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Analysis of G × E Interaction for Selection of Stable Wheat Genotypes for Grain Yield and Yield Traits in Northern Bangladesh

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Abstract

In the present study carried out, twelve wheat (*Triticum aestivium* L.) genotypes were evaluated for eight morphological traits at six different environments in northern part of Bangladesh, namely Panchaghar (E1), Thakurgaon (E2), Nilphamari (E3), Lalmonirhat (E4), Dinajpur (E5), and Rangpur (E6) during Rabi season 2020 to 2021, respectively. The data collected were subjected to variability and correlation analyses, followed by stability analysis using additive main effects and multiplicative interaction (AMMI) model, genotype and genotype × environment interaction effects (GGE) biplot. Variability was observed among the genotypes for the following traits *viz.*, plant height (cm), spike length (cm), number of tillers per plant, number of spikelets per spike, spike weight per plant, grains weight per spike (g), thousand seed weight (g) and grain yield (t/ha). Correlation analysis showed that the trait thousand seed weight was significantly associated with grain yield. The G × E was smaller than the genetic variation of grain yield as it portrayed the maximum contribution of genotypic effects (58.34%). GGE biplot showed E6 as a highly discriminating and representative environment. It also identified environment-specific genotypes viz., BARI Gom 32 for E6, BARI Gom 30 for (E2 and E4) and BARI Gom 26 for E1 were particular environment and the genotypes viz.,

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BARI Gom 21, BARI Gom 23, and BARI Gom 30 were highly suitable for all the six environments. The genotypes with minimum genotype stability index (GSI) viz., BARI Gom 21 (17), BARI Gom 23 (22), and BARI Gom 30 (25) were observed with wide adaptation and high yields across all the six environments. In summary, we identified stable genotypes adapted across environments for grain yield. These genotypes can be used as parent/prebreeding materials in future wheat breeding programs.

Keywords

GGE, AMMI, GSI, G × E Interaction, Wheat, Yield

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the major grain crops in the world and provides food for about two billion peopled [1]. It is grown on more than 200 million hectares of land worldwide, wheat is now the most widely cultivated cereal in the world, as well as one of the most important crops for global food security [2]. It is the primary source of carbohydrates along with essential minerals, vitamins, and lipids [3]. In order to meet the growing demand from an increasing world's population, there is a need to increase wheat productivity worldwide [4]. It has been predicted that the needs for wheat production will increase by 2050 due to the development of the industry and the acceleration of urbanization [5], and meet the food requirements of the global population, an additional 70% - 100% increase in food production is needed by 2050, with an increment of more than 4,400,000 t/year [6]-[8].

Bangladesh is primarily an agrarian economy with high population density, where food security remains a major concern [9]. Wheat is the second most important staple cereal after rice. Wheat consumption accounts for about 12% of total cereal consumption [10] and more than 80% of Bangladesh's wheat consumption is met through imports. The country imported 6.8 million tons of wheat in 2019 to meet the growing domestic demand [11]. With more than 6 million tons imported annually, Bangladesh has emerged as the fifth biggest importer of wheat in recent years [12]. Currently, wheat is cultivated on 0.35 million ha with production of 1.2 million ton [13]. Out of Bangladesh's 64 districts, Wheat is cultivated in 56 districts [14], with major concentration in the cooler north and northwest Rangpur and Rajshahi divisions. More than 49% of the total cropland in Bangladesh is classified as suitable for wheat cultivation, 25% as moderately to marginally suitable, and 26% as not suitable [15].

Today, more than ever, great attention has been paid to agro-ecological conditions and issues of climate changes [16] [17]. Constant striving to intensify agricultural production, excessive using of chemicals, fertilizers, as well as massive irrigation has led to degradation of arable land, pollution of the environment and significant climate change [18]. Additionally, stressful environmental conditions can contribute to a significant decrease in grain yield and quality. Consequently, biotic stresses such as pests and disease cause considerable damage to the crops. For example, susceptible genotypes with high disease severity have resulted in more than 30% of grain yield losses [19]. Therefore, increasing grain yield and yield stability have been prioritized by breeding programs to maintain wheat productivity. However, such a goal is challenged by the genotype-by-environment interaction (GEI) because a polygenic attribute like grain yield is controlled by numerous major and minor effect genes that interact with each other and the environment [20] [21].

Since the increment in one yield component might have a positive or negative effect on the other components, a large number of studies have been conducted to investigate the genetic basis of these traits of wheat. Breeders frequently use yield components to improve the grain yield, despite the fact that these components compensate each other in practice and an increase in one causes a decrease in the other [22] [23]. Grain yield is one of the complex quantitative traits, which has high environmental interaction. Hence, it is essential to carry out selection based on yield stability evaluation than average performance in multiple environmental conditions [24]-[26]. Genotype × environment interaction (GEI) is a major obstacle for the crop to attain full genetic gain [27]. One major step toward the development of improved crop genotypes is the assessment of the nature of interactions that exist between genotypes and the production environment for a particular trait [28]. Wheat yield depends on genetic and environmental factors and their interaction [29]. Differential genotypic responses to different environments are collectively called genotype-by-environment interaction [30]. To study this effect, several techniques have been employed to estimate the effect of yield and yield related traits across different environments. The use of stability parameters was confirmed to exploit interaction effect of genotypes grown in diverse environment.

Statistical tools such as the Additive Main Effect and Multiplicative Interaction (AMMI) [31] and genotype and genotype-by-environment interaction (GGE) biplot analyses [32] [33] have been reported as appropriate for use in GEI analyses. The AMMI is one of the most widely used and powerful approaches to the analysis of genotype-by-environment interaction. It can be used to understand and structure interactions between genotypes and environments. The AMMI model combines analysis of variance (ANOVA) to test the main effects of both genotypes (G) and environments (E) and principal components analysis (PCA) to analyse the residual G × E interaction (GEI) component. It separates G, E and GEI as is required for most agricultural research purposes.

The AMMI is ordinarily the model of choice when the main effects and interactions are both important, which is the most common case with yield trials [34] [35]. Applications of the AMMI model to yield trials have been used during the last two decades and there have been several recent review articles [36] [37]. Previous G × E studies on several traits have demonstrated that wheat genotypes is sensitive to environmental changes. According to Popović *et al.* [37]; Spanic *et al.* [38]; Ljubičić *et al.* [39]; Plavšin *et al.* [40] changes in environmental conditions have been reported to affect wheat genotypes there yield and agronomic traits. Although the main aim of this investigation was to follow the stability of genotypes, from the wheat breeding view it was very important to consider which wheat genotypes reacted favorably to the environments. With this background knowledge, the objectives of this study were to: 1) determine the relative contributions of the genotype, environment and their interaction in eight important agronomic traits with grain yield of twelve wheat genotypes using AMMI models; 2) identify the high yielding and stable wheat genotype across different environment and to; 3) identify the best suitable genotypes for across environments and for a particular environment, based on grain yield across the Rangpur division in northern part of Bangladesh.

