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GENETIC ARCHITECTURE FOR HEAT TOLERANCE IN BREAD WHEAT (*TRITICUM AESTIVUM* L.)

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ABSTRACT

The demand for wheat is expected to increase due to population explosion but climatic factors such as heat stress are causing serious threat to wheat production. The present investigation was, therefore carried out to study the genetic variability for yield and its attributing morphological, physiological and quality traits. The comparative analysis of genotype performance across both environments revealed that heat stress had a pronounced detrimental impact on all traits evaluated. Severe heat stress resulted in decreased yield, while simultaneously enhancing flour quality traits such as WGC, PC, and SV in the wheat genotypes. The effective tillers/plant, spike length, grains/spike, biological yield/plant (g), harvest index, grain yield/plant (g), grain filling rate (g/day), grain filling duration and stem solidness showed moderate to high GCV and PCV, high heritability and moderate to high genetic advance as per cent mean under both conditions which may be attributed to the preponderance of additive gene action and possessed high selective value and thus, selection pressure could profitably be applied on these characters for their rationale improvement and also showed greater diversity among the genotypes for these traits. The genotype GS/2019-20/7004 was found to be superior for the traits GY, ET, GFD, CCI and NDVI under heat stress environments. The mentioned genotypes offer substantial potential for upcoming wheat breeding projects aimed at increasing wheat yield by enhancing tolerance to environmental stressors.
***Keywords* :** wheat, heat stress, genetic variability, heritability

Introduction

Globally, there are many constraints in wheat production which poses a great challenge for farmers and breeders. Undoubtedly, one of the unavoidable hurdles is the unpredictable variability in rainfall and temperature, particularly the prevalence of heat stress, observed in arid, tropical, and subtropical areas across the globe. Indeed, high temperatures stand out as a frequent and significant form of abiotic stress among other environmental factors. According to a 2019 report by the United Nations Environment Programme (UNEP), the continuous increase in greenhouse gas emissions is projected to result in a substantial rise of approximately 3.5°C in global temperatures by the end of the century. Wheat, the second most vital staple food globally, thrives across six continents, adapting to diverse eco-climatic conditions. It contributes substantially to global nutrition, providing approximately 21% of proteins and 20% of calories consumed worldwide (Anonymous, 2012 and Mishra *et al.*, 2021). Globally, wheat spans approximately 224.09 million hectares, claiming the largest acreage among all crops, with a yearly output of around 794.44 million metric tons (USDA, 2021). However, with the population steadily rising, demands are shifting once more. It is estimated that wheat output will need to increase by 60% in order to meet the demands of the growing population, which is expected to reach 9 billion people by the year 2050 (Rosegrant and Agcaoili, 2010). Hence, it's imperative to boost yields by at least 1.6% annually while enhancing tolerance to both abiotic and biotic stresses (Narayanan, 2018). However, meeting this demand faces a significant hurdle in the form of high temperature stress during crucial wheat growth stages, notably the grain filling stage. Still, as a crop for the cool season, it is vulnerable to heat stress. Heat stress is one of the biggest barriers to wheat production in the context of a changing environment. Achieving this goal necessitates the development of high-yielding, climate-smart varieties resilient to abiotic stressors through rigorous selection in real-world field conditions.

After rice, India's short, dry winter season (November to March) produces around 80 percent of the world's wheat. India is a subtropical country. Research indicates that the main cause of India's low wheat output yield is late seeding. Every day that the ideal sowing date of November 30 is missed results in a 1.3% daily drop in wheat output (Saadalla *et al*., 1990). It happens when the time it takes to load grain with wheat is shortened by pushing it into exceptionally high temperatures between late March and mid-April. Heat stress is therefore one of the primary factors limiting wheat output in India. Wheat is a crop for the colder months, but it can be grown in a range of agroclimatic zones. The optimal temperature range for growth is roughly 25˚C, with minimum and maximum values ranging between 3˚ and 4˚C and 30˚ and 32˚C, respectively (Briggle *et al*., 1980). Heat stress occurs when the average daily temperature in the coolest month of the winter falls below 17.5˚C (Fischer *et al*., 1978).

