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Stability, Adaptability Analysis of Wheat Genotypes by AMMI with BLUP for Irrigated Late Sown Trials in North Western Plains Zone

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ABSTRACT

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Effects of the environment, GxE interaction, and genotypes were highly significant by AMMI analysis for wheat genotypes evaluated under irrigated late sown multi-location trials in the North-Western Plains zone of the country during 2018-19 and 2019-20. The preference order of genotypes had been altered with the utilization of more number of IPCA's in AMMI and WAASB based measures. Genotypes WH1124, PBW752, PBW771 had marked by adaptability and superiority indexes. Two significant PC has explained 83.6% of the total variation in the Biplot analysis and adaptability measures placed in a separate quadrant. A separate cluster of Superiority Indexes had also observed while considering various averages. This group maintained the right angles with a group of MASV & MASV1 measures. The second year of study had reflected that HD3059, UP3033, HD3334, and PBW771wheat genotypes were selected by adaptability and superiority indexes of genotypes. About 74% of the total variation accounted for by PC1 & PC2 in Biplot analysis. Adaptability measures expressed strong bondage and were placed in a different quadrant. The cluster of Superiority indexes of wheat genotypes seen in a different quadrant.

Introduction

Prime objective under multi location crop breeding trials is to understand the GxE interaction efficiently and ways to exploit it for selection of highly productive genotypes (Agahi *et al.*, 2020). Good number of statistical analytic tools has been developed to estimate GxE interactions (Ajay *et al.*, 2020). Mostly AMMI analysis is used as it considers fixed-effect of genotypes under statistical model (Bocianowski *et al.*, 2019). Recently it may be reasonable to consider genotypes,

environments, or both to be random effects in mixed model approach (Piepho *et al.*, 2008). Currently, the BLUP mixed model is the most adequate procedure for genetic evaluation in breeding, and it has become necessary for understanding the G x E interaction (Ashwini *et al.*, 2021). Methods convert measures of adaptability and stability along with yield into a single measure, such as of Annicchiarico (1992) and Lin and Binns (1988), were preferred in practical use as allowed a simpler interpretation, especially when number of genotypes were elevated at number of

locations (Kang 1993; Rao and Prabhakaran 2005; Farshadfar, 2008; Farshadfar *et al.*, 2011). Taking into account the benefits of AMMI and BLUP, a measure Superiority Index had been put forward for stability and adaptability of genotypes (Oliveto *et al.*, 2019). The present study dealt with the merits of the analysis of GxE interaction and yield stability through AMMI with BLUP techniques for wheat genotypes evaluated under multi locations trials in the North Western Plains zone of India.

Materials and Methods

The states of Punjab, Haryana, Delhi, Rajasthan (except Kota and Udaipur divisions), Western Uttar Pradesh (except Jhansi division and hilly areas), parts of Jammu and Kashmir (Jammu and Kathua districts) and parts of Himachal Pradesh (Paonta Valley and Una districts) categorised as the North Western Plains Zone of India. During cropping seasons of 2018-19 and 2019-20 ten promising wheat genotypes in advanced trials evaluated at fourteen major locations of the zone and nine genotypes at thirteen locations were evaluated respectively. Field trials were conducted at research centers in randomized complete block designs with

three replications. Recommended agronomic practices were followed to harvest good yield. Details of locations and genotype parentage were reflected in tables 1 & 2 for ready reference.

Stability measure as Weighted Average of Absolute Scores calculated as

WAASB = $\frac{\sum_{k=1}^p |IPCA_{ik} \times EP_k|}{\sum_{k=1}^p EP_k}$; WAASB_i was the weighted average of absolute scores of the *i*th genotype (or environment); $IPCA_{ik}$ the score of the *i*th genotype (or environment) in the *k*th IPCA, and EP_k was the amount of the variance explained by the *k*th IPCA. Superiority index allowed variable weights to yield and stability measure (WAASB) to select genotypes that combine high performance and stability as SI = $\frac{(rG_i \times \theta_Y) + (rW_i \times \theta_S)}{(\theta_Y + \theta_S)}$; where rG_i and rW_i were the rescaled values for yield and WAASB, respectively, for the *i*th genotype; G_i and W_i were the yield and the WAASB values for *i*th genotype. SI superiority index for the *i*th genotype that weighted between yield and stability, and θ_Y and θ_S were the weights for yield and stability assumed to be of order 65 and 35 respectively in this study,

