ISSN 0258-7122 (Print), 2408-8293 (Online)
Bangladesh J. Agril. Res. 48(3): 359-370, September 2023

GENOTYPE-ENVIRONMENT INTERACTION OF MAIZE HYBRIDS THROUGH AMMI MODEL AT DIFFERENT LOCATION IN BANGLADESH

A. N. M. S. KARIM[1], Z. A. TALUKDER[2], R. SULTANA[3]
M. K. ALAM[4] AND M. Q. I. MATIN[5]

Abstract

Eighteen promising single crosses of maize and two check varieties (BHM-9 and 981) were assessed for genotype environment interaction (GEI) and stability for the selection of promising one(s) in three agro-ecological zones of Bangladesh. The AMMI (additive main effects and multiplicative interaction) model was used to analyze the GEI over three locations to select desired hybrid having higher yield and other potential attributes. Both genotypes (G) and environment (E) exhibited significant variation for all the characters studied. The environment of Gazipur and Ishwardi were poor but Dinajpur was favorable for the tested maize hybrids. Considering the mean, bi and S^2di value, all the genotypes showed differential response of adaptability under different environmental conditions. Hybrids E12 (BIL28 × BIL96) and E15 (BIL95 × BIL79) showed the higher yield as well as stable across locations regarding response and stability parameters.

Keywords: Stability, maize hybrids, heterosis, different locations

Introduction

Maize is one of the most important food grains in the world. It is the highest yielding grain crop having various uses. A great combination of high market demand with relatively low production cost, ready market and high yield has generated great interest among the farmers in maize cultivation. Day by day it is gaining popularity in the country due to vast demand, particularly for poultry industry. In 2020-21, maize was cultivated in 11.86 lac acre of land in Bangladesh and production was 41.16 lac mtons (BBS, 2022).

Multi-environment yield trials are commonly conducted to study the stability of the superior genotypes before releasing a variety. (Genotype × environment Interaction) is usually used when different genotypes are tested in a number of environments. The large GEI variation usually impairs the accuracy of yield estimation and reduces the relationship between genotypic and phenotypic values (Nachit *et al*., 1992). Numerous methods for multi-environment trials data have been developed to reveal the patterns of G×E interaction (Yamada, 1962), joint

---

[1]Senior Scientific Officer, Plant Genetic Resources Centre, Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh, [2]Senior Scientific Officer, Plant Breeding Division, BARI, Gazipur, Bangladesh, [3] Chief Scientific Officer, Plant Breeding Division, BARI, Gazipur, Bangladesh, [4]Scientific Officer, Plant Breeding Division, BARI, Gazipur, Bangladesh, [5]Senior Scientific Officer, Oil Seed Research Centre, BARI, Gazipur, Bangladesh.

regression (Finlay and Wilkinson, 1963; Eberhart and Russel, 1966) and currently AMMI ((additive main-effects and multiplicative interaction) (Gauch, 1992) and GGE biplot (genotype main effect plus genotype by environment interaction). AMMI model combines the analysis of variance of genotypes and the environment main effects with principal component analysis of the GEI into a unified approach (Gauch and Zobel, 1996). Crossa *et al.*, (1990) indicated that the AMMI model can be used to analyze the GEI to identify the superior hybrid maize genotypes and to select the best test environments for hybrid maize genotype evaluation. More precise GEI estimates can be obtained with the AMMI model which makes easier to interpret the results (Durate and Vencovsky, 1999). The objective of this study was to use the AMMI analysis model to assess the stability of some maize hybrids and verify the influence of a sample of environments at different locations of Bangladesh (Gazipur, Dinajpur and Ishwardi) in the productive performance of these hybrids.

