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Evaluation of heat stress tolerance and stability analysis in bread wheat (*Triticum aestivum* L.) genotypes

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Abstract

This study evaluates the stability and heat stress tolerance of 40 wheat varieties across six environments. Significant differences in genotype, environment, and their interactions were found, indicating substantial performance variation. Environments E1 and E4 excelled, while E3 and E6 underperformed. Varieties like HD 2687 and CPAN 6143 were stable for total chlorophyll, while DW 36 and HD 2189 were stable for effective tillers. UP 2338 and UP 262 showed stability for biological yield, and HD 2687 and CPAN 3074 were stable for grains per ear. All genotypes were consistent for grain weight per ear, with ten varieties showing stability. Seven genotypes, including CPAN 3074 and HD 2189, were stable for protein content. Heat stress tolerance was assessed, with UP 2338 and PBW 226 showing tolerance for biological yield under late sowing. The study highlights the complex relationship between stability and heat stress tolerance, providing insights for breeding resilient wheat varieties.

Keywords: Bread wheat, *Triticum aestivum* L, stress tolerance and stability

1. Introduction

Howard (1924) [16] remarked that “Wheat production in India is a gamble in temperature,” a statement that remains relevant today. Continuous heat stress affects 7 million hectares, while terminal heat stress impacts 40% of the world’s irrigated wheat-growing areas (Fisher & Byerlee, 1991). In many parts of the Asian subcontinent, the rice-wheat cropping system exacerbates crop damage due to heat stress under late planting conditions, significantly limiting wheat yields (Aslam *et al*., 1989) [3]. Increasing food demand and global warming are likely to further expose wheat crops to heat stress environments. Consequently, breeding for heat stress tolerance is a crucial goal of wheat improvement programs. However, identifying heat stress-tolerant traits and developing simple, fast, and reliable screening tests for heat tolerance have been major challenges.

Yield reduction in wheat under heat stress can result from accelerated phasic development (Warrington *et al*., 1977; Rawson & Bagga, 1979; Frank & Bauer, 1979) [23, 20, 14], accelerated senescence (Kuroyanagi & Paulsen, 1985) [19], increased respiration, reduced photosynthesis (Blum, 1986; Conroy *et al*., 1994) [4, 7], and inhibition of starch synthesis in developing kernels (Jenner, 1994) [17]. Heat stress tolerance is evaluated by the relative reduction in grain yield from normal to heat stress environments under full irrigation (Fischer & Maurer, 1978; Shpiler & Blum, 1986) [11, 21]. Surveys have identified heat stress tolerance for yield among cultivated T. aestivum and T. durum genotypes (Bruckner & Frohberg, 1987; Shpiler & Blum, 1991; Gavuzzi *et al*., 1993; Morgunov, 1994) [5, 22, 15, 26].

Breeding for high temperature stress especially terminal heat stress, in wheat is increasingly becoming importance in India because of fast growing area in northern plains under delayed plantings which exposes the crop to high temperature stress in post anthesis phase. Wheat growing regions of central and peninsular India have also attracted attention towards the necessity to breed for high temperature stress. Wheat production in the country has always been regarded as a gamble with seasonal temperatures; the crop is exposed to excessively high temperatures, at sowing and during grain filling in all regions It is difficult to adequately define heat stress in plants because of the pattern of thermal adaptation, the duration of the exposure, and the growth stage of the crop. The rate of change of temperature, the duration and the degree of high temperature all contribute to the intensity of heat stress. Where heat stress occurs, it is important that crops possess a certain degree of heat tolerance to survive the stress period.

Leaf being the organ of photosynthesis; the surface area of leaves per plant should be an important determinant in production of photosynthates as suggested by Watson (1947) [24]. It is well known that photosynthetic efficiency depends on leaf area, chlorophyll content and the gas exchange. Correlation between leaf area and yield suggests the importance of chlorophyll and leaf area in determining yield (Alluwar and Deotale, 1991) [2]. Chlorophyll content in leaf tissue varies with species, age of plant and growing seasons (Yurkovskii *et al.*, 1977) [25].

2. Materials and Methods

The study evaluated forty bread wheat (Triticum aestivum L.) cultivars, including three check varieties, at Ch. Charan Singh University, Meerut, during the rabi seasons of 2002–2003 and 2003–2004. Using a randomized block design with three replications, experiments were conducted on three sowing dates each year: November 25 (normal), December 28/30 (late), and January 27/28 (very late). Each genotype was grown in single 2-meter rows with 30 cm row spacing and 10 cm plant spacing. Standard agronomic practices were followed, with November sowings considered non-stress and December/January sowings as heat stress environments.

