

Genotype Environment Interaction ($G \times E$) in Rapeseed Mustard Genotypes

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Abstract

Nine rapeseed-mustard genotypes were grown in four different agro ecological regions (AEZs) such as Gazipur, Satkhira, Khulna and Cox's Bazar in 2023-2024 to observe their performance over locations and to select the best one(s). Yield stability analyzed employing Eberhart and Russell's model (1966). The environmental mean and genotypic mean ranged from 1020 (kg/ha) to 1889 (kg/ha) and 1119 (kg/ha) to 1619 (kg/ha), respectively. The regression coefficient (bi), deviation from regression (S^2di) values of these genotypes ranged from 0.236 to 1.311 and 146.70 to 881.30, respectively. The regression coefficient (bi), deviation from regression (S^2di) values of these genotypes for days to maturity (DM) ranged from -0.130 to 2.116 and 0.36 to 28.19, respectively. The minimum DM recorded in BS-14 (80.50) which was followed by BHS-01 (91.5), BAUS-01 (92.33). The maximum days for maturity recorded in BAUS-01 (94.08). The mean genotypes or environments in AMMI biplot located on the same parallel line, relative to the ordinate, have similar yield, while those located on the right side of the center of the axis have higher yields than those on the left hand side. The first interaction principal component axis (IPCA1) and means of genotypes and environments with the biplot accounting for up to 87.2% of the treatment sum of squares. Genotypes with IPCA1 scores near zero had little interaction across environments while genotypes with very high IPCA1 values had considerable interactions across environments. Among the

genotypes, BS-16, BHS-01, BS-18 and BAUS-01 exhibited the higher grain yield, $bi \sim 1$ and $S^2di \sim 0$ indicated that they were stable across the environments. Among the locations, Khulna was highly suitable for mustard cultivation followed by Satkhira and Cox's Bazar.

Keywords

Rapeseed-Mustard, Over Locations, Eberhart and Russell's Model, AMMI Model

1. Introduction

The potential of genotypes and stability of their performance can be judged by multi environment trials [1]. It is more practical to develop and release varieties which are adapted to more than a single environment and can be successfully grown over a range agro ecological regions. Agronomic zoning is used to stratify environments in sub regions within which the interactions are not significant [2]. These methods are dependent on the genotypes and environments under study and may not be much informative if linearity fails [3]. For quantitative traits like yield, the relative performance of different genotypes often varies from one environment to another. So, genotype \times environment interaction does exist when phenotypic response made by a change in environment is not the same for all genotypes [4].

Genotype \times environment interaction is a valuable concept in plant breeding programme for the selection and improvement of genotypes that perform well across environments [5]. Several statistical approaches designed to measure genotypic stability. However, no single method is sufficient to measure the performance of genotypes across different environments. A genotype may be considered more stable and adaptive if its yield fluctuation is less when cultivated over different seasons [6].

Yield of mustard and its component being quantitative in nature would be useful to gain knowledge about the nature and magnitude of genetic variability and its interaction with environment. Interactions between genotypes and environments are particularly interesting because they do reflect the fluctuations in environment if genetic makeup is known and in most cases prediction can be made well ahead [7].

Therefore, estimating heritability including the genotype \times environment interaction variation for the total variance is more appropriate for prediction of genetic advance due to selection. Genotypes that can adjust their phenotypic state in response to environmental vulnerability in such a way that they provide maximum stable economic return, can be termed "buffered" or stable [7]. So, it is necessary to identify the stable genotypes that are suitable for wide range of environments. Several authors conducted experiments for this purpose, which have been carried out by [8]-[11].

Statistically, $G \times E$ interactions are detected as a significantly different pattern of response among the genotypes across environments and biologically, this will occur when the contributions (or level of expression) of the genes regulating the trait differ among environments [12]. Therefore, an ideal approach in plant breeding is to develop cultivars that have fairly uniform performance (low $G \times E$) over a range of environments with the ability to utilize the resources in high yielding environment.

Rapeseed-mustard is a major oilseed crop in Bangladesh. It contributes a lion share to the total edible oil production in the country. Rapeseed and mustard cover 66.48% area of total oil crops [13]. Production of oilseed crops dramatically increased by many folds (14.9 times) from 64,000 MT in 1960 to 956,000 MT in 2019 although encountered a pitfall in 1975 (237,000 MT), 1980 (246,000 MT) and 2005 (274,000 MT). This increase of oilseed crops was attributed to the combined effect of area expansion and a massive yield increase from 0.18MT/ha in 1960 to 2.1 MT/ha in 2019 implying a significant adoption of high yielding varieties and improved management practices [14]. The Oilseed Research Centre of BARI has already developed 22 rapeseed and mustard varieties, which comprise 10 *Brassica rapa*, 7 *B. juncea* and 5 *B. napus*. Their adaptability across environments is needed to be justified. The experiment has been undertaken to observe the performance of some rapeseed-mustard genotypes in different agro ecological regions in Bangladesh and to select the best one(s) over locations.

