Genotype X Environment Interactions and Yield Stability of Tef (*Eragrostis tef*) Genotypes Grown in Central Parts of Ethiopia

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Abstract: Tef [*Eragrostis tef* (Zucc.) Trotter] is one of the most significant cereal crops farmed in Ethiopia; it is the first crop in terms of area coverage; nevertheless, its production has been partially hampered by low grain yield and less stability of the released tef genotypes. This study was done to determine the degree of stability and genotype by environment interactions in tef genotypes. Twelve advanced tef genotypes were examined in seven environments under rain-fed conditions using the RCB Design with four replications. AMMI analysis indicated that the environments (E), genotypes (G), and genotype by environment interaction (GEI) were all significantly (p 0.001) affected the yield of tef grains, showing the presence of genetic variation and the potential selection of stable genotypes. As a result, 73.5% of the total sum of squares could be explained by factors such as the environment proving that the test sites' various surroundings led to significant differences in grain output. Principal component analysis was used to further split the GEI; the first two multiplicative axis terms (PCA1 and PCA2) explained 50.8% and 22.5% (73.3%) of the GEI sum of squares, respectively. The standard check Quncho had a grain yield of 1790 kg ha^{-1}, while G12 (DZ-CR-387XDZ-01-974-(RIL# 26B) had a grain yield of 2090 kg ha^{-1}and also more stable, according to the mean grain yield value of the examined genotypes over environments. As a result, this genotype would be used to boost tef production and productivity as well as serve as parent material for tef breeding.

Keywords: AMMI Analysis, Genotype, GGE Biplot, GEI, PCA, Stability, Tef

1. Introduction

Tef, *Eragrostis tef* (Zucc.) Trotter is a warm-season cereal crop and the tiniest grain on the planet. It is one of the underutilized crops that can contribute to food security and crop diversification. It is one of the underutilized crops that can help with crop diversity and food security. According to the study of Tadele and Hibistu, it is nourishing and well suited to Ethiopia's growing circumstances, but little has been done to maximize its potential for the domestic or global markets [1]. Tef is grown annually in Ethiopia on more than 3.1 million hectares, involving more than 7.1 million households and producing more than 5.7 million tons of grain, with a national average of 1.914 t/ha [2]. Tef can adapt to harsh environmental conditions and is found in wide range of socioeconomic situations. In its main growing locations, it can withstand both drought and water logging conditions, and it is not particularly vulnerable to pest and disease epidemics [3]. Tef grain has a high level of fiber, minerals, and vitamins as well as all eight essential amino acids and is gluten-free [4]. In terms of forage, it also boasts great feed quality, a high crude protein content, a quick growth rate, and the ability to support several harvests [5].

Low yield and poor stability of the cultivating genotypes have contributed to several limitations in tef production [6]. The phenotypic performance of the crop and its general and specialized adaptation to various environments are determined by the genotype environment interaction [7]. Because genotype x environment (G x E) interaction is based on data from multi-environment trials, it is one of the most challenging problems in plant breeding advancement [8].

Some of the most popular stability models are Additive Main Effects and Multiplicative Interaction (AMMI) and the genotype, genotype by Environment Interaction (GGE) to

estimate the magnitude of GXE interactions and to identify high-yielding and better-adapted genotypes [9-11]. The main purposes of GGE biplots are to rank the genotypes and environments under study and to graphically represent the GE interaction [12]. The AMMI model is a hybrid model with both additive and multiplicative components of a two-way data structure that allowed a breeder to achieve an accurate forecast on genotypic potentiality and environmental influences on it.

Some of the most popular stability models, such as Additive Main Effects and Multiplicative Interaction (AMMI) and the genotype, genotype by Environment Interaction (GGE) are used to estimate the magnitude of GXE interactions and identify high-yielding and better-adapted genotypes. The main objectives of GGE biplots are to rank the genotypes, examine environments, and graphically represent GE interaction [9-12]. A breeder was able to accurately predict genotypic potentiality and environmental influences on it using the hybrid AMMI model.