- **Heat susceptibility index:** Heat susceptibility index (s) to measure the degree of heat stress tolerance of a genotype with respect to various traits were calculated using formula of Fisher and Maurer (1978) [11].

$$S = (1 - Y/Yp)/D$$

Where, y is the mean yield or mean yield component of a genotype in a stress environment, Yp, the mean yield or mean yield component of a genotype in a stress free environment. The stress intensity, $D = 1 - X/Xp$, where X is the mean y of all genotypes, Xp is the mean Yp of all genotypes.

- Potential capacity for supporting grain filling from stem reserves (PSR): PSR was measured in terms of the ratio of final grain weight of the ear from defoliated and bagged plants to that of non-stressed plants following Fokar *et al.* (1998) [13].

$$\text{PSR} = \frac{\text{Grain weig ht per ear of defoliated and bagged spike}}{\text{Grain weig ht per ear of non - stressed controls}} \times 100$$

Five main ears of the five selected plants of normal sowing were manually defoliated at anhesis by excising all leaf laminae. Ears of defoliated plants were covered with brown kraft paper bag to reduce ear photosynthesis. Bagged ears were given fungicide treatment to make them free of molds or insects.

- **Heat degree days (HDDs):** Heat degree days were calculated for each phenological phase in normal and heat stress conditions using the following formula. A base temperature of 4.5 °C (Fisher, 1985) was used for all genotypes.

$$\text{Heat Degree Days (HDDs)} = \sum(\text{Mean daily temperature} - \text{base temperature})$$

3. Result and Discussion

3.1 Analysis of Heat Susceptibility Index (HSI)

The heat susceptibility index (HSI) was employed to evaluate the genotypes for their tolerance or susceptibility to heat stress. Using data from two different environments (normal and heat stress), the HSI for each genotype was calculated using the formula by Fisher and Maurer (1978) [11]. Genotypes were classified based on their HSI values: those with low HSI values were deemed heat stress tolerant ($HSI \leq 0.50$ for highly tolerant, $0.50 < HSI \leq 1.00$ for moderately tolerant, and $HSI > 1.00$ for susceptible). The HSI estimates for seventeen traits, including grain yield and protein content, across forty wheat genotypes in two environmental conditions (normal vs. late and normal vs. very late) over two years are detailed in Tables 1, 2, 3, and 4. The findings are discussed under the following headings.

3.1.1 Study in normal vs late sowing over two years

The estimates of heat susceptibility index (S) for seventeen traits including grain yield, protein content other quantitative traits of forty genotypes of wheat in normal vs. late sowings in two years are presented in Table 1.

Table 1: Heat tolerant varieties (S value ≤ 0.50)

Trait	Genotypes
Total chlorophyll at seedling stage	PH 132, UP 2425
Total chlorophyll at flag leaf emergence	PH 132
Plant height	MUW 74
Ear length	UP 2358, PBW 226
Spikelets per ear	CPAN 2043, MUW 45, UP 2425, JOB 666
Biological yield	UP 2338, PBW 226, UP 2425
Grain yield	PH 132
100-grain weight	HD 2329, PBW 226, PBW 435, MUW 118, VL 695
Harvest index	PBW 226
Protein content	K 9320, Infector, HD 2687, UP 2383, CPAN 3074, PH 132, CPAN 2043, HD 2189, UP 262, VL 634, CPAN 3001, PBW 325, MUW 45, UP 2425, Kalyan sona, UP 2358, MUW 118

Table 2: Moderately heat tolerant varieties (0.50 < S value ≤ 1.00)

Trait	Genotypes
Total chlorophyll at seedling stage	CPAN 3074, CPAN 6143, CPAN 3001, PBW 233, PBW 343, VL 695
Total chlorophyll at flag leaf emergence	UP 2338, MP 847, HD 2189, UP 262, Kalyan sona, UP 2358, K 8020, MUW 118, Malviya, MUW 74, CPAN 4061, VL 695
Days to anthesis	K 9320, Infector, HD 2687, PBW 373, HD 2329, PBW 226, CDWR 9523, PBW 343, JOB 666, RAJ 3777, WH 562, K 8020, MUW 118, Malviya, MUW 74, VL 695
Flag leaf area	CPAN 6143, CPAN 3001, MUW 118

