



Assessing phenotypic variability and environmental interactions in wheat (*Triticum aestivum*) using the Eberhart and Russell Model

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ABSTRACT

The stability of wheat (*Triticum aestivum* L.) genotypes across diverse environments is crucial for breeding programmes aiming to improve yield potential and resilience to climate variability. The present study was carried out during winter (*rabi*) seasons of 2019–2020 and 2020–2021 at Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana to evaluate 16 morphological traits in wheat under normal sown conditions, drought stress, heat stress and combined drought and heat stress utilizing the Eberhart and Russell stability model. The trial was conducted in randomized complete block design (RCBD). Significant genotype-by-environment ($G \times E$) interactions were observed, underscoring the importance of selecting stable, high-yielding genotypes. Genotypes BRW 3806, DBW 303, and HD 2967 demonstrated superior yield stability across environments, making them ideal candidates for climate-resilient wheat breeding. Early-maturing genotypes DBW 110 and HD 2967 showed promise in escaping terminal heat stress, while genotypes with reduced plant height HD 2967, were well-suited for minimizing lodging risk. Spike and grain characteristics, including spike length and grain weight per spike, were directly correlated with higher yield potential, particularly in genotypes WH 1235 and BRW 3806. The study highlights the importance of integrating traits early maturity, reduced plant height and enhanced grain characteristics into aimed at enhancing wheat productivity and resilience are crucial for adapting to the challenges posed by climate change.

Keywords: Climate change, ER model, Food security, Stability, Wheat

The rise in climate change is leading to more frequent and intense environmental phenomena, including altered rainfall patterns, wildfires, drought, soil salinity, floods, extreme heat etc. (Duchenne-Moutien and Neetoo 2021). These disturbances have both direct and indirect impacts on sustainable agriculture, food security, and the livelihoods of communities (FAO 2023). By the year 2050, the global population is anticipated to approach 9 billion, leading to an expected rise in wheat demand by 60–70%. To meet this demand, the world will need to produce an additional one billion tonnes of cereal, all while dealing with limited resources (CGIAR 2023). Bread wheat (*Triticum aestivum* L.) is a vital member of the grass family Poaceae and serves as one of the primary cereal crops globally (Aulakh 2022). Currently, global wheat production stands at 793.37 million tonnes, with the European Union, China, India, Russia, and the United States leading in production (USDA-FAS 2023). In India, wheat plays a vital role in both agricultural output

and food consumption. It covers 21% of the country's total cultivated area (31.82 million hectares) and contributes 35% to total food production (98.38 million tonnes).

India's population is projected to reach 1.7 billion by 2050, escalating wheat demand by 60–70%. This translates into the necessity of producing an additional one billion tonnes of cereals globally by 2050, all while managing finite resources such as land and water (CGIAR 2023). However, the national average productivity of 3443 kg/ha (ICAR-IIWBR 2023) falls short of meeting future demand, emphasizing the urgent need for innovative breeding approaches to address yield deficits. To address these challenges, identification of stable and climate resilient varieties in wheat breeding has become increasingly important (Belete *et al.* 2024). This method allows breeders to evaluate both mean performance and stability parameters, helping them make more informed selections. By incorporating stable, high-yielding genotypes into breeding programs, breeders can develop wheat varieties that perform consistently well across diverse environmental conditions. This is especially crucial in regions with limited resources or suboptimal growing environments, where crop resilience and adaptability are essential for sustaining agricultural productivity. As climate variability becomes

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more pronounced, understanding the genetic basis of stability and yield is vital. Through stability analysis, wheat breeding programmes can better respond to the challenges posed by climate change and rising food demand, ensuring global food security for future generations (Khare *et al.* 2024). This stagnation in yield gains, combined with terminal heat stress in the North Western Plain Zone (NWPZ) of India, is a critical issue affecting wheat production. In NWPZ, where delayed monsoon onset and erratic end-of-season rainfall are common, late sowing during the *rabi* season exacerbates the negative effects of terminal heat stress, leading to substantial yield losses. The lack of sufficient genetic variation for heat tolerance in wheat breeding programs has further compounded the problem (Bhandari *et al.* 2024).