2. Materials and Methods

Nine rapeseed-mustard genotypes such as BS-11, BS-16, BS-18, BS-19, BS-14, BAUS-01, BAUS-02, BHS-01 and BAUS-03 were grown in 2023-2024 at Gazipur, Satkhira, Khulna and Cox's Bazar. Gazipur—Old Brahmaputra Floodplain (Agro Ecological Zone—9), organic matter low to medium, fertility level low. Satkhira—High Ganges River Floodplain (Agro Ecological Zone—11), organic matter and fertility status low. Khulna-Gopalganj Khulna Beels (Agro Ecological Zone—14), organic matter and fertility level is medium. Cox's Bazar—Chittagong Coastal Plains (Agro Ecological Zone—23), organic matter low, fertility level medium. Unit plot size was 5 rows 3 m long and row to row distance 30 cm and plant to plant distance 5 cm after thinning. The experiment was conducted following RCB design with 3 replications and treatments were the nine genotypes. Fertilizers were applied @ 260, 170, 90, 160, 5 and 10 kg/ha of Urea, TSP, MOP, Gypsum, Zinc-oxide and Boric acid respectively [15]. Half of urea and all other fertilizers will be used as basal dose and rest half of urea just before flowering. Plant height (cm), no. of branches/plant, no. of siliqua/plant, no. of seeds/siliqua, days to 50% flowering, days to maturity 1000-seed weight (g) and seed yield (kg/ha), disease and insect reaction were recorded. Data were annualized using cropstat 7.2. Yield stability was analyzed employing [16].

3. Results and Discussion

Nine rapeseed-mustard genotypes such as BS-11, BS-16, BS-18, BS-19, BS-14,

BAUS-01, BAUS-02, BHS-01 and BAUS-03 were evaluated in four agro ecological regions for eight characters. The combined analysis of variance for eight characters were presented in **Table 1**. The mean sum of square for genotypes were highly significant for most of the characters studied except thousand seed weight (g) and yield (kg/ha). Similarly, environmental variances were also highly significant for those characters including thousand seed weight (g). Variances due to genotype \times environment interaction were highly significant for four traits such as plant height, no. of seeds per siliqua, days to 50% flowering and days to maturity. Significant genotype and environmental variances recorded in the study of [17]-[20]. AMMI Component 1 and 2 showed variation for plant height, no. of seeds per siliqua, days to 50% flowering and days to maturity except days to 50% flowering in AMMI Component 2. $G \times E$ (Linear) revealed insignificant variation for all the characters except no. of seeds per siliqua and days to maturity. The pooled deviation (nonlinear portion of variance) which is unpredictable portion of $G \times E$ interaction was significant for only four characters such as plant height, no. of seeds per siliqua, days to 50% flowering and days to maturity.

Table 1. Full joint analysis of variance including the portioning of the $G \times E$ interactions of mustard varieties.

Source of variation	df	Mean sum of squares							
		PH (cm)	NBP	NSP	NSS	DFF	DM	TSW(g)	Yield (kg/ha)
Genotype (G)	8	1225.80**	0.5017	3852.73**	89.7073**	21.8133**	100.369**	0.0575	105815
Environments (E)	3	1892.58**	3.9575**	17259.0**	17.2561**	16.9414**	120.777**	5.385**	0.0114
Interaction $G \times E$	24	271.941**	0.4443	560.789	18.4239**	6.73302*	14.4295**	0.1678	66699.5
AMMI Component 1	10	226.591**	0.7033	743.847	35.3864**	13.4765**	19.2249**	0.2536	84794.1
AMMI Component 2	8	365.179**	0.3026	544.769	8.8792**	3.1644	15.4418*	0.1432	72505.1
AMMI Component 3	6	333.286	0.2015	277.054	2.8794	0.2520	5.0876	0.0576	28800.9
$G \times E$ (Linear)	8	34.753	0.2098	905.354	6.0913*	2.9797	20.234**	0.1756	43268.0
Pooled deviation	16	294.617**	0.5616	388.507	24.5902**	3.4648**	11.5274*	0.1639	78415.2
Pooled Error	70	110.013	0.5040	550.344	2.7934	8.6097	6.2188	0.1787	73176.6

Plant height (PH) (cm), no. of branches/plant (NBP), no. of siliqua/plant (NSP), no. of seeds/siliqua (NSS), days to 50% flowering (DFF), days to maturity (DM), 1000-seed weight (TSW) and seed yield/ha (kg/ha). * indicates significance at 5% level of probability; ** indicates significance at 1% level of probability, the same below.

Table 2. Stability analysis for PH (cm) of mustard varieties over four environments.