Mohamadi and Amri, 2008	Geometric Adaptability Index	$GAI = \sqrt[n]{\prod_{k=1}^n \bar{X}_k}$
Zali <i>et al.</i> , 2012	Modified AMMI stability Value	$MASV = \sqrt{\sum_{n=1}^{N-1} \frac{SSIPC_n}{SSIPC_{n+1}} (PC_n)^2 + (PC_{n+1})^2}$
Ajay <i>et al.</i> , 2019	MASV1	$MASV1 = \sqrt{\sum_{n=1}^{N-1} \left(\frac{SSIPC_n}{SSIPC_{n+1}} PC_n \right)^2 + (PC_{n+1})^2}$
Resende and Durate, 2007	Relative performance of genotypic values across environments	$PRVG_{ij} = VG_{ij} / VG_i$
Resende and Durate, 2007	Harmonic mean of Relative performance of genotypic values	$MHPRG_i = \text{Number of environments} / \sum_{j=1}^k \frac{1}{PRVG_{ij}}$
Oliveto <i>et al.</i> , 2019	Superiority Index	$SI = \frac{(rG_i \times \theta_Y) + (rW_i \times \theta_S)}{(\theta_Y + \theta_S)}$

AMMISOFT version 1.0, available at <https://scs.cals.cornell.edu/people/hugh-gauch/> utilized for AMMI analysis of wheat genotypes evaluated under multi-location trials in the Peninsular Zone and further analysis carried out by SAS software version 9.3. Stability measures had been compared with recent analytic measures of adaptability calculated as the relative performance of genetic values (PRVG) and harmonic mean based measure of the relative performance of the genotypic values (MHPRVG) for the simultaneous analysis of stability, adaptability, and yield (Mendes *et al.*, 2012).

Results and Discussion

First-year of study (2018-19)

AMMI based stability measures permit to evaluate of the stability of genotypes after the reduction of the noise from the GxE interaction effects. Highly significant effects of the environment (E), GxE interaction, and genotypes (G) were observed (Table 3). Analysis observed the greater contribution of environments, GxE interactions, and genotypes to the total sum of squares (SS) as compared to the residual effects. Further SS attributable to GxE interactions was partitioned as attributed to GxE interactions Signal and GxE interactions Noise. AMMI analysis is appropriate for data sets where-in SS due to were of magnitude at least of due to additive genotype main effects (Gauch 2013). The SS for GxE interactions Signal was higher compared to genotype main effects, indicated appropriateness of AMMI analysis. Environment explained about 42.8% of the total sum of squares due to treatments. Moreover up to 80% contribution of environmental effects reported in various crops (Oyekunle *et al.*, 2017). Genotypes explained only 15.6% of the total sum of squares, whereas GxE interaction accounted

for 24.6% of treatment variations in yield. Further interaction was divided into four significant multiplicative terms explained 97 % and the remaining 2.8% was discarded residual.

Ranking of genotypes vis-à-vis number of IPCA's

The IPCA scores of genotypes in the AMMI analysis are an indication of stability or adaptability over environments. The greater the IPCA scores, the more specific adapted is a genotype to certain locations. The more the IPCA scores approximate to zero, the more stable or adapted the genotypes is overall the locations. The ranking of genotype as per absolute IPCA-1 scores were WH1124, PBW752 (Table 4). While for IPCA-2, genotypes DBW173, WH1021 would be of choice. Values of IPCA-3 favoured DBW173, WH1021 wheat genotypes. As per IPCA-4, HD3059, PBW752 genotypes would be of stable performance. Analytic measures of adaptability MASV and MASV1 consider all significant IPCAs of the analysis. Values of MASV1 identified genotypes WH1124, PBW771 would express stable yield whereas genotypes PBW771, WH1124 be of stable performance by MASV measure respectively (Ajay *et al.*, 2019).