Heat tolerance improving strategies could be helpful in sustaining wheat production. Plant breeders consistently prioritize harnessing the genetic diversity found within existing germplasm to attain desired traits (Pour-Aboughadareh *et al*., 2018). Conventional breeding for heat tolerance involves the identification of potential germplasm, its utilization in hybridization programed and finally, the selection of tolerant lines (using associated traits) by growing them under heat stress conditions. Genotypic coefficients of variation, phenotypic coefficients of variation, heritability and genetic advance are quite helpful for getting a clear picture of existing variability and transmissibility of associated traits. Developing heat-resilient, high-yielding wheat cultivars is essential to tackle the mounting challenges of global climate warming. Extensive efforts have been devoted to date towards crafting heat-tolerant wheat genotypes.

The goal of the investigation was to

1 Evaluate the variations in the morphological, physiological and quality parameters that contribute to yield between genotypes that are heat tolerant and sensitive under both optimum and heat stress conditions;
2 Determine the essential characteristics that might be helpful in breeding and choosing wheat with heat tolerance.

Material and Methods

Location, experimental site and experimental material

The experiments were conducted at College Farm, N. M. College of Agriculture, Navsari Agricultural University, Navsari (20°37' North latitude and 72°54' East longitude at an altitude of 11.98 m above the mean sea level) under irrigated condition. The experimental material consisted of forty-eight wheat lines (Table 1). These lines were evaluated for crop seasons under two conditions: non stress (Normal sowing: 29th November 2021) and stress (Late sowing: 6th January 2022) using RBD design with three replications.

Different parameters

Days to heading, days to anthesis, days to maturity, plant height, effective tillers/plant, spike length, grains/spike, thousand grain weight, grain yield/plant, harvest index, biological yield/plant, grain filling duration, grain filling rate, canopy temperature, chlorophyll content, normalized differential vegetative index (NDVI) with grain quality traits such as starch content (%), protein content (%), sedimentation value (ml) and wet gluten (%) were assessed using the Near Infrared Transmittance (InfratecTM) machine manufactured by FOSS, Sweden Company. protection in this area were implemented.

Environmental evaluation

During the crop growing season (November to May), weather features were collected from the Department of Agricultural Meteorology at NMCA, NAU, Navsari. Figure-1 illustrates the annual precipitation (in millimetres), along with the minimum and maximum temperatures, as well as the relative humidity throughout the entire period of crop growth. Based on the meteorological data provided, delaying the sowing date by 38 days for heat stress has proven to be more effective in addressing the increased temperatures compared to sowing at the usual time.

Results and Discussion

Mean performance under optimum and heat stress environment

In crop breeding programs targeting the development of new varieties with enhanced yield potential, the efficacy of selection primarily hinges on the extent of genetic variability within the plant population. The comparative analysis of cultivar performance across various environments highlighted a pronounced influence of heat stress on the traits under investigation. Specifically, the mean values for DH, DA, DM, PH, SL, GS, TGW, HI, BY, GFD, GFR, CCI, NDVI, SC, and GY decreased under high-temperature conditions. In contrast, the mean values for CT, PC, WGC, and SV increased under heat stress (Table 2 and 3; Figure-2). This reduction shortened the grain filling period, ranging from 25 to 40 days under heat stress, compared to 28 to 52 days under optimal conditions. The chlorophyll content index was higher under optimal conditions than under heat stress at the heading stage, with average values of 37.72 in OE and 35.98 in HSE. Similarly, the NDVI, a key indicator for assessing vegetation health, was higher during the grain filling stage under OE (0.79) compared to HSE (0.72), indicating a significant reduction in plant greenness under heat stress. Canopy temperature increased by 20% under heat stress, with mean CT of 28.91°C in OE and 34.83°C in HSE during the grain filling stage, indicating that the late-sown crop experienced severe terminal heat stress. Stem solidness, an important architectural trait for maintaining an erect plant stand, contributes more significantly under OE (28.23%) compared to HSE (23.51%). This stress also led to increases in PC, WGC, and SV, with mean values rising by 8%, 5%, and 2%, respectively. For example, PC averaged 15.00% in HSE compared to 13.89% in OE, while WGC and SV values were 34.79% and 47.12 mL in HSE, compared to 32.92% and 45.82 mL under optimal conditions. Conversely, starch content (SC) decreased under heat stress, with a mean value of 62.09% compared to 62.57% under normal conditions. Grain yield (GY) also showed a substantial reduction of 20% due to heat stress, ranging from 5.27 (GW-173) to 9.62 (GS/2019-20/6046) g/plant under optimal conditions but dropping to 3.30 (EHT-2018-19/406) to 8.75 (GS/2019-20/6046) g/plant in the heat-stressed environment. The genotype GS/2019-20/7004 was found to be superior for the traits ET, GY, GFD, CCI, and NDVI under heat stress environments due to its higher greenness and maximum chlorophyll content when it headed into the grain filling stage. This revealed that these genotypes had successfully completed photosynthetic activities, indicating that they fared better under heat stress.