Materials and Method

The experiment was conducted at three locations namely Gazipur, Dinajpur and Ishurdi during rabi 2017-18. Eighteen hybrids viz., E1 (CML551 × CLO2450), E2 (CLG1831 × CML223), E3 (BIL121 × BIL95), E4 (CML451 × CML285), E5 (CML429 × CML170), E6 (BIL153 × BIL95), E7 (CML191 × CML162), E8 (CML491 × CML502), E9 (BIL72 × BIL95), E10 (CML491 × CML502), E11 (CML431 × CML451), E12 (BIL28 × BIL96), E13 (CML285 × CML429), E14 (CML551× CML431), E15 (BIL95 × BIL79), E16 (CML170 × CML192), E17 (CML154 × CML502), E18 (BIL72 × BIL28) and two check varieties BHM-9 and 981 were evaluated in this study. The experiment was laid out in alpha lattice design with 2 replications. Seeds of each entry were sown in two rows, 4m long plots with 60 cm and 25 cm spacing between rows and hills, respectively. Seeds were sown at Gazipur on 27 November, Dinajpur on 23 November and Ishurdi on 12 December, 2017. One healthy seedling per hill was kept after thinning. Fertilizers were applied @ 250, 55, 110 40, 5 and 1.5 kg/ha of N, P, K, S, Zn and B respectively (FRG, 2018). Two border rows at both end of each replication was used for minimize the border effect. Data on days to pollen shedding, days to silking was recorded on whole plot basis. Ten randomly selected plants were used for recording observations on plant and ear height. All the plants in two rows were considered for plot yield and converted to t/ha.

The analysis of variance (ANOVA) was used and the GE interaction was estimated by the AMMI model (Zobel et al., 1988). In this procedure, the contribution of each genotype and each environment to the GE interaction is assessed by use of the biplot graph display in which yield means are plotted against the scores of the first principal component of the interaction (IPCA1). The computational program for AMMI analyses was developed by Duarte and Vencovsky (1999). The stability parameters, regression coefficient (bi) and deviation from regression (S^2di) were estimated according to Eberhart and Russel (1966). Significance of differences among bi value and unity was tested by t-test while between S^2di and zero by F-test. All the data were processed and analyzed using Crop Stat and PBTools (1.2) program.

Results and Discussion

Results of combined analysis of variance for five characters of twenty hybrids at three environments are presented in Table 1. The mean sum of squares for the genotypes were highly significant for all the traits which revealed the presence of genetic variability in the studied materials. Environments mean sum of squares were highly significant for all of the characters. The highly significant effects of environment indicated high differential genotypic response across the different environments. The variation in soil structure and moisture across the environments were considered as a major underlying causal factor for the G×E interaction. Environment relative magnitude was much higher than genotypic effect, suggesting that performance of each genotype was influenced more by environmental factors. Stability analysis for days to pollen shedding, days to silking, plant height, ear height and yields were presented in Table 2-6.

Table 1. Full joint analysis of variance including the partitioning of the G×E interaction of maize hybrids over three locations during 2017-18

Source of variation	Df	Mean sum of squares				
		Days to pollen shedding	Days to silking	Plant height (cm)	Ear height (cm)	Grain yield (t/ha)
Genotypes (G)	19	8.58**	8.85**	273.75**	189.92**	2.07**
Environment (E)	2	1312.18**	1350.24**	8076.71**	5302.88**	10.19**
Interaction G × E	38	4.00	3.75	137.53	108.90	1.51
AMMI Component 1	20	4.96**	4.80**	180.52**	126.34**	1.62**
AMMI Component 2	18	2.93**	2.58**	89.76**	89.52**	1.38*
G×E (Linear)	19	4.78**	2.86**	181.69**	127.51**	1.44**
Pool deviation	19	4.78	4.64	93.37	90.29	1.58
Pooled error	78	6.29	6.32	342.71	260.62	1.88

*P<0.05, **P<0.01.

Days to pollen shedding along with the value of phenotypic index (Pi,) regression coefficient (bi), deviation from regression (S^2di) are presented in Table 2. The genotypic mean for pollen shedding ranged from 94 to 99 days (BHM-9). Positive and negative Pi index observed in ten hybrids each. The hybrids which showed negative Pi index represent earliness. Talukder et al., (2016) found positive and negative Pi in their studied materials of maize hybrids. The hybrids E13, E14 and E5 exhibited comparatively a higher value for days to pollen shedding and E9 and E6 were for earliness. The bi and S^2di values for days to pollen shedding ranged from 0.73 to 1.28 and 0.06 to 17.96, respectively. Negative Pi index, non-significant regression coefficient (bi) and deviation from regression (S^2di), indicating the stability of these genotypes over all the environments with earliness.