The current study conducted at three different sowing dates in NWPZ of India identifies potential breeding materials that can be integrated into future wheat breeding programmes. These breeding materials were specifically selected to combat terminal heat stress, which is a growing concern in the region. It addresses a significant gap in wheat breeding by providing insights into the stability and adaptability of wheat genotypes under heat stress conditions, which is critical for regions facing delayed or erratic rainfall patterns.

MATERIALS AND METHODS

Materials: The present study was carried out during winter (*rabi*) seasons of 2019–2020 and 2020–2021 at Chaudhary Charan Singh Haryana Agricultural University, Hisar (29.09°N latitude; 75.43°E longitude, and an elevation of 215.2 m amsl), Haryana (Fig. 1). The genetic material consisted of 60 diverse genotypes (Table 1) grown in randomized complete block design (RCBD) under four different environments. Four checks were used i.e. WH 1105 for timely sown irrigated condition, HD 3043 for drought stressed condition, RAJ 3765 for heat stressed condition and lastly WH 730 for combined stressed condition.

Crop evaluation ecologies: The genotypes were sown in November (11 November 2019 and 16 November 2020) for timely sown and rainfed (drought stress) conditions and in December (20 December 2019 and 22 December 2020) for late sown (heat stress) and rainfed (combined drought + heat stress) conditions. During the crop growth period, day temperatures ranged from approximately 30°C to 15°C, while night temperatures varied between 15°C and 5°C while during the flowering stage, typically

observed around 22 January to 4 February, the day temperature was approximately 22°C, and night temperature was about 10°C. Furthermore, rainfall was observed in two distinct peaks, viz. one around 12–25 November and another during 5–18 February, with cumulative rainfall reaching approximately 30 mm in these periods. Minimal to no rainfall was recorded in the other weeks.

G × E analysis: A total of 16 morphological attributes contributing to yield were measured throughout the study period. These attributes included various growth and yield components that are critical for assessing the performance of the genotypes under the different stress conditions outlined above. The data collected from these distinct sites underwent stability analysis utilizing Eberhart and Russell model (1966). It's simply based on regression. A genotype was considered stable if it exhibited a high mean value, a regression coefficient close to one, and a deviation that did not significantly differ from zero ($S^2_{di}=0$). The analysis was conducted using R Studio. This rigorous approach to stability analysis allowed for the identification of genotypes that are not only high-yielding but also resilient under varying environmental conditions. The basic model employed as follows:

$$Y_{ij} = \mu_i + \beta_i I_j + S_{ij}$$

Where Y_{ij} , Mean of the i^{th} variety at the j^{th} environment; μ_i , Mean of i^{th} variety over all environments; β_i , Regression coefficient reflects how the i^{th} variety responds to different environmental conditions; S_{ij} , Deviation from regression represents the performance of the i^{th} variety in the j^{th} environment; I_j , Environmental index is calculated by subtracting the grand mean from the average performance of all varieties in the j^{th} environment.

Based on the Fig. 1, irrigation could be scheduled to align with periods of high temperature and low rainfall; early growth stage (October–November), irrigation may