Entry	PH (cm)							
	Location				Genotypic Mean	P. Index (Pi)	bi	S ² di
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	124.1	122.5	152.6	118.8	129.5	6.713	1.02	7.66
BS-16	141.1	101.1	178.2	176.2	149.2	26.36**	1.73	258.45
BS-18	114.2	102.0	130.3	117.7	116.1	-6.734	0.74	7.685
BS-19	125.9	101.1	156.1	97.03	120.0	-2.773	1.68	55.56
BS-14	71.83	73.90	110.6	84.53	85.21	-37.59**	1.17	10.12
BAUS-1	131.2	110.3	151.2	99.67	123.1	0.321	1.28	66.31
BAUS-2	112.7	119.5	143.2	108.7	121.0	-1.769	0.93	21.20
BHS-01	103.4	127.1	116.8	143.4	122.7	-0.106	-0.27	100.92
BAUS-03	134.4	143.8	157.2	118.1	138.4	15.57**	0.72	61.62
Site Mean	117.7	111.3	144.0	118.2	-	-	-	-

Continued

E. Index (Ij)	-5.140	-11.52*	21.23**	-4.570	-	-	-	-
LSD (0.05)	23.74	18.08	16.08	6.94	-	-	-	-

The PH (cm) along with the value of phenotypic indices (Pi), regression coefficient (bi) and deviation from regression (S^2di) were presented in **Table 2**. The environmental mean and genotypic mean ranged from 111.3 to 144.0 and 85.21 to 149.2, respectively. The regression coefficient (bi), deviation from regression (S^2di) values of these genotypes ranged from -0.27 to 1.73 and 7.66 to 258.45, respectively. The lowest overall mean for PH was recorded in BS-14 (85.21 cm) followed by BS-18 (116.1), BS-19 (120.0) and BAUS-02 (121.0) indicating dwarf varieties. The highest PH was found in BS-16 (149.2).

Five entries showed negative phenotypic index while the other four had positive phenotypic index for PH (cm). Again, negative and positive phenotypic index (Pi) reflects the short statured and tallness for this character, respectively. The negative and positive environmental index (Ij) reflected the early maturing and late maturing environments for this character, respectively. The environment Gazipur (Ij = -5.140), Satkhira (Ij = -11.52*) and Cox's Bazar (Ij = -4.570) were favourable for dwarf varieties while Khulna (Ij = 21.23**) environment was suitable for long staturedness. The three genotypes such as BS-18, BS-14 and BAUS-02 having negative phenotypic index, coupled with near unit regression co-efficient and non significant deviation from regression recorded stable.

Table 3. Stability analysis for NBP of mustard varieties over four environments.

Entry	NBP							
	Location				Genotypic Mean	P. Index (Pi)	bi	S^2di
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	4.10	5.93	5.33	4.27	4.91	-0.109	0.76	0.77
BS-16	4.77	5.40	6.11	5.30	5.39	0.377	0.77	0.07
BS-18	4.20	4.40	5.22	5.40	4.81	-0.213	0.68	0.22
BS-19	3.60	5.20	6.00	5.67	5.12	0.099	1.59	0.04
BS-14	4.37	4.07	6.22	4.40	4.76	-0.254	0.86	0.97
BAUS-1	4.10	4.80	6.44	4.77	5.03	0.010	1.27	0.43
BAUS-2	3.53	4.93	5.22	5.60	4.82	-0.195	1.23	0.22
BHS-01	2.70	5.53	4.22	5.90	4.59	-0.428	1.45	1.78
BAUS-03	5.37	5.87	6.00	5.69	5.73	0.713**	0.39*	0.01
Site Mean	4.08	5.13	5.64	5.22	-	-	-	-
E. Index (Ij)	-0.936**	0.108	0.624	0.204	-	-	-	-
LSD (0.05)	1.19	0.94	1.88	0.64	-	-	-	-

The NBP along with the value of phenotypic indices (Pi), regression coefficient (bi) and deviation from regression (S^2di) were presented in **Table 3**. The environmental mean and genotypic mean ranged from 4.08 to 5.64 and 4.76 to 5.73, respectively.

In Gazipur, the highest NBP was found from BAUS-03 (5.37) followed by BS-

16 (4.77) and BS-18 (4.20) and the lowest in BHS-01 (2.70). The maximum NBP was recorded in BS-11 (5.93), the lowest in BS-14 (4.07) in Satkhira. BAUS-01 (6.44) and BHS-01 (5.90) showed the maximum NBP in Khulna and Cox's Bazar, respectively.

Four genotypes showed positive phenotypic index while the other five genotypes had negative phenotypic index for yield. Thus, positive phenotypic index represented the higher yield and negative represents the lower yield among the genotypes. Again, positive and negative environmental index (I_j) reflected the rich or favourable and poor or unfavourable environments for this character, respectively. Thus the environment of Gazipur was poor whereas Satkhira, Khulna, and Cox's Bazar was favourable environments for mustard production.