Table 2. Stability analysis for days to 50% pollen shedding of maize hybrids over three environments

Genotype	Locations			Overall mean	Pi	bi	S^2di
	Gazipur	Dinajpur	Ishwardi				
E1	90	108	96	98	0.78	1.12	0.4
E2	92	104	97	97	0.45	0.73	1.84
E3	91	108	98	99	-0.21	1.05	1.66
E4	92	105	98	98	1.11	0.79	3.61
E5	92	106	99	99	1.95	0.87	5.38
E6	87	102	93	94	-2.88	0.93	0.99
E7	92	105	97	98	0.95	0.83	0.95
E8	92	104	91	96	-1.83	0.84	17.96
E9	88	103	91	94	-3.05	0.98	3.25
E10	88	106	91	95	-2.05	1.18	6.56
E11	92	105	95	97	-0.05	0.84	0.80
E12	90	108	93	97	-0.21	1.15	5.93
E13	91	110	97	99	2.83	1.23	0.06
E14	91	108	98	99	1.95	1.02	2.0
E15	90	107	97	98	0.93	1.05	1.66
E16	87	105	95	95	-1.71	1.10	3.36
E17	93	107	96	99	1.61	0.87	1.05
E18	91	107	95	98	0.95	1.05	0.34
E19 (BHM-9)	86	105	97	96	-1.21	1.10	13.71
E20 (981)	89	108	89	98	-1.88	1.28	0.40
Mean	90	106	95	97	-	-	-
E. Index (Ij)	-6.95	8.89	-1.93	-	-	-	-
LSD (0.05)	3.93	5.04	4.63	-	-	-	-

Pi= phenotypic indices, bi= regression co-efficient and S^2di=deviation from regression

Days to silking along with the value of phenotypic index (Pi), regression co-efficient (bi), deviation from regression (S^2di) is presented in Table 3. The regression co-efficient ranged from 0.73 to 1.28. The genotypic mean for days to silking ranged from 97 to 102 days. Eight hybrids showed positive Pi index while the rest twelve including checks showed negative Pi index for days to silking. The hybrids which exhibited negative Pi index represent earliness. The bi and S^2di values for days to silking ranged from 0.73 to 1.28 and 0.06 to 19.47, respectively. Negative phenotypic index (Pi), a non-significant regression coefficient (bi) and a non-significant deviation from regression (S^2di) value of hybrids considered to be stable across the environment.

Table 3. Stability analysis for days to 50% silking of maize hybrids over three environments

Genotype	Locations			Overall mean	Pi	bi	S^2di
	Gazipur	Dinajpur	Ishwardi				
E1	92	110	97	100	-0.02	1.12	0.4
E2	94	111	98	101	1.30	0.73	1.84
E3	94	110	99	101	1.30	1.05	1.66
E4	93	107	99	100	-0.02	0.79	3.61
E5	95	109	101	102	2.14	0.87	5.38
E6	92	103	95	97	-3.02	0.93	0.99
E7	94	109	98	100	0.47	0.83	0.95
E8	96	107	93	99	-1.19	0.84	17.96
E9	90	106	93	96	-3.52	0.98	3.25
E10	95	109	92	99	-1.02	1.18	6.56
E11	94	108	95	99	-0.69	0.84	0.80
E12	95	110	95	100	-1.90	1.15	5.93
E13	94	114	98	102	2.47	1.23	0.06
E14	95	111	99	102	0.92	1.02	2.00
E15	96	110	98	101	-0.07	1.05	1.66
E16	92	108	96	98	-1.35	1.10	3.36
E17	96	109	98	101	0.97	0.87	1.05
E18	96	112	96	101	1.64	1.05	0.34
E19 (BHM-9)	91	108	97	98	-1.92	1.10	13.71
E20 (981)	92	110	91	98	-2.02	1.28	19.47
Mean	94	109	96	100	-	-	-
E. Index (Ij)	-5.95	9.37	-3.42	-	-	-	-
LSD (0.05)	3.51	6.20	4.35	-	-	-	-