2. Materials and Methods

2.1. Environments of Experimental Sites

Field experiments were conducted at six different environments in the Rangpur Division, Northern part of Bangladesh, namely, Panchaghar (E1) (26˚20'N latitude and 88˚34'E longitude), Thakurgaon (E2) (26˚03'N latitude and 88˚46'E longitude), Nilphamari (E3) (25˚98'N latitude and 88˚91'E longitude), Lalmonirhat (E4) (25˚91'N latitude and 89˚45'E longitude), Dinajpur (E5) (25˚37'N latitude and 88˚39'E longitude), and Rangpur (E6) (25˚44'N latitude and 89˚15'5.98"E longitude) during Rabi season 2020 to 2021, respectively. The environments E1, E2, E3, E4, E5 and E6 are popular wheat growing regions that fall under different agroecological zones of Rangpur Divisions viz., Old Himalayan Piedmont Plain (AEZ 1), Active Tista Floodplain (AEZ 2), Tista Meander Floodplain (AEZ 3), High Barind Tract (AEZ 26) and North Eastern Barind Tract (AEZ 27) in Bangladesh (**Figure 1**). Details of the soil and meteorological conditions during the crop growth period are presented in **Table 1**.

2.2. Plant Materials and Experimental Design

Twelve wheat genotypes were used in this study (**Table 2**). Seeds of these wheat genotypes were obtained from the Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur, Bangladesh. The field trial was conducted using a randomized complete block design (RCBD) with three replications in each environment. Establishment and management of the experiment land were prepared by conventional ploughing three times through a power tiller for fine tilth and the basal fertilizer of 100 kg N + 80 Kg P_2O_5 + 20 Kg K_2O + 60 kg $CaSO_4 \cdot 2H_2O$ + 3 t/ha organic manure (FYM) was applied. Each genotype was planted in each environment had six rows of 2.5 m long spaced 20 cm apart with a plot area of 1.2 m × 2.5 m (3 m^2). Initial germination and seed moisture content were 97% and 10%, respectively, and these were determined as defined by ISTA [41].

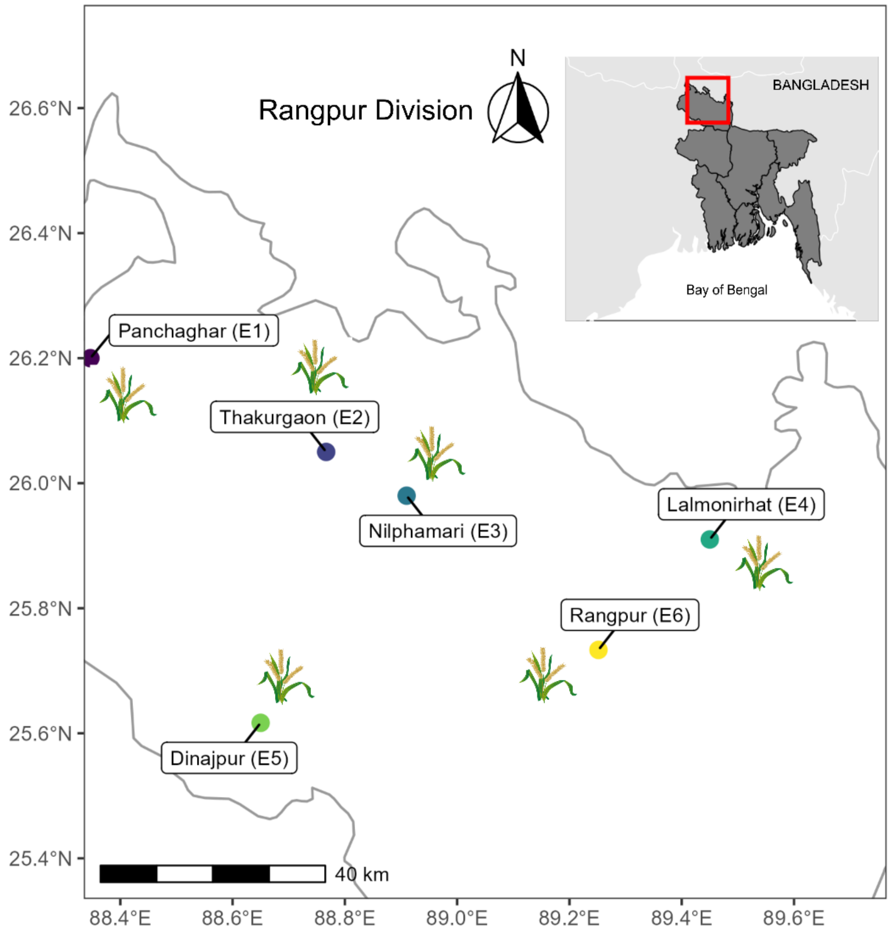

Figure 1. Spatial distribution of field experiment locations across Rangpur Division. Six districts were utilized as experimental sites: Panchaghar (E1), Thakurgaon (E2), Nilphamari (E3), Lalmonirhat (E4), Dinajpur (E5), and Rangpur (E6), representing the agro-ecological diversity of the region. Map coordinates range from 88.4˚E to 89.6˚E longitude with a 40 km scale reference.

Table 1. Weather parameters during the Rabi season 2020-2021.

Environments	Soil type	Months	Temperature (˚C)			Rainfall (mm)	Rainy days	Humidity (%)	Pressure (mb)
			Max	Min	Mean				
Panchaghar (E1)	Sandy loam to Sand (pH: 5.5 - 6.5)	Nov-20	28.21	19.34	25.21	1.7	4	57	1016.2
		Dec-20	25.42	17.05	22.17	2.3	3	55	1015.3
		Jan-21	25.07	16.22	22.15	5.2	2	48	1014.1
		Feb-21	29.05	18.24	25.27	0.7	1	34	1014.1
		Mar-21	35.31	21.41	30.33	7.1	3	25	1010.7
		Mean	28.61	18.45	25.02	3.40	2.60	43.80	1014.08
Thakurgaon (E2)	Clay loam to Sandy loam (pH: 6.2 - 6.7)	Nov-20	30.22	20.14	26.34	4.6	3	56	1014.6
		Dec-20	27.51	18.12	23.41	0.0	0	49	1014.6
		Jan-21	28.12	17.14	23.31	0.2	0	44	1013.6
		Feb-21	31.11	18.28	26.26	0.6	1	33	1013.2