The regression coefficient (bi), deviation from regression (S²di) values of these genotypes ranged from 0.39* to 1.59 and 0.01 to 1.78, respectively. These differences in bi values indicated that all the genotypes responded differently to different environments. Considering the mean, bi and S²di, it was evident that all the genotypes showed different response of adaptability under different environmental conditions. Among the genotypes, BAUS-03, BS-16, BS-11 and BS-19 exhibited the higher grain yield, bi~1 and S²di~0 indicated that the hybrids were stable across the environment. Regression co-efficient and deviation from regression showed insignificant values for all the genotypes except BAUS-03.

Table 4. Stability analysis for NSP of mustard varieties over four environments.

Entry	NSP							
	Location				Genotypic Mean	P. Index (Pi)	bi	S ² di
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	80.07	181.5	197.7	215.2	168.6	27.96*	1.28	205.42
BS-16	76.57	120.5	144.7	102.6	111.1	-29.58*	0.60	50.72
BS-18	84.12	141.0	184.0	148.5	139.4	-1.242	0.94	5.72
BS-19	68.30	152.5	213.3	208.6	160.7	20.04	1.48	130
BS-14	54.67	44.00	87.33	96.77	70.69	-69.96**	0.34	158.02
BAUS-1	84.33	157.9	231.3	154.0	156.9	16.23	1.32	108.89
BAUS-2	90.87	169.8	180.7	148.6	147.5	6.845	0.86	63.81
BHS-01	71.23	167.1	223.3	162.0	155.9	15.29	1.42	34.47
BAUS-03	107.6	167.1	188.3	157.1	155.1	14.41*	0.76	19.97
Site Mean	79.75	144.6	183.4	154.8	-	-	-	-
E. Index (I _j)	-60.89**	3.957	42.76**	14.18	-	-	-	-
LSD (0.05)	42.80	45.20	51.03	12.53	-	-	-	-

The NSP along with the value of phenotypic indices (Pi), regression coefficient (bi) and deviation from regression (S²di) were presented in **Table 4**. The environmental mean and genotypic mean ranged from 79.75 to 183.4 and 70.69 to 168.6, respectively.

Six genotypes showed positive phenotypic index while the other three genotypes had negative phenotypic index for yield. Thus, positive phenotypic index represented the higher yield and negative represents the lower yield among the

genotypes. Again, positive and negative environmental index (I_j) reflected the rich or favourable and poor or unfavourable environments for this character, respectively. Thus all the three environments were favourable for mustard production except Gazipur.

The regression coefficient (b_i), deviation from regression (S^2d_i) values of these genotypes ranged from 0.34 to 1.48 and 5.72 to 205.42, respectively. These differences in b_i values indicated that all the genotypes responded differently to different environments. Considering the mean, b_i and S^2d_i , it was evident that all the genotypes showed different response of adaptability under different environmental conditions. Among the genotypes, BAUS-01, BHS-01 and BS-11 exhibited the higher grain yield, $b_i \sim 1$ and $S^2d_i \sim 0$ indicated that the hybrids are stable across the environment. None of the genotypes showed significant values for regression coefficient and also deviation from regression.

Table 5. Stability analysis for NSS of mustard varieties over four environments.

Entry	NSS							
	Location				Genotypic Mean	P. Index (Pi)	b_i	S^2d_i
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	11.50	13.00	14.00	16.10	13.65	-3.168	0.37	5.19
BS-16	11.70	20.93	14.33	16.47	15.86	-0.959	0.20	22.76
BS-18	23.73	12.40	24.33	16.97	19.36	2.541	1.15	45.21
BS-19	10.33	13.13	14.00	16.80	13.57	-3.251	0.56	9.75
BS-14	29.10	30.00	29.67	21.43	27.55	10.73**	0.90	22.80
BAUS-01	11.87	12.07	15.67	11.80	12.85	-3.968	1.30	0.48
BAUS-02	11.60	24.80	15.00	21.67	18.27	1.449	-0.15	54.61
BHS-01	18.33	11.00	26.67	14.60	17.65	0.832	3.39	34.60
BAUS-03	11.87	12.67	15.33	10.57	12.61	-4.209**	1.29	1.33
Site Mean	15.56	16.67	18.78	16.27	-	-	-	-
E. Index (I_j)	-1.258	-0.151	1.960	-0.551	-	-	-	-
LSD (0.05)	3.44	2.79	3.50	0.85	-	-	-	-

The NSS along with the value of phenotypic indices (Pi), regression coefficient (b_i) and deviation from regression (S^2d_i) were presented in **Table 5**. The environmental mean and genotypic mean ranged from 15.56 to 18.78 and 12.61 to 27.55, respectively.

In Gazipur, the highest NSS was found from BS-14 (29.10) followed by BS-18 (23.73) and BHS-01 (18.33). In Satkhira, BS-14 produced the highest yield (30.00) followed by BAUS-02 (24.28) and BS-16 (20.93). The maximum production recorded in BS-14 (29.67) in Khulna which was followed by BHS-01 (26.67), BS-18 (24.33). In Cox's Bazar the maximum yield recorded in the genotype BAUS-02 (21.67) followed by BS-14 (21.43) and BS-18 (16.97).