Plant height along with the value of phenotypic index (Pi), regression coefficient (bi), deviation from regression (S^2di) is presented in Table 4. The genotypic mean for plant height ranged from 182 (E7) to 223 cm (E17). Twelve hybrids showed positive Pi index while rest eight showed negative Pi index in plant height. The hybrids which showed positive Pi index represent taller and negative Pi index showing genotypes represent dwarf plant. Hybrid E13exhibited a negative phenotypic index (Pi), significant regression coefficient (bi) value and non-significant S^2di value, indicating a semi-dwarf plant type, and were highly responsive to the favorable environment of Gazipur and Ishwardi locations. The bi and S^2di values for plant height ranged from 0.31 to 1.80 and 0.22 to 443.07, respectively.

Table 4. Stability analysis for plant height (cm) of maize hybrids over three environments

Genotype	Locations			Overall mean	Pi	bi	S^2di
	Gazipur	Dinajpur	Ishwardi				
E1	215	220	184	206	5.00	0.63	443.07
E2	184	245	200	209	8.06	1.49	172.03
E3	187	242	173	201	-0.15	1.80	53.82
E4	190	230	200	207	5.67	0.98	71.93
E5	190	247	191	210	8.34	1.63	11.52
E6	178	230	191	200	-1.32	1.28	121.7
E7	193	262	213	223	21.67	1.67	286.1
E8	177	195	190	187	-13.99	0.31	93.2
E9	188	205	184	192	-8.82	0.54	2.89
E10	191	227	189	202	1.34	1.07	0.22
E11	201	220	190	204	2.50	0.71	50.75
E12	205	235	186	209	7.67	1.14	139.56
E13	178	237	173	196	-4.82	1.77*	1.00
E14	192	220	180	198	-3.65	0.98	50.36
E15	200	222	185	202	1.34	0.87	94.52
E16	180	197	183	187	-14.16	0.44	7.60
E17	182	197	168	182	-18.66	0.66	86.95
E18	188	202	193	195	21.67	0.33	13.41
E19 (BHM9)	195	232	205	211	9.50	0.92	70.54
E20 (981)	195	220	191	202	0.67	0.78	2.94
Mean	191	224	189	201	-	-	-
E. Index (Ij)	-10.57	23.17	-12.6	-	-	-	-
LSD (0.05)	29.73	44.75	24.66	-	-	-	-

Ear height along with the value of phenotypic index (Pi), regression coefficient (bi), deviation from regression (S^2di) is presented in Table 5. The genotypic mean for ear height ranged from 83 cm to 107 cm. Twelve hybrids showed positive Pi index while the rest eight showed negative Pi index for ear height. The hybrids which showed positive Pi index represent taller and negative Pi index signify dwarfness of plant. The bi and S^2di values for ear height ranged from 0.24 to 1.97 and 0.01 to 367.19, respectively.

Table 5. Stability analysis for ear height (cm) of maize hybrids over three environments

Genotype	Locations			Overall mean	Pi	bi	S^2di
	Gazipur	Dinajpur	Ishwardi				
E1	107	135	79	107	5.00	1.53	291.42
E2	83	140	90	104	8.50	1.86	62.33
E3	90	140	79	103	-0.15	1.97	18.71
E4	81	107	92	93	5.67	0.70	79.27
E5	95	115	84	98	8.34	0.91	44.95
E6	74	117	98	96	-1.32	1.04	348.2
E7	80	132	104	105	21.67	1.36	367.19
E8	86	100	95	93	-13.99	0.30	42.41
E9	77	97	75	83	8.82	0.74*	0.06
E10	84	117	86	96	1.34	1.12	10.21
E11	86	100	85	90	2.50	0.51*	0.01
E12	97	112	87	99	7.67	0.73	31.05
E13	92	130	77	99	-4.82	1.63	59.37
E14	98	122	82	101	-3.65	1.17	96.84
E15	102	127	86	105	1.34	1.21	88.71
E16	73	95	79	82	-14.16	0.64	27.72
E17	79	90	68	79	-18.66	0.58	47.16
E18	92	97	89	93	-6.65	0.24	4.38
E19 (BHM9)	93	115	101	103	9.50	0.61	48.81
E20 (981)	89	112	77	93	1.34	1.05	46.89
Mean	88	115	89	86	-	-	-
E. Index (Ij)	-10.57	23.17	-12.60	-	-	-	-
LSD (0.05)	25.58	41.23	25.28	-	-	-	-