Under timely sown, the genotype HTWYT/2019-20/8 had the highest protein content (15.63%), wet gluten content (36.43%) and sedimentation value (49.70 ml). This genotype is used for making good-quality bread and chapati. The genotype HTWYT/2019-20/17 (63.87%) recorded the highest value for starch content. Heat stress caused by delayed sowing improves some of the baking-quality related traits has been reported by Mahdavi *et al.* (2022). Under heat stress conditions, high temperature increase the protein content, wet gluten content and sedimentation value as compared to timely sown condition but reduces the starch content and overall yield because negative correlations found between yield and protein content. Severe heat decreased yield, whereas improved flour quality traits protein content, sedimentation value and wet gluten in the wheat genotypes has been reported by Mahdavi *et al.* (2022). Under heat stress, genotype HTWYT/2019-20/2 contain high protein content (16.73 %), high wet gluten (38.66 %) and high sedimentation value (51.17 ml) promising for making good quality bread and chapati while, RWP-2019-29 (63.23%) was observed highest value of starch content.

Genetic Variability

The genotypic coefficient of variation (GCV) was slightly lower than the phenotypic coefficient of variation (PCV) for all examined traits under both conditions (Table 2 and 3), suggesting that environmental factors had minimal influence on these traits.

Optimum environment: The PCV ranged from 1.23% to 58.83%, while the GCV ranged from 0.88% to 58.04% (Table 2 and 3). Higher values of GCV and PCV were consistently noted for ET (25.03%, 26.47%), SS (58.04%, 58.83%) and GFR (20.78%, 23.39%). Moderate GCV and PCV values were noted for SL (10.56%, 11.00%), GS (13.62%, 14.41%), HI (16.15%, 19.94%), BY (19.28%, 21.12%), GFD (14.37%, 15.33%) and GY (13.67%, 16.22%) across both sowing conditions. Low GCV and PCV values were noted for the following traits *viz*., DH (6.55%, 6.83%), DA (6.07%, 6.50%), DM (5.63%, 6.04%), PH (6.02%, 9.17%), SC (0.88%, 1.23%), CT (5.42%, 8.04%), SV (3.02%, 5.02%), NDVI (2.84%, 3.36%), WGC (3.58%, 5.14%), PC (4.85% and 7.01%) and CCI (6.78%, 7.76%).

Heat stress environment: The PCV ranged from 1.27% to 67.94%, with the GCV ranging from 0.86% to 67.19% (Table 2 and 3). Higher values of GCV and PCV were consistently noted for ET (20.05%, 21.78%), SS (67.19%, 67.94%) and grain yield per plant (20.16%, 22.65%). Moderate GCV and PCV values were noted for SL (11.41, 12.55), GS (12.83, 14.17), HI (13.01, 15.02), BY (15.77, 18.17), GFD (10.04%, 12.43%) and GFR (18.95%, 23.56%). Low GCV and PCV values were noted for the characters *viz*., DH (4.91%, 5.49%), DA (4.71%, 5.22%), DM (5.44%, 5.82%), PH (5.48%, 6.74%), SC (0.86%, 1.27%), CT (1.25%, 2.19%), SV (2.38%, 4.85%), NDVI (2.77%, 4.38%), WGC (2.77%, 5.13%), PC (3.09%, 6.23%) and CCI (8.17%, 8.49%).

