stress reduced wheat (*Triticum aestivum* L.) productivity and quality, threatening global food security, especially in climate-vulnerable places like Ongole, Andhra Pradesh. This study evaluated the impact of heat stress on grain yield and its major contributing morpho-physiological and grain quality traits across 43 diverse wheat genotypes, including three standard checks, over two **rabi** seasons (2023-24 in Talwandi Sabo as control and 2024-25 in Ongole under terminal heat stress). Analysis of variance indicated significant differences among genotypes for all examined traits in both the environments, confirming notable genetic variability. Terminal heat stress in Ongole led to significant decrease in mean grain yield per plot (from 340.21 to 6.04 g), biological yield per plot (from 868.92 to 38.8 g) and other yield-related traits when compared to the control environment. Traits including grain yield per plot, biological yield per plot, number of grains per spike, and test weight demonstrated high heritability, with values such as 97.41 for grain yield per plot under stress, alongside significant genetic advance as a percentage of mean, exemplified by 119.66 for grain yield per plot under stress. The findings showed that additive gene action had a major impact and that these traits can be selected for even under stress. Heat stress indices (HSI, HTI, YSI, TOL and DI) differentiated genotypes for heat tolerance, demonstrating genotypes with improved stability and performance under terminal heat stress. Terminal heat stress severely impacted wheat yield components, yet genetic promise for heat-resilient types was shown. The found genotypes and features with high heritability and favourable stress indices should inform focused breeding strategies to improve wheat adaptability and productivity in heat-stressed Andhra Pradesh and similar locales.

Key words: Genetic variability, grain yield, heritability, terminal heat stress, wheat

INTRODUCTION

Wheat (*Triticum aestivum* L.) stands as a global staple, providing a significant portion of the world's dietary calories and protein. Its extensive cultivation across diverse agro-climatic zones underscores its indispensable role in ensuring food security for a burgeoning global population. However, the productivity and stability of wheat cultivation are increasingly threatened by the escalating challenges posed by climate change, particularly the rise in ambient temperatures. Among the various abiotic stresses, terminal heat stress, defined as exposure to temperatures exceeding 30^{0}C during the critical anthesis and grain-filling stages, is a major limiting factor for wheat production (Ramunaidu *et al.,* 2023). This period is highly sensitive to temperature fluctuations, as heat stress can drastically alter physiological processes, leading to premature senescence, reduced photosynthetic efficiency, impaired nutrient translocation, and a shortened grain-filling duration. Consequently, these physiological disruptions culminate in a significant reduction in both grain quantity and quality (Riaz *et al.,* 2021; Ullah *et al.,* 2021). Scientific consensus suggests a 3-4 yield drop for every 1°C increase above 28°C during grain filling (Abdurezake *et al.,* 2024; Khanzada *et al.,* 2025). Heat-resilient wheat cultivars are needed to protect agricultural productivity in climate-vulnerable locations due to such high yield penalties.

Understanding heat tolerance genetics and finding hardy genotypes is essential for producing wheat varieties for harsh conditions. Breeding programs to improve heat tolerance needed evaluation of the germplasm for genetic heterogeneity. For efficient selection

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techniques, morpho-physiological features directly affected by heat stress and yield, must be evaluated (Abidin *et al.,* 2024). This study examined the effects of heat stress on grain production and its primary contributing features in a broad range of wheat genotypes in Ongole, Andhra Pradesh, under terminal heat stress conditions.

MATERIALS AND METHODS

Two **rabi** seasons: 2023-24 and 2024-25 were utilized to assess wheat performance at different temperatures (Fig. 1). Near Talwandi Sabo, Punjab, the control environment (2023-24) had maximum temperatures of 20.0°C to 28.0°C. In Ongole, Andhra Pradesh, the terminal heat stress environment (2024-25) had average maximum temperatures ranging from 50.8°C to 71.6°C, significantly higher than maximum temperatures during crucial growth stages. This large temperature difference ensured considerable heat stress, especially in the reproductive phase, allowing yield to be precisely assessed. The control experiment at Talwandi Sabo (2023-24) was conducted in field conditions. To ensure moisture management and heat isolation for the terminal heat stress trial, the experiment at Ongole (2024-25) was conducted using plastic UV protected poly grow bags (12x12 inches). In addition, seedling and physiological traits were assessed for both the seasons in a separate lab-based experiment.

Three standard checks (WH 1270, HD 3386 and DBW 222) and 43 different wheat genotypes were tested. These genotypes were sown in Talwandi Sabo (control) on December 7, 2023, and Ongole (heat stress) on December 24, 2024. Ongole's later planting date was carefully intended to expose the crop to peak high temperatures during anthesis and grain filling. The trial used a randomized block design (RBD) with three replications per site. Each experimental plot had two rows with 25 cm row-to-row spacing and 10 cm plant-to-plant spacing. Except for heat stress, standard agronomic procedures, including fertilizer doses (80:40:40 kg/ha N:P:K) were used to ensure excellent development.

