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SELECTION OF STABLE WHEAT GENOTYPES UNDER DIFFERENT AGRO-ECOLOGICAL ZONES OF PUNJAB, PAKISTAN

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SUMMARY

Wheat is a globally significant cereal crop crucial for ensuring food security. Plant breeders strive to enhance yield potential by developing optimized and stable genotypes. In Pakistan, an agricultural country facing food security challenges, annual multi-environment trials (MET)'s systematic conduct transpire across various research stations in Punjab province. Precise data analysis of these trials is paramount in strengthening the national agricultural research system. The primary objective of this study was to identify stable wheat genotypes by analyzing data from MET trials in 31 distinct environments within the Punjab province during 2020–2021. The study comprised 50 wheat genotypes laid out under an alpha lattice design. The collected data underwent an analysis based on additive main effects and multiplicative interaction (AMMI) in combination with other stability measures. The findings revealed that genotype G41 (HYT100-27) exhibited superior performance, ranking within the top five across all five stability measures. Likewise, G27 (TWS17042) and G22 (HYT100-100) genotypes have four stability measures recommending these. Notably, G1 (HYT100-74) demonstrated the highest average yield across all locations and gained support from two additional stability measures. Therefore, G41, G27, G22, and G1 emerged as the most stable and productive genotypes among all those studied. Regarding the environments, MLSI proved the most desirable, followed by RARL. Conversely, the ARFG and ARFK resulted as the least ideal environments.

Keywords: AMMI, AMMI Stability Index (ASI), wheat, genotype by environment interaction (GGE), biplot, stability measures, multi-environment trials

Key findings: The additive main effects and multiplicative interaction (AMMI) analysis, with other stability analyses, helped in identifying stable genotypes from multi-environment trials conducted in 31 different environments in the Punjab province of Pakistan. The genotypes HYT100-27, TWS17042, HYT100-100, and HYT100-74 exhibited high stability, gaining classification as most stable genotypes. Moreover, the MLSI and RARL proved the most desirable environments for wheat cultivation.

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INTRODUCTION

Pakistan's agricultural sector has major crops classification, such as, cereal crops, minor crops like fruits and vegetables, livestock, fishing, and forestry (Anwar *et al.*, 2021). This sector is significant for the country's economic growth, ensuring food security, creating employment opportunities, and reducing scarcity. It contributes 19.2% of the gross domestic product (GDP) and employs approximately 38.5% of the labor force. Notably, important crops contribute 22.5% to the value addition of the agricultural sector and 4.3% to the GDP. Other crops contribute 11.7% to the sector's development and 2.2% of the GDP. However, the farming sector faces numerous challenges, including water scarcity, global warming, and droughts, as it strives to meet the demands of the country's large population. Wheat, with a world production of 761.5 million MT, holds tremendous significance as one of the world's essential crops. A global demand projection for wheat will reach 858 million MT by 2050 due to the increasing global population (Alexandratos and Bruinsma, 2012).

Wheat (*Triticum*) is the major cereal crop of Pakistan and occupies a large area of land in the rabi season. Being an essential staple crop, its cultivation covers over 8.9 million ha (22 million acres) in the country and contributes 1.8% to the GDP of the country. Compared with the 8.82 million ha (21.8 million acres) cultivated last year, the area under cultivation during 2020–2021 increased by 4.2%. Notably, achieving a record-breaking production of 27.3 million MT of wheat reflected an 8.1% increase compared with the previous year's production of 25.3 million MT. However, despite these achievements, wheat productivity in Pakistan remains relatively low compared to other agricultural nations, exacerbating current food security challenges.

Relatedly, the government and agronomic scientists engaged in continuous efforts to attain self-sufficiency in wheat production. Breeders and researchers actively focus on developing new and more stable varieties through multi-environment trials to enhance wheat yield. The analysis of these trials places significant emphasis on genotype-environment interactions (GEI), as they play a crucial role in selecting efficient and stable genotypes. Researchers' long-term interest in developing strategies helps determine higher genotypes in plant performance experiments (Yan *et al.*, 2000; Tembo, 2021; Ahmad *et al*., 2023). The method of multilocation trials is a systematic approach used for increasing the yield stability of new varieties of crops in different environments (Letta *et al.*, 2008). For agricultural reasons, the AMMI model was considered superior (Gauch *et al.*, 2008).

The complications arising from genotype × environment (G×E) interactions have emerged as significant focal points for researchers due to the considerable and unpredictable variations in environmental conditions. Studying the G×E interactions enables the researchers to address several inquiries regarding the varietal stability across diverse agroecologies and provide insight into characterizing genotypes based on varying levels of productivity (Yau, 1995). The partitioning methods of G×E interactions into components assigned to each genotype would be useful for breeders. Several parameters are now available for estimating the stability of genotypes tested over an environmental range. AMMI analysis combines variance and principal component analysis (PCA) into a single assessment with additive and multiplicative parameters (Zobel *et al.*, 1988; Gauch *et al.*, 2008).

Along with these important analyses, other stability parameters proposed by Finlay and Wilkinson (1963) and Eberhart and Russell (1966) used the regression of average genotype yield on an environmental index and deviation from the regression as a secondary estimate of stability to evaluate the strength of genotypes across environments are also beneficial for breeders. The ecovalence stability index of Wricke and stability variance have also measured the contribution of each genotype to the genotype by environment interactions (Shukla, 1972). Identifying genotypes that exhibit consistent performance requires research on the interactions between genotype and environment and evaluation of genotype performances in various wheat-growing locations. The goal of this study is to determine the stable wheat genotypes in Punjab by analyzing multi-environment trials of wheat in different environments in Punjab, Pakistan.

MATERIALS AND METHODS

The study collected multi-environmental data from the Wheat Research Institute at the Ayub Agriculture Research Institute in Faisalabad. These data encompassed the results of multi-environment trials conducted at 31 distinct locations in Punjab, as indicated in Table 1. These locations serve as prominent sites for the national wheat improvement program's multi-location variety testing, and they effectively represent various wheat agroecology across Pakistan.

Table 1. Details of test environments with their code.