Since it includes both the traditional additive main effects for GEI and the multiplicative components into an integrated least square analysis, it has been heavily employed [13, 14]. This makes it more effective in the selection of stable genotypes. According to Yan and colleagues study, AMMI uses principal component analysis (PCA) to examine the non-additive residuals left over from the ANOVA and regular ANOVA to examine the main effects (additive part) [12].

Since it incorporates both the typical additive main effects for GEI and the multiplicative components into an integrated least square analysis it has been widely used [13, 14]. As a result, it is more successful in choosing stable genotypes. Yan and his colleagues claim that AMMI examines the major effects (additive part) of the ANOVA using principal component analysis (PCA) and regular ANOVA to evaluate the non-additive residuals [12]. Using multi-location data from tef, various researchers also have shown the usefulness of the AMMI procedure [8, 15, 16].

2. Materials and Methods

2.1. Plant Materials

Twelve recombinant inbred lines from two crossing parental lines including the standard and local checks were evaluated in multi-environment. The single seed descent (SSD) technique was used to create the 10 promising recombination inbred lines from two distinct crosses (Table 1). The cultivar DZ-01-974 (Dukam) was utilized as the pollen parent, and DZ-CR-387 (Quncho) was used as the ovule parent in these two crosses. The cultivar Quncho was utilized to pyramid the characteristic into the high grain yielding cultivar Dukam because it has a very white seed. The variety Quncho, which was extremely well-liked in practically all tef-producing locations, served as the standard check variety [8, 15]. The local check, on the other hand, is a farmer's variety that is often grown close to each of the test locations.

Table 1. Detailed descriptions of the genotypes.

Code No	Genotypes	Source
1	Local check	Holeta Area Tef
2	DZ-CR-387XDZ-01-974-(RILNO 23A)	NVT GI 2014 and 2015
3	DZ-CR-387XDZ-01-974-(RILNO 26A)	NVT GI 2014 and 2015
4	DZ-CR-387XDZ-01-974-(RILNO 27A)	NVT GI 2014 and 2015
5	DZ-CR-387XDZ-01-974-(RILNO 39B)	NVT GI 2014 and 2015
6	DZ-CR-387XDZ-01-974-(RILNO 42A)	NVT GI 2014 and 2015
7	DZ-CR-387XDZ-01-974-(RILNO 77C)	NVT GI 2014 and 2015
8	DZ-CR-387XDZ-01-974-(RILNO 86B)	NVT GI 2014 and 2015
9	DZ-CR-387XDZ-01-974-(RILNO 113C)	NVT GI 2014 and 2015
10	DZ-CR-387XDZ-01-974-(RILNO 144D)	NVT GI 2014 and 2015
11	DZ-CR-387 (Standard Check)	Quncho (Widely popularized tef)
12	DZ-CR-387XDZ-01-974-(RILNO 26B)	NVT GI 2014 and 2015

Where DZ-CR- stands for Debre Zeit tef line developed through Cross and DZ-01- Stands for Debre Zeit tef lines developed through Selection. NVTGI- National Variety Trial Group One. and RIL- Recombinant Inbred Lines.

2.2. Management and Design of Experiments

During the two primary cropping seasons of 2014 and 2015, the field experiment utilized a randomized complete block design with four replications of 2 m × 2 m (4 m^2) plot size. The field experiment was run by the agronomic procedures suggested by the research for each test site.

2.3. Collection of Data

For data analysis, a quintal per hectare was calculated from grams of clean, sun-dried seed as the measured grain yield value (gy) for each plot.

2.4. Analysis of the Data

To determine whether there is genetic variation among experimental genotypes and to confirm the homogeneity of the error variances, the first analysis of variance was performed for each environment. To find any potential interactions between genotypes and environments, a combined analysis of variance for the environment (location*year) and genotypes was conducted. For the analysis of variance, Proc GLM (general linear model) suitable for the experimental design was employed using SAS software version 9.3 [17]. Adaptability and stability analyses

were done using the multivariate AMMI and GGE-biplot methods after the significance of the GxE interaction was determined.