Data were collected on morpho-physiological traits pertinent to yield and its reaction to heat stress. The parameters measured included

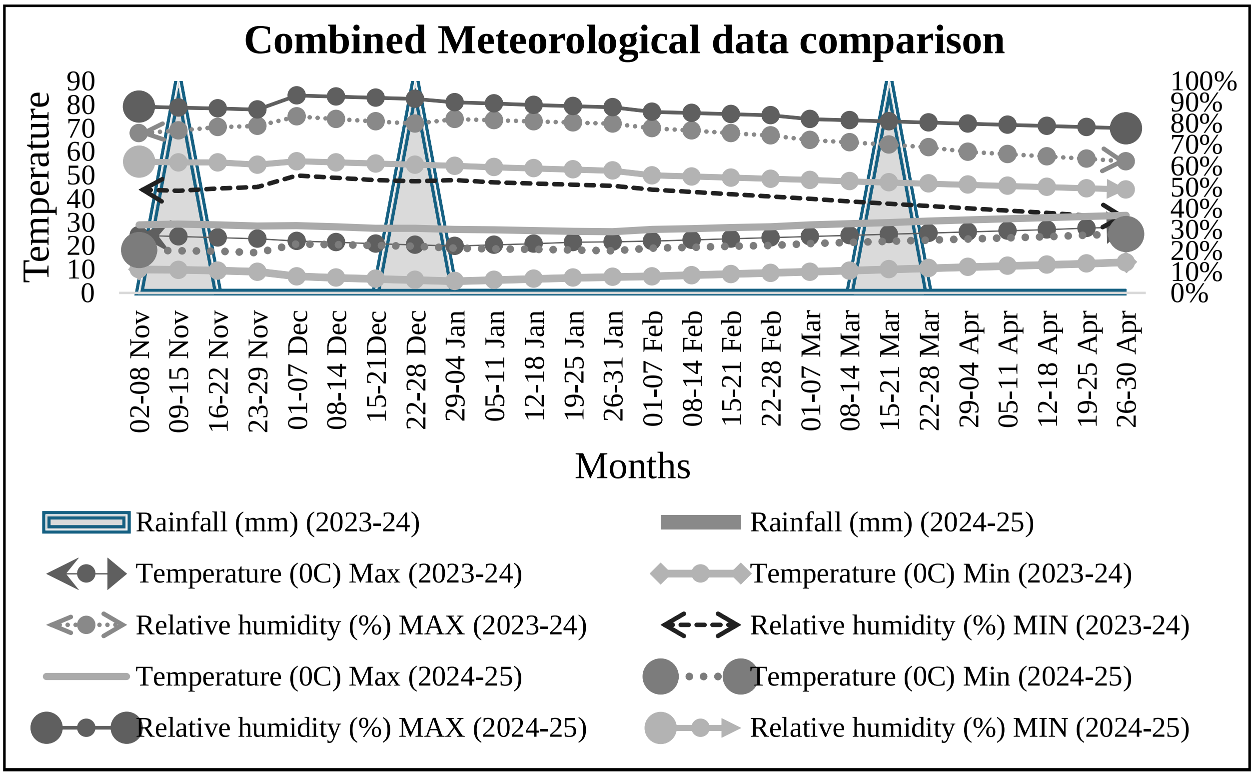

Fig. 1. Meteorological data showing average maximum and minimum temperatures (shown by the line graph) and rainfall (implied by the lower row of numbers) throughout both **rabi** season of 2023-24 at the experimental site in Talwandi Sabo, Bathinda, Punjab and 2024-25 at the experimental site in Ongole, Andhra Pradesh.

grain yield per plot (g), biological yield per plot (g), grain yield per plant (g), biological yield per plant (g), number of grains per spike, test weight (g), plant height (cm), days to 50% flowering, days to maturity, peduncle length (cm), number of tillers per plant, flag leaf length (cm), flag leaf width (cm), flag leaf area (cm²), spike length (cm), grain weight per spike (g) and harvest index (%). Protein content (%) was evaluated as a critical parameter of grain quality. Physiological observations including germination percentage, germination speed index, root length, shoot length, seedling length, seedling dry weight, seed vigour indices I and II, and seedling fresh weight were recorded to enhance the understanding of plant performance.

Heat tolerance for each genotype was calculated using stress indices from grain yield data in both the conditions. A lower Heat Susceptibility Index (HSI) indicated better tolerance to stress-induced yield decrease. High Heat Tolerance Index (HTI) values indicated a genotype's stress-tolerant yield. A higher Yield Stability Index (YSI) showed more yield stability. It was the ratio of yield during stress to yield under non-stress situations. A lower TOL indicated lower yield loss and assessed to the absolute yield difference between stress and non-stress situations. Drought Index (DI) measured environmental stress intensity.