To study how the ranks of genotype are altered with different numbers of IPCA used in the WAASB estimation, the genotype's ranks were obtained considering the WAASB estimated with 1, 2,...,4IPCA. When using only one IPCA, $WAASB = |IPCA1|$. The ranking was increasing; so, the genotype with the smallest WAASB value had the first-order rank. Preferences of genotypes had varied with increasing use of many IPCA as WH1124, PBW752 based on W1 whereas WH1124, HD3059 as per W2 values while WH1124, HD3059 by values of W3 (Table

5). Stability measure WAASB based on all significant IPCA's settled for WH1124, HD3059 genotypes for considered locations of the zone for stable high yield. The genotype ranking was altered by the extent to which IPCAs were included in the WAASB estimation. This reinforced the benefits of using the WAASB index since it captured the variations of all IPCAs to compute the stability (Olivoto *et al.*, 2019).

Stable productive genotypes by AMMI & BLUP tools

An average yield selected PBW771, PBW752, wheat genotypes (Table 6). This method is simple, but not fully exploiting all information contained in the dataset. A geometric mean is used to evaluate the adaptability of genotypes and genotypes with high GM will be desirable. Geometric mean observed PBW771, PBW752 were top-ranked genotypes. As proposed by Resende (2007), a method to rank genotypes considering the

yield and stability simultaneously is the harmonic mean of genetic values (HMGV). In the context of mixed models, the Harmonic Mean of Genotypic Values were calculated as genotypes with greater values would be recommended. Harmonic Mean of yield expressed higher values for PBW771, PBW752, genotypes. For stability analysis of the Harmonic Mean of Relative Performance of Genotypic Values (HMRPGV) method, the genotypes can be simultaneously sorted by genotypic values (yield) and stability using the harmonic means of the yield so that the smaller the standard deviation of genotypic performance among the locations. Values of HMRPGV ranked PBW771, PBW752 the genotypes' performance among the locations. When considering the yield and adaptability simultaneously, the recommended approach is the relative performance of genetic values (RPGV) over crop years. Relative Performance of Genotypic Values had settled for PBW771, PBW752 wheat genotypes.

Table.1 Details of locations and parentage of evaluated wheat genotypes (2018-19)

Code	Genotype	Parentage	Location	Latitude	Longitude	Mean sea level
G 1	PBW 752	(PBW621/4/PBW343/YR10/6*AVOCET/3/3*PBW343/5/PBW621)	Delhi	28°4'N	77°13'E	228
G 2	DBW 173	(KAUZ/AA//KAUZ//PBW602)	Bawal	28°10'N	76°50'E	266
G 3	WH 1021	(NYOT95/SONAK)	Hisar	29°10'N	75°46'E	229
G 4	HD 3059	(KAUZ//ALTAR84/AOS/3/MILAN/KAUZ/4/HUITES)	Karnal	29°43'N	70°58'E	245
G 5	WH 1124	(MUNIA/CHTO//AMSEL)	Rohtak	28°53'N	76°35'E	222.5
G 6	PBW 771	(PBW550/YR15/6*AVOCET/3/2*PBW550)	Shikohpur	28°36'N	76°98'E	259
			Jammu	32°40'N	74°54'E	356
			Ludhiana	30°54'N	75°48'E	247
			Kapurthala	31°22'N	75°22'E	229
			Gurdaspur	30°02'N	75°24'E	265
			Bathinda	30°09'N	74°55'E	211
			Faridkot	30°40'N	74°04'E	200
			Durgapura	26°51'N	75°47'E	390
			Tabiji	26°35'N	74°61'E	508
			Sriganganagar	29°66'N	75°53'E	175.6
			Alwar	27°7'N	76°1'E	271
			Nagina	29°28'N	78°32'E	245
			Bulandshahr	28°40'N	77°84'E	195
			Ujhani	28°06'N	79°34'E	
			Pantnagar	29°02'N	79°48'E	243.8
			Kashipur	29°21'N	78°96'E	218

Table.2 Details of locations and parentage of evaluated wheat genotypes (2019-20)