Yield along with the value of phenotypic index (Pi), regression coefficient (bi), deviation from regression (S^2di) are presented in Table 6. The environmental mean and genotypic mean ranged from 9.51 t/ha to 10.88 t/ha and 8.28 t/ha to 11.82 t/ha, respectively. Among the hybrids, E2 (CLG1831 × CML223) produced the highest yield (11.82 t/ha). Ten genotypes showed positive phenotypic index while the other genotypes had negative phenotypic index for yield. Thus, positive phenotypic index represents the higher and negative represents the lower yield among the genotypes. The regression coefficient (bi) values of these genotypes ranged from -0.13 to 3.82. These differences in bi values indicated that all the genotypes responded differently to different environments. Considering three stability parameters viz. mean, bi and S^2di, it was evident that all the genotypes showed different response of adaptability under different environmental conditions. The regression coefficient should be better considered as an indicator for genotypic responses to varying environments said by Solomon et al., (2008). Dinajpur was favourable environments for maize cultivation as they showed positive environmental index (Ij).

Table 6. Stability analysis for grain yield (t/ha) of maize hybrids over three environments

Genotype	Locations			Overall mean	Pi	bi	S^2di
	Gazipur	Dinajpur	Ishwardi				
E1	13.07	9.24	11.09	11.13	1.05	1.99	3.33
E2	11.56	12.04	11.85	11.82	1.73	-0.28	0.04
E3	11.78	9.28	9.44	10.17	0.09	1.87	0.32
E4	10.38	11.06	8.81	10.08	0.02	0.71	2.12
E5	10.69	8.58	9.01	9.43	-0.64	1.42	0.44
E6	11.72	10.05	6.67	9.48	-0.59	3.19	2.83
E7	10.51	11.07	8.27	9.95	-0.12	1.11	3.11
E8	11.62	9.75	9.41	10.26	0.18	1.66	0.02
E9	11.23	8.80	10.84	10.30	0.21	0.78	2.79
E10	11.93	8.58	13.26	11.26	1.17	0.03	11.58
E11	10.39	10.16	8.64	9.73	-0.34	1.02	0.74
E12	11.98	10.75	10.89	11.20	0.05	0.84	0.16
E13	12.66	8.98	7.32	9.65	-0.42	3.82	0.08
E14	10.15	10.44	9.39	9.99	-0.08	0.35	0.46
E15	11.89	10.88	10.36	11.04	0.69	1.26	0.16
E16	7.71	8.45	8.67	8.28	-1.79	-0.70*	0
E17	9.97	8.94	7.61	8.84	-1.23	1.55	0.35
E18	9.07	10.2	10.3	9.85	-0.22	-0.94*	0.02
E19 (BHM-9)	10.64	10.24	9.58	10.15	-0.58	0.45	1.21
E20 (981)	13.07	11.31	10.78	11.72	0.87	-0.13	0.17
Mean	10.88	9.84	9.51	10.08	-	-	-
E. Index (Ij)	-0.23	0.80	-0.56	-	-	-	-
LSD (0.05)	1.74	1.81	1.90	-	-	-	-

The biplot (Gabriel, 1971) has become a popular data conception tool in many scientific research areas, including psychology, medicine, business, sociology, ecology, and agricultural sciences. All types of biplots are useful conditional on the research objectives (Yan and Tinker, 2005). The AMMI biplot provide a visual expression of the relationship between the first interaction principal component axis (AMMI component 1) and mean of genotypes and environment (Fig. 1) as well as relationship of IPCA1 and IPCA 2. Genotypes with an IPCA1 score near zero displayed little interaction across the environments while genotypes with very high IPCA1 values showed considerable interactions across environments. From the Fig. 1 it was observed that hybrids E15 and E20 were high yielder as well as stable across locations because they had low interaction effects and suitable for all environments. Entry E5 and E18 had high interaction effects. The entries E1, E2 and E10 had high mean value and negative interactions which were suitable for unfavorable environment.