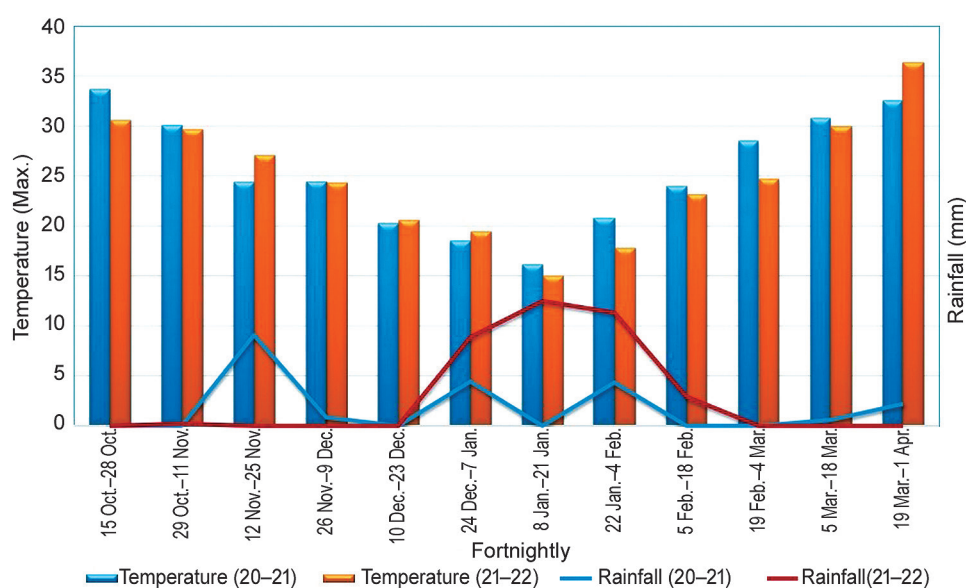


Fig. 1 Weekly averaged meteorological data throughout the agricultural seasons of 2020–2021 and 2021–2022.

Table 1 Sixty bread wheat genotypes and their pedigree

Sr. No.	Treatment	Pedigree	Sr. No.	Treatment	Pedigree
1.	BRW 3806	NI5439/MACS2496	31.	MP 3288	DOVE/BUC/DL 788-2
2.	C 306	REGENT 1974/3*CHZ//2C591/3/P19/C281	32.	NIAW 3170	SKOLL/ROLF07
3.	DBW 14	RAJ3765/PBW-343	33.	NIAW 3624	DL 1022 X NIAW 1415
4.	DBW 71	PRINIA/UP2425	34.	NIAW 3643	RAJ 4083 X NIAW 1275
5.	DBW 74	WBLI*/BRAMBLING	35.	PBW 763	PBW621/3/ YR10/6*AVOCET//4*PBW343/4/2*PBW621/5/ PBW621/3/Y R15/6*AVOCET//4*PBW343/4/2*PBW621
6.	DBW 110	KIRITATI/4/2*SERI1B*2/3/KAUZ*2/ BOW//KAUZ	36.	PBW 773	FRANCOLIN*1*2/KIRITATI
7.	DBW 187	NAC/TH.AC//3*PVN/3/MIRLO/ BUC/4/2*PASTOR/5/KACHU/6/ KACHU	37.	QST 1910	HD2967/WH1080
8.	DBW 221	36IBWSN284/22ESWYT28	38.	QST 1911	HD2967/ WH1184
9.	DBW 252	PFAU/MILAN/5/CHEN/ AE.SQ(TAUS)//BCN/3/VEE#7/ BOW/4/PASTOR	39.	RAJ 3765	HD 2402/VL 639
10.	DBW 296	SOKOLL/3/PASTOR// HXL7573/2*BAU/4/MASSIV/ PPR47.89C	40.	RAJ 4480	WR989/PBW587
11.	DBW 299	WAXWING*2/KRONSTADF2004*2// BECARD	41.	RW 5	RAJ 4014/WH730
12.	DBW 303	WBLI*2/BRAMBLING/4/BABAX/ LR42//BABAX*2/3/SHAMA*2/5/ PBW343	42.	RWP-2018-28	PBW343/ HI1544
13.	DPW 621-50	KAUZ//ALTAR84/AOS/3/MILAN/ KAUZ/4/HUITES T.s.irrP.H 97c.m	43.	RWP-2018-31	HD3108/DPW621-50
14.	GW 477	GW366/BOW898	44.	RWP-2018-32	HD3131/DBW90
15.	HD 2888	C-306/T.SPHAEROCOCCUM// HW2004	45.	RWP-2019-28	DBW 39/ HP1963
16.	HD 2932	KAUZ/STAR//HD2643	46.	RWP-2019-29	HI1544/ WH1080
17.	HD 2967	ALD/CUC//URES/HD2160M/HD2278	47.	RWP-2019-30	HD2964/PBW631
18.	HD 3043	PJN/BOW//OPATA*2/3CROC_1/ Ae.squarrosa (224)//OPATA	48.	RWP-2019-31	HD 3249/DBW 316
19.	HD 3059	KAUZ//ALTAR84/AOS/3/MILAN/ KAUZ/4/HUITES	49.	TAW 185	GW492/HP1968
20.	HD 3086	DBW14/HD2733//HUW468	50.	TAW 186	GW322/PHSL10
21.	HD 3226	GRACKLE/HD2894	51.	WH 711	S 308/ CHR//KAL
22.	HD 3237	HD3016/HD2967	52.	WH 730	CPAN 2092/Improved Lok-1
23.	HD 3293	HD2967/DBW46	53.	WH 1021	NYOT 95/SONAK
24.	HD 3298	CL1449/PBW343//CL882/HD2009	54.	WH 1063	BARBET 1 Selection
25.	HI 1621	W15.92/4/PASTOR// HXL7573/2*BAU/3/WBLI1	55.	WH 1105	MILAN/S87230//BABAX
26.	HI 1653	NADI/COPIO/NADI	56.	WH 1124	MUNIA/CHTO//AMSEL
27.	HI 1654	SKOLL/3/PASTOR// HKL7573/2*BAU/4/PANDION// FILIN/2*PASTOR/3/BERKUT	57.	WH 1138	PBW65*2/Pastor
28.	HI 1655	MACS2496/HI1531	58.	WH 1142	NYOT 95/SONAK
29.	K 1317	K0307/K9162	59.	WH 1202	D67.2/PARANA66.270//AE.SQ.(320)/3/ CUNNINGHAM
30.	LOK 54	Raj 3777/WH671	60.	WH 1235	METSO/ER2000/5/2*SERI*3// RL6010/4*YR/3/PASTOR/4/BAV92