Continued

		Mar-21	37.07	21.25	31.09	2.3	2	24	1008.9
		Mean	30.80	18.98	26.08	1.54	1.20	41.20	1012.98
Nilphamari (E3)	Fine sandy loam to fine sand (pH: 5.1 - 6.0)	Nov-20	30.31	21.71	26.34	3.8	4	67	1012.7
		Dec-20	29.11	19.21	25.42	0.0	0	54	1013.4
		Jan-21	29.05	19.11	25.21	4.0	1	48	1012.4
		Feb-21	31.19	19.26	26.09	0.0	0	47	1012.1
		Mar-21	34.19	23.08	30.13	1.8	4	63	1009.1
		Mean	30.77	20.47	26.63	1.92	1.80	55.80	1011.94
Lalmonirhat (E4)	Sandy loam to coarse sandy loam (pH: 5.7 - 6.0)	Nov-20	28.15	19.24	24.11	8.9	3	61	1013.9
		Dec-20	27.12	17.02	23.62	1.9	2	51	1014.1
		Jan-21	27.01	16.43	23.16	1.0	1	44	1013.2
		Feb-21	32.17	18.21	26.11	0.1	0	32	1012.6
		Mar-21	37.31	21.19	31.24	3.5	3	26	1008.2
		Mean	30.35	18.41	25.64	3.08	1.80	42.80	1012.4
Dinajpur (E5)	Fine sandy loam to loamy sand (pH: 4.8 - 5.2)	Nov-20	30.19	20.41	26.37	4.7	3	87	1013.7
		Dec-20	28.01	18.41	24.31	0.0	0	47	1014.0
		Jan-21	29.24	17.18	24.27	0.0	0	42	1013.2
		Feb-21	32.12	18.71	27.01	0.6	2	33	1012.5
		Mar-21	38.42	23.14	32.71	0.5	2	23	1007.8
		Mean	38.42	23.14	32.71	0.5	2.00	23.00	1007.8
Rangpur (E6)	Loam to loamy Sand (pH: 4.6 - 5.6)	Nov-20	31.12	21.72	27.18	3.3	3	60	1012.3
		Dec-20	29.91	19.52	25.11	0.0	0	50	1013.1
		Jan-21	29.17	19.22	25.01	2.3	2	42	1012.1
		Feb-21	32.44	19.05	27.66	0.1	1	37	1011.5
		Mar-21	38.14	2.34	32.73	7.5	8	46	1007.8
		Mean	32.15	16.37	27.53	2.64	2.80	47.00	1011.36

Table 2. Description (background information) of twelve wheat genotypes used for the study.

Codes	Genotypes	Cross/Pedigree	BAW	Release	Maturity	Yield
			no.	year	d	t/ha
G1	BARI Gom 31	KAL/BB/YD/3/PASTOR	1182	2017	104 - 109	4.5 - 5.0
G2	BARI Gom 32	SHATABDI/GOURAB	1202	2017	95 - 105	4.6 - 5.0
G3	BARI Gom 29	SOURAV/7/ KLAT/SOREN//PSN/ 3/BOW/4/VEE#5. 10/5/CNO 67/ MFD// MON/3/ SERI/6/NL297	1151	2014	105 - 110	4.0 - 5.0
G4	BARI Gom 30	BAW 677/Bijoy	1161	2014	100 - 105	4.0 - 5.5
G5	BARI Gom 28	CHIL/2*STAR/4/BOW/ CROW//BUC/ PVN/3/2*VEE#10	1141	2012	102 - 108	4.0 - 5.5
G6	BARI Gom 27	WAXWING*2/VIVISTI	1120	2012	105 - 110	3.5 - 5.4

Continued

G7	BARI Gom 25	ZSH 12/HLB 19// 2* NL297	1059	2010	102 - 110	3.8 - 5.0
G8	BARI Gom 26	ICTAL 123/3/RAWAL 87//VEE/HD 2285	1064	2010	104 - 110	4.0 - 5.0
G9	BARI Gom 23 (Bijoy[a])	NL297*2/LR25	1006	2005	103 - 112	4.3 - 5.0
G10	BARI Gom 24 (Prodip[a])	G. 162/BL 1316//NL 297	1008	2005	102 - 110	4.3 - 5.1
G11	BARI Gom 21 (Shatabdi[a])	MRNG/BVC//BLO/PVN/3/PJB 81	936	2000	105 - 110	3.6 - 5.0
G12	BARI Gom 19 (Sourav[a])	NAC/VEE (NL 560)	897	1998	102 - 110	3.5 - 4.6

[a]Names in parenthesis represents the local names of the released variety; BAW, Bangladesh advanced wheat accession; d, day; no., number; t/ha, ton per hectare.

2.3. Agronomic Practices and Data Collection

Agronomic practices and plant protection measures accomplished throughout the crop growth period as per the local farmer's practices and irrigation (3 times) was applied. The morphological observations were recorded on 20 randomly selected plants in each genotype and each environment with three replications based on the descriptors of wheat [42]. The traits viz., plant height (cm), spike length (cm), number of tillers per plant, number of spikelets per spike, spike weight per plant, grains weight per spike (g), thousand seed weight (g) and grain yield (t/ha) were recorded. The mean data used in the analysis was the average value of each genotype from each environment with three replications.

2.4. Statistical Analysis

The mean data of 20 randomly selected plants in each genotype for each trait were used for determining the range and overall mean of each environment. Correlation between grain yield and other yield attributing traits in each environment were performed using SPSS 16.0 version (SPSS. Inc USA, 2007). The G × E SPSS output consists of ready-to-use input files in R-package for multivariate analysis and univariate stability results. The morphological trait was subjected to analysis of variance (ANOVA) to determine phenotypic variations among the genotypes, locations, genotype by location using R-package. Simple correlation coefficients were determined using Spearman's rank (a simplified version of R statistical software) developed by the R Core Team [43]. The Graphical user interface (GUI) package of R studio was used for GGE biplots, consisting of two concepts, the biplot concept [44] and the GGE concept [45]. The GGE biplots are a graphical picture to illustrate G × E interaction and genotype ranking based on mean and stability. The graph generated is based on mega environment evaluation (which-won-where pattern), Genotype evaluation (mean versus stability), and tested environment raking (discriminative versus representative). The GGE biplots were constructed using the first and second principal components (PC1 and PC2) that were derived by subjecting environment-centered means grain yield to singular value decomposition. The options used for data analysis were environment centering (Centering = 2), no standardization (Scale = 0) and no transformation

(Transform = 0). The biplot was based on environment-focused singular-value partitioning (SVP = 2), which is suitable for picturing the relationships among the genotypes and locations.