Code	Genotype	Parentage	Location	Latitude	Longitude	Mean sea level
G 1	HD3334	(DBW 50/WR2502)	Delhi	28°4'N	77°13'E	228
G 2	HD3059	(KAUZ//ALTAR84/AOS/3/MILAN/KAUZ/4/HUITES)	Hisar	29° 10' N	75° 46'E	229
G 3	HD3332	(PFAU/SERI.1B)	Karnal	29° 43' N	70° 58'E	245
G 4	DBW173	(KAUZ/AA//KAUZ//PBW602)	Rohtak	28° 53' N	76° 35'E	222.5
G 5	WH1021	(NYOT95/SONAK)	Shikohpur	28° 36' N	76° 98'E	259
G 6	PBW811	(BECARD/2*FRNCLN)	Ludhiana	30° 54' N	75° 48'E	247
G 7	DBW291	(KRL236/DBW16)	Kapurthala	31° 22' N	75° 22'E	229
G 8	WH1264	(P12256/P12332//WH1142)	Gurdaspur	30° 02' N	75° 24'E	265
G 9	PBW812	(BWL 0762/PBW621//HD 3086)	Bathinda	30° 09' N	74° 55'E	211
G 10	JKW261	(ISENGRAIN/KBIRD//MUNAL#1)	Faridkot	30° 40' N	74° 04'E	200
G 11	DBW290	(QUAIU#1/5/KIRITATI/4/2*SERI.1B*2/3/KAUZ*2/BO W//KAUZ/6/BECARD(35th ESWYT 140)	Durgapura	26°51'N	75° 47'E	390
G 12	PBW771	(PBW550//YR15/6*AVOCET/3/2*PBW550)	Srigangana gar	29° 66'N	75° 53'E	175.6
G 13	PBW813	(KRICHAUFF/4/2*BW9250*3//Yr10/6*Avocet/3/BW 9250*3//Yr 15/6*Avocet	Nagina	29° 28' N	78° 32'E	245
G 14	HD3331	(31stESWYT-135/3/HD2329/WR544//PBW343/NW3041)	Bulandsha hr	28° 40'N	77° 84'E	195
G 15	HD3298	(CL1449/PBW343//CL882/HD2009)	Ujhani	28° 06' N	79° 34'E	
G 16	WH1124	(MUNIA/CHTO//AMSEL)	Modipura m	29°05' N	77° 70'E	226
G 17	UP3033	(NIAW 1544/UP2763)	Pantnagar	29° 02'N	79° 48'E	243.8
			Kashipur	29° 21'N	78° 96'E	218

Table.3 AMMI analysis of wheat genotypes for irrigated late sown multi location trials during 2018-19& 2019-20

Source	Degree of freedom 18-19	Degree of freedom 19-20	Mean Sum of Squares 18-19	Mean Sum of Squares 19-20	Level of significance 18-19	Level of significance 19-20
Treatments	125	305	250.5698	214.92	.0000000 ***	.0000000 ***
Genotypes (G)	5	16	1178.312	556.53	.0000000 ***	.0000000 ***
Environments (E)	20	17	808.3152	1744.59	.0000000 ***	.0000000 ***
Interactions GxE	100	272	92.63365	99.22	.0000000 ***	.0000000 ***
IPC1	24	32	206.8943	269.40	.0000000 ***	.0000000 ***
IPC2	22	30	86.01315	158.63	.0000000 ***	.0000000 ***
IPC3	20	28	63.69132	111.87	.0000001 ***	.0000000 ***
IPC4	18	26	47.51667	99.02	.0014130 **	.0000000 ***
IPC5		24		98.97		.0000000 ***
IPC6		22		59.39		.0000000 ***
IPC7		20		57.93		.0000000 ***
Residual	16	90	17.28031	34.01	0.4364813	.0000000 ***
Error	378	918	16.97693	11.07		
Total	503	1223	75.02685	61.91		