No.	Environments	Code	S.No.	Environments	Code
1	PSC Khanewal	PKWL	17	NARC, Islamabad	NARC
2	RRS. Bahawalnagar	RBAH	18	UAF FSD	UFSD
3	Dhakkar, Pakpattan	DPKT	19	ABRI	ABRI
4	Army Stud Farm, Depalpur	ASFD	20	UAF Burewala	UBRW
5	Renalakhurd	RNLA	21	KROR	KROR
6	MMRI, Yousafwala (Ysfw)	MMRI	22	RARI (N)	RARN
7	ARF, Sargodha	ARFS	23	RARI (L)	RARL
8	SSRI, Pindi Bhattian	SSRI	24	JAHANIAN	JHAN
9	Govt. SEED FARM CHILLIANWALA	GFCH	25	MULTAN	MLTN
10	ARF, Gujranwala	ARFG	26	Rahim Yar Khan	RYKN
11	ARF, Kot Nainan	ARFK	27	Mailsi (MLSI)	MLSI
12	RRI, Kala Shah Kaku	RRIK	28	Alipur (ALPR)	ALPR
13	WRI, Fsd Rainfed	WFDR	29	WRI, FSD	WFSD
14	BARI Chkwl	BARI	30	Kallur Kot	KKOT
15	BARS FJ	BAFJ	31	Azri Bhakkar	AZBK
16	GRS Attock	GRAT			

The trials ran at each selected location using an alpha lattice design with two replications. Each location tested a comprehensive set of 50 genotypes, outlined in Table 2. Adhering to specific recommendations for each site ensured the implementation of standard management practices. Recording various agronomic parameters occurred; however, this study considered only yield data. The Alpha designs initially presented by Patterson and Williams (1976) had further improvements from John and Williams (1995) to be used primarily in the context of numerous trials in the field of agriculture. Analysis of variances proceeded at the individual location level, with the combined data across multiple environments, using different packages available in the R software, specifically the metan suite (Olivoto and Lúcio, 2020). Also, a combined analysis of variance (ANOVA) across multiple environments continued. Engaging the AMMI and GGE biplots visualized the relationship between environments and genotypes. These biplots provided graphical representations that aided in understanding the interactions and patterns between genotypes and environmental conditions. The stability and the impact of different locations on grain protein content in durum wheat genotypes using AMMI analysis employed the method by Haile *et al.* (2007).

Table 2. Fifty wheat genotypes with codes used in the study.

GN	Genotype	GN	Genotype	GN	Genotype	GN	Genotype
G1	HYT 100-74	G14	10136	G27	TWS17042	G40	V-19332
G2	180059	G15	NR-546	G28	V-19306	G41	HYT 100-27
G3	NR-553	G16	V-19310	G29	BF-1902	G42	TWS17060
G4	V-18381	G17	17534	G30	17FJ10	G43	V-18485
G5	NR-544	G18	PGMB-17-6	G31	HYT 100-76	G44	V-19324
G6	V-19308	G19	RS-2086	G32	Saim -20	G45	18BT017
G7	EV.18101	G20	V-19317	G33	WV-1197	G46	V-19347
G8	V-19335	G21	HYT 100-47	G34	180003	G47	TWS1849
G9	V-18594	G22	HYT 100-100	G35	NR-551	G48	Rustam 2020
G10	Ani-17	G23	195715	G36	V-19325	G49	BF-1910
G11	EV.18102	G24	IS-2123	G37	V-18352	G50	Akbar-19
G12	17FJ16	G25	Pakistan-13	G38	HYT 100-89		
G13	BF-7786	G26	IS-3234	G39	NR-545		

The AMMI approach integrates ANOVA for the main effects with PCA for the genotype-environment interaction. It also has proved to be useful in investigating complex GEI.

The statistical model:

$$Y_{ijk} = \mu + g_i + e_j + b_k\left(e_j\right) + \left(ge\right)_{ij} + \varepsilon_{ijk} \quad (1)$$

Where:

Y_{ijk} is the yield for i^{th} genotype, j^{th} environment, and k^{th} replicate,

μ is the overall mean,

g_i is the main effect of i^{th} genotype,

e_j is the main effect on j^{th} environment,

ge_{ij} is the effects of GE interaction,

$b_k\left(e_j\right)$ is the effect of the replication k within the j^{th} environment, and

e_{ijk} are the experimental random errors which assumed to be independent with identical distribution, $e_{ijk} \sim N\left(0, \frac{\sigma^2}{k}\right)$

AMMI method separates the GEI into further components:

$$\left(ge\right)_{ij} = \sum_{v=1}^{n} \lambda_v \alpha_{iv} \gamma_{jv} + \rho_{ij} \quad (2)$$

Where:

λ_v denotes the eigenvalue for the PCI with v axis,

a_{iv} and γ_{jv} are the PC scores for i^{th} genotype and j^{th} environment with v axis,

ρ_{ij} denotes the residual that contains all multiplicative terms not included in the model, and n is the number of PC retained by the AMMI model.

AMMI model mixed the additive effects and the multiplicative effects of a two-way data structure in one model. The statistical equation for additive main effects and multiplicative interaction model for replicated experiments (Hongyu *et al.*, 2014) follows.

$$Y_{ijk} = \mu + g_i + e_j + b_k\left(e_j\right) + \sum_{v=1}^{n} \lambda_v \alpha_{iv} \gamma_{jv} + \rho_{ij} + \varepsilon_{ijk} \quad (3)$$

Indeed, the use of the Additive Main Effects and Multiplicative Interaction (AMMI) model and the Genotype and Genotype × Environment (GGE) biplot has become increasingly popular among researchers for the selection of elite genotypes in various crops, including wheat, castor, and orange-fleshed sweet potatoes (Karuniawan *et al.*, 2021; Omrani *et al.*, 2022; Memon *et al.*, 2023).

Stability statistical methods, such as, joint regression and deviation from regression models (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966), have wide employment in agricultural research. Furthermore, measures proposed by Shukla (1972) ,Wricke, (Lin and Binns, 1988) superiority index, coefficient of variation (CV%) by Francis and Kannenberg (1978), and coefficient of determination by Pinthus (1973) have helped to assess genotype behavior across different environments. These analytical methods enable the simultaneous evaluation of yield and stability components, aiding in identifying high-yielding and stable genotypes. Researchers have emphasized the importance of these approaches for studying the overall performance of genotypes across various environments (Hernandez *et al.*, 1993; Kang, 1993; Bajpai and Prabhakaran, 2000).