The AMMI stability value (ASV) was calculated by the method formulated by Purchase *et al.* [46].

$$AVS = \sqrt{\left[\frac{SS_{PC1}}{SS_{PC2}}\left(PC_1\right)\right]^2 + \left(PC_2\right)^2}$$

where SS represents the sum of squares of first (PC_1) and second (PC_2) interaction principal component axes; and PC_1 and PC_2 are the genotypic scores obtained from the AMMI model.

Genotype selection index (GSI) was obtained by following the method devised by Farshadfar and Sutka [47].

$$\text{GSI}_i = \boldsymbol{RY}_i + \boldsymbol{RASV}_i$$

where GSI_i denotes the genotype selection index for i^{th} genotype, RY_i is rank of mean grain yield for i^{th} genotype, $RASV_i$ represents rank for the AMMI stability value for the i^{th} genotype.

GGE analysis was performed using the software GEA-R version 4.1 Angela *et al.* [48] with the model equation:

$$Y_{ij} - \mu + G_i + E_i + \sum \lambda_k \alpha_{ik} \gamma_{jk} + e_{ij}$$

where Y_{ij} is the yield of i^{th} genotype in the j^{th} environment; G_i and E_j represent the genotype and environment deviations from the grand mean, respectively; μ denotes the grand mean λ_k is the eigenvalue of the PCA axis k; α_{ik} and γ_{jk} indicate the genotype and environment PC scores, respectively, for the axis k and e_{ij} denotes the error term.

3. Results

Analysis of variance showed significant difference among all the morphological traits under study. The variation in grain yield and yield traits is presented in **Table 3(a)**, **Table 3(b)**. The mean of plant height ranged from 93.3 cm (E4) to 98.4 cm (E6). The trait days to spike length varied from 9.75 cm (E4) to 11.5 cm (E1). The environment E5 showed minimum mean value for number of tillers per plant (6.13) whereas E6 expressed maximum mean of 6.75. The mean of number of spikelets per spike ranged from 17.4 (E2) to 20.4 (E1). The mean of spike weight per plant varied from 2.25 g (E3) to 2.71 g (E1), and mean of grains weight per spike observed in 1.73 g (E5) to 2.03 g (E1). The trait thousand seed weight recorded minimum mean of 51.1 g (E2) to a maximum of 53.5 g (E6). Grain yield ranged from a minimum mean of 3.75 t/ha in E5 to a maximum of 3.81 t/ha in E4. The genotypic correlations between grain yield and other morphological traits in wheat across six environments are given in **Table 4**. Among the 168 associations, 56 were having significant positive association, while 35 were having significant negative association. The trait thousand seed weight was identified as the important yield attributing trait that showed highly significant positive association with grain yield in all the six tested environments. The stability analyses were carried out for grain yield in six environments viz., Panchaghar (E1), Thakurgaon (E2), Nilphamari (E3), Lalmonirhat (E4), Dinajpur (E5), and Rangpur (E6).

Table 3. (a) Mean and range of grains yield and morphological traits of wheat in E1, E2 and E3 environments. (b) Mean and range of grains yield and morphological traits of wheat in E4, E5 and E6 environments.

(a)

Characters	Panchaghar (E1)			Thakurgaon (E2)			Nilphamari (E3)		
	Mean ± SE	Min	Max	Mean ± SE	Min	Max	Mean ± SE	Min	Max
PH	94.0 ± 2.48	38	111	93.4 ± 1.51	77	128	95.0 ± 0.93	82	103
SL	11.5 ± 0.19	10	13.8	10.3 ± 0.27	6.2	13.6	10.4 ± 0.25	7.4	13.6
NOT	6.58 ± 0.21	4.0	9.0	6.52 ± 0.28	4.0	11.0	6.25 ± 0.28	3.0	9.0
NOS	20.4 ± 0.23	16.8	23.2	17.4 ± 0.48	10.7	22.5	19.5 ± 0.56	13.1	25.2
SW	2.71 ± 0.12	1.55	4.41	2.51 ± 0.13	0.69	4.39	2.25 ± 0.10	1.08	3.84
GW	2.03 ± 0.10	1.00	3.55	1.93 ± 0.12	0.45	3.55	1.82 ± 0.08	0.70	2.90
TSW	51.2 ± 1.01	38.4	62.9	51.1 ± 1.00	39.8	61.2	51.6 ± 0.74	39.5	60.2
GY	3.78 ± 0.07	2.79	4.42	3.77 ± 0.06	2.87	4.46	3.78 ± 0.07	2.59	4.42

(b)

Characters	Lalmonirhat (E4)			Dinajpur (E5)			Rangpur (E6)		
	Mean ± SE	Min	Max	Mean ± SE	Min	Max	Mean ± SE	Min	Max
PH	93.3 ± 1.55	62	108	97.5 ± 1.93	71	120	98.4 ± 1.91	58	110
SL	9.75 ± 0.22	7.2	12.6	11.0 ± 0.20	8.8	13.2	10.5 ± 0.16	8.3	12
NOT	6.38 ± 0.22	3.0	9.0	6.13 ± 0.27	3.0	9.0	6.75 ± 0.27	4.0	10.0
NOS	17.9 ± 0.35	14.4	22.3	19.6 ± 0.35	16.3	26.3	18.5 ± 0.26	15.5	21.4
SW	2.60 ± 0.13	0.41	4.39	2.43 ± 0.16	0.63	4.26	2.59 ± 0.13	0.59	3.93
GW	1.92 ± 0.10	0.19	3.35	1.73 ± 0.11	0.42	3.05	1.82 ± 0.12	0.22	2.92
TSW	52.3 ± 0.92	38.4	60.2	51.2 ± 0.83	38.4	60.1	53.5 ± 0.90	38.4	62.4
GY	3.81 ±0. 06	2.87	4.42	3.75 ± 0.07	2.87	4.42	3.76 ± 0.05	2.88	4.16

E1, Panchaghar; E2, Thakurgaon; E3, Nilphamari; E4, Lalmonirhat; E5, Dinajpur; E6, Rangpur; SE, Standard Error; Min, Minimum; Max, Maximum; PH, Plant height (cm); SL Spike length (cm); NOT, Number of tillers per plant; NOS, Number of spikelets per spike; SW, Spike weight per plant; GW, Grains weight per spike (g); TSW, Thousand seed weight (g); GY, Grain yield (t/ha).

Table 4. Genotypic correlations between grain yield and morphological traits in wheat genotypes.