Four genotypes showed positive phenotypic index while the other five genotypes had negative phenotypic index for yield. The positive phenotypic index represented the higher yield and negative represents the lower yield among the genotypes. Again, positive and negative environmental index (I_j) reflected the rich or

favourable and poor or unfavourable environments for this character, respectively. The environment of Khulna was favourable environments and the rest three were unfavourable for mustard production.

The regression coefficient (b_i), deviation from regression (S^2d_i) values of these genotypes ranged from -0.15 to 0.90 and 0.48 to 54.61 , respectively. These differences in b_i values indicated that all the genotypes responded differently to different environments. Considering the mean, b_i and S^2d_i , it was evident that all the genotypes showed different response of adaptability under different environmental conditions. Among the genotypes, BS-14, BS-18 and BHS-01 exhibited the higher grain yield, $b_i \sim 1$ and $S^2d_i \sim 0$ indicated that the hybrids are stable across the environment. All the genotypes showed insignificant values for regression coefficient and also deviation from regression.

Table 6. Stability analysis for DFF of mustard varieties over four environments.

Entry	DFF							
	Location				Genotypic Mean	P. Index (Pi)	b_i	S^2d_i
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	43.00	39.00	42.00	42.67	41.67	0.046	0.28	4.78
BS-16	40.67	39.67	43.67	46.00	42.50	0.880	1.91	2.20
BS-18	43.33	37.67	45.33	44.00	42.58	0.963	0.86	15.08
BS-19	41.33	40.33	42.33	43.00	41.75	0.130	0.67	0.78
BS-14	32.67	36.67	35.67	39.33	41.75	-5.537**	1.82	1.98
BAUS-1	42.33	39.00	42.67	42.67	41.67	0.463	0.46	4.18
BAUS-2	41.33	51.33	41.33	45.33	44.83	3.213	0.26	33.31
BHS-01	36.33	42.67	41.00	44.33	41.08	-0.537	2.06	5.84
BAUS-03	41.00	43.00	42.00	43.67	42.42	0.796	0.68	0.73
Site Mean	40.22	41.04	41.78	43.44	-	-	-	-
E. Index (Ij)	-1.398	-0.583	0.157	1.824	-	-	-	-
LSD (0.05)	4.32	3.20	1.35	2.64	-	-	-	-

The DFF along with the value of phenotypic indices (Pi), regression coefficient (b_i) and deviation from regression (S^2d_i) were presented in **Table 6**. The environmental mean and genotypic mean ranged from 40.22 to 43.44 and 41.08 to 44.83, respectively. The regression coefficient (b_i), deviation from regression (S^2d_i) values of these genotypes ranged from 0.26 to 2.06 and 0.73 to 33.31, respectively.

The minimum DFF recorded in BS-14 (32.67) which was followed by BHS-01 (36.33) in Gazipur. The maximum DFF recorded in BS-18 (43.33). The minimum DFF were recorded minimum in rest three locations such as Satkhira (36.67), Khulna (35.67) and Cox's Bazar (39.33).

Two entries showed negative phenotypic index while the other seven had positive phenotypic index for DFF. Positive phenotypic index represented the late maturing and negative represented the early maturing genotypes. The negative and positive environmental index (Ij) reflected the early maturing and late maturing environments for this character, respectively. The environment of Satkhira (Ij = -0.583) and Gazipur (Ij = -1.398) were early maturing whereas Cox's Bazar (Ij = 1.824) and

Khulna ($I_j = 0.157$) was late maturing environments for this character. Two varieties such as BS-14, BHS-01 having negative phenotypic index, near unit regression coefficient and non significant deviation from regression recorded stable.

Table 7. Stability analysis for days to maturity (DM) of mustard varieties over four environments.

Entry	Days to maturity (DM)							
	Location				Genotypic Mean	P. Index (Pi)	bi	S ² di
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	103.3	88.00	93.00	93.33	94.42	1.796	1.26	30.06
BS-16	104.3	90.00	93.67	105.7	98.42	5.796**	2.12*	0.36
BS-18	95.67	86.33	94.67	98.67	93.83	1.213	1.18	13.69
BS-19	102.3	88.33	92.67	100.7	96.00	3.380	1.78	2.39
BS-14	82.67	81.00	80.67	77.67	80.50	-12.12**	-0.13	6.16
BAUS-1	94.33	88.67	90.00	96.33	92.33	-0.2870	0.97	0.71
BAUS-2	93.00	94.33	89.67	94.00	92.75	0.130	0.17	6.27
BHS-01	89.67	92.00	85.67	97.67	91.25	-1.37	0.69	28.19
BAUS-03	95.00	91.00	91.00	99.33	94.08	1.463	0.98	4.39
Site Mean	95.59	88.85	90.11	95.93	-	-	-	-
E. Index (I _j)	2.972	-3.769**	-2.509*	3.306	-	-	-	-
LSD (0.05)	0.91	0.65	0.78	0.59	-	-	-	-

Days to maturity (DM) along with the value of phenotypic indices (Pi), regression coefficient (bi) and deviation from regression (S²di) were presented in **Table 7**. The environmental mean and genotypic mean ranged from 88.85 to 95.93 and 80.50 to 98.42, respectively. The regression coefficient (bi), deviation from regression (S²di) values of these genotypes ranged from -0.130 to 2.12 and 0.36 to 30.06, respectively.