Under both the sowing conditions higher values of GCV and PCV were observed for effective tillers/plant and stem solidness, while the traits grain filling rate and grain yield/plant showed higher GCV and PCV values under timely sown condition and heat stress condition, respectively which suggested that there is a huge scope for improvement by applying selection in the required direction and also exhibited a vast variation among genotypes for these characters in respective conditions. Low GCV and PCV values under both conditions were recorded for the characters viz., days to heading, days to anthesis, days to maturity, plant height (cm), canopy temperature (°C), chlorophyll content index, normalized differential vegetative index, protein content (%), starch content (%), wet gluten content (%), sedimentation value (ml) its indicate a narrow range of variability for these traits and also restricting the scope of selection for these traits. The results were in agreement with Wahidy *et al.* (2016)., Jain *et al.* (2017)., Neeru *et al.* (2017)., Bhanu *et al.* (2018)., Kumar *et al.* (2018)., Raaj *et al.* (2018)., Tomar *et al.* (2019)., Thakur *et al.* (2020)., Shehrawat *et al.* (2021) and Lamara *et al.* (2022).

Broad sense heritability (H^2_b%) and Genetic advance as per cent of mean (GAM)

Optimum environment: Traits such as for ET (89.45%, 48.78), SL (92.13%, 20.89), GS (89.40%, 26.54), BY (83.35%, 36.27), HI (65.62%, 26.94), SS (97.33%, 117.97), GFD (87.81%, 27.74), GFR (78.95%, 38.05) and GY (71.05%, 23.75) exhibited both high heritability and substantial GAM (Table 3). For the CCI (76.21%, 12.19), a combination of high heritability and moderate GAM was noted. High heritability with low GAM was observed for NDVI (71.43%, 4.94); moderate heritability with low GAM was observed for CT (45.44%, 7.53), PC (47.81%, 6.91), SC (51.51%, 1.31), WGC (48.61%, 5.51) and SV (36.27%, 3.75).

Heat stress environment: ET (84.77%, 38.03), SL (82.63%, 21.36), GS (82.01%, 23.93), BY (75.39%, 28.22), GY (79.24%, 36.97), GFR (64.71%, 31.43), and SS (97.78%, 136.87) exhibited high heritability coupled with substantial GAM (Table 2 and 3). DM (87.32%, 10.47), TWG (75.60%, 15.32), GFD (65.25%, 16.71) and CCI (92.58%, 16.20) showed high heritability paired with moderate GAM. High heritability with low genetic advance as per cent of mean was observed for DH (80.15%, 9.07), DA (81.35%, 8.75) and PH (66.02%, 9.17) indicative of non-additive gene action. NDVI (40.00%, 3.61) and SC (46.51%,1.21) displayed moderate heritability with low GAM. CT (24.57%,1.28), PC (24.63%,3.16), WGC (29.24%,3.09), and SV (24.16%,2.41) demonstrated low heritability alongside low GAM.

Under both conditions high heritability coupled with high genetic advance as per cent of mean was recorded for effective tillers/plant, spike length (cm), grains/spike, biological yield/plant (g), grain yield/plant (g), grain filling rate (g/day) and stem solidness indicating the role of additive gene effects and less effect of environmental factors on the expression of the traits. Thus, the improvement of these traits could be achieved through direct phenotypic selection. The low heritability with low genetic advance as per cent of mean was observed for canopy temperature, protein content (%), gluten content (%) and sedimentation value (ml), it indicates that the character is highly influenced by environmental effects and selection would be ineffective. Similar results were also obtained by Islam *et al.* (2017), Meles *et al.* (2017), Bhanu *et al.* (2018), Tomar *et al.* (2019), Alemu *et al.* (2020), Kanwar *et al.* (2020), Porte *et al.* (2020), Thakur *et al.* (2020), Shehrawat *et al.* (2021), Hossain *et al.* (2021), Lamara *et al.* (2022) and Mahdavi *et al.* (2022).

Understanding the genetic variability within a crop species is vital for successful plant breeding programs. This knowledge broadens the range of traits available for selection, increasing the likelihood of developing superior varieties. Examining both heritable and non-heritable factors within the total variability streamlines the breeding process, offering precise insights into the evaluated population. In the present investigation, effective tillers/plant, spike length, grains/spike, biological yield/plant (g), harvest index, grain yield/plant (g), grain filling rate (g/day), grain filling duration and stem solidness showed moderate to high GCV and PCV, high heritability and moderate to high genetic advance as per cent mean under both conditions indicating additive gene action. Elevations in PCV, GCV, H^2_b, and GAM promote stable selection by aiding in the accumulation of alleles, mostly because additive genes are more common (Jamil *et al.* 2020). Therefore, direct phenotypic selection could be used to increase these features and also showed greater diversity among the genotypes for these traits for both conditions.