Plant height	CPAN 6143, CPAN 3001, Malviya
Ear length	MUW 74, WH 595
Effective tillers per plant	Infector, MACS 2846, Malviya, CPAN 4061
Days to maturity	Infector, PBW 373, UP 2338, MP 847, HD 2329, HD 2189, UP 262, CPAN 6143, MUW 45, UP 2425, PBW 233, PBW 343, JOB 666, PBW 435, K 8020, MUW 118, MUW 74, CPAN 4061, WH 595
Grain filling duration	Infector, DW 36, HD 2189, UP 262, CPAN 6143, CDWR 1910, MUW 45, UP 2425, K 8020, MUW 118, CPAN 4061, WH 595
Spikelets per ear	K 9320, Infector, PBW 373, UP 2383, CPAN 3001, Kalyan sona, CPAN 4061
Biological yield per plant	Infector, CDWR 9523, CPAN 3001, PBW 233, VL 695
Number of grains per ear	K 9320, MP 847, PBW 325, Malviya, MUW 74, VL 695
Grain weight per ear	PBW 373, UP 2383, CPAN 3001, MUW 45, K 8020, WH 595
Grain yield per plant	HD 2687, UP 2338, PBW 343
100-grain weight	JOB 666, WH 595
Protein content	PBW 373

Table 3: Heat Susceptible Varieties (S value > 1.00)

Trait	Genotypes
Days to maturity	None
Protein content	18 genotypes
Harvest index	Lok1, Hind 162 (Khanna-Chopra and Viswanathan, 1999) [18]
Grain weight	Lok1, Hind 162 (Khanna-Chopra and Viswanathan, 1999) [18]
Grain yield	PBW 343, HD 2687, HD 2329 (Dhanda and Munjal, 2006) [8]

These tables summarize the heat tolerant, moderately heat tolerant and susceptible wheat genotypes based on the S value criterion for various traits. The findings indicate that a significant number of genotypes are sensitive to heat stress, particularly for protein content. Previous studies have also identified specific varieties that are susceptible to heat stress in terms of harvest index, grain weight, and grain yield.

Table 4: Heat Tolerant Varieties in Very Late Sowing Conditions (S value ≤ 0.50)

Trait	Genotypes
Flag leaf area	MUW 74
Plant height	UP 2425
Effective tillers	PH 132
Spikelets per ear	JOB 666
Grains per ear	K 8020

Table 5: Moderately Heat Tolerant Varieties in Very Late Sowing Conditions (0.50 < S value ≤ 1.00)