To detect significant genetic differences for each attribute, all data were analyzed using a randomised block design. Phenotypic, genotypic and environmental coefficients of variation were investigated. Genetic advancement as a percentage of mean (GAM) and wide-sense heritability (h^2) was calculated to assess genetic control and feature improvement in both the situations. BIOSTAT was utilized for all statistical analyses.

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) performed over both experimental years indicated highly significant differences among the 43 wheat genotypes across all 16 morpho-physiological and grain quality traits examined (Tables 1 and 2). This variation indicated that the evaluated germplasm had important genetic variability for selection in breeding programs (Geneti *et al.*, 2022; Kumar *et al.*, 2022).

Mean performance data revealed environmental impacts on seedling and physiological traits across seasons (Table 1). In the 2023-24 control environments, mean germination percentage (GP) was 92.44%, seedling dry weight (DW) was 0.17 mg, seed vigour index II (SVI-II) was 16.01% and protein content (PC) was 11.94%. Under 2024-25 stress conditions, most traits slightly declined: GP to 85.09%, DW to 0.16 mg and SVI-II to 14.11%. Conversely, mean protein

Table 1. Mean performance during 2023-24 and 2024-25

	Mean performance under field conditions 2023-24									
	GP	SOG	RL	ShL	SdL	FW	DW	SVI-I	SVI-II	PC
Mean	92.44	8.01	14.78	16.11	30.68	0.81	0.17	2834.39	16.01	11.94
C.V.	5.51	6.23	2.53	4.32	4.91	5.00	5.84	10.71	41.21	3.27
S.E.	2.54	0.25	0.19	0.35	0.75	0.02	0.01	151.71	3.30	0.20
C. D. (P=0.05)	7.12	0.70	0.52	0.97	2.11	0.06	0.01	424.50	9.23	0.55
C. D. (P=0.01)	9.41	0.92	0.69	1.29	2.79	0.07	0.02	560.94	12.20	0.72
Minimum	82.75	6.91	10.64	13.05	22.20	0.47	0.12	2041.53	10.54	9.60
Maximum	98.00	8.98	17.88	20.07	36.96	1.15	0.49	3492.26	44.40	15.70
	Mean performance under grow bags 2024-25									
Mean	85.09	13.91	14.43	15.86	30.41	0.70	0.16	2616.97	14.11	12.69
C.V.	4.85	4.86	5.57	5.24	8.02	6.20	6.36	9.80	7.94	3.30
S.E.	2.06	0.34	0.40	0.42	1.22	0.02	0.01	128.21	0.56	0.21
C. D. (P=0.05)	5.78	0.95	1.12	1.16	3.41	0.06	0.01	358.75	1.57	0.59
C. D. (P=0.01)	7.63	1.25	1.49	1.54	4.51	0.08	0.02	474.06	2.07	0.77
Minimum	50.25	12.31	10.29	12.80	22.19	0.36	0.10	1118.25	5.03	10.10
Maximum	97.00	14.83	17.53	19.81	37.03	1.04	0.49	3548.75	46.17	15.90

Where: GP – Germination percentage; SOG – Speed of germination; RL – Root length (cm); ShL – Shoot length (cm); SdL – Seedling length (cm); FW – Seedling fresh weight (g); DW – Seedling dry weight (mg); SVI-I – Seed vigour index I; SVI-II – Seed vigour index II and PC = Protein content (%).

Table 2. Mean performance during 2023-24 and 2024-25

	Mean performance field conditions 2023-24															
	DF	DM	PH	PL	NTP	FLL	FLW	FLA	SL	NGPS	GWPS	BYP	GYP	GYPP	BYPP	TW
Mean	91.69	132.16	98.49	18.73	4.69	27.71	1.51	31.83	12.29	53.73	2.01	19.42	9.02	340.21	868.92	26.75
C. V.	5.4	2.42	5.86	6.22	7.65	6.33	6.23	6.23	5.81	7.51	9.02	9.52	10.21	10.49	9.65	8.51
S. Em	2.86	1.85	3.33	0.67	0.21	1.01	0.05	1.15	0.41	2.33	0.1	1.07	0.53	20.61	48.41	1.31
C. D. (P=0.05)	8.04	5.2	9.37	1.89	0.58	2.85	0.15	3.22	1.16	6.55	0.29	3	1.49	57.97	136.14	3.7
C. D. (P=0.01)	10.66	6.9	12.42	2.51	0.77	3.78	0.2	4.27	1.54	8.68	0.39	3.98	1.98	76.83	180.44	4.9
Minimum	85	126	85.3	14.23	3.73	14.7	1.07	11.77	9.23	33.9	0.93	11.3	5.9	209.1	342.13	17.7
Maximum	102.33	137.33	132.33	24.2	5.6	43.9	2.9	95.2	22.97	83.6	3.9	58.3	17.3	481.53	1241.6	33.5
Replication	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Treatment	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	Mean performance grow bags 2024-25															
Mean	58.4	105	59.5	7.77	1.69	22.3	0.83	16.9	7.22	14.8	0.42	2.28	0.7	6.04	38.8	28.1
C. V.	6.21	5.91	5.66	6.09	7.59	5.88	4	6	6.19	7.82	10.9	9.65	11.6	9.6	10.6	4.59
S. Em	2.09	3.58	1.95	0.27	0.07	0.76	0.02	0.58	0.26	0.67	0.03	0.13	0.05	0.33	2.36	0.75
C. D. (P=0.05)	5.89	10.07	5.47	0.77	0.21	2.13	0.05	1.64	0.73	1.88	0.07	0.36	0.13	0.94	6.65	2.1
C. D. (P=0.01)	7.81	13.35	7.26	1.02	0.28	2.82	0.07	2.18	0.96	2.49	0.1	0.47	0.17	1.25	8.81	2.78
Minimum	44.3	88.33	47.1	4.33	1.07	14.3	0.73	9.83	4.77	4.13	0.1	1.03	0.1	1.03	16	18.2
Maximum	93.7	111.3	71	15.4	2.9	37.2	0.93	30.7	9.5	34.5	0.93	4.97	1.93	14.2	71.3	40
Replication	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Treatment	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