	E	PH	SL	NOT	NOS	SW	GW	TSW	GY
PH	E1	1							
	E2	1							
	E3	1							
	E4	1							
	E5	1							
	E6	1							

Continued

SL	E1	0.741**	1						
	E2	−0.503	1						
	E3	0.687*	1						
	E4	−1.476**	1						
	E5	0.548*	1						
	E6	0.812*	1						
NOT	E1	0.757**	0.841**	1					
	E2	−5.520 **	0.574	1					
	E3	−3.102*	0.712**	1					
	E4	0.638*	0.689*	1					
	E5	0.144	−0.235	1					
	E6	−2.547	−0.316	1					
NOS	E1	1.413**	0.050	1.915**	1				
	E2	−0.827**	0.988**	0.581*	1				
	E3	−0.622*	0.859**	0.128**	1				
	E4	−1.068**	1.342**	0.399	1				
	E5	−0.943**	0.537*	−0.813**	1				
	E6	2.348*	−1.221**	−2.222**	1				
SW	E1	0.374	0.571	−0.159	1.191**	1			
	E2	−2.194**	0.004	1.293**	0.604*	1			
	E3	0.914**	0.104	−0.574*	−0.272	1			
	E4	−1.084**	0.688*	0.092	0.343	1			
	E5	0.567	0.241	−1.266**	0.142*	1			
	E6	−1.484**	0.457*	0.124*	−0.124*	1			
GW	E1	0.240	0.255	0.025	1.282**	1.001**	1		
	E2	−0.631	0.189*	0.117	−0.547*	0.821*	1		
	E3	0.202	0.091	−0.541	−0.192	1.016**	1		
	E4	−1.194**	0.640*	−0.354	0.262	0.987**	1		
	E5	0.725	1.862**	0.421*	0.721*	−1.266**	1		
	E6	−0.434	0.541	0.227*	0.457**	2.847*	1		
TSW	E1	0.167	0.309	0.954**	−1.041**	−0.990**	−0.975**	1	
	E2	−0.571*	2.187	0.387**	3.0587*	−0.584**	1.266**	1	
	E3	−21.929*	5.845**	7.814*	2.115**	16.817*	21.034*	1	
	E4	0.889**	−0.701*	−1.069**	−0.299	−0.383	0.476	1	
	E5	−0.329	0.548	−2.591**	1.195**	8.254*	6.254**	1	
	E6	0.903**	2.584**	2.468*	−0.215*	−0.551	−0.070	1	
GY	E1	−0.035	−0.383	0.055	0.250	−0.029	−0.032	−0.326	1
	E2	0.240	−0.243	−0.677*	−0.150	−0.287	0.211	−0.261	1
	E3	−1.074**	−0.039	0.841	0.189	−0.556	−0.527	−2.932**	1
	E4	−0.556	0.121	−1.101**	−0.100	−0.203	0.199	1.288**	1
	E5	0.628*	0.022	−1.018**	−0.048	−0.502	−0.302	−0.531	1
	E6	2.528**	−0.117*	0.421*	0.420	0.232	0.110	2.095**	1

E1, Panchaghar; E2, Thakurgaon; E3, Nilphamari; E4, Lalmonirhat; E5, Dinajpur; E6, Rangpur; PH, Plant height (cm); SL Spike length (cm); NOT, Number of tillers per plant; NOS, Number of spikelets per spike; SW, Spike weight per plant; GW, Grains weight per spike (g); TSW, Thousand seed weight (g); GY, Grain yield (t/ha). Values are presented as mean ± SD. Significance was determined by one-way ANOVA with Dunnett's post-hoc test. **p < 0.05, **p < 0.01, ***p < 0.001.

3.1. Analysis of Stability for Grain Yield

Analysis of Variance AMMI analysis of variance for pooled mean grain yield of 12 genotypes from six environments (E1, E2, E3, E4, E5 and E6) explained that the major portion of the total sum of squares contributed by genotypic effects (58.34%) followed by GEI effects (24.55%) and environmental effects (17.10%) (**Table 5**). AMMI ANOVA revealed significant differences among 12 wheat genotypes and six environments. This depicts that the grain yield of wheat influenced by genotype (G), environment (E) and the interaction between genotype and environment (GEI). AMMI analysis further partitioned the GEI into the first two multiplicative terms namely PC1 and PC2 with a contribution of 40.80% and 29.70% of GEI sum of squares. The presence of a significant proportion of GEI necessitates the analysis of the stability of wheat genotypes over environments.

Table 5. AMMI analysis of variance for mean grain yield of 12 wheat genotypes from six different locations during Rabi season 2020-2021.

	Sum of squares	Degrees of freedom	Mean sum of squares	F-value	Explained (%)
Environment	0.0740	5	0.0148	0.10	17.10
Genotype	2.3683	11	0.2153	2.13	58.34
Environment × Genotype	22.817	55	0.4148	3.30	24.55
PC1	9.3200	15	0.6213	6.36	40.80
PC2	6.7680	13	0.5206	9.53	29.70
PC3	0	38	0	0	00

3.2. Alliance of Trial Environments

Grain yield analysis of wheat revealed that the average environment means ranged from 3.75 t/ha (E5) to 3.81 t/ha (E3). Seven genotypes showed above-average yield in the E1 environment. Six genotypes in E2, ten genotypes in E3, and nine genotypes in the E4, E5 and E6 environment outperformed the average yield of the corresponding genotypes in a particular environment (**Table 6**). The present study showed that the environment E1 was found with the longest vector having more discriminating power compared to the other five environments. The Average Environment Axis (AEA) view compared the environments in relation to an ideal environment. The environment E1 had the smallest angle with the AEA, hence the E1 environment is highly representative. The Average Environment Coordinate (AEC) axis projected the stability of the accessions. The highly stable genotypes indicated by a small perpendicular line to the AEC axis whereas the increase in the length of the perpendicular line denoted the decrease in stability of the genotypes. Genotypes (G5, G2, G12 and G11) were highly stable with low to good yielding ability. The genotype G4 was highly unstable because it was far away from the AEC axis followed by G10, G8 and G6. These genotypes expressed good yielding ability (**Figure 2**).