Trait	Genotypes
Chlorophyll content at seedling stage	K 9320, HD 2687, PBW 373, UP 2383, CPAN 3074, CPAN 2043, HD 2329, CPAN 1964, PBW 226, CDWR 9523, DW 36, VL 634, CPAN 3001, PBW 325, Kalyansona, CDWR 9536, JOB 666, RAJ 3777
Chlorophyll content at flag leaf emergence	CPAN 2043, HD 2329, PBW 226, CDWR 9523, CPAN 3001, PBW 325, UP 2425, PBW 343, CDWR 9536, UP 2358, WH 562, VL 695, WH 595
Days to anthesis	K 9320, Infector, HD 2687, UP 2383, MP 847, PH 132, CPAN 2043, HD 2329, CPAN 6143, PBW 233, JOB 666, WH 562, K 8020, MUW 118, Malviya, MUW 74, VL 695
Flag leaf area	HD 2687, UP 2338, CPAN 3074, PH 132, CPAN 1964, PBW 226, CDWR 9523, HD 2189, CPAN 3001, UP 2425, PBW 343, JOB 666, RAJ 3777, UP 2358, K 8020, WH 595
Plant height	HD 2687, CPAN 1964, CDWR 9523, DW 36, HD 2189, CPAN 6143, Kalyansona, WH 562, Malviya, VL 695
Ear length	K 9320, HD 2687, CPAN 3074, PH 132, VL 634, PBW 233, Kalyansona, CDWR 9536, K 8020, JOB 666, Malviya, MUW 74, CPAN 4061, VL 695
Effective tillers per plant	HD 2687, PBW 226, CPAN 3001, PBW 343, Kalyansona, UP 2358, Malviya, MUW 74
Days to maturity	Infector, PBW 373, MP 847, PH 132, CPAN 1964, HD 2189, PBW 435, MUW 118, Malviya, MUW 74, VL 695, WH 595
Grain filling duration	PBW 373, PH 132, CPAN 1964, DW 36, HD 2189, UP 262, VL 634, CDWR 1910, MUW 45, UP 2425, UP 2358, WH 562, MUW 74
Spikelets per ear	Infector, HD 2687, UP 2383, CPAN 3074, UP 262, PBW 325, PBW 233, PBW 343, Kalyansona, CDWR 9536, RAJ 3777, UP 2358, PBW 435, MUW 118, Malviya, CPAN 4061
Biological yield	HD 2687, UP 2338, PBW 226, VL 634, CPAN 3001, MUW 45, UP 2425, PBW 233, Kalyansona, CDWR 9536, RAJ 3777, MUW 118
Grains per ear	HD 2687, CPAN 2043, HD 2329, PBW 325, PBW 233, PBW 435, MUW 118, Malviya
Grain weight per ear	HD 2687, UP 2383, MP 847, CPAN 2043, HD 2329, PBW 343, Kalyansona, CDWR 9536, WH 562, PBW 435, K 8020, MUW 74, CPAN 4061, WH 595
Grain yield	HD 2687, UP 2338, MP 847, PH 132, HD 2329, UP 2425, CDWR 9536, RAJ 3777, MUW 118, VL 695, WH 595
100-grain weight	K 9320, UP 2383, PBW 226, CPAN 6143, CPAN 3001, PBW 325, UP 2425, PBW 233, Kalyansona, CDWR 9536, JOB 666, K 8020, Malviya, VL 695, WH 595
Harvest index	UP 262
Protein content	CPAN 3074, CPAN 1964, HD 2189, UP 262, CPAN 6243, UP 2358, PBW 435, K 8020, Malviya, MUW 118

These tables summarize the heat tolerant and moderately heat tolerant wheat genotypes based on the S value criterion for various traits under very late sowing conditions.

3.2 Stablity Analysis vs. Heat Susceptibility Index Analysis

Table 6: Stability Analysis vs. Heat Susceptibility Index for Various Genotypes

Genotype	Trait	Stability	Heat Tolerance	Condition
CPAN 3001	Total chlorophyll content at seedling stage, Biological yield	Stable	Moderately heat stress tolerant	Both years
PBW 325	Grains per ear	Stable	Moderately heat stress tolerant	-
WH 595	Grain weight per ear	Stable	Moderately heat stress tolerant	-
UP 2425	Total chlorophyll at seedling stage, Plant height	Stable	Heat tolerant	-
MUW 118	-	Stable	Moderately heat stress tolerant	Very late conditions
VL 695	-	Stable	Moderately heat stress tolerant	Very late conditions
WH 595	-	Stable	Moderately heat stress tolerant	Very late conditions
CPAN 3074	Protein content	Stable	Moderately heat tolerant	Very late conditions
HD 2189	Protein content	Stable	Moderately heat tolerant	Very late conditions
CPAN 6143	Protein content	Stable	Moderately heat tolerant	Very late conditions
UP 2358	Protein content	Stable	Moderately heat tolerant	Very late conditions
PBW 435	Protein content	Stable	Moderately heat tolerant	Very late conditions
MUW 118	Protein content	Stable	Moderately heat tolerant	Very late conditions
K 9320	100 grain weight	Stable	Moderately heat tolerant	Very late conditions
UP 2338	100 grain weight	Stable	Moderately heat tolerant	Very late conditions
PBW 226	100 grain weight	Stable	Moderately heat tolerant	Very late conditions
CPAN 3001	100 grain weight	Stable	Moderately heat tolerant	Very late conditions
CPAN 3074	Ear length	Stable	Moderately heat tolerant	Very late conditions
PBW 233	Ear length	Stable	Moderately heat tolerant	Very late conditions
K 8020	Ear length	Stable	Moderately heat tolerant	Very late conditions
Infector	Spikelets per ear	Stable	Moderately heat tolerant	-
HD 2687	Spikelets per ear	Stable	Moderately heat tolerant	-
CPAN 3074	Spikelets per ear	Stable	Moderately heat tolerant	-
UP 262	Spikelets per ear	Stable	Moderately heat tolerant	-