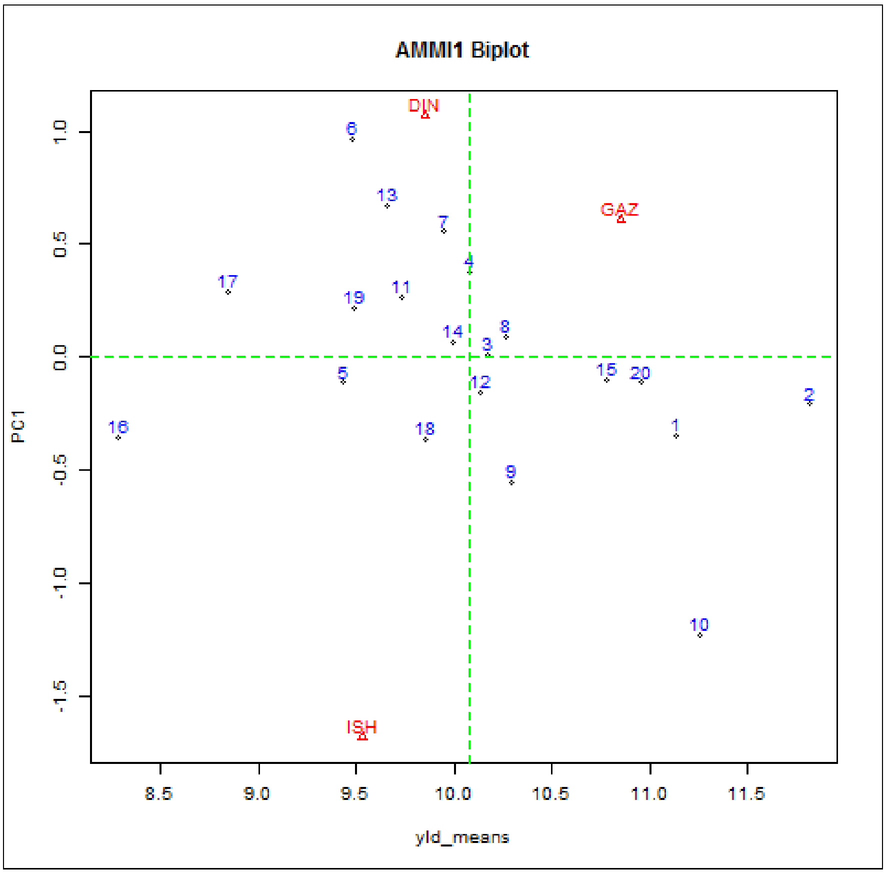

Fig.1. Biplot of the first AMMI interaction (IPCA1) score (Y –axis) plotted against mean yield (X- Axis) of twenty maize hybrids and three environments

Since IPCA2, scores also play a significant role in explaining the GEI; the IPCA1 scores were plotted against the IPCA2 score for further explanation of adaptation (Fig 2). The hybrid E12 and E15 were stable over locations for yield as located within the circle. This result can be observed directly in Figure 2 by the genotypes with high values in relation to "average mean coordination" (Yan et al., 2007). The performances of other hybrid were unstable due to their dispersed position.