Conclusion

Plant genotypes are responding to the global warming by modifying certain characteristics. As temperatures rise, there is an urgent need to develop cultivars capable of tolerating sudden fluctuations without compromising yield. A critical first step is to assess the potential of the current wheat germplasm to withstand high temperatures. Recent research highlights the significant influence of heat stress on wheat genetic resources, affecting both physiological and quality traits. The stable traits effective tillers/plant, spike length, grains/spike, biological yield/plant (g), harvest index, grain yield/plant (g), grain filling rate (g/day), grain filling duration and stem solidness across environments can be valuable in early-stage genotype selection, aiding in the identification of candidates for further utilization in advancement-oriented breeding programs. Through, the genotypes GS/2019-20/7004 has emerged as a standout performer under heat stress conditions.

Table 1 : A list of wheat genotypes

Sr. No.	Genotype	Sr. No.	Genotype
1.	HTWYT/2019-20/2	**25.**	GS/2019-20/3060
2.	HTWYT/2019-20/8	**26.**	EHT-2018-19/401
3.	HTWYT/2019-20/11	**27.**	EHT-2018-19/403
4.	HTWYT/2019-20/17	**28.**	EHT-2018-19/406
5.	HTWYT/2019-20/30	**29.**	GS/2018-19/7042
6.	HTWYT/2019-20/34	**30.**	GS/2019-20/7004
7.	HTWYT/2019-20/40	**31.**	EHT-2019-20/732
8.	EHT-2018-19/407	**32.**	EHT-2019-20/735
9.	HPYT-2019-20/416	**33.**	GS/2018-19/6027
10.	HPYT-2019-20/418	**34.**	GS/2019-20/4003
11.	HPYT-2019-20/449	**35.**	HTWYT/2018- 19/36
12.	EHT-2018-19/443	**36.**	QST 1910
13.	CWYT 2018-19-630	**37.**	RWP 2019-31
14.	CWYT 2018-19-644	**38.**	DT RIL 110
15.	GS-2018-19/1007	**39.**	WYCYT 2018-20
16.	SAWYT-2018-19/309	**40.**	DT RIL 1
17.	RWP-2019-29	**41.**	GS/2018-19/4049
18.	GS/2019-20/5042	**42.**	WYCYT-2018-13
19.	DBW-166	**43.**	K 1317 ©
20.	GS/2019-20/6046	**44.**	GW 499 ©
21.	HI 1628	**45.**	HD 2932 ©
22.	HTWYT/2019- 20/39	**46.**	LOK 1 ©
23.	GS/2019-20/1003	**47.**	GW 173 ©
24.	GS/2019-20/3056	**48.**	GW 11 ©
© = Check variety			

Table 2 : Variability, heritability (broad sense) and genetic advance percentage means estimate studied morphological traits across optimum environment (OE) and heat stress environment (HSE).

SOV		Min	Max	Mean	GCV	PCV	H^2_b	GAM
Days to heading	OE	48.00	66.33	55.03	6.55	6.83	91.88	12.93
	HSE	47.33	61.66	54.10	4.91	5.49	80.15	9.07
Days to anthesis	OE	51.00	69.66	59.79	6.07	6.50	87.11	11.67
	HSE	49.00	66.00	57.20	4.71	5.22	81.35	8.75
Days to maturity	OE	81.66	114.33	98.15	5.63	6.04	86.91	10.82
	HSE	74.00	106.00	89.10	5.44	5.82	87.32	10.47
Plant height (cm)	OE	55.49	80.98	72.77	6.02	9.17	43.10	8.14
	HSE	55.45	76.31	68.85	5.48	6.74	66.02	9.17
Effective tillers/plant	OE	3.33	9.00	5.41	25.03	26.47	89.45	48.78
	HSE	2.80	7.63	4.39	20.05	21.78	84.77	38.03
Spike length (cm)	OE	5.04	11.22	8.15	10.56	11.00	92.13	20.89
	HSE	4.58	9.05	7.58	11.41	12.55	82.63	21.36
Grains per spike	OE	21.80	52.07	40.16	13.62	14.41	89.40	26.54
	HSE	27.87	47.75	37.29	12.83	14.17	82.01	23.93
Thousand grain weight (g)	OE	33.03	47.38	41.24	7.82	10.13	59.66	12.45
	HSE	29.60	41.99	36.57	8.55	9.84	75.60	15.32
Biological yield/plant (g)	OE	10.08	26.23	17.90	19.28	21.12	83.35	36.27
	HSE	10.47	21.79	15.37	15.77	18.17	75.39	28.22
Harvest index (%)	OE	30.87	56.96	40.12	16.15	19.94	65.62	26.94
	HSE	23.31	58.97	36.39	13.01	15.02	57.12	23.38
Grain yield/plant (g)	OE	5.27	9.62	6.98	13.67	16.22	71.05	23.75
	HSE	3.30	8.75	5.53	20.16	22.65	79.24	36.97