The minimum DM recorded in BS-14 (80.50) which was followed by BHS-01 (91.25), BAUS-01 (92.33). The maximum days for maturity recorded in BS-16 (98.42). Satkhira region was favourable for early maturity (88.85) followed by Khulna (90.11) and Gazipur (95.59). Three genotypes showed negative phenotypic index while the other six hybrids had positive phenotypic index for DM. Positive phenotypic index represented the late maturing and negative represented the early maturing genotypes. Again, negative and positive environmental index (I_j) reflected the early maturing and late maturing environments for this character, respectively. The environment of Satkhira (-3.769**) and Khulna (-2.509*) were early maturing whereas Gazipur (2.97) and Cox's Bazar (3.306) was late maturing environments for this character. Three varieties such as BS-14, BHS-01, BAUS-01 having negative phenotypic index, near unit regression coefficient and non significant deviation from regression recorded stable.

Table 8. Stability analysis for TSW (g) of mustard varieties over four environments.

Entry	TSW (g)							
	Location				Genotypic Mean	P. Index (Pi)	bi	S ² di
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	4.36	2.29	4.33	4.35	3.83	0.103	1.32	0.01
BS-16	3.87	3.12	4.33	3.90	3.80	0.073	0.60	0.06

Continued

BS-18	4.37	2.22	4.33	3.71	3.66	-0.072	1.27	0.07
BS-19	4.18	2.38	4.00	4.31	3.72	-0.013	1.14	0.05
BS-14	3.66	2.68	4.00	4.43	3.69	-0.038	0.83	0.21
BAUS-1	4.12	2.71	3.67	4.21	3.68	-0.053	0.82	0.11
BAUS-2	3.95	2.25	4.00	4.24	3.61	-0.120	1.15	0.06
BHS-01	4.58	2.44	4.67	4.21	3.98	0.244	1.34	0.02
BAUS-03	4.53	3.09	4.00	2.81	3.61	-0.124	0.53	0.71
Site Mean	4.18	2.58	4.15	4.02	-	-	-	-
E. Index (Ij)	0.450**	-1.156**	0.417**	0.288	-	-	-	-
LSD (0.05)	0.91	0.65	0.78	0.59	-	-	-	-

The TSW (g) along with the value of phenotypic indices (Pi), regression coefficient (bi) and deviation from regression (S^2di) were presented in **Table 8**. The environmental mean and genotypic mean ranged from 2.58 g to 4.18 g and 3.61 g to 3.98 g, respectively.

In Gazipur, the highest TSW was found from BHS-01 (4.58 g) followed by BAUS-03 (4.53 g) and BS-11 (4.36 g). In Satkhira, BS-16 produced the highest yield (3.12 g) followed by BAUS-03 (3.09 g) and BS-14 (2.68 g). The maximum production recorded in BHS-01 (4.67 g) in Khulna which was identical with BS-11, BS-16, BS-18 (4.33g) and BS-14, BS-19, BAUS-03 (4.00g). In Cox's Bazar the maximum yield recorded in the genotype BS-14 (4.43 g) followed by BS-11 (4.35 g) and BAUS-02 (4.24 g).

Three genotypes showed positive phenotypic index while the other six genotypes had negative phenotypic index for yield. Thus, positive phenotypic index represented the higher yield and negative represents the lower yield among the genotypes. Again, positive and negative environmental index (Ij) reflected the rich or favourable and poor or unfavourable environments for this character, respectively. Thus the environment of Satkhira was unsuitable whereas Khulna, Gazipur and Cox's Bazar was suitable environments for mustard production.

The regression coefficient (bi), deviation from regression (S^2di) values of these genotypes ranged from 0.53 to 1.34 and 0.01 to 0.71, respectively. These differences in bi values indicated that all the genotypes responded differently to different environments. Considering the mean, bi and S^2di , it was evident that all the genotypes showed different response of adaptability under different environmental conditions. Among the genotypes, BS-16, BS-11 and BHS-01 exhibited the higher grain yield, $bi \sim 1$ and $S^2di \sim 0$ indicated that the hybrids are stable across the environment. All the genotypes showed insignificant values for regression coefficient and also deviation from regression.

Table 9. Stability analysis for yield (kg/ha) of mustard varieties over four environments.