RESULTS and DISCUSSION

Selection of environments

Employing statistical tests assessed the assumptions of homogeneity of residual variances and normality of residuals to identify suitable environments for subsequent analysis from the total of 31 surroundings. The Bartlett test aids in examining the homogeneity assumption, while the Shapiro-Wilk test leads in evaluating the normality assumption. These performed tests ensured the appropriateness of the selected environments for further analysis in the study. The Bartlett test yielded a highly significant test statistic of 1151.3 and a p-value of less than 0.000, indicating a violation of the assumption of homogeneity of variances. Likewise, the Shapiro-Wilk normality test produced a test statistic of 0.9602 and a p-value of less than 0.000, leading to a violation of the normality assumption. Consequent use of the residual variances as a criterion resulted in only 14 environments selected (Figure 1), satisfying both the assumption of homogeneity of variances (Bartlett test statistic of 19.78, p-value = 0.101) and the assumption of normality (Shapiro-Wilk test statistic of 0.9994, p-value = 0.961).

Combined and AMMI analysis of variances

The results of the AMMI analysis of variance using data from 50 wheat genotypes tested in 14 selected environments are available in Table 3. The results indicated that genotypes, environment, and interaction (GEI) significantly affected yield, revealing that genotypes respond differently across the selected test environments. The interaction sum of squares further divides into eight significant interaction principal components (PC1-PC8).

The AMMI analysis revealed that the interaction between genotype and environment was significant, and the first eight principal components account for 90% of the total variation in GEI. In AMMI analysis, primary components sought to represent the interaction effects between genotypes and conditions. Principal components are a linear combination of the original variables (genotypes and environments) that capture the maximum variation in the data.

The IPCA's score was 11.8% of the total for GEI. The study used only the first two PCs to construct the GGE biplot. The first two PCs account for 42% of the variation. The genotypes sorted according to their average yield performance had two colors: assigning those above the overall mean the blue color and those below the average yield with the red color (Figure 2). It shows that 24 genotypes fall below the overall mean harvest, whereas 26 genotypes have a higher average than the total yield average.

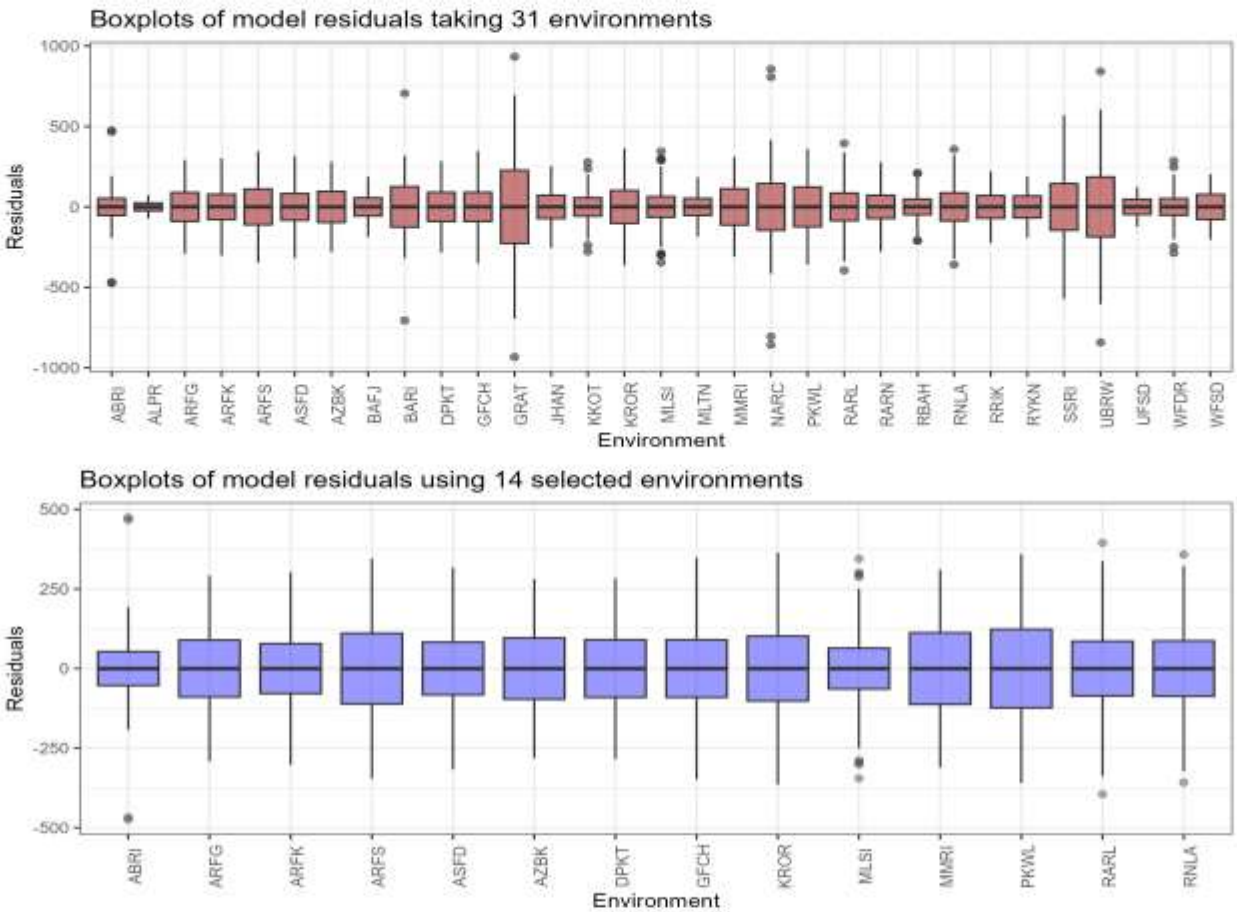

Figure 1. Residual box plots of all environments (top) and selected environments (bottom).

Table 3. Combined AMMI analysis of variance of 50 wheat genotypes tested at 14 selected environments.