be moderate, with rainfall contributing to moisture. Peak vegetative stage (December–January), reduced irrigation due to lower temperatures and residual soil moisture. Flowering and grain filling (February), increased irrigation required due to minimal rainfall and critical growth needs. Maturity (March–April): Frequent irrigation may be needed due to rising temperatures and limited rainfall.

RESULTS AND DISCUSSION

The stability of crop genotypes across various environmental conditions is becoming increasingly vital due to climate change. Wheat, as a staple crop grown in a wide range of agro-climatic regions, is particularly vulnerable to fluctuations in temperature, moisture levels, and nutrient availability. With climate change predicted to exacerbate these environmental variations, identifying climate-resilient cultivars is now indispensable. In breeding programmes, the primary objective is to select genotypes that not only demonstrate high yield potential but also exhibit stability across diverse environments. The results obtained from the stability analysis, using the Eberhart and Russell (1966) model across 16 morphological traits in wheat, carry significant implications for crop improvement. The mean sum of squares due to genotype $\times$ environment interaction ($G \times E$) when tested against pooled error was significant for traits days to heading (DH), days to anthesis (DA), days to maturity (DM), plant height (PH), flag leaf length (FL), peduncle length (PDN), number of tillers per meter (T/M), number of grains per spike (GR/S), grain weight per spike (GW/S), 1000-grain weight (TGW), biological yield per plot (BY/P), harvest index (HI) and grain yield per plot (GY/P). The $G \times E$ interaction mean squares were found