Entry	Yield (kg/ha)							
	Location				Genotypic Mean	P. Index (Pi)	bi	S^2di
	Gazipur	Satkhira	Khulna	Cox's Bazar				
BS-11	908.6	1469.0	1920	1252	1387	-84.88	1.16	36.68

Continued

BS-16	1276	1626	1453	2146	1625	152.8	0.24	220.33
BS-18	1006	1333	2150	1797	1572	99.17	1.29	141.95
BS-19	844.4	1292	2000	1275	1353	-119.5	1.31	51.95
BS-14	646.9	985.7	1680	1165	1119	-352.9**	1.17	97.25
BAUS-1	1111	1751	1800	1449	1528	55.24	0.81	100.75
BAUS-2	947.5	1904	1950	1715	1629	156.7	1.19	119.73
BHS-01	1273	1294	2150	1420	1534	62.00	0.97	147.5
BAUS-03	1164	1866	1900	1085	1504	31.44	0.86	219.10
Site Mean	1020	1502	1889	1478	-	-	-	-
E. Index (Ij)	-452.7**	29.88	416.9**	5.922	-	-	-	-
LSD (0.05)	68.14	46.30	11.32	24.40	-	-	-	-

The yield (kg/ha) along with the value of phenotypic indices (Pi), regression coefficient (bi) and deviation from regression (S^2di) were presented in **Table 9**. The environmental mean and genotypic mean ranged from 1020 kg/ha to 1889 kg/ha and 1119 kg/ha to 1629 kg/ha, respectively.

In Gazipur, the highest yield was found from BS-16 (1276 kg/ha) followed by BHS-01 (1273 kg/ha) and BAUS-03 (1164 kg/ha). In Satkhira, BAUS-02 produced the highest yield (1904 kg/ha) followed by BAUS-03 (1866 kg/ha) and BAUS-01 (1751 kg/ha). The maximum production recorded in BS-18 (2150 kg/ha) in Khulna which was identical with BS-19 (2000 kg/ha) and BAUS-02 (1950 kg/ha). In Cox's Bazar the maximum yield recorded in the genotype BS-16 (2146 kg/ha) followed by BS-18 (1797 kg/ha) and BAUS-02 (1715 kg/ha). But the variety BS-14 produced the lowest mean yield (1119 kg/ha) in all four locations.

Six genotypes showed positive phenotypic index while the other three genotypes had negative phenotypic index for yield. Thus, positive phenotypic index represented the higher yield and negative represents the lower yield among the genotypes. Again, positive and negative environmental index (Ij) reflected the rich or favourable and poor or unfavourable environments for this character, respectively. Thus the environment of Gazipur was poor whereas Khulna, Satkhira and Cox's Bazar was favourable environments for mustard production. Khulna was highly suitable for mustard cultivation followed by Satkhira and Cox's Bazar.

The regression coefficient (bi), deviation from regression (S^2di) values of these genotypes ranged from 0.24 to 1.31 and 36.68 to 220.33, respectively. The differences in bi (**Table 9**) values indicated that all the genotypes responded differently to different environments. Considering the mean, bi and S^2di , it was evident that all the genotypes showed different response of adaptability under different environmental conditions. Among the genotypes, BS-16, BHS-01, BS-18 and BAUS-01 exhibited the higher grain yield, $bi \sim 1$ and $S^2di \sim 0$ indicated that the hybrids are stable across the environment. All the genotypes showed insignificant values for regression co-efficient and also deviation from regression. [21] studied GxE of 71 Indian mustard varieties over 6 environment in two several years and selected one genotype well stable in all environment and one to a specific environment. [22] studied 25 mustard genotypes in 3 environment found 6 as stable. [17] studied 57

mustard over 3 environments selected 3 as stable. [18] conducted stability analysis in 11 genotypes, 2 seasons in 3 environment and found one genotype stable in case of yield. [23] studied GxE in mustard of 8 cultivars in 10 locations of different agro climate and selected 2 genotypes stable due to low deviations from regression coupled with b value near 1.

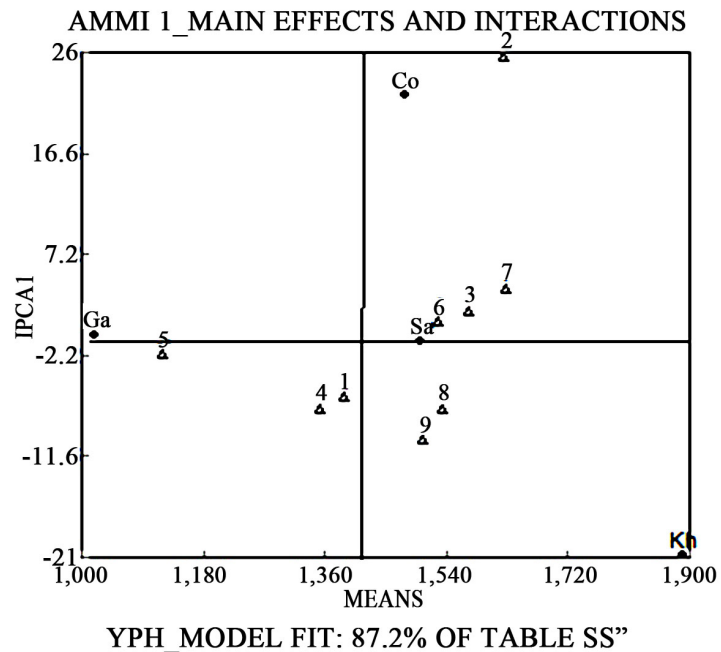


Figure 1. Biplot of the first AMMI interaction (IPCA1) score (Y-axis) plotted against mean yield (X-axis) of nine genotypes and four environments.