Sources	d.f.	Sum of Square	Mean Square	F. value	P (>F)	Proportion	Accumulated
Environments	13	1527041714.8	117464747.29**	1897.1	<0.001	70.6	
Replications (ENV)	14	3711869.1	265133.50**	4.3	<0.001		
Blocks (REP*ENV)	252	19010635.6	75439.03*	1.2	0.0370		
Genotypes	49	74794838.0	1526425.26**	24.7	<0.001	3.5	
Gen × Env	637	255557122.4	401188.58**	6.5	<0.001	11.8	
PC1	61	60126697.8	985683.57**	15.9	<0.001	23.5	23.5
PC2	59	46960868.4	795946.92**	12.9	<0.001	18.4	41.9
PC3	57	31003901.1	543928.09**	8.8	<0.001	12.1	54.0
PC4	55	26493672.6	481703.14**	7.8	<0.001	10.4	64.4
PC5	53	21954215.1	414230.47**	6.7	<0.001	8.6	73.0
PC6	51	16491407.3	323360.93**	5.2	<0.001	6.5	79.4
PC7	49	16063955.8	327835.83**	5.3	<0.001	6.3	85.7
PC8	47	12441721.3	264717.47**	4.3	<0.001	4.9	90.6
Residual (PC's)	205	24020683.0	117174.06**	1.9	<0.001	9.3	100.0
Error	434	26872141.1	61917.38				
Total	2036	2162545443.3	1062153.95				

*, ** significant at 0.05 and 0.01, Ns=not significant.

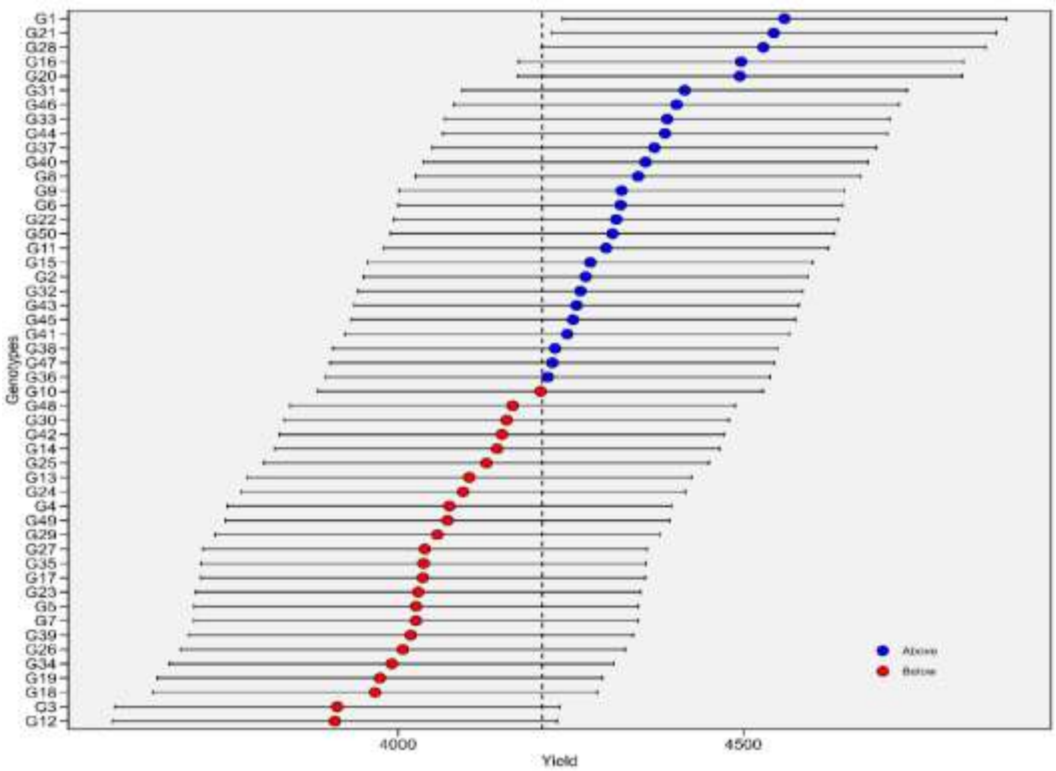

Figure 2. Genotype performance sorted from lowest to highest in respect to mean yield intervals.

Stability analysis

In the presence of significant genotype-by-environment (G×E) interaction, estimating stability parameters is a requirement. Table 4 presents computations of the average grain yield for each of the 50 genotypes with the corresponding stability parameters. These stability parameters provide insights into the performance and adaptability of the genotypes across different environments.

The interaction principal component one (IPCA-1) scores and the IPCA-2 scores in the AMMI model are stability indicators. The genotypes with a lower ASI value prove more stable, and those with a higher ASI are unstable. According to ASI, G31 was most stable with an ASI value of 0.557, followed by G41 (0.681), G1 (0.683), G39 (0.747), G37 (0.776), G42 (0.851), G38 (0.861), G16 (0.998), G45 (1.110), and G27 (1.128), which are the top stable genotypes, whereas the genotypes G8 (6.559), G6 (4.943), G2 (4.794), G44 (4.433), and G43 (4.398) were the most unstable for grain yield (Table 4). The stable genotypes (G31, G41, G37, G38, G16, and G45) showed a mean grain yield above the grand mean of 4208.6. However, the most unstable genotypes were G43, G44, G2, G6, and G8, with an average yield above the overall average yield.

According to Shukla (1972) r_i^2, genotypes G41, G27, G22, G46, G38, G42, G39, G4, G13, and G16 exhibited desirable characteristics in terms of stability variance. These genotypes demonstrated lower variance, indicating greater stability versus others in the study. Pinthus (1973) proposed that the greater value of R^2 indicates a more stable genotype. Considering R^2, the genotypes G41, G27, G22, G46, G38, G42, G39, G4, G13, and G16 were more stable compared with other genotypes. Corresponding to Wricke's E stability statistic reveals that the wheat genotypes G41, G27, G22, G46, G38, G42, G39, G4, G13, and G16 exhibit superior

Table 4. Mean yield and other stability measures for 50 wheat genotypes along with their ranks.