3.3. Response of Varied Adaptation to Genotype

AMMI analysis showed the interaction component PC1 with 40.8% of the total interaction sum of squares, whereas PC2 attributed for 29.7%. The performance of genotypes in a specific environment, as well as the overall performance across all the test environments, can be effectively analyzed in the presence of two or more PCA axes. PC1 scores for grain yield over six locations were plotted against genotype and environment scores along with the environments (E1, E2, E3, E4, E5 and E6) (**Figure 2**). The genotypes plotted on right side of the central axis formed based on grand mean, exhibited high yield compared to those on the left side of the axis. Four genotypes (E4) exhibited the above-average performance with positive interaction effect were present in the quadrant I. Three genotypes in the quadrant IV also showed the above-average performance but having a negative interaction effect. About two genotypes along with the environment E5 falling under quadrant II showed below-average performance with a positive interaction effect. The environment E3 is between quadrant (I and II), E1, E2 and E6 is between quadrant III and IV. About three genotypes present in quadrant III also exhibited below-average performance with negative interaction. About five genotypes having PC1 score nearer to zero as it exhibited between −0.13 to 0.30 (**Table 6**) which were stable across all the test environments (E1, E2, E3, E4, E5 and E6). A set of four genotypes found to be less stable as it explained moderately larger scores.

Table 6. Mean grain yield, AMMI stability value (ASV) and genotype selection index (GSI) of wheat accessions.

Codes	Genotypes	E1	E2	E3	E4	E5	E6	Mean	PC 1 scores	PC 2 scores	ASV	GSI
G1	BARI Gom 31	3.85	3.50	4.10	3.80	3.79	3.58	3.77	0.58	0.32	1.26	98
G2	BARI Gom 32	4.01	3.97	2.82	3.89	2.95	3.77	3.56	-0.39	-0.21	0.85	50
G3	BARI Gom 29	4.29	3.83	3.80	3.72	3.79	3.84	3.87	0.47	0.93	1.36	55
G4	BARI Gom 30	2.88	3.90	3.82	4.23	3.97	3.55	3.72	-0.25	-0.25	0.58	25
G5	BARI Gom 28	3.74	3.70	3.92	4.08	3.69	3.77	3.81	-0.41	0.05	0.86	36
G6	BARI Gom 27	4.06	3.97	4.05	2.95	4.06	3.84	3.82	0.61	-0.45	1.36	92
G7	BARI Gom 25	3.59	4.24	3.81	3.95	4.17	3.93	3.94	0.81	-0.07	1.71	99
G8	BARI Gom 26	3.98	2.95	4.00	3.97	3.42	3.26	3.59	-0.56	0.02	1.18	75
G9	BARI Gom 23 (Bijoy[a])	4.14	3.79	3.67	3.55	3.84	3.79	3.79	-0.20	-0.14	0.44	22
G10	BARI Gom 24 (Prodip[a])	2.99	3.97	4.07	3.87	3.93	3.97	3.80	-0.13	-0.16	0.32	45
G11	BARI Gom 21 (Shatabdi[a])	3.74	3.66	4.38	3.90	3.54	3.85	3.84	-0.07	-0.22	0.26	17
G12	BARI Gom 19 (Sourav[a])	3.97	3.75	2.95	3.83	3.88	4.01	3.73	0.30	-0.36	0.73	58
	Mean checks	3.77	3.76	3.78	3.81	3.75	3.76					

[a]Names in parenthesis represents the local names of the released variety; E1, Panchaghar; E2, Thakurgaon; E3, Nilphamari; E4, Lalmonirhat; E5, Dinajpur; E6, Rangpur.

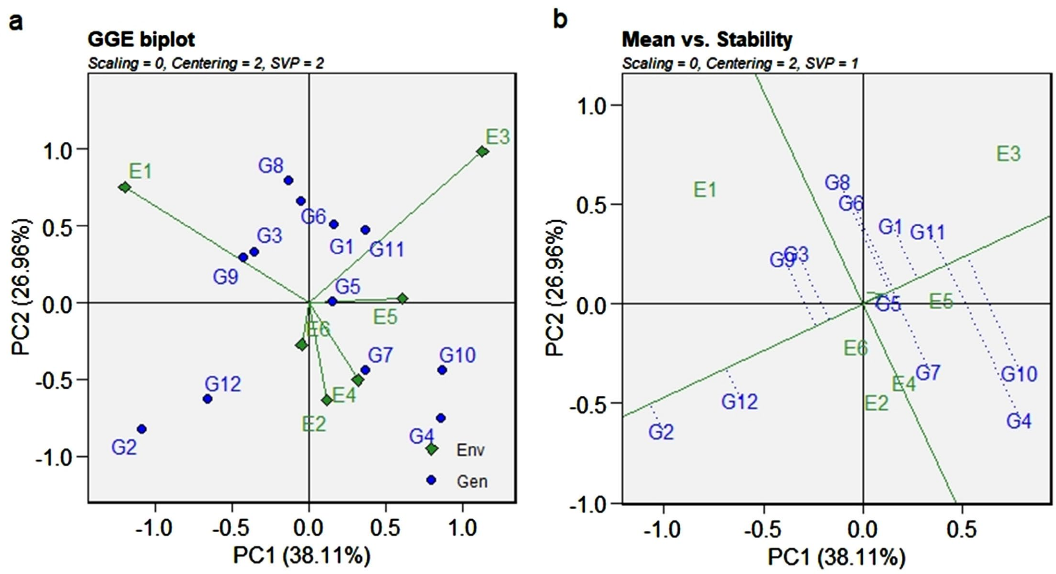

Figure 2. (a) GGE biplot based on environment focused scaling for the comparison of six environments in relation to average environment axis (AEA). (b) Average Environment Coordination (AEC) view based on environment focused scaling for the pooled mean performance and the stability of 12 wheat genotypes.

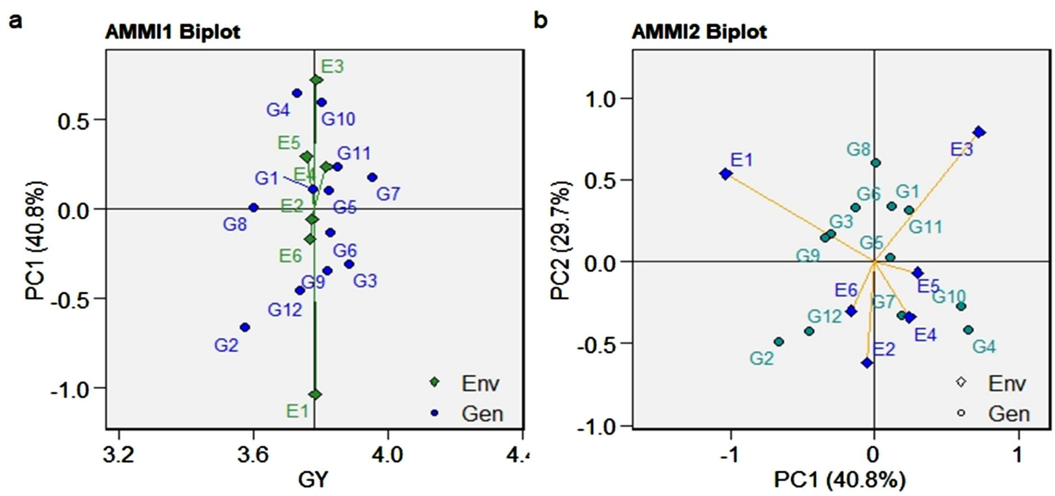

Figure 3. (a) AMMI1 biplot showing main effects and PC1 interaction effects of 12 wheat genotypes and six environments on grain yield (GY) of wheat. (b) AMMI2 biplot of first two principal components (PC1 vs PC2) of interaction effects.