non-significant for spike length (SL), spike weight (SW) and number of spikelets/spike (S/S). However, pooled deviation when tested against pooled error was significant for DH, DA, DM, FL, PDN, SW, GR/S, S/S, GW/S, TGW, BY and HI. The highly significant $G \times E$ interactions observed for key traits emphasize the varying responses of genotypes under different environmental conditions (Table 2). These findings underscore the importance of identifying genotypes that are both high-yielding and stable across a range of environments. Kumar *et al.* (2020) conducted a stability analysis on wheat genotypes under rainfed conditions using the ER model. Genotypes exhibiting $bi \neq 1$ and $S^2di = 0$ are particularly valuable, as they suggest reliable performance (Supplementary Table 1, 2, 3, 4). Similar to our study, Pandey *et al.* (2021) focused on wheat genotypes under diverse agro-climatic zones of India using the ER model. They found that the genotypes with regression coefficients closer to unity and minimal deviations performed better across different environments. Their findings reinforced the importance of incorporating stable genotypes into breeding programs to mitigate the effects of environmental variability caused by climate change.

Phenological parameters: The findings of this research emphasize the importance of selecting and breeding wheat genotypes that exhibit desirable physiological traits in response to environmental stresses. As climate change continues to impact agricultural productivity, the identification of genotypes with early heading, flowering, and maturity becomes increasingly crucial, particularly in regions with shorter growing seasons or where early sowing is beneficial. Both days to heading and days to anthesis are critical indicators of a plant's phenological

Table 2 Combined analysis of variance across various environments for different wheat traits

Source of Variation	DF	DH	DA	DM	PH	FL	PDN	T/M	SL
MSS									
Gen	59	14.59**	13.79**	10.04**	150.32**	5.79**	24.06**	69.54**	0.75**
Env	3	899.68**	1258.90**	6885.02**	1864.18**	619.88**	331.83**	2340.09**	18.80**
Gen $\times$ Env	177	1.23**	1.35**	2.74**	7.18**	1.63**	1.76**	9.33**	0.09
Env + Gen $\times$ Env	180	16.20	22.31	117.44	38.13	11.94	7.26	48.18	0.40
Pooled deviation	120	0.81**	0.73**	1.77**	4.74**	1.50**	1.27**	6.96	0.06
Pooled Error	236	0.62	0.31	0.50	2.01	0.98	0.83	8.55	0.10
Source of Variation	DF	SW	GR/S	S/S	GW/S	TGW	BY/P	HI	GY/P
MSS									
Gen	59	0.12**	25.73**	1.69**	0.05**	8.65**	132342.71**	28.09**	26041.19**
Env	3	5.05**	1069.66**	48.07**	1.26**	158.03**	10212568.28**	91.78**	1216389.31**
Gen $\times$ Env	177	0.02	9.05**	0.48	0.01**	1.39**	27193.97**	7.27**	3112.43**
Env + Gen $\times$ Env	180	0.11	26.73	1.28	0.03	4.00	196950.21	8.68	23333.71
Pooled deviation	120	0.02*	8.51**	0.43**	0.01**	1.38**	25513.15**	7.69**	1168.96
Pooled Error	236	0.02	3.13	0.39	0.01	0.78	16687.06	3.18	2199.78

Gen, Genotype; Env, Environment; DH, Days to heading; DA, Days to anthesis; DM, Days to maturity; PH, Plant height; FL, Flag leaf length; PDN, Peduncle length; T/M, Number of tillers/meter; SL, Spike length; SW, Spike weight; GR/S, Number of grains/spike; S/S, Number of spikelets/spike; GW/S, Grain weight/spike; TGW, 1000-Grain weight; BY/P, Biological yield/plot; HI, Harvest index; GY/P, Grain yield/plot.