Gen	Mean		ASI		Sd_i^2		CV (%)		b_i	r_i^2		R^2		W_i		P_i	
G1	4676.2	(1)	0.68	(3)	195120.0	(38)	24.44	(10)	0.965	217052.3	(31)	0.838	(35)	5521933.4	(31)	250219.7	(2)
G2	4288.7	(19)	4.80	(48)	286588.3	(46)	32.58	(44)	1.188	346649.0	(47)	0.849	(34)	8756667.6	(47)	612919.6	(21)
G3	3810.7	(49)	2.66	(22)	109584.1	(18)	27.62	(27)	0.912	142909.6	(15)	0.881	(28)	3671333.8	(15)	1132120.1	(50)
G4	4034.7	(35)	1.16	(11)	78440.9	(11)	25.88	(19)	0.917	111921.0	(8)	0.905	(18)	2897856.7	(8)	816571.5	(35)
G5	3962.0	(43)	3.33	(34)	109640.7	(19)	31.27	(41)	1.093	143962.7	(16)	0.914	(15)	3697617.4	(16)	921146.4	(42)
G6	4360.6	(13)	4.94	(49)	336844.1	(49)	28.28	(30)	1.002	351870.2	(48)	0.775	(47)	8886988.7	(48)	589204.2	(20)
G7	3967.3	(42)	2.28	(19)	166729.4	(33)	25.75	(16)	0.855	213934.6	(29)	0.823	(42)	5444116.3	(29)	956871.8	(44)
G8	4395.1	(12)	6.56	(50)	318491.2	(48)	33.78	(47)	1.265	419957.0	(49)	0.853	(33)	10586434.7	(49)	588716.5	(19)
G9	4352.0	(15)	3.72	(38)	104537.0	(17)	33.36	(46)	1.298	237473.7	(36)	0.940	(4)	6031652.9	(36)	478017.4	(13)
G10	4204.0	(27)	4.36	(43)	412993.8	(50)	30.94	(40)	1.044	427432.4	(50)	0.756	(49)	10773021.2	(50)	726213.7	(30)
G11	4338.6	(17)	2.25	(18)	121102.2	(22)	32.17	(43)	1.240	214677.1	(30)	0.927	(9)	5462649.9	(30)	462971.6	(11)
G12	3807.5	(50)	4.36	(45)	185664.4	(36)	35.41	(49)	1.173	243025.8	(37)	0.889	(23)	6170233.4	(37)	1104689.4	(49)
G13	4082.9	(32)	3.07	(31)	77893.9	(10)	30.65	(37)	1.116	119363.3	(9)	0.934	(7)	3083616.3	(9)	700540.9	(29)
G14	4125.2	(31)	2.96	(27)	128636.4	(25)	22.78	(7)	0.790	205546.2	(27)	0.831	(39)	5234743.0	(27)	764392.9	(32)
G15	4312.9	(18)	4.36	(44)	227109.4	(41)	33.83	(48)	1.268	334237.2	(46)	0.887	(25)	8446869.9	(46)	627132.7	(23)
G16	4603.5	(4)	1.00	(8)	97105.9	(16)	25.58	(15)	1.038	123124.0	(10)	0.913	(16)	3177483.1	(10)	309198.1	(5)
G17	3977.0	(40)	1.75	(16)	133607.6	(28)	30.57	(36)	1.062	161086.1	(22)	0.896	(19)	4125017.4	(22)	920589.7	(41)
G18	3886.6	(48)	3.23	(32)	175580.0	(34)	32.81	(45)	1.105	210170.7	(28)	0.881	(27)	5350169.0	(28)	1007323.5	(47)
G19	3891.3	(47)	2.99	(28)	59478.2	(7)	36.03	(50)	1.265	171170.7	(23)	0.956	(1)	4376730.7	(23)	995349.6	(46)
G20	4590.2	(5)	2.96	(26)	157607.9	(31)	30.70	(38)	1.241	250792.4	(38)	0.911	(17)	6364086.2	(38)	257782.7	(3)
G21	4649.8	(2)	4.23	(41)	307513.9	(47)	25.80	(18)	0.978	324231.1	(45)	0.781	(46)	8197117.6	(45)	285980.7	(4)
G22	4353.2	(14)	1.65	(14)	31618.3	(2)	22.60	(6)	0.879	76265.1	(3)	0.938	(6)	2007885.7	(3)	467646.8	(12)
G23	3972.0	(41)	3.24	(33)	110915.8	(21)	25.19	(13)	0.860	158762.2	(21)	0.867	(30)	4067012.4	(21)	878475.7	(40)
G24	4049.3	(34)	3.02	(29)	207088.2	(40)	27.79	(28)	0.943	231066.4	(32)	0.825	(41)	5871726.1	(32)	820461.1	(36)
G25	4082.7	(33)	1.66	(15)	50740.9	(4)	20.90	(4)	0.744	156822.4	(20)	0.893	(20)	4018597.3	(20)	787651.5	(33)
G26	3952.9	(44)	3.46	(37)	79693.4	(13)	20.14	(2)	0.671	236747.9	(35)	0.835	(38)	6013536.1	(35)	988835.1	(45)
G27	3981.0	(39)	1.13	(10)	36246.1	(3)	25.79	(17)	0.918	71053.5	(2)	0.939	(5)	1877803.5	(2)	863652.2	(37)
G28	4641.0	(3)	2.75	(23)	155939.5	(30)	24.01	(9)	0.953	180636.7	(24)	0.859	(32)	4613002.0	(24)	229524.6	(1)
G29	4005.8	(37)	3.90	(40)	198164.1	(39)	26.76	(24)	0.892	232707.9	(33)	0.814	(44)	5912697.8	(33)	865085.6	(38)
G30	4132.7	(29)	4.35	(42)	234532.3	(43)	27.99	(29)	0.964	255095.0	(39)	0.815	(43)	6471480.6	(39)	691236.9	(28)
G31	4472.0	(7)	0.56	(1)	95984.2	(15)	27.11	(26)	1.072	126642.9	(12)	0.919	(11)	3265314.7	(12)	377089.4	(8)
G32	4279.7	(21)	3.41	(35)	233395.4	(42)	31.71	(42)	1.165	285828.5	(43)	0.866	(31)	7238588.4	(43)	559128.4	(17)
G33	4447.4	(8)	3.46	(36)	256141.6	(45)	28.81	(34)	1.082	282457.7	(41)	0.837	(37)	7154453.7	(41)	434158.7	(10)
G34	3920.3	(46)	1.37	(13)	147104.4	(29)	25.89	(20)	0.857	194309.4	(25)	0.838	(36)	4954271.7	(25)	1017174.9	(48)
G35	3983.8	(38)	2.79	(24)	122729.9	(23)	28.60	(33)	0.991	146080.2	(17)	0.889	(22)	3750471.1	(17)	941825.9	(43)
G36	4217.8	(26)	2.83	(25)	70896.6	(8)	21.94	(5)	0.805	142891.3	(14)	0.888	(24)	3670875.5	(14)	652975.2	(24)
G37	4429.5	(10)	0.78	(5)	109648.2	(20)	25.04	(12)	0.967	134761.7	(13)	0.893	(21)	3467960.7	(13)	398269.4	(9)
G38	4220.1	(25)	0.86	(7)	51265.9	(5)	24.98	(11)	0.938	81994.2	(5)	0.930	(8)	2150884.6	(5)	573035.8	(18)
G39	3947.7	(45)	0.75	(4)	78760.2	(12)	28.47	(31)	0.994	103758.5	(7)	0.918	(12)	2694122.4	(7)	876194.8	(39)
G40	4413.5	(11)	3.07	(30)	132124.2	(27)	30.82	(39)	1.202	205034.3	(26)	0.917	(13)	5221965.3	(26)	358699.0	(7)
G41	4264.7	(22)	0.68	(2)	29995.7	(1)	26.34	(21)	1.012	57000.7	(1)	0.954	(2)	1527046.0	(1)	533847.2	(15)
G42	4127.3	(30)	0.85	(6)	74469.1	(9)	26.59	(23)	0.970	100704.7	(6)	0.917	(14)	2617899.1	(6)	690241.9	(27)
G43	4283.4	(20)	4.40	(46)	162127.3	(32)	20.64	(3)	0.715	283130.5	(42)	0.769	(48)	7171245.4	(42)	665085.5	(25)
G44	4446.6	(9)	4.43	(47)	185740.2	(37)	19.77	(1)	0.697	319073.2	(44)	0.738	(50)	8068376.3	(44)	535063.9	(16)
G45	4258.2	(23)	1.11	(9)	129714.0	(26)	26.84	(25)	0.992	152783.9	(19)	0.885	(26)	3917795.4	(19)	620562.6	(22)
G46	4478.7	(6)	1.25	(12)	51920.8	(6)	25.53	(14)	1.023	78533.0	(4)	0.940	(3)	2064493.4	(4)	356485.5	(6)
G47	4234.0	(24)	2.48	(20)	236314.0	(44)	28.54	(32)	1.015	255491.4	(40)	0.829	(40)	6481374.4	(40)	682614.6	(26)
G48	4148.5	(28)	2.66	(21)	123567.6	(24)	26.47	(22)	0.950	149818.7	(18)	0.880	(29)	3843783.1	(18)	744050.0	(31)
G49	4029.3	(36)	1.81	(17)	92134.1	(14)	30.24	(35)	1.079	124258.5	(11)	0.922	(10)	3205800.1	(11)	812152.3	(34)
G50	4340.0	(16)	3.80	(39)	181297.9	(35)	23.25	(8)	0.835	235417.1	(34)	0.805	(45)	5980320.2	(34)	522076.7	(14)