Table.4 Modified AMMI stability values as per significant IPCA's 2018-19

Genotype	IPCA1	IPCA2	IPCA3	IPCA4	MASV1	MASV	W1	W2	W3	WAASB	R _{IPCA1}	R _{MASV1}	R _{MASV}	R _{W1}	R _{W2}	R _{W3}	R _{WAASB}
PBW 752	-0.344	-3.991	-0.673	-0.210	7.307	6.408	0.344	1.415	1.282	1.156	2	4	5	2	4	3	3
DBW 173	2.945	-0.239	0.030	-0.842	7.786	4.859	2.945	2.150	1.772	1.662	5	5	3	5	5	5	5
WH 1021	-4.868	0.570	0.208	0.374	12.826	7.953	4.868	3.606	2.999	2.691	6	6	6	6	6	6	6
HD 3059	0.724	0.630	3.513	-0.203	6.682	5.756	0.724	0.696	1.200	1.082	3	3	4	3	2	2	2
WH 1124	0.055	1.992	-1.903	-2.138	5.383	4.843	0.055	0.624	0.852	1.003	1	1	2	1	1	1	1
PBW 771	1.488	1.038	-1.175	3.019	5.680	4.587	1.488	1.356	1.324	1.523	4	2	1	4	3	4	4

R_{W1}, R_{W2}, R_{W3}, R_{W4}, R_{W5}, R_{W6}, R_{WAASB} = Rank of genotypes as per number of IPCA's in WAASB values

Table.5 Superiority index and analytic adaptability measures based on BLUP's of genotypes 2018-19

Genotype	AMu	Rk	SI au	Rk	GMu	Rk	SI gu	Rk	HMu	Rk	SI hu	Rk	MHRPGVu	Rk	RPGVu	Rk
PBW 752	49.64	2	88.71	3	49.24	2	89.57	2	48.84	2	90.70	2	1.040	2	1.047	2
DBW 173	48.00	4	66.92	4	47.38	4	66.41	4	46.73	4	65.90	5	1.001	4	1.007	4
WH 1021	41.34	6	0.00	6	40.74	6	0.00	6	40.16	6	0.00	6	0.854	6	0.873	6
HD 3059	45.89	5	64.54	5	45.47	5	65.45	5	45.04	5	66.42	4	0.961	5	0.966	5
WH 1124	49.50	3	90.89	1	48.96	3	90.81	1	48.41	3	90.95	1	1.036	3	1.039	3
PBW 771	50.83	1	89.22	2	50.31	1	89.22	3	49.74	1	89.22	3	1.064	1	1.069	1

AMu, GMu, HMu = Arithmetic, Geometric, Harmonic Mean for BLUP values; SI au, SI gu, SI hu = Superiority index as per Arithmetic, Geometric, Harmonic Mean; RPGVu, MHRPGVu = Relative performance and Harmonic mean of Relative Performance as per BLUP of genotypes; Rk = Rank of genotypes

Table.6 Loadings of BLUP based stability measures as per two significant PC's (2018-19)

Measure	PC1	PC2
IPCA1	0.2156	-0.0297
IPCA2	-0.0247	-0.1598
IPCA3	-0.0852	-0.5192
IPCA4	-0.0112	0.4375
MASV1	-0.2668	0.1137
MASV	-0.2320	-0.0195
W1	-0.2409	0.2502
W2	-0.2390	0.3333
W3	-0.2603	0.2209
WAASB	-0.2459	0.3098
AMu	0.2647	0.1977
SI au	0.2740	0.0190
GMu	0.2655	0.1891
SI gu	0.2738	0.0135
HMu	0.2662	0.1797
SI hu	0.2736	0.0075
RPGVu	0.2640	0.2040
MHRPGVu	0.2667	0.1775
83.68	73.62	10.06