response to environmental conditions. For days to heading, the mean values ranged from 89.19 days (DBW 110) to 99.75 days (RWP-2018-32), with an overall mean of 93.29 days. Genotypes such as C 306, PBW 763, and RW 5, with lower-than-average mean values, a regression coefficient greater than unity, and non-significant deviations from regression, are well-suited for early heading in optimal conditions. Genotypes DBW 110, HD 2967, and WH 1021, with a regression coefficient less than unity, were suitable for early heading in sub-optimal conditions. Similarly, for days to anthesis, which ranged from 92.69 days (DBW 110) to 102.94 days (RWP-2018-32) with an overall mean of 96.23 days, genotypes like C 306, PBW 763, and RW 5 were identified as early flowering in optimal environments, while DBW 110, HD 2967, and NIAW 3170 were better suited for suboptimal conditions. The genotypes showed a range of days to maturity from 130.38 days (HD 3043) to 136.81 days (NIAW 3624), with an overall mean of 133.09 days. Genotypes DBW 303, HI 1654, and WH 1021 were suitable for early maturity in ideal growing conditions (e.g. adequate water supply, moderate temperatures) while DBW 14, HD 3059, and RAJ 3765 were better suited for conditions with limited water availability or higher stress, such as drought-prone environments. These results suggest that incorporating genotypes with early flowering and early maturity traits into breeding programs can be particularly beneficial in regions where early sowing or short-duration growth seasons are advantageous. Studies conducted by Reynolds *et al.* (2012), Al-Karaki (2012) and Rizwan *et al.* (2021) have similarly shown that early-maturing wheat varieties help mitigate the effects of terminal heat stress, which is expected to intensify with climate change. While Dutta *et al.* (2023) recently worked on stability analysis in wheat using the ER model in eastern India, where moisture stress is a frequent concern. Their study emphasized early-maturing varieties with stable yield and high grain weight, which are critical for regions facing the threat of delayed rainfall.

Vegetative traits: The study revealed a wide variation in plant height, ranging from 83.68 cm (NIAW 3624) to 121.10 cm (C 306), with an overall mean of 96.32 cm. Genotypes like HD 2967, WH 711, and WH 1105, with lower mean values, regression coefficients greater than unity, and non-significant deviations from regression, were suitable for favourable environments. The genotypes with suitable traits for favourable conditions, may achieve greater light interception, leading to higher biomass accumulation. In contrast, genotypes such as DPW 621-50, NIAW 3624, and WH 730, which exhibited lower regression coefficients, were identified as more suitable for drought-prone or nutrient-limited environments, where water stress and low fertility conditions prevail. For flag leaf length, which ranged from 23.10 cm (K 1317) to 28.28 cm (HD 3043) with an overall mean of 25.75 cm, genotypes RAJ 3765 and WH 1142, with longer flag leaves and significant regression coefficients, were deemed suitable for favorable conditions, while GW 477 and MP 3288 were better suited to suboptimal

environments. Peduncle length ranged between 28.55 cm (RWP-2019-31) and 38.95 cm (WH 1235), with an overall mean of 32.99 cm. Genotypes like DBW 110 and WH 1142 performed well in optimal environments, while C 306 and LOK 54 were more suited to suboptimal conditions. The number of tillers per meter ranged from 100.13 (NIAW 3643) to 123.56 (RW 5), with a mean of 116.42. Genotypes DBW 221, HD 2967, and PBW 773 were found suitable for favorable conditions, while C 306 and PBW 763 performed better in suboptimal environments. The variation in plant height and tillering indicates significant genotype-environment interactions, suggesting that some genotypes may possess inherent traits for canopy management and resource allocation.

Overall genotypes WH 1105 and HD 2967, with suitable traits for favorable conditions (e.g., high water availability and moderate temperatures), may achieve greater light interception, leading to higher biomass accumulation. In contrast, genotype NIAW 3624, identified for poorer environments, may exhibit shorter stature or fewer tillers, indicating a trade-off between growth and resource use under stress. This variation in growth traits points to the need for further investigation into how physiological changes, such as alterations in stem elongation rates or tiller development, contribute to overall plant performance.