Where: DF – Days to 50% flowering; DM – Days to maturity; PH – Plant height (cm); PL – Peduncle length (cm); NTP – Number of tillers per plant; FLL – Flag leaf length (cm); FLW – Flag leaf width (cm); FLA – Flag leaf area (cm^2); SL – Spike length (cm); NGPS – Number of grains per spike; GWPS – Grain weight per spike (g); BYP – Biological yield per plant (g); GYP – Grain yield per plant (g); GYPP – Grain yield per plot (g); BYPP – Biological yield per plot (g) and TW – Test weight (g).

content slightly increased to 12.69%, potentially due to a "concentration effect" from reduced starch accumulation. Observed variability (C.V.) further confirmed differing environmental influences and genetic responses.

Terminal heat stress in Ongole (2024-25) as shown in Table 2, significantly affected most yield-related traits in comparison to the favourable conditions observed in Talwandi Sabo (2023-24). A significant decrease in mean grain yield per plot was recorded, falling from 340.21 g under control conditions to 6.04 g under heat stress, indicating a reduction of approximately 98.2%. The mean biological yield per plot decreased significantly from 868.92 to 38.8 g, representing a reduction of 95.5%. Other essential yield components exhibited notable decline: The average number of grains per spike decreased from 53.73 to 14.76 (a reduction of 72.5%), and the average plant height fell from 98.49 to 59.53 cm (a reduction of 39.6%). The findings aligned with earlier studies that emphasized the negative impact of elevated temperatures on wheat yield and its components, attributed to shortened grain-filling periods and decreased biomass accumulation (Farhad *et al.,* 2023; Fu *et al.,* 2023). The temperature range in Ongole (50.8°C to 71.6°C maximum) during the reproductive phase was notably elevated, which accounted for the significant decrease in yield. The mean test weight, which indicates grain plumpness and quality, improved from 26.75 g in 2023-24 to 28.12 g in 2024-25. Despite a considerable yield loss, some genotypes may have responded differently or compensated under intense stress, causing the surprise increase.

The ANOVA results indicated that a significant amount of genetic variability remained even though trait averages generally decreased under heat stress. The variability was needed to identify and select heat-tolerant genotypes (Tables 3 and 4). The genotypic coefficient of variation (GCV) for grain yield per plot was 18.52 in 2023-24 and 58.86 in 2024-25. PCV levels were 21.29 and 59.63 over the same periods. A minor difference between GCV and PCV, especially during heat stress, suggested that genetics influenced in these traits was more than the environment, making them appropriate for direct selection. Biological yield per plot (GCV: 36.95 vs. 36.26; PCV: 38.16 vs. 37.77) and number of grains per spike (GCV: 21.66 vs. 51.46; PCV: 22.93 vs. 52.05) also showed similar tendencies.

Genetic traits with high heritability (h^2) and genetic advance (GAM) are mostly affected by additive gene action, which makes it easier to

Table 3. Variability (genotypic and phenotypic), heritability and genetic advance for different yield and yield components recorded during **rabi** 2023-24 (Talwandi Sabo, Control)

S. No.	Genetic parameters	GCV	PCV	h^2 (Broad Sense)	GA	GAM
1.	50% flowering	3.10	6.23	24.793	2.92	3.18
2.	Days to maturity	1.23	2.72	20.531	1.52	1.15
3.	Plant height	6.92	9.07	58.268	10.72	10.89
4.	Peduncle length	9.97	11.75	71.994	3.26	17.43
5.	No.of tillers/Plant	8.89	11.73	57.429	0.65	13.87
6.	Flag leaf length	20.60	21.55	91.368	11.24	40.56
7.	Flag leaf width	22.12	22.98	92.646	0.66	43.86
8.	Flag leaf area	38.29	38.79	97.417	24.77	77.84
9.	Spike length	24.04	24.73	94.475	5.91	48.13
10.	No. of grains/spike	21.66	22.93	89.271	22.65	42.16
11.	Grain weight/spike	29.61	30.95	91.513	1.17	58.34
12.	Biological yield/plant	36.95	38.16	93.774	14.31	73.71
13.	Grain yield/plant	22.35	24.57	82.742	3.78	41.88
14.	Grain yield/plot	18.52	21.29	75.694	112.92	33.19
15.	Biological yield/plot	21.94	23.97	83.787	359.42	41.36
16.	Test weight	11.51	14.31	64.634	5.10	19.06

Where: GCV – Genotypic coefficient of variation; PCV – Phenotypic coefficient of variation; h^2 – Heritability; GA – Genetic advance and GAM – Genetic advance as percentage of mean.