Table.7 Modified AMMI stability values as per significant IPCA's 2019-20

Genotype	IPCA1	IPCA2	IPCA3	IPCA4	IPCA5	IPCA6	IPCA7	MASV1	MASV	R _{IPCA1}	R _{MASV1}	R _{MASV}
HD3334	-0.225	-0.603	-1.448	1.331	-1.072	0.276	0.191	3.947	3.575	3	2	3
HD3059	0.292	-1.083	-0.068	0.671	-2.036	0.040	-2.093	5.233	4.486	4	9	9
HD3332	0.094	-1.551	0.973	1.842	0.688	-0.361	-0.720	4.535	4.168	2	5	7
DBW173	2.254	-0.578	-3.305	-0.292	-0.336	0.875	1.146	6.971	6.140	14	14	14
WH1021	-4.025	-1.290	-1.221	-2.027	-0.680	-1.456	0.980	8.891	7.223	17	17	17
PBW811	-1.682	0.314	0.169	1.532	-0.139	1.985	0.199	4.885	4.337	13	7	8
DBW291	0.832	1.175	0.099	-0.157	-0.361	0.528	-0.013	2.848	2.401	7	1	1
WH1264	-0.306	-1.627	0.044	1.406	0.079	-1.113	-0.283	4.035	3.700	5	4	4
PBW812	1.228	-1.052	0.245	-1.182	0.628	-0.675	-1.120	3.973	3.450	12	3	2
JKW261	3.056	1.616	0.763	-1.295	-1.347	-1.565	-0.272	7.604	6.219	16	16	16
DBW290	0.962	-1.073	1.007	-2.158	0.215	2.306	-0.097	5.637	5.289	10	10	12
PBW771	0.958	-0.523	1.886	0.128	1.230	0.032	1.636	4.687	4.149	9	6	5
PBW813	0.882	-1.351	0.027	0.070	1.826	-0.683	0.923	4.987	4.155	8	8	6
HD3331	0.031	2.671	0.488	1.167	-1.559	-0.431	1.482	6.342	5.547	1	13	13
HD3298	-1.125	2.480	-1.709	-0.696	1.906	0.220	-1.594	7.147	6.177	11	15	15
WH1124	-2.464	0.492	2.027	-1.053	-0.979	0.556	-0.085	6.178	5.138	15	12	11
UP3033	-0.762	1.983	0.024	0.714	1.936	-0.535	-0.279	5.734	4.824	6	11	10

Table.8 Weighted average of absolute scores and ranks of wheat genotypes 2019-20

Genotype	W1	W2	W3	W4	W5	W6	WAASB	R _{W1}	R _{W2}	R _{W3}	R _{W4}	R _{W5}	R _{W6}	R _{WAASB}
HD3334	0.225	0.365	0.589	0.704	0.754	0.718	0.682	3	1	2	3	4	4	3
HD3059	0.292	0.585	0.478	0.508	0.713	0.663	0.760	4	2	1	1	3	2	4
HD3332	0.094	0.634	0.704	0.881	0.855	0.818	0.811	2	3	4	6	5	5	5
DBW173	2.254	1.633	1.979	1.718	1.532	1.484	1.461	14	14	15	15	13	14	14
WH1021	4.025	3.011	2.640	2.545	2.295	2.232	2.148	17	17	17	17	17	17	17
PBW811	1.682	1.175	0.967	1.054	0.931	1.010	0.955	13	11	8	11	8	10	9
DBW291	0.832	0.959	0.781	0.684	0.641	0.632	0.591	7	6	5	2	1	1	1
WH1264	0.306	0.796	0.640	0.759	0.668	0.701	0.672	5	4	3	5	2	3	2
PBW812	1.228	1.163	0.973	1.005	0.955	0.934	0.946	12	10	10	10	9	8	8
JKW261	3.056	2.522	2.157	2.024	1.933	1.906	1.795	16	16	16	16	16	16	16
DBW290	0.962	1.003	1.004	1.183	1.053	1.146	1.075	10	7	11	12	11	12	12
PBW771	0.958	0.797	1.023	0.884	0.931	0.864	0.916	9	5	12	7	7	7	7
PBW813	0.882	1.056	0.843	0.723	0.871	0.857	0.861	8	9	6	4	6	6	6
HD3331	0.031	1.009	0.901	0.942	1.025	0.981	1.015	1	8	7	9	10	9	11
HD3298	1.125	1.627	1.644	1.497	1.552	1.453	1.462	11	13	13	13	14	13	15
WH1124	2.464	1.733	1.794	1.679	1.586	1.509	1.412	15	15	14	14	15	15	13
UP3033	0.762	1.214	0.968	0.928	1.063	1.024	0.974	6	12	9	8	12	11	10