For the maximum exploration of GEI, the PC1 scores visualized against PC2 in the form of a graph (**Figure 3**). The three genotypes with PC2 value ranging between −0.07 to 0.05 located nearer to the center of the biplot, produced highly stable grain yield across all the test environments. Three genotypes fall under medium stable genotypes category which surrounded the highly stable genotypes in the graph. The highly unstable six genotypes that were far away from the center, had also been identified from the biplot. Furthermore, the biplot showed a highly interactive environment as E6 and E2 as well as the genotypes (G2 and G4) that contributed largely to the GEI. The genotypes G8, G1 and G11 particularly performed well in E1 and E3. The genotypes G7 and G10 were particularly adapted to E4 and E5, whereas the genotype G2 (E6 and E2) and G4 had more interaction with E4 and E5. According to ASV, the genotypes close to 0 (G11, G10 and G9) were highly stable, whereas the genotypes having high value (G7, G6, G3, and G8) were found to be highly unstable (**Table 6**). GSI integrates both yield and stability across environments. Genotypes with lower GSI (G11, G9, and G4) were desirable since they combine high mean yield performance with stability.

3.4. Genotype and Genotype by Environment (GGE) Biplots

The GGE biplot analyses (which-won-where, genotype ranking, discriminativeness, representativeness and relationship among environments) for grain yield (**Figures 4(a)-(d)**). **Figure 4(a)** shows the which-won-where grain yield performance of the wheat genotypes evaluated in the six environments. Locating the most suitable accession for each environment can be done by which-won-where pattern analysis. In this, a polygon is produced by joining the genotypes far away from the origin consisted of all the other genotypes inside the polygon. The polygon is further portioned into five different sectors using the rays (dot line) that were starting from biplot origin and passing perpendicular to the sides of the polygon. The genotypes in a sector are similar in performance compared to the genotypes in other sectors. E3 and E5 environment is more suitable for the following genotypes viz., G11 and G5 which are located in the different sector whereas the environment E2 and E4 is highly desirable for G4 and G10. The sector that consisted of the E1 environment contained G8, G6, and G1 genotypes thus portraying that the E1 environment is highly suitable for the expression of most of the genotypes. Few of those genotypes that highly performed in E6 were G2, and G12. The genotypes plotted at each vertex of the polygon were the best performing genotype to the environment nearer to the vertex. In this case, G2, G4, G10, G11, and G8 were the peak genotypes that are highly suitable for the environments E1, E2, E3, E4, E5, and E6 respectively.

An ideal genotype should have both high mean performance and high stability across environments. The center of the concentric circle (**Figure 4(b)**) is the location for the ideal genotype. Among the test genotypes, the one closest to the point is the best. However, G11 had the highest grain yield among the 12 genotypes; G1 that possessed both high mean grain yield and high stability is closest to the ideal genotype for grain yield with consistency of performance across environments. The 'discrimination and representativeness' view (**Figure 4(c)**) have the graphical ability to unravel the discriminating ability and representativeness present among the six test environments. The plot is more relevant for genotypes evaluation as it was constructed by genotype-metric preserving (SVP = 2). Thus, genotypes G7 (BARI Gom 25) had maximum yield across environments followed by G4 (BARI Gom 30), G11 (BARI Gom 21), G6 (BARI Gom 27) and G5 (BARI Gom 28) while G10 (BARI Gom 24) followed by G9 (BARI Gom 23), and G1 (BARI Gom 31) were recorded lowest yields. Thus, genotypes G2 (BARI Gom 32) and G4 (BARI

Gom 30) were showed more variability *i.e.* highly unstable whereas entry G12 (BARI Gom 19) and G8 (BARI Gom 26) were more stable. The GGE-biplot approach, which was based on environment focused scaling, was used to estimate the relationships between the environments (**Figure 4(d)**). This GGE biplot approach suggested that E2 and E6 were the most closely correlated environments with E6 and E5 closely behind. However, the largest correlation coefficients were between E3 between E1. Some contradictions between the figures and actual correlations were predictable because the biplot did not estimate 100% of the GGE variation.