2.5. AMMI and GGE Biplot Analysis

The studies were performed using the R software's AMMI and GGE biplot package and Multi-Environment Trial Analysis (metan) v1.18.0. AMMI method combines PCA and ANOVA into one analysis with both additive and multiplicative properties [18]. In the first section of AMMI, the major effects of genotype and environment are assessed using conventional ANOVA methods. After the primary effects have been removed, the PCA of the interaction is performed in the second phase. The interaction GE was investigated in an AMMI model to identify tef genotypes better suited to various habitats [18]. Most stable genotypes may not always have the best yield performance, this suggest that stability per se may not be the only selection criteria [19, 20]. To categorize stable genotypes, yield and stability were combined into a single index [6, 8].

Using the GGE-biplot methodology, which combines the biplot concept to analyze data visually, results from the multi-environment yield experiment (MEYTs) were examined [12, 21]. In this method, the components (G and GE) that are significant in genotype evaluation and that are also sources of variance in the GEI analysis of MEYTs data are shown using a biplot to visually analyze the data in order to appreciate the GxE interaction and find stable and adaptable genotypes [12, 23]. Environment vectors are the lines joining the test environment to the biplot origin, and environment vector angle is the cosine of the angle between two vectors of environments which estimate the correlation between them, in this order when the angle is acute, they are highly correlated otherwise their relation decrease as it become large [24].

3. Result and Discussion

In Table 2, AMMI (Additive Main effect and Multiplicative Interaction) analysis of variance for grain yield across twelve (12) tef genotypes evaluated across seven (7) environments have shown. Genetic variation and the potential selection of stable entries were revealed by AMMI analysis results that demonstrated variation among E, G, and GE to be highly significant at the P 0.001 level. Sum squares (SS) partitioning revealed the environment impact to be the largest contributor of variance, followed by the genotype x environment interaction and genotype main effect. Given that changes in G and GE are typically smaller, environment most often explains the differences in genotype variation [22]. Additionally; the use of the AMMI model for GEI partitioning indicated that the first two principal component axes (IPCAs) of AMMI were highly significant at (P <0.001) using an approximation. using a test F-statistic [27].

The AMMI with IPCA1 and IPCA2 is the most effective prediction model for the cross-validation of yield variation explained by the genotype-environment interaction [6, 8, 15, 16, 26]. Grain yield components of variances from AMMI exhibited impacts of genotypes and environments as well as genotype by environment interaction (GEI) effects that were highly significant at P <0.001. Total sum of square shows 73.5%, 1.5%, and 5.6% effects of the environment, genotypes, and the genotype by environment interaction, respectively. The test environments were diverse, with significant variances between environmental means, which accounts for the majority of the variation in grain production, according to a total sum of squares for the environments (Table 2). The validity of the multi-environment experiments was therefore determined by this outcome. The main causes of variation may be variations in temperature, rainfall, soil type, soil fertility, and moisture availability.

Additionally, the AMMI analysis revealed that the first and second interaction principal components (PC1 and PC2)) explained 50.8% and 22.5% of the interaction sum squares respectively. This means they together contributed to 73.3% of the overall GEI (Figure 1). The model was sufficient to explain the entire component of the genotype x environment interaction [22]. The influence of the mean squares for PC1 on the GEI for grain yield was highly significant (P <0.001). According to the significant interaction result shows, the genotypes react differently in various contexts. The high variation in genotype traits for tef genotype grain yield demonstrated in the current study is consistent with previous reports on genotype variability by other authors [6, 8, 15].

Table 2. AMMI analysis of Grain Yield.

Source Variations	D. F	Sum Square	Mean Square	F value	P value	Var. Explained (%)	G X E. Explained (%)
ENV	6	20813.3	3468.9***	299.08	6.7e-106	73.5	
REP (ENV)	21	1197.2	57***	4.9	2.71e-10	4.23	
GEN	11	424.5	38.6***	3.3	2.86e-04	1.5	
GEN: ENV	66	1590.7	24.1***	2.0	3.65e-05	5.6	
PC1	16	808.1	50.5***	4.4	0.00e+00		50.8
PC2	14	357.2	25.5***	2.2	8.50e-03		22.5
PC3	12	212.3	17.7ns	1.5	1.14e-01		13.3
PC4	10	106.4	10.6ns	0.9	5.15e-01		6.7
PC5	8	65.0	8.1ns	0.7	6.91e-01		4.1
PC6	6	41.7	6.95	0.6	7.30e		2.6
Residuals	231	2679.3	11.6				
Total	401	28295.6	70.56				