Table 4. Variability (genotypic and phenotypic), heritability and genetic advance for different yield and yield components recorded during **rabi** 2024-25 (Ongole, heat stress)

S. No.	Genetic parameters	GCV	PCV	h^2 (Broad Sense)	GA	GAM
1.	50% flowering	15.28	16.50	85.834	17.05	29.17
2.	Days to maturity	5.19	7.87	43.541	7.40	7.06
3.	Plant height	10.16	11.63	76.284	10.88	18.28
4.	Peduncle length	28.43	29.08	95.617	4.45	57.27
5.	No. of tillers/plant	25.37	26.48	91.776	0.85	50.07
6.	Flag leaf length	14.97	16.08	86.637	6.41	28.69
7.	Flag leaf width	4.74	6.21	58.397	0.06	7.47
8.	Flag leaf area	20.63	21.49	92.197	6.89	40.81
9.	Spike length	13.94	15.25	83.508	1.90	26.24
10.	No. of grains/spike	51.46	52.05	97.742	15.47	104.81
11.	Grain weight/spike	52.61	53.72	95.919	0.44	106.15
12.	Biological yield/plant	37.65	38.87	93.83	1.71	75.13
13.	Grains yield/plant	66.11	67.11	97.037	0.94	134.15
14.	Grain yield/plot	58.86	59.63	97.408	7.23	119.66
15.	Biological yield/plot	36.26	37.77	92.189	27.83	71.72
16.	Test weight	19.28	19.82	94.63	10.87	38.64

Where: GCV = Genotypic coefficient of variation; PCV = Phenotypic coefficient of variation; h^2 = Heritability; GA = Genetic advance; GAM = Genetic advance as percentage of mean.

select them directly (Qaseem *et al.,* 2019; Djanaguiraman *et al.,* 2020). In the control environment (2023-24), grain yield per plot had 75.69 heritability and 33.19 genetic advance. Heritability was 97.41, and GAM was 119.66 for grain yield per plot during terminal heat stress (2024-25). Despite the large output loss, genetic control over grain yield was more evident under stress, suggesting selection-based genetic improvement (Tehseen *et al.,* 2022).

Biological yield per plot (h^2 = 93.83, GAM = 75.13), number of grains per spike (h^2 = 97.74, GAM = 104.81) and test weight showed a strong genetic impact and improvement during heat stress. Previous research has shown that these morpho-physiological features are crucial for wheat heat tolerance (Mosavian *et al*., 2021; Shenoda *et al*., 2021). Under stress, high heritability values indicate that hereditary factors explain most of the observed differences in these traits, making them easier to choose (Li *et al.,* 2020).

Strong seedling vigour is essential for crop establishment (Tables 5 and 6). The mean germination rate was 85.09%. Seed Vigour Index-II ranged from 8.68 (G18 - WH 1080) to 35.3 (G15 - WH 1194). Grain protein averaged 12.00% under stress, ranging from 9.80% (G14

- WH 1270) to 14.80% (G38 - PBW 593). G1 (WH 1124–14.40%), G17 (WH 283) and G6 (HD 2967 - 13.80%) had high protein content. The concentration effect caused by decreased starch increased protein during heat stress (Lamba *et al*., 2023). However breeding high-protein, acceptable yield genotypes like G38 (PBW 593) were beneficial. Future research may examine metabolic changes in tolerant lineages. High variability and heritability were observed in days to 50% flowering (14.26, 85.83 and 27.17%), protein content (11.07, 11.20, 97.78 and 22.56%), and seedling dry weight and seedling vigour-II (very high GCV, PCV, $h^2bs > 99\%$, GAM > 50%).

Multiple heat stress indices were utilized to identify each of the genotypes performance under terminal heat stress. First two principal components (F_1 and F_2) explained 86.41% of the stress indices' variability (Table 7). Factor 1 (F_1) accounted for 56.435% of variability and showed positive loadings from yield under stress (Ys: 0.970), Heat Tolerance Index (HTI: 0.815), Yield Stability Index (YSI: 0.969), and Drought Index (DI: 0.952; Table 8).