Source of variation (SOV); genotypic coefficient of variation (GCV%); phenotypic coefficient of variance (PCV%); broad sense heritability (H^2_b); genetic advance per percent means (GAM).

Table 3 : Variability, heritability (broad sense), and genetic advance percentage means estimate studied physio-quality traits across optimum environment (OE) and heat stress environment (HSE).

SOV		Min	Max	Mean	GCV	PCV	H^2_b	GAM
Grain filling duration	OE	28	52.33	38.31	14.37	15.33	87.81	27.74
	HSE	25.00	40.00	31.90	10.04	12.43	65.25	16.71
Grain filling rate (g/day)	OE	0.13	0.32	0.19	20.78	23.39	78.95	38.05
	HSE	0.11	0.30	0.17	18.95	23.56	64.71	31.43
Canopy temperature (°C)	OE	25.00	32.27	28.91	5.42	8.04	45.44	7.53
	HSE	32.20	35.95	34.83	1.25	2.19	24.57	1.28
Chlorophyll content index	OE	32.84	45.61	37.72	6.78	7.76	76.21	12.19
	HSE	30.01	44.68	35.98	8.17	8.49	92.58	16.20
NDVI	OE	0.75	0.85	0.79	2.84	3.36	71.43	4.94
	HSE	0.67	0.79	0.72	2.77	4.38	40.00	3.61
Stem solidness (%)	OE	3.81	100	28.23	58.04	58.83	97.33	117.97
	HSE	3.80	94.71	23.51	67.19	67.94	97.78	136.87
Protein content (%)	OE	12.37	15.63	13.89	4.85	7.01	47.81	6.91
	HSE	13.70	16.73	15.00	3.09	6.23	24.63	3.16
Starch content (%)	OE	61.17	63.87	62.57	0.88	1.23	51.51	1.31
	HSE	60.67	63.23	62.09	0.86	1.27	46.51	1.21
Wet gluten content (%)	OE	29.80	36.43	32.92	3.58	5.14	48.61	5.15
	HSE	31.83	38.66	34.79	2.77	5.13	29.24	3.09
Sedimentation value (ml)	OE	41.10	49.70	45.82	3.02	5.02	36.27	3.75
	HSE	42.87	51.17	47.12	2.38	4.85	24.16	2.41

Source of variation (SOV); genotypic coefficient of variation (GCV%); phenotypic coefficient of variance (PCV%); broad sense heritability (H^2_b); genetic advance per percent means (GAM).