Spike characteristics: The spike length ranged from 8.41 cm (NIAW 3624) to 10.20 cm (HD 3237), with an overall mean of 9.50 cm. Genotypes HD 3226, RWP-2018-32, and WH 1235 exhibited better performance in both well-irrigated and moderate stress conditions, depending on their regression coefficients. Spike weight ranged from 2.68 g (HD 2888) to 3.43 g (RW 5), with an overall mean of 3.15 g. Genotypes such as HD 3237 and RWP-2019-29 were found suitable for favorable environments with number of grains per spike varied from 56.75 (HD 2888) to 67.55 (BRW 3806), with an overall mean of 61.34. Genotypes HD 3086, WH 1105, and HD 3043 were suitable for both optimal and suboptimal environments. Number of spikelets per spike ranged from 18.50 (HD 2888) to 21.86 (WH 1142) with a mean of 20.53. HD 3237 and DBW 74 were identified as suitable for well-irrigated and moderately stressed environments, respectively. Grain weight per spike ranged from 1.93 g (NIAW 3624) to 2.52 g (WH 1235), with an overall mean of 2.36 g. BRW 3806, WH 1105, and HD 2967 were suitable for favorable conditions while thousand-grain weight ranged from 32.94 g (NIAW 3624) to 40.77 g (QST 1911), with an overall mean of 37.60 g. Genotypes DBW 221 and HD 2967 showed better performance in optimal conditions, while C 306 and MP 3288 were suited for drought-stressed conditions.

Genotypes with better canopy management and spike characteristics were found to be stable, contributing to higher productivity under both stressed and non-stressed environments. Ahmed *et al.* (2022) conducted a study in Egypt using the Eberhart and Russell (ER) model to identify wheat cultivars with stable yields under extreme heat conditions. Their findings highlighted that genotypes

exhibiting stable flowering and grain-filling stages demonstrated higher adaptability, making them crucial for breeding heat-tolerant varieties. Overall, genotypes exhibiting longer spikes and higher grain weights, such as HD 3237 and RW 5, may leverage improved reproductive efficiency, which can be vital under varying environmental conditions. Research indicates that wheat genotypes with longer spikes and higher grain weights can enhance reproductive efficiency, which is crucial under suboptimal environmental conditions. For instance, a study on wheat's response to salinity stress found that sensitive cultivars exhibited decreased spike length, suggesting that maintaining longer spikes under such stress is beneficial (Patwa *et al.* 2024). Additionally, drought conditions during anthesis have been shown to reduce the number of grains/spike and grain weight, underscoring the importance of selecting genotypes that sustain these traits under water-limited environments (Bapela *et al.* 2022). The physiological basis for this could involve enhanced resource allocation to reproductive structures or superior grain filling processes, as suggested by the significant relationships observed in the data (Golan *et al.* 2024).

Yield attributing characters: Biological yield/plot ranged from 1907.50 g (NIAW 3643) to 2677.50 g (HD 3226), with an overall mean of 2276.52 g. Genotypes BRW 3806, HD 3059, and WH 711 were found suitable for both favourable and suboptimal conditions depending on their regression coefficient. The mean harvest index ranged from 25.44 (NIAW 3624) to 40.66 (DBW 74), with an overall mean of 35.15%. Genotypes PBW 773 and QST 1911, which exhibited a high mean, a significant regression coefficient below one, and non-significant deviations, were identified as well-suited for stressed environments. GY ranged from 519.28 g (NIAW 3624) to 906.88 g (BRW 3806), with an overall mean of 796.22 g. The twelve genotypes BRW 3806, DBW 303, HD 2967, HD 3086, HD 3226, HD-3237, HD 3298, PBW 773, QST 1910, QST 1911, WH 1105 and WH 1202 were found to be suitable for favourable environments due to their high mean values compared to the overall mean, significant regression coefficients greater than one, and non-significant deviations from regression. The 12 genotypes BRW 3806, DBW 303, HD 2967, HD 3086, HD 3226, HD-3237, HD 3298, PBW 773, QST 1910, QST 1911, WH 1105 and WH 1202 demonstrated high mean values relative to the overall average, significant regression coefficients exceeding one, and non-significant deviations from regression, indicating their suitability for more favorable environments. Five genotypes DBW 74, GW 477, HD 3043, PBW 763 and WH 730 having a high mean value for grain yield as compared to the overall mean, a significant regression coefficient less than unity, and a non-significant deviation from regression were found to be suitable for sub-optimal environments. Yadav *et al.* (2021) in their study on wheat cultivars, found that genotypes with lower regression coefficients but non-significant deviations from regression were best suited for stressed environments like drought or high salinity. The study underscored the