In the variables map, the active variables (dots and vectors) were aligned with strong positive vectors along the F_1 axis, indicating a strong positive relationship with this component. F_2 explained 29.977% of variability. Yield under Control (Yc: 0.975) and Tolerance (TOL: 0.906) had considerable positive loadings (Fig. 2). Yc and TOL had strong positive vectors along the F_2 axis in the variables plot. This diagram showed that F_1 favoured performance and stability under stress, while F_2 prioritized yield in controlled situations and stress sensitivity. Yc and TOL were positioned with strong positive vectors along the F_2 axis (Fig. 3). This graphical representation confirmed that F_1 primarily emphasized performance and stability under stress conditions, while F_2 highlighted yield under control environments and stress sensitivity. The dots in the Biplot represent the "active observations" (the different wheat genotypes), showing their

Table 5. Variability (genotypic and phenotypic), heritability and genetic advance for different yield and yield components recorded during **rabi** 2023-24 under field conditions

Genetic parameters	GP	SOG	RL	ShL	SdL	FW	DW	SVI-I	SVI-II	PC
GCV	1.99	5.13	11.41	9.02	9.24	20.31	33.49	8.58	25.55	13.28
PCV	5.86	8.07	11.69	10.00	10.46	20.92	33.99	13.72	48.49	13.68
h^2 (Broad sense)	11.6	40.4	95.3	81.3	77.9	94.3	97.00	39.1	27.8	94.3
Genetic advancement 5%	1.29	0.54	3.39	2.70	5.16	0.33	0.12	313.56	4.44	3.17
Gen. adv. as % of mean 5%	1.40	6.72	22.94	16.75	16.80	40.63	67.95	11.06	27.74	26.57

Where: GP – Germination percentage; SOG – Speed of germination; RL – Root length (cm); ShL – Shoot length (cm); SdL – Seedling length (cm); FW – Seedling fresh weight (g); DW – Seedling dry weight (mg); SVI-I – Seed vigour index I; SVI-II – Seed vigour index II and PC – Protein content (%).

Table 6. Variability (genotypic and phenotypic), heritability and genetic advance for different yield and yield components recorded during **rabi** 2024-25 under grow bags

Genetic parameters	GP	SOG	RL	ShL	SdL	FW	DW	SVI-I	SVI-II	PC
GCV	10.60	4.49	11.42	9.05	12.33	23.47	39.61	20.85	46.41	10.69
PCV	11.66	6.61	12.71	10.46	14.71	24.28	40.12	23.04	47.09	11.18
h^2 (Broad sense)	82.7	46.1	80.8	74.9	70.3	93.5	97.5	81.9	97.2	91.3
Genetic advancement 5%	16.90	0.87	3.05	2.56	6.48	0.33	0.13	1017.24	13.30	2.67
Gen. adv. as % of mean 5%	19.86	6.28	21.15	16.13	21.31	46.75	80.56	38.87	94.24	21.03

Where: GP – Germination percentage; SOG – Speed of germination; RL – Root length (cm); ShL – Shoot length (cm); SdL – Seedling length (cm); FW – Seedling fresh weight (g); DW – Seedling dry weight (mg); SVI-I – Seed vigour index I; SVI-II – Seed vigour index II and PC – Protein content (%).

Table 7. Principal component analysis for wheat genotypes

	F_1	F_2	F_3	F_4	F_5	F_6
Eigenvalue	3.950	2.098	0.784	0.147	0.019	0.001
Variability (%)	56.435	29.977	11.205	2.098	0.266	0.019
Cumulative (%)	56.435	86.412	97.617	99.715	99.981	100.000