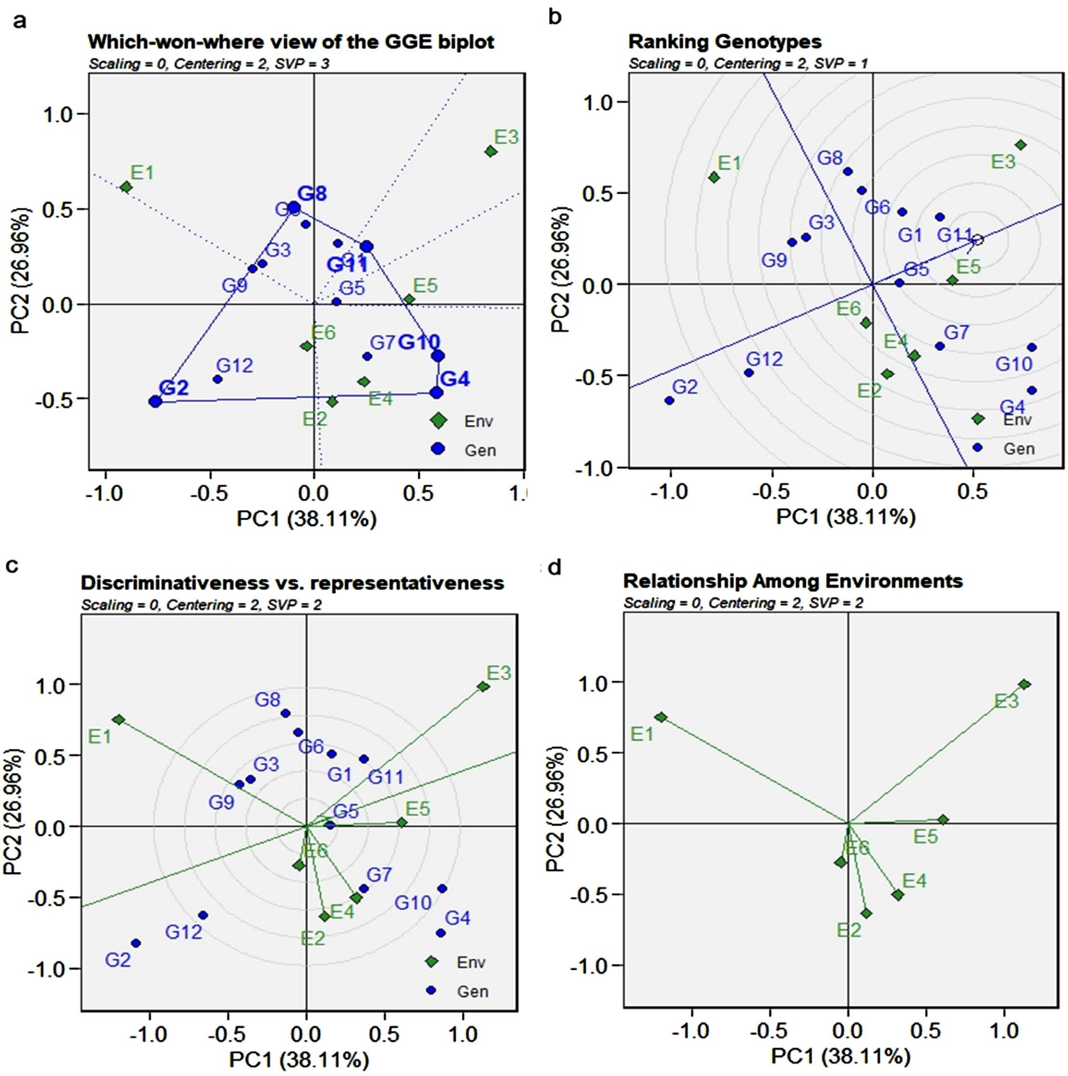

Figure 4. GGE Biplot for root yield indicating (a) superior genotype in a particular environment (b) ranking of genotypes (c) discriminativeness vs. representativeness (d) relationship among environments.

4. Discussion

In the present study, there existed considerable trait variation among the 12 wheat genotypes studied, besides thousand seed weight was identified as the key character for yield increase in wheat. The grain yield performance of 12 wheat genotypes were evaluated in six different environments [Panchaghar (E1), Thakurgaon (E2), Nilphamari (E3), Lalmonirhat (E4), Dinajpur (E5), and Rangpur (E6)] of Rangpur Division, Northern part of Bangladesh for the identification of stable genotypes adapted across environments. The selected environments for our study are popular wheat growing regions that fall under five different agro-ecological zones of Rangpur Division. The selection for yield improvement is a complex phenomenon, should be decided in accounting genotypes along with the environmental interactions. Stability models help in studying the G × E interaction and assists in identifying the specifically and generally adapted genotypes for particular and all the test environments, respectively [35] [44]. The best performing and most stable accessions identified will be utilized for prebreeding purpose to develop promising wheat genotypes. GGE biplot investigated the G × E interaction in a more precise manner. In the present study, the cosine of the angle between all the environments was higher than 90◦ indicating the negative association among the environments. On the contrary, Yan and Kang [32] reported a positive correlation between two environments. This negative correlation between environments depicts the presence of high cross over G × E interaction. The ability of any test environment can be visualized with the aid of discriminating power and representativeness view of the environment [49]. The length of the environment vectors is proportional to the standard deviation within the respective environments on the biplot and displays the discriminating ability of the environments [33].

The environment E6 was more discriminating in comparison with the other five environments. The representativeness of the environments can be assessed in the presence of AEA. The E6 environment was designated as the most representative environment. In the view of discriminating power and representativeness, the generally adapted genotypes will be selected from the environment E6, whilst the specifically adapted genotypes will be selected from environments E1, E2, E3, E4, and E5. The results of discriminating ability and representativeness were in line with the reports of Kaya and Akcura [50] and Nehe *et al.* [51] in wheat. The highly stable genotypes viz., G5, G3, G6, G9, and G7 identified concerning AEC and showed low to better yielding ability. The genotypes G4, G10, G11, and G2 were highly unstable as located far away from the AEC, exhibited good yielding ability. The results were in accordance with the interpretation of Taghouti *et al.* [52] in wheat. According to which-won-where pattern analysis, G4, G8, and G2 were the vertex cultivars in E1, E2, E3, E4, E5, and E6 environments, respectively for expressing the better yielding ability. The promising performance of vertex genotypes in the desired environment was also been reported by Kaya *et al.* [50] in wheat. AMMI results revealed the major contribution of the genotypic effects followed by GEI effects and environmental effects. The high value in PC1 was sufficient to study the total G × E interaction that was in accordance with the findings of Win *et al.* [53]. Based on the performance of genotypes across different environments, AMMI1 classified the genotypes as most stable and high yielding genotypes (G7, G3, and G11), less stable and high yielding genotypes (G6, G5, and G10) and most stable and low yielding genotypes viz., G2, and G8 as reported by Kilic [54] in barley. From AMMI2 biplot the highly interactive environment (E6 and E2) and genotypes (G2, G4, and G8) were identified. The precise adaptation of genotypes to the appropriate environment has also been visualized with the help of biplot. E3 was more suitable for the genotype G8 and G6. The genotype G4 expressed the high yielding potential in E4 and E5, whereas the genotype G6, G3, and G9 showed positive interaction with E1. The morphological trait thousand seed weight was the yield driving trait in all the six environments. Nehe *et al.* [51] also reported the better performance of particular wheat genotypes for each environment under study. Based on GSI, the following genotypes viz., G11 (BARI Gom 21), G9 (BARI Gom 23), and G4 (BARI Gom 30) were identified as stable and high yielding across all the test environments under study.

5. Conclusion

The present study revealed that the genotypes namely BARI Gom 32 (G2) (E6), BARI Gom 30 (G4) (E2 and E4), and BARI Gom 26 (G8) (E1) were suitable for the particular environment and the genotypes viz., BARI Gom 21, BARI Gom 23, and BARI Gom 30 were highly suitable for all the six environments. Genetic potential of the genotype and prevailing irregularity of environmental conditions like the variation in weather factor, soil types, and diverse ecologies of tested environment might contribute to the superior/inferior performance/stability of the genotypes over locations. The genotypes used in this study previously known for its pests and disease resistance. Further, the present study revealed the stability of grain yield performance over environments. Hence, the prudent use of these genotypes as parent material hold great parent/prebreeding in future breeding programmes in wheat to develop varieties with high yield coupled with resistance to biotic stresses.

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Conflicts of Interest

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

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