ASI=AMMI Stability Index; P_i =Superiority Index; W_i =Wricke's E; r_i^2 =Shukla; b_i = Regression Coefficient, R^2 = Determination coefficient, Deviation from regression (Sd_i^2).

characteristics than other genotypes. It is pertinent to mention that the outcomes derived from the stability variance parameter proposed by Shukla align with Wricke's E stability statistic, as both metrics yield an identical ranking for the genotypes under investigation. The evaluation also employed the superiority index (Pi) model, whereby genotypes exhibiting lower Pi values resulted as stable genotypes (Lin and Binns, 1988). Consequently, ranking G28, G1, G20, G21, G16, G46, G40, G31, G37, and G33 were in ascending order as the most stable genotypes. The comparison of different stability measures used to rank the best genotypes appears in Table 5.

Table 5. Ranking of top 10 wheat genotypes with respect to different stability measures.

Ranking	Mean	ASI	Sd_i^2	CV (%)	r_i^2	R^2	W_i	P_i
1	G1	G31	G41	G44	G41	G19	G41	G28
2	G21	G41	G22	G26	G27	G41	G27	G1
3	G28	G1	G27	G43	G22	G46	G22	G20
4	G16	G39	G25	G25	G46	G9	G46	G21
5	G20	G37	G38	G36	G38	G27	G38	G16
6	G46	G42	G46	G22	G42	G22	G42	G46
7	G31	G38	G19	G14	G39	G13	G39	G40
8	G33	G16	G36	G50	G4	G38	G4	G31
9	G44	G45	G42	G28	G13	G11	G13	G37
10	G37	G27	G13	G1	G16	G49	G16	G33

ASI=AMMI Stability Index; P_i =Superiority Index; W_i =Wricke's E; r_i^2 =Shukla; R^2 = Determination coefficient, Deviation from regression (Sd_i^2).

The regression analysis of an average genotype grain yield content on the environment index yielded regression coefficients b_i ranging from 0.67 to 1.30. As per the findings of Eberhart and Russell (1966), ideal genotypes would possess the highest performance across a broad spectrum of environments, exhibiting a regression coefficient of one and minimal deviation mean squares. Genotypes with b_i values greater than one would adapt to more-favorable environments, whereas those with bi values less than one would be adaptable to less–favorable conditions. Some of the genotypes, for instance, G1, G6, G16, G21, G28, G31, G33, G37, G38, G41, G45, G46, and G47, had mean grain yield above the overall mean, and the values of b_i were close to unity, suggesting the genotypes performed positively to the testing environments. Considering the second highest b_i and relatively small deviation mean square (Sd_i^2), G19 and G9 showed to be the most responsive and adapted to more favorable environments based on the mean grain yield. Meanwhile, using Sd_i^2, the G41, G22, G27, G25, G38, G46, G19, G36, G42, and G13 resulted as more stable wheat genotypes. Based on the CV, the top 10 stable wheat genotypes were G44, G26, G43, G25, G36, G22, G14, G50, G28, and G1.