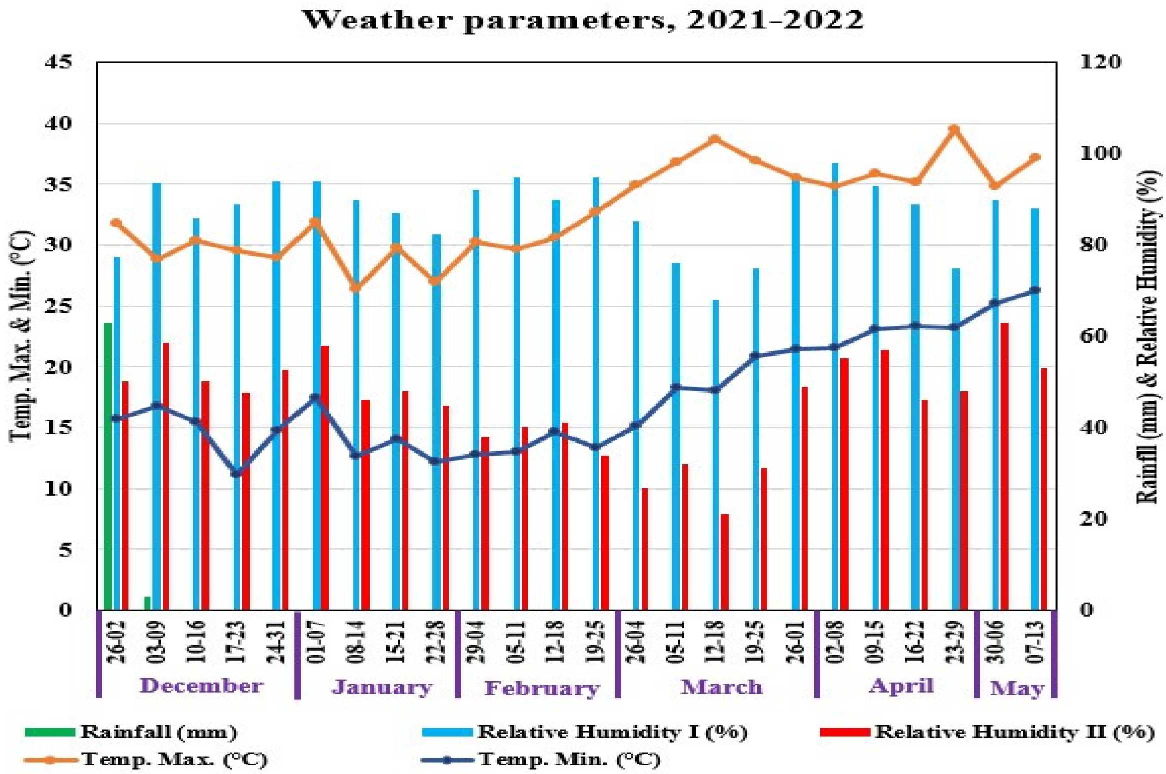

Fig. 1 : Weather data on rainfall, humidity, and temperature during the 2021-22 crop season.

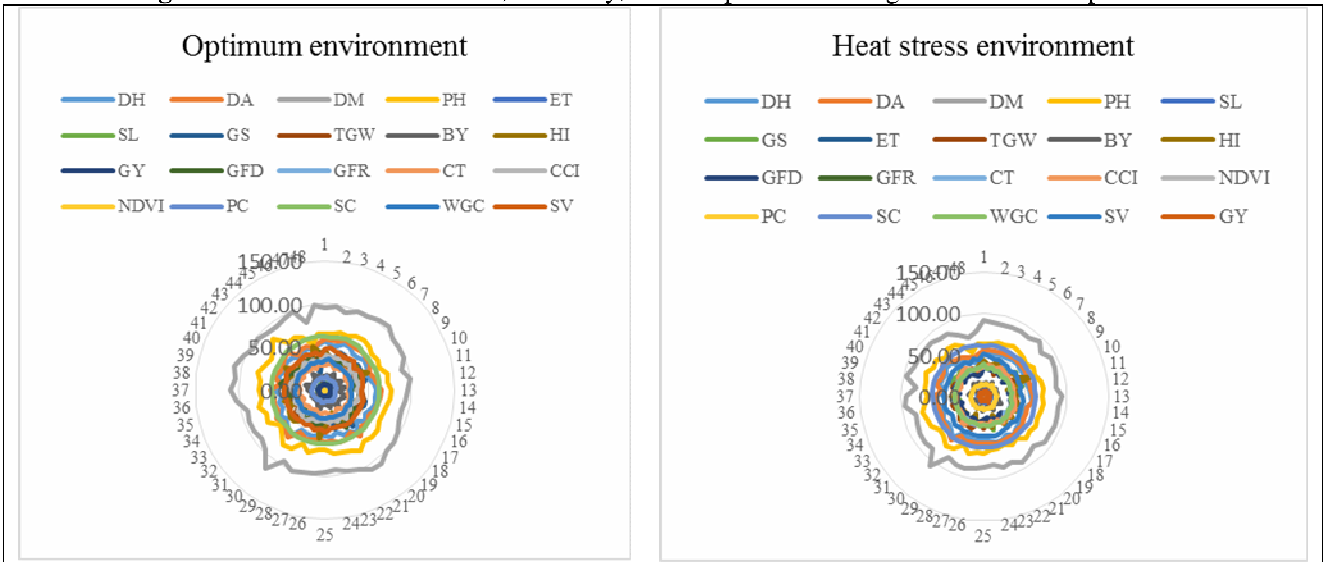

Fig. 2: The mean performance of forty-eight genotypes under both conditions.

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