Table.9 Superiority index and analytic adaptability measures based on BLUP's of genotypes 2019-20

Genotype	AMu	Rk	SI au	Rk	GMu	Rk	SI gu	Rk	HMu	Rk	SI hu	Rk	MHRPGVu	Rk	RPGVu	Rk
HD3334	48.27	9	86.52	3	47.84	9	86.76	3	47.41	9	86.97	3	1.011	9	1.016	9
HD3059	49.68	2	93.68	1	49.19	2	92.91	1	48.72	3	92.34	1	1.034	3	1.049	2
HD3332	48.55	8	85.39	5	48.16	8	85.71	5	47.77	8	86.01	5	1.016	8	1.024	8
DBW173	49.43	3	76.37	9	49.15	3	76.88	9	48.84	2	77.24	9	1.037	2	1.044	3
WH1021	49.13	4	58.97	14	48.75	4	59.11	14	48.37	4	59.24	14	1.029	4	1.036	5
PBW811	47.75	10	77.09	8	47.34	10	77.69	8	46.92	11	78.20	8	0.998	11	1.007	10
DBW291	47.63	12	84.51	6	47.24	12	85.28	6	46.84	12	85.93	6	0.995	12	1.006	11
WH1264	45.13	15	66.87	12	44.56	15	67.83	12	44.00	15	68.69	12	0.938	15	0.950	15
PBW812	46.30	13	68.13	11	45.92	13	69.59	11	45.53	13	70.83	11	0.969	13	0.976	13
JKW261	46.25	14	48.73	16	45.70	14	49.23	16	45.17	14	49.81	16	0.964	14	0.971	14
DBW290	44.65	16	54.76	15	44.06	16	55.86	15	43.49	16	56.88	15	0.930	16	0.936	16
PBW771	49.07	5	86.34	4	48.68	5	86.38	4	48.27	5	86.40	4	1.024	6	1.038	4
PBW813	39.80	17	28.92	17	38.63	17	28.92	17	37.44	17	28.92	17	0.801	17	0.834	17
HD3331	48.70	7	81.76	7	48.28	7	81.83	7	47.84	7	81.81	7	1.019	7	1.026	7
HD3298	47.68	11	65.25	13	47.30	11	66.07	13	46.93	10	66.81	13	0.999	10	1.004	12
WH1124	48.97	6	74.50	10	48.48	6	74.09	10	47.99	6	73.68	10	1.024	5	1.029	6
UP3033	50.08	1	91.39	2	49.76	1	91.39	2	49.43	1	91.39	2	1.051	1	1.056	1

Table.10 Loadings of BLUP based stability measures as per two significant PC's (2018-19)

Measure	PC1	PC2
IPCA1	-0.0750	0.1120
IPCA2	0.0477	-0.1184
IPCA3	-0.0744	0.0515
IPCA4	-0.2293	-0.0677
IPCA5	-0.0314	0.1262
IPCA6	-0.0849	-0.0325
IPCA7	0.0658	0.0260
MASV1	0.2898	-0.0689
MASV	0.2774	-0.0710
W1	0.2906	-0.0285
W2	0.3097	-0.0227
W3	0.3102	-0.0574
W4	0.3108	-0.0588
W5	0.3140	-0.0622
W6	0.3163	-0.0475
WAASB	0.3157	-0.0543
AMu	0.0068	-0.3596
SI au	-0.1706	-0.3044
GMu	0.0068	-0.3596
SI gu	-0.1721	-0.3033
HMu	0.0071	-0.3592
SI hu	-0.1733	-0.3021
RPGVu	0.0024	-0.3592
MHRPGVu	0.0100	-0.3593
72.60	46.56	32.04

Fig.1 Biplot graphical analysis of stability and superiority indexes of genotypes 2018-19

stable performance. WH1264, PBW811, DBW290 genotypes pointed by IPCA-5 measure. Genotypes PBW771, HD3059, HD3298 identified by absolute values of IPCA-6. Lastly, IPCA-7 settled for DBW291, WH1124, DBW290 genotypes for the studied locations of the zone. Analytic measures of adaptability MASV and MASV1 consider all significant IPCAs of the analysis. Values of MASV1 identified genotypes DBW291, HD3334, and PBW812 would express stable yield whereas genotypes DBW291, PBW812 & HD3334 be of stable performance by MASV measure respectively.