Based on the average grain yield, which is the primary parameter for genotype selection, the genotypes G1, G21, G28, G16, G20, G46, G31, G33, G44, and G37 demonstrated the highest mean grain yield across environments in the order mentioned. Figure 3 presents multiple stability parameters in the form of eight bar graphs. In these graphs, the smaller bars indicate genotypes with higher stability, except for b_i and R^2. In the case of R^2, the higher bars showed more stable genotypes and in b_i, the bars nearer to one represented more stable genotypes.

AMMI Biplot analysis on wheat grain yield

AMMI analysis and G×E biplots are popular methods plant breeding researchers employ to assess the stability and adaptability of genotypes and to select genotypes that perform well across different environments. Several studies have used AMMI analysis and G×E biplots to choose stable genotypes in various crops, such as, cotton (Farias *et al*., 2016), chickpea (Erdemci, 2018), barley (Kendal and Dogan, 2015; Verma *et al*., 2016; Solonechnyi *et al*., 2018), okra (Alake and Ariyo, 2012), rice (Devi *et al*., 2020), peanut (de Oliveira and de Godoy, 2006), and rapeseed (Sara *et al*., 2019). These studies have identified durable genotypes that perform well across diverse surroundings and receive

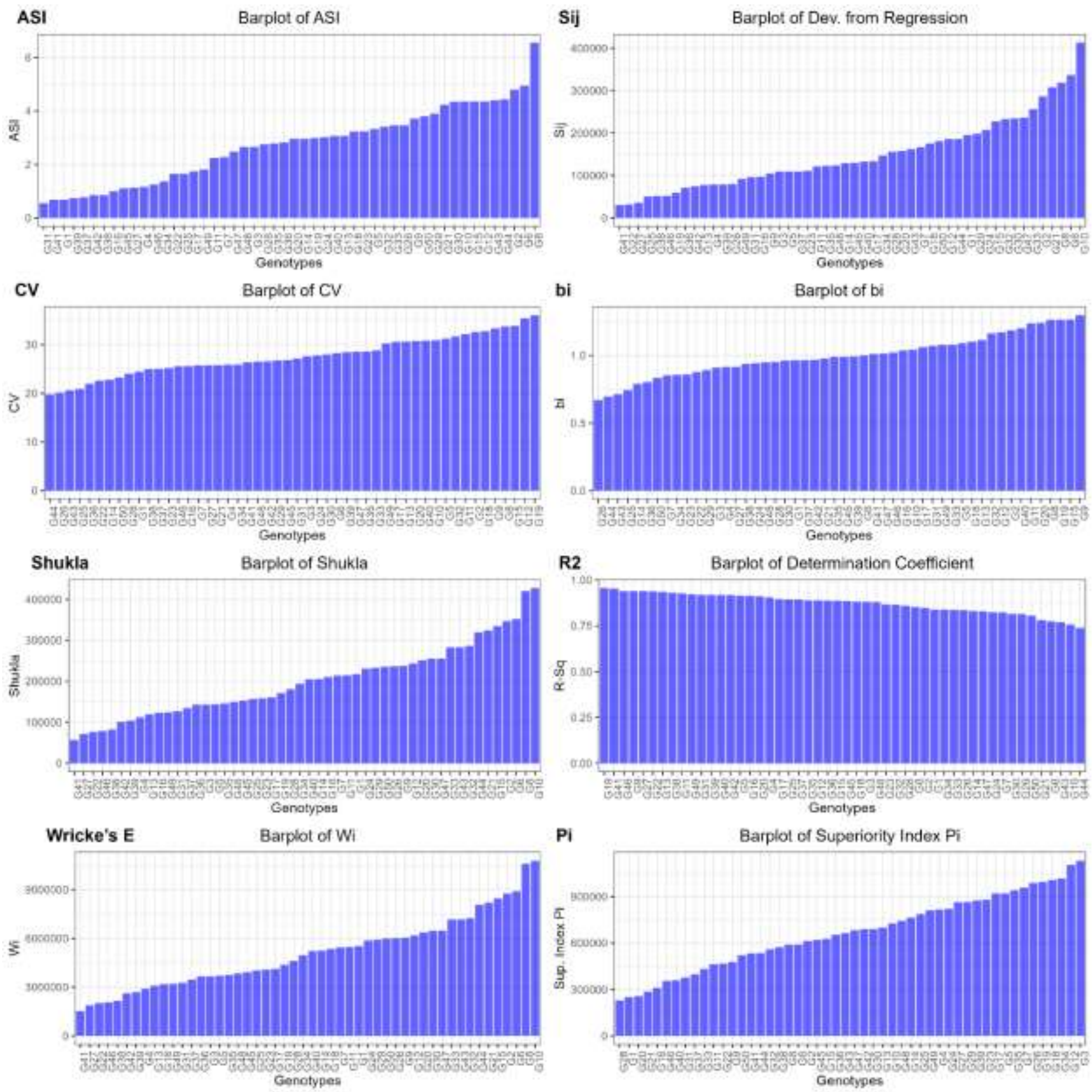

Figure 3. Bar graphs of various stability measures.

recommendations for cultivation in specific regions. These are effective techniques for selecting sturdy genotypes for high productivity and stability across varied locations.

The genotypes that exhibit proximity to the origin (x and y coordinates), classified as more stable, indicated their similarity in yield performance across different environments (Figure 4A). Notably, genotypes G38, G45, and G41, showing relatively close to zero, suggested their stability and wide adaptability. Conversely, genotypes G8, G6, and G30 occurred somewhat distant from the origin, indicating their instability and limited adaptability. Furthermore, the AMMI biplot analysis revealed that genotype G1 exhibited the highest average grain yield of 4676.2 and had an IPCA1 value fairly close to zero, signifying its stability and wide adaptability (Figure 4A). These genotypes are better suited to specific environments compared with other