The AMMI model combines regular analysis of variance for additive effects with principal component analysis (PCA) for multiplicative structure within the interaction. AMMI also provides a visual representation patterns in the data through a biplot that makes use of the first interaction principal component axis (IPCA1) and the mean yields of both the genotypes and environments [24].

The AMMI biplot provides a visual expression of the relationships between the first interaction principal component axis (IPCA1) and means of genotypes and environments (Figure 1) with the biplot accounting up to 87.2% of the treatment sum of squares. The IPCA1 was highly significant and explained the interaction pattern better than other interaction axes. The mean genotypes or environments in AMMI biplot located on the same parallel line, relative to the ordinate, have similar yield, while those located on the right side of the center of the axis has higher yields than those on the left hand side (Figure 1).

The biplot showed four grouping of genotypes having two of them such as 4 (BS-19), and 1 (BS-11) were low yielding and unstable. The genotype 5 (BS-14) was low yielding but moderately stable, 6 (BAUS-1), 3 (BS-18), 7 (BAUS-2), 2 (BS-16) were high yielding and stable hybrids. The genotype 8 (BHS-01) and 9 (BAUS-03) were high yielder but highly unstable.

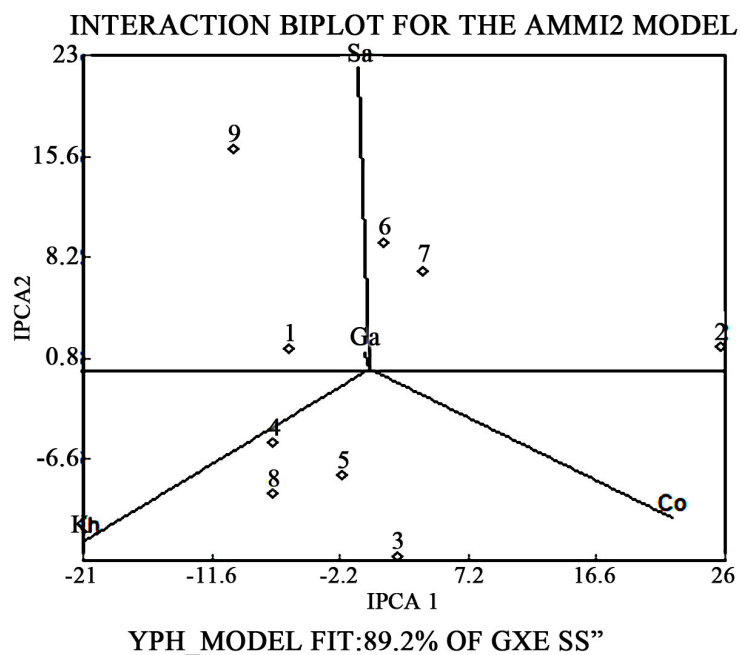


Figure 2. Biplot of the first AMMI interaction (IPCA2) score (Y-axis) plotted against AMMI interaction (IPCA1) (X-axis) of nine genotypes and four environments.

Since the IPCA2 scores also play a significant role in explaining the GEI, so, the IPCA1 scores were plotted against the IPCA2 scores for further exploring adaptation (**Figure 2**). According to **Figure 2**, the entry 9 (BAUS-03), 2 (BS-16), 3 (BS-18), 8 (BHS-01) were unstable due to their dispersed position. The genotypes 6 (BAUS-1), 1 (BS-11), 7 (BAUS-2), 5 (BS-14), 4 (BS-19) showed to be more stable when plotting the IPCA1 and IPCA2 scores. Genotypes with IPCA1 scores having near zero showed little interaction across environments while genotypes with very high IPCA1 values had considerable interactions across environments. The underlying causes of the interaction observed can therefore be based on both the genetic differences between these genotypes and the different environments [25].

4. Conclusion

Among the genotypes, BS-16, BHS-01, BS-18 and BAUS-01 exhibited the higher grain yield, $bi \sim 1$ and $S^2di \sim 0$ indicated that they were stable across the environment. The environment of Gazipur was unsuitable whereas Khulna, Satkhira and Cox's Bazar were favourable environments for mustard production in that season. Khulna was highly suitable for mustard cultivation followed by Satkhira and Cox's Bazar. The experiment could be repeated further for final conclusion.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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