Genotype preferences vary as HD3331, HD3332, HD3334, HD3059 based on W1 whereas HD3334, HD3059, HD3332, WH1264 as per W2 values while HD3059, HD3334, WH1264, HD3332 by values of W3 (Table 9). Genotypes HD3059, DBW291, HD3334, PBW813 were pointed by W4; W5 favoured DBW291, WH1264, HD3059, HD3334, and lastly by W6 measure DBW291, HD3059, WH1264, HD3059 genotypes would be of choice. Stability measure WAASB based on all significant IPCA's settled for DBW291 WH1264 HD3334 HD3059 genotypes for considered locations of the zone for stable high yield. It is observed that the genotype ranking was altered by the extent to which IPCAs are included in the WAASB estimation. This reinforces the benefits of using the WAASB index since it captures the variations of all IPCAs to compute the stability.

Stable Productive genotypes by AMMI & BLUP tools

Mean yield selected UP3033, HD3059, DBW173, WH1021 wheat genotypes (Table 10). Geometric mean observed UP3033, HD3059, DBW173, WH1021, were top-ranked genotypes. Harmonic Mean of yield expressed higher values for UP3033,

DBW173, HD3059, WH1021 genotypes. Values of HMRPGV ranked UP3033 DBW173, HD3059, WH1021 the performance of the genotypes among the locations. Relative Performance of Genotypic Values had settled for UP3033, HD3059, DBW173, PBW771 wheat genotypes.

While assigning 65 and 35 weights to average yield (AM) and stability, the Superiority index pointed out HD3059, UP3033, HD3334, and PBW771 genotypes would maintain high yield and stable performance. SI measure considered GM and stability, selected HD3059, UP3033, HD3334, and PBW771 genotypes. Values of SI, using HM and stability, favoured the same set of wheat genotypes HD3059, UP3033, HD3334, and PBW771. Analytic measures of adaptability RPGV pointed out UP3033, DBW173, PBW771, and MHRPGV settled for UP3033, DBW173, HD3059, and WH1021 as more adaptable genotypes.

Biplot analysis of measures

The relationships among different measures of wheat genotypes were expressed in a biplot of PC1 and PC2 (Table 11). The first two PCs accounted for 72.6% (PC1 = 46.5% and PC2 = 32%) of the total variation in the original variables. Stability measures as per utilization of the number of Interaction Principal Components were clustered with AMMI based MASV & MASV1 measures (Figure 2). Arithmetic, geometric, harmonic means along with corresponding analytic measures of adaptability were clustered together in one group. Moreover, the measures of this group expressed nearly right angle to MASV, MASV1 & stability indexes. Superiority indexes were placed together in one group in a different quadrant. The performance of genotypes as per SI measures will not corroborate with genotypes behaviour based on stability, MASV & MASV1 measures.

Superiority Index measures considering 65/35 ratio to yield of genotypes by arithmetic, geometric, harmonic means, and stability by WAASB measures had maintained the distances from measures based on AMMI or WAASB criterion.

In conclusion the G×E interaction study in multi-environment trials had been carried out by a well-established AMMI model. The simultaneous consideration of stability measures and yield would be more appropriate to recommend high-yielding stable wheat genotypes. In the present study, the main advantages of AMMI and BLUP had been combined to increase the reliability of multi-locations trials analysis. An additional advantage was provided by Superiority Indexes to assign variable weights to the yield and stability performance. Depending upon the goal of crop breeding trials, the researchers may prioritize the productivity of a genotype rather than its stability (and vice-versa). The stability index of genotype performance has the potential to provide reliable estimates of stability in future studies along with a joint interpretation of performance and stability in biplots while considering the number of significant IPCA's.

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Conflict of interest

The authors declared no conflict of interests.

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