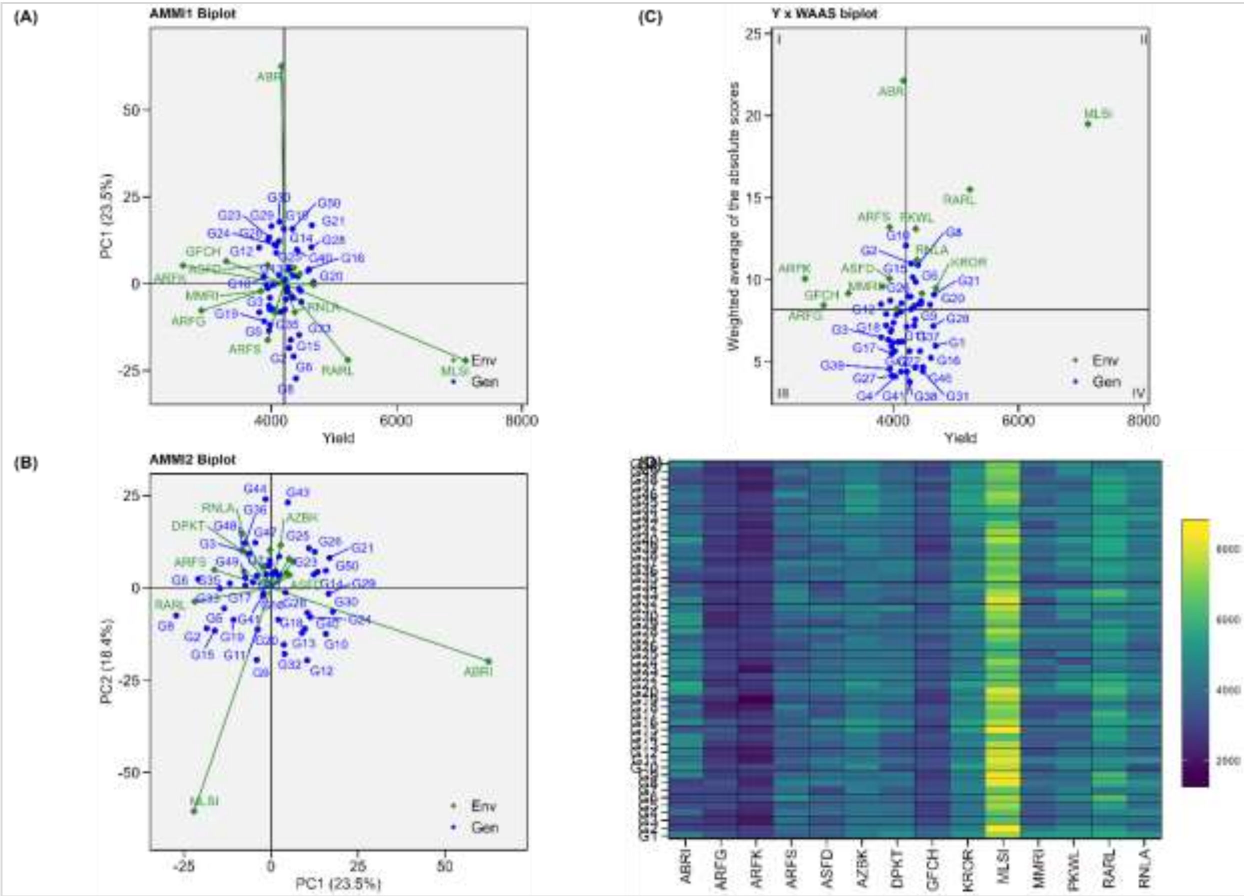

Figure 4. The AMMI1 and AMMI2 biplots indicating GE interaction for 50 wheat genotypes across 14 environments in the climate of Punjab (A and B). The biplot rendered based on grain yield × WAASB statistic for selection of high-yielding and stable wheat genotypes (C). The grain yield variation of investigated 50 wheat genotypes across 14 environments during 2021–2022 (D).

genotypes. Moreover, the AMMI1 biplot analysis showed that five locations, i.e., MLSI, RARL, RNLA, KROR, AZBK, and PKWL, exhibited average yields higher than the overall average. On the other hand, the remaining eight environments had average grain yields below the overall average, with ARFK and ARFG being the lowest-performing environments.

The AMMI 2 biplot, depicted in Figure 4B, shows the environmental scores. Based on this biplot, environments and genotypes close to the origin showed the lowest effects on genotype by environment interaction, whereas genotypes and surroundings with a larger distance from the source of the biplot showed the most influence in creating genotype by environment interaction.

Specifically, the environments ASFD, PKWL, GFCH, ARFK, KROR, MMRI, and ARFG display short spokes, suggesting their limited contribution to GEI. These environments have a relatively lower impact on the interaction between genotypes and the environment. On the other hand, the locations MLSI, ABRI, RNLA, DPKT, ARFS, RARL, and AZBK possess longer vectors than other environments. It indicates their high discriminating ability and significant contributions toward creating GEI. Overall, the AMMI 2 biplot provides insights into the relative importance of different environments in influencing GEI, with environs having longer vectors playing a more prominent role in shaping GEI, and those with shorter spokes have a lesser impact.

The genotypes G1, G4, G16, G17, G27, G31, G37, G38, G39, G41, G42, G45, G46, and G49 exhibited wide adaptability and stability across all environments. These genotypes have close grouping in the plot, demonstrating their similarity in yield performance across different ecosystems. In contrast, genotypes G2, G6, G8, G9, G10, G12, G15, G21, G25, G26, G30, G32, G36, G43, G44, and G47 displayed limited adaptability. These genotypes have wide dispersal in the plot and demonstrate varying mean yields or distinct response patterns across environments. Figure 4D illustrates the variability in productivity among 50 wheat genotypes in diverse locations. The MLSI environment exhibited a higher average yield for most genotypes, followed by RARL. Conversely, the environments ARFG and ARFK displayed lower average wheat yields for most genotypes.

CONCLUSIONS

The multi-environment wheat trials with 50 genotypes using alpha lattice design occurred at 31 different sites in the Punjab province, Pakistan. In conclusion, the presented study has provided important information on the stability of wheat genotypes across multiple environments using AMMI analysis and stability parameters. The findings suggest that the performance of genotypes varies significantly across ecologies, indicating the importance of evaluating genotypes in several locations. The selection of stable genotypes employed a combination of eight stability measures, such as, the AMMI Stability Index (ASI), Superiority Index, Wricke's E, Shukla, Regression Coefficient, Determination Coefficient, and Deviation from regression along with mean yield. The study concluded that the genotypes G41(HYT100-27), G27(TWS17042), G22(HYT100-100), and G1(HYT100-74) are notably the most stable genotypes, with the MLSI and RARL as the most desirable environments. These results may provide valuable insights for wheat breeders and growers in selecting stable genotypes for cultivation in different environments.

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