Table 8. Stress indices for each of the wheat genotypes

S. No.	Genotypes	Grain yield/plant		HSI	HTI	YSI	TOL	DI
		Yc (2023-24)	Ys (2024-25)					
1.	WH 1124	8.70	0.57	17.77	4.93	0.07	8.13	0.05
2.	WH 1100	8.73	0.27	83.41	2.33	0.03	8.47	0.01
3.	WH 1136	12.63	0.97	8.76	12.22	0.08	11.67	0.11
4.	WH 1140	9.50	1.53	2.38	14.56	0.16	7.97	0.35
5.	WH 1126	8.27	0.83	7.52	6.89	0.10	7.43	0.12
6.	WH 1202	11.67	1.00	7.49	11.67	0.09	10.67	0.12
7.	WH 1160	7.87	0.60	14.18	4.72	0.08	7.27	0.07
8.	WH 715	7.93	0.37	39.45	2.91	0.05	7.57	0.02
9.	WH 542	8.50	0.73	10.15	6.23	0.09	7.77	0.09
10.	WH 522	7.90	0.30	59.31	2.37	0.04	7.60	0.02
11.	WH 1132	8.37	0.30	62.96	2.51	0.04	8.07	0.02
12.	WH 1063	9.50	0.30	71.80	2.85	0.03	9.20	0.01
13.	WH 1185	6.10	0.43	21.23	2.64	0.07	5.67	0.04
14.	WH 1270	10.90	0.37	54.93	4.00	0.03	10.53	0.02
15.	WH 1105	7.17	0.20	122.34	1.43	0.03	6.97	0.01
16.	WH 1182	6.17	0.30	45.79	1.85	0.05	5.87	0.02
17.	WH 283	7.97	0.67	11.52	5.31	0.08	7.30	0.08
18.	WH 1127	11.90	0.57	24.76	6.75	0.05	11.33	0.04
19.	WH 1164	7.87	0.10	545.53	0.79	0.01	7.77	0.00
20.	WH 1134	7.80	0.47	23.62	3.64	0.06	7.33	0.04
21.	WH 1152	7.60	0.90	5.81	6.84	0.12	6.70	0.15
22.	WH 1135	7.97	0.70	10.42	5.58	0.09	7.27	0.09
23.	WH 1184	10.30	0.50	27.53	5.15	0.05	9.80	0.03
24.	HD 2307	5.90	1.47	1.45	8.66	0.25	4.43	0.52
25.	HD 2687	9.47	0.60	17.30	5.68	0.06	8.87	0.05
26.	HD 3043	9.93	0.43	35.59	4.30	0.04	9.50	0.03
27.	HD 3386	13.00	1.93	2.08	25.13	0.15	11.07	0.41
28.	HD 3219	8.60	0.50	22.76	4.30	0.06	8.10	0.04
29.	HD 3182	7.37	1.07	3.89	7.86	0.14	6.30	0.22
30.	PBW 761	7.60	0.60	13.66	4.56	0.08	7.00	0.07
31.	PBW 163	7.23	0.93	5.08	6.75	0.13	6.30	0.17
32.	PBW 706	9.6	0.867	8.16	8.32	0.09	8.73	0.11
33.	PBW 769	10.267	0.5	27.44	5.13	0.05	9.77	0.03
34.	PBW 826	8.667	0.6	15.74	5.20	0.07	8.07	0.06
35.	PBW 677	7.2	1.733	1.28	12.48	0.24	5.47	0.59
36.	PBW 681	10.467	1.867	1.73	19.54	0.18	8.60	0.47
37.	PBW 644	10.133	0.2	174.42	2.03	0.02	9.93	0.01
38.	PBW 750	9.267	0.367	46.41	3.40	0.04	8.90	0.02
39.	PBW 165	7.067	1.567	1.57	11.07	0.22	5.50	0.49
40.	PBW 475	17.3	0.233	220.81	4.03	0.01	17.07	0.00
41.	DBW 222	8.867	0.433	31.60	3.84	0.05	8.43	0.03
42.	DBW 303	9.6	0.767	10.55	7.36	0.08	8.83	0.09
43.	DBW 187	9.033	0.567	18.50	5.12	0.06	8.47	0.05

Where: Yc – Grain yield per plant (2023-24); Ys – Grain yield per plant (2024-25); HSI – Heat susceptibility index; HTI – Heat tolerance index; YSI – Yield stability index; TOL – Tolerance index and DI – Drought index.

distribution relative to these principal components and stress indices.

PBW 475 (G40) had the highest grain output per plant (17.30 g) under heat stress in Ongole (Table 8). The genotype was heat-tolerant with an HSI of 0.233 and an HTI of 4.03. The Yield Stability Index (YSI) was 0.01 far below its expected yield. Its high yield under stress and good Heat Stress Index (HSI) and Heat Tolerance Index (HTI) made it a suitable option for developing heat-tolerant high-yielding cultivars. In contrast, genotypes like WH 1164 (G19) had a high heat susceptibility index (HSI) of 545.53 and a low yield stability index (YSI) of 0.01, indicating heat stress vulnerability and poor yield stability. This showed that germplasm responded differently to heat stress. HD 3386 (G27) and other genotypes had better stress indices during heat stress. An HSI of 2.08 and a high HTI of 25.13 showed

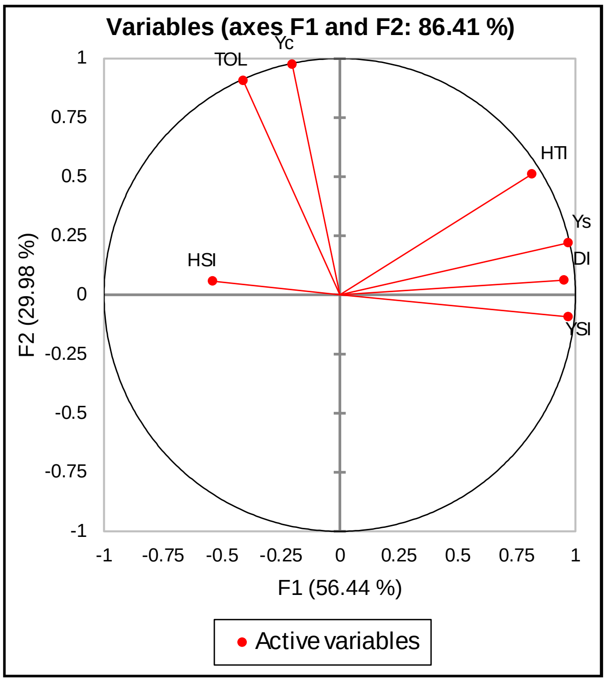

Fig. 2. Variables plot demonstrating heat stress indicators (active variables) distributed throughout the first two main components (F_1 and F_2), accounting for 86.41% of variability. F_1 promotes performance and stability under stress, while F_2 emphasizes controlled yield and stress sensitivity.