importance of stability analysis in identifying genotypes with inherent stress tolerance mechanisms. Singh *et al.* (2019) examined genotype-environment interactions in wheat across Northern India using the ER model. Their study focused on identifying high-yielding and stable genotypes under fluctuating climatic conditions. Their results indicated that stable genotypes had better adaptation mechanisms such as high water-use efficiency and efficient nutrient utilization.

Overall, the high biological yield of genotypes like HD 3226 and BRW 3806 reflects their capacity to convert resources into biomass effectively, while high harvest indices signify efficient partitioning of this biomass into grain. This ability to optimize yield potential under stress conditions may involve physiological mechanisms such as improved nutrient uptake efficiency or enhanced drought tolerance, which enable plants to maintain productivity even in suboptimal conditions.

Research by Trethowan *et al.* (2007) and Sharma *et al.* (2015) supported the development of wheat varieties that thrive under drought, heat and poor soil conditions. Such varieties ensure yield stability under climate variability, which is becoming increasingly important due to global climate change. The genotypes performing better at sub-optimal conditions may have physiological adaptations that allow them to perform adequately under stress, possibly through mechanisms like enhanced root growth for better water uptake or improved photosynthetic efficiency under limited resources. Understanding these physiological responses can guide breeding programs aimed at developing varieties capable of withstanding the pressures of climate change.

The results from this stability analysis provided valuable insights into identifying genotypes that exhibit both high yield potential and stability across diverse environments. Traits such as early maturity, which mitigate the impact of terminal heat stress, and stable grain yield, essential for food security in suboptimal conditions, are critical in the face of climate change. Early-maturing genotypes like C 306 and PBW 763 can be integrated into breeding programs to avoid terminal heat stress and ensure yield stability in regions with short growing seasons. Genotypes demonstrating high tillering capacity and grain weight under both optimal and stressed conditions, such as BRW 3806 and HD 2967, should be prioritized for yield enhancement. Additionally, genotypes with longer flag leaves and peduncles, such as RAJ 3765 and WH 1142, play a crucial role in improving the plant's ability to capture light and produce biomass, contributing to both yield and resilience. Genotypes HD 2967 and WH 1105, with controlled plant height and reduced lodging risk, should be used to improve crop management and yield efficiency, particularly in regions prone to strong winds or heavy rains. Under combined heat and drought stress conditions, stable lines like HD 3237, DBW 74, and WH 730 exhibit consistent performance and are well-suited for environments facing both stresses, ensuring reliable yield stability. These results underscore the importance of incorporating genotypes with high yield potential and environmental stability into

future breeding programs, ensuring the sustainability of wheat production in increasingly variable climates. This study highlights the potential of utilizing specific wheat genotypes that exhibit favorable physiological responses to environmental stresses. By focusing on traits such as early heading, maturity, optimal growth characteristics, and high biological yield, breeding programs can significantly contribute to enhancing wheat productivity and resilience amid climate uncertainty. A key takeaway from this study is that, while the AICRP system has already released varieties suitable for the North Western Plain Zone (NWPZ), this paper offers recommendations for future wheat breeding programs, specifically suggesting genotypes for crossing to improve yield stability and resilience in the face of environmental stresses. The findings of this study suggest the incorporation of early-maturing, high tillering, and stable wheat genotypes into breeding programs, particularly for environments experiencing heat and drought stress. These genotypes can provide a foundation for sustainable wheat production. The integration of such genotypes with high adaptability will improve crop resilience and productivity, which is critical for ensuring food security in the context of climate variability.

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