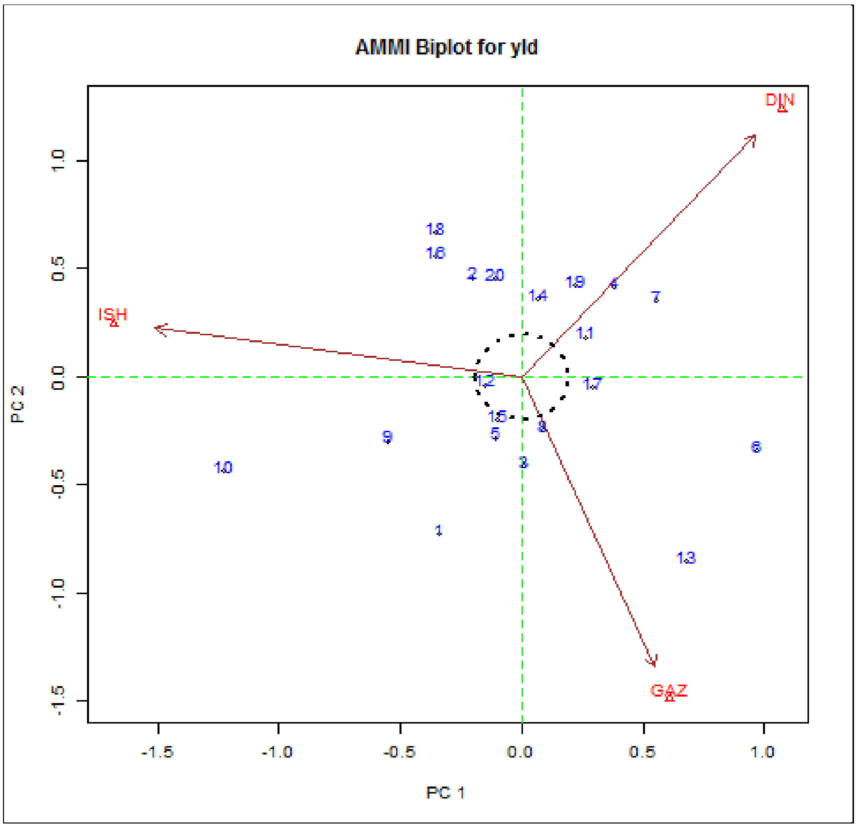

Fig. 2 Biplot of the first AMMI interaction (IPCA2) score (Y –axis) plotted against AMMI interaction (IPCA1) (X-Axis) of twenty maize hybrids and three environments.

The graph "which-won-where" enables to identify potential mega-environments (Yan et al., 2000 and Yan and Hunt, 2001). The genotypes that are utmost from the origin are connected with a straight line forming a polygon. The lines starting from the origin divide the polygon into several sectors. The genotype at the vertex of the polygon performs best in the environment falling within the sectors (Yan 2002; Yan and Tinker, 2006). The locations within one sector are the ones where the certain genotype had the best yield and can be considered as mega-environments only for that genotype where biplots for yields were shown in Fig 3. The hybrid E1 was high yielder and suitable only at Gazipur location. On the other hand, the genotype E10 was found high yielder and stable at Ishwardi and Dinajpur locations.

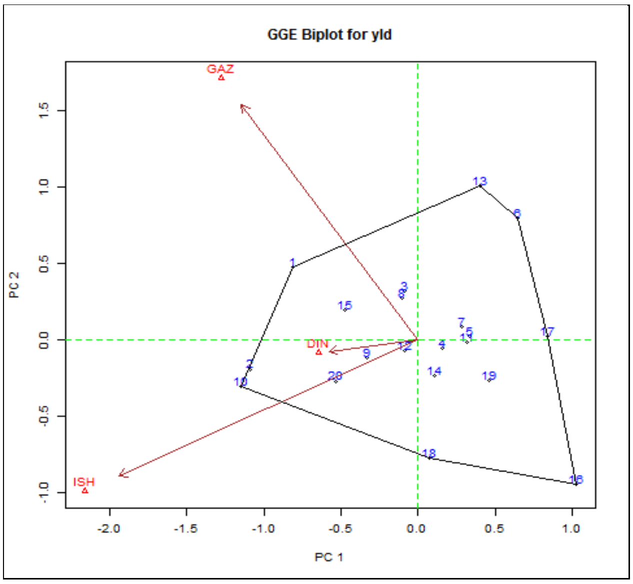

Fig. 3. GGE biplot showing "which won where" for yield of twenty maize hybrids and three environments

Conclusion

The AMMI statistical model has been used to determine the G×E interaction outline of grain yield of 20 promising hybrid maize varieties. The genotypes and environments had exhibited strong interaction. Considering the yield potentially and stability parameters, two tested hybrids viz. E12 (BIL28 × BIL96) and E15 (BIL95 × BIL79) showed the highest grain yield as well as stable for overall environments and need to be further evaluated in large plots before release as commercial hybrids across ecological zones in Bangladesh.