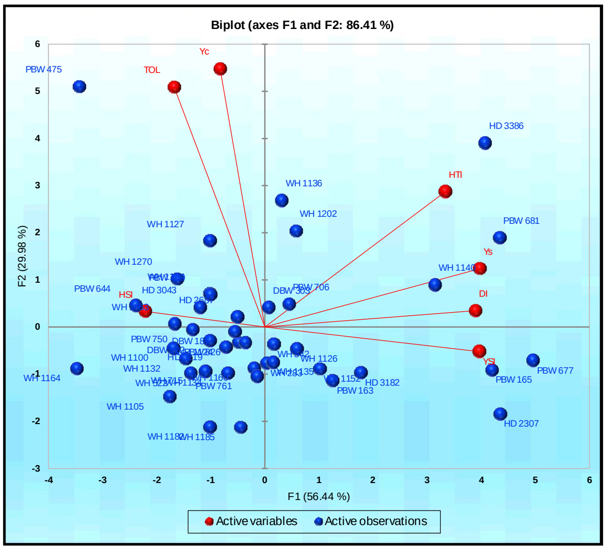

Fig. 3. Biplot illustrating the relationship between the first two principal components (F_1 and F_2), which collectively explain 86.41% of the variability in heat stress indices, and the active variables (stress indices) and active observations (wheat genotypes). F_1 (56.44%) represents performance and stability under stress (associated with Ys, HTI, YSI and DI), while F_2 (29.98%) represents yield under control conditions and stress sensitivity (associated with Yc and TOL).

that the standard check was heat-tolerant. WH 1140 (G4) showed HSI of 2.38, HTI of 14.56, YSI of 0.16, and TOL of 7.97. Similarly, PBW 681 (G36) had 1.73 (HSI), 19.54 (HTI), 0.18 (YSI), and 8.60 (TOL) and PBW 677 (G35) had HSI of 1.28, HTI of 12.48, YSI of 0.24, and TOL of 5.47. Selecting parental lines for terminal heat stress-resistant breeding programs requires genotypes with favourable stress indices. Previous research using stress indices to determine wheat heat tolerance was successful (Kumar *et al*., 2023; Lamba *et al*., 2023). Terminal heat stress significantly reduced wheat yield and its components. The high genetic diversity and heritability of important traits in stress circumstances supported genetic improvement. Heat-tolerant genotypes and stress indices helped to generate climate-resilient wheat cultivars for Ongole, Andhra Pradesh (Groli *et al.*, 2024; Yadav *et al.*, 2024).

CONCLUSION

This study examined the effects of terminal heat stress on wheat productivity and explored the genetic potential for creating heat-resilient varieties, with a focus on regions such as Ongole, Andhra Pradesh. The findings clearly indicated the significant adverse effects of elevated temperatures during the reproductive phase on wheat yield and its associated traits. A notable decrease in mean grain yield per plot was recorded, falling from 340.21 g under optimal conditions to only 6.04 g under terminal heat stress, indicating an approximate decline of 98.2%. Significant reductions were observed in biological yield per plot (95.5%) and the number of grains per spike (72.5%). The significant yield losses highlighted the necessity for breeding programs aimed at enhancing heat tolerance to address the negative impacts of climate change on wheat production. The study identified significant genetic variability among the tested wheat genotypes regarding all morpho-physiological and grain quality traits, despite the severe impacts observed. Key yield-related traits, including grain yield per plot, biological yield per plot, number of grains per spike and test weight demonstrated high heritability (e.g., 97.41 for grain yield per plot under stress) alongside significant genetic advance as a percentage of mean (e.g., 119.66

for grain yield per plot under stress). This suggested that additive gene action primarily influenced the inheritance of these traits, making them highly suitable for enhancement by direct selection, even in stressful environments.

Various heat stress indices helped to discover genotypes with increased heat tolerance. PBW 475 (G40) had the highest grain yield per plant at 17.30 g under heat stress, a low Heat Susceptibility Index (HSI) of 0.233, and a high Heat Tolerance Index (HTI) of 4.03. The genotype HD 3386 (G27) had HSI: 2.08, HTI: 25.13 and genotype WH 1140 (G4) had HSI: 2.38, HTI: 14.56. Similarly, genotype PBW 681 (G36) had HSI: 1.73, HTI: 19.54 and genotype PBW 677 (G35) had HSI: 1.28, HTI: 12.48. These genotypes performed better and were more stable under heat stress.

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