3.3 Potential Capacity for Supporting Grain Filling from Stem Reserves (PSR)

Potential capacity for supporting grain filling from stem reserves (PSR) was estimated in this study by final grain weight under the defoliation treatment as percent of the control and the results are presented in Table 7. Data in Table 8, as expected, revealed that grain weight in defoliated spikes was considerably lower than the spikes of control plant, indicating a larger role of leaves in supporting grain weight. The results of correlation of PSR with grain weight presented in Table 8 indicated significant positive correlation between these two traits in all the six environments. If the grain weight of defoliated and bagged spike is decreased, the PSR values also decreased, it seems to be that grain weight per ear for non-stressed control and grain weight per ear of stressed control had positive significant correlation. This suggested that a high potential capacity to utilize stem reserves for grain filling may be linked with accelerated leaf senescence. Hence, delayed leaf senescence as a genetic trait should not be taken a priori as an advantage under heat stress, and it should be reviewed in the context of the whole plant and its grain filling capacity from stem reserves. Fokar *et al.* (1998) [13] also reported that significant ($p \leq 0.01$) and often very high correlation existed across cultivars for grain weight per ear, kernel number and kernel weight reduction between heat stress and defoliation treatment, they also found an overall high level of association between reproductive performance under heat stress and the defoliation treatment across the seven tested cultivars.

Table 7: Estimates of phenotypic correlation coefficients between PSR and gain weight per ear under normal and heat stress environment over two years.

	Normal sowing	Late sowing	Very late sowing
Ist year	0.42*	0.52**	0.46**
IInd year	0.62**	0.47**	0.48**

Table 8: Grain weight of 40 genotypes of wheat under control and defoliated condition.

Genotypes	Control	Defoliated	PSR
K- 9320	1.63	1.21	74.23
Infector	1.53	1.15	75.16
HD 2687	2.12	1.61	75.94
UP 2338	1.67	1.20	71.86
PBW 373	1.65	1.24	75.15
UP 2383	1.60	1.21	75.63
CPAN 3074	2.07	1.59	76.81
MP 847	1.94	1.54	79.38
PH 132	2.34	1.71	73.08
CPAN 2043	1.69	1.20	71.01
HD 2329	1.79	1.25	69.83
CPAN 1964	2.03	1.72	84.73
PBW 226	2.13	1.62	76.06
CDWR 9523	1.62	1.24	76.54
DW 36	1.54	1.10	71.43
HD 2189	1.75	1.26	72.00
UP 262	1.70	1.20	70.59
VL 634	1.51	1.16	76.82
CPAN 6143	1.85	1.36	73.51
CDWR 1910	1.83	1.41	77.05
CPAN 3001	1.81	1.36	75.14
PBW 325	1.73	1.26	72.83
MUW 45	1.91	1.51	79.06
UP 2425	1.49	1.23	82.55
PBW 233	1.55	1.25	80.65
PBW 343	1.63	1.32	80.98
KALYANSONA	1.47	1.21	82.31
CDWR 9536	1.54	1.32	85.71
JOB 666	1.32	1.12	84.85
RAJ 3777	1.54	1.20	77.92
UP 2358	1.31	1.12	85.50
WH 562	1.41	1.23	87.23
PBW 435	1.77	1.15	64.97
K 8020	1.52	1.23	80.92
MUW 118	1.44	1.20	83.33
MALVIYA	1.74	1.43	82.18
MUW 74	1.77	1.32	74.58
CPAN 4061	1.75	1.21	69.14
VL 695	1.58	1.32	83.54
WH 595	1.87	1.15	61.50

4. Conclusion

This study on bread wheat (*Triticum aestivum* L.) highlights the stability and heat tolerance of 40 genotypes across varying environments. Key findings show significant genotype-environment interactions, particularly under late sowing conditions that impose heat stress, which is increasingly relevant due to climate impacts on wheat production. Genotypes such as HD 2687 and CPAN 6143 demonstrated stability in chlorophyll content, while others like UP 2338 and PBW 226 excelled in biological yield under heat stress. The heat susceptibility index (HSI) further identified specific genotypes with lower susceptibility scores, indicating a stronger resilience to heat stress. Stability and tolerance traits, including protein content and grain yield consistency, suggest these genotypes could be advantageous in breeding programs aimed at improving wheat resilience to rising temperatures.

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