References

Bangladesh Bureau of Statistics (BBS). 2022. Statistics & Information Division (SID), Ministry of Planning, Government of The People's Republic of Bangladesh. p 133.

Crossa, J. 1990. Statistical analysis of multilocation trails. Advances in Agronomy. **44:** 55-85.

Duarte, J.B. and R. Vencovsky. 1999. Interação Genótipos x Ambientes: Uma introdução à análise .AMMI. Funpec,Ribeirão Preto, 60p. (sériemonografias, 9).

FAO. 2022. The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Main report. Rome.

https://doi.org/10.4060/cb9910en

Fertilizer Recommendation Guide (FRG). 2018. Bangladesh Agricultural Research Council. New Airport Road, Farmgate, Dhaka-1215. p79.

Eberhart, S.A. and W.A. Russel. 1966. Stability parameters for comparing varieties. *Crop Sci*. **6:** 36-40.

Finlay, K.W. and G.N. Wilkinson. 1963. The analysis of adaptation in a plant breeding programme. *Australian J. Agric. Res.* **14(6):** 742-754.

Gauch, H.G. 1992. Statistical analysis of regional yield trials: AMMI analysis of factorial designs. Elsevier, Amsterdam. p 278.

Gauch, H.G. and R.W. Zobel. 1996. AMMI analysis of yield trials. In: Genotype by Environment Interaction (Kang, M.S., Gauch, H.G., ed.). CRC Press, Boca Raton, FL. p 85122.

Gabriel, K.R. 1971. The biplot graphic display of matrices with application to principal component analysis. Biometrika **58:**453–467.

Talukder, M.Z.A., A.N.M.S. Karim, S. Ahmed and M. Amiruzzaman. 2016. Combining ability and heterosis on yield and its component traits in maize (Zea mays L.). *Bangladesh J. Agril. Res.* **41(3):** 565-577.

Nachit, M.N., M.E. Sorrells, R.W. Zobel, H.G. Gauch, R.A. Fischer and W.R. Coffman. 1992. Association of environmental variables with sites' mean grain yield and components of genotype environment interaction in durum wheat. *J. Genet. Breed*. **46:** 369-372.

Solomon, A., N. Mandefro and Z. Habtamu. 2008. Genotype-Environment Interaction and Stability Analysis for Grain Yield of Maize (Zea mays L.) in Ethiopia. *Asian J. Plant Sci.* **2:**163-169.

Yamada, Y. 1962. GEI and genetic correlation of the same trait under different environments. Japan J. Genet. **37:** 498-509.

Yan, W., L.A. Hunt, Q. Sheng and Z. Szlavnics. 2000. Cultivar evaluation and mega environment investigation based on the GGE biplot. *Crop Sci*. **40:** 597-605.

Yan, W. and L.A. Hunt. 2001. Interpretation of genotype× environment interaction for winter wheat yield in Ontario. Crop Sci. **41:** 19-25.

Yan, W. and N.A. Tinker. 2005. An integrated system of biplot analysis for displaying, interpreting, and exploring genotype-by-environment interactions. *Crop Sci*. **45:** 1004-1016.

Yan, W. and N.A. Tinker. 2006. Biplot analysis of multi-environment trial data: Principles and applications. Canadian *J. Plant Sci.* **86:** 623-645.

Yan W, M.S. Kang, B. Ma, S. Woods and P.L. Cornelious. 2007. GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Sci.* **47:** 643-653.

Zobel, R.W., M.J. Wright and H.G. Gauch. 1988. Statistical analysis of a yield trial. *J. Agron.,* **80:** 388-393.