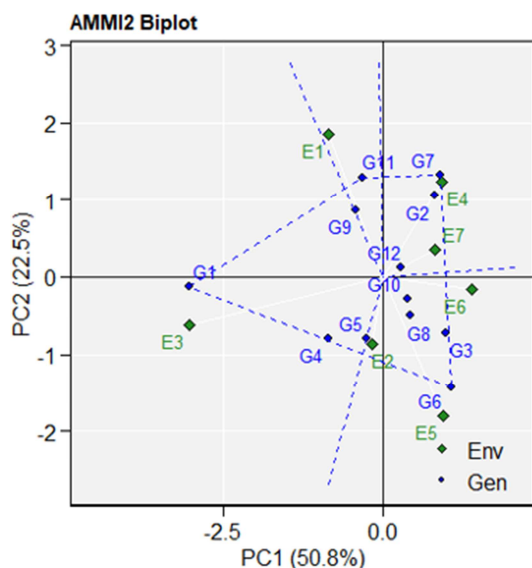Where *** indicate significant at (p < 0.001) and ns =Non-significant at P<0.05)

Figure 1. *AMMI2 Biplot.*

3.1. Grain Yield Mean Performance and Stability of Genotypes

An average environment coordination (AEC) approach was used to assess the genotypes' stability and mean yield performance [22].

3.1.1. Grain Yield Mean Performance

The 12 advanced tef genotypes' mean grain production performances in each of the seven environments are shown in Table 3. The genotypes' mean grain yields varied across all

environments, with G1 (local check) at E6 (Adadi-2015) having the lowest mean yield of 8.32 kg ha^{-1} and G9 (DZ-CR-387XDZ-01-974-(RILNO 113C) at E4 (Holeta-2015) having the highest mean yield of 4032 kg ha^{-1}. G12 (DZ-CR-387XDZ-01-974-(RILNO 26B) was the highest yielding and most consistent genotype out of those that were examined. According to recent studies [8, 15] the enormous variation in grain yield between environments may be caused by the wide variation in climatic and edaphic parameters, which makes the selection and recommendations for stable genotypes across environments more difficult.

Significant G-E effects found in this study suggest that the genotypes studied do not perform consistently across test conditions. This makes it possible to investigate the character and size of G E, which is not possible using a conventional analysis of variance. The considerable GEI in the current investigation suggests that the tef genotypes' performance varied across testing conditions (Figure 2). The implication was that the genotypes react differently in various circumstances. The results of the genotype x environment interaction (GEI) showed that the genotypes produced a statistically higher grain yield (30%) than the common check variety Quncho. Genotype G12, a good candidate variety, provided a grain yield of 2090 kg ha^{-1} in contrast to the standard check variety Quncho, which provided a grain yield of 1790 kg ha^{-1}. Therefore, genotype twelve (G12) will be verified and released as a new commercial variety after national variety releasing committee confirm it and it can also use for breeding purpose as parent material.

Table 3. *Grain yield mean performance and superior stability coefficient rank of genotypes across seven environments.*

Genotypes	Holeta-2014	Ginchi-2014	Adadi-2014	Holeta-2015	Ginchi-2015	Adadi-2015	Suba 2015	Means
G1	19.15	18.23	23.68	33.80	8.50	8.32	10.7	17.48
G2	19.44	18.65	13.40	39.01	9.63	18.39	15.65	19.16
G3	14.98	19.19	14.83	39.16	14.24	16.33	17.5	19.46
G4	16.70	17.70	18.26	32.86	11.05	14.31	13.72	17.79
G5	19.13	22.21	17.52	36.05	14.07	15.87	15.37	20.0
G6	14.58	18.85	13.00	36.91	15.96	15.81	12.93	18.28
G7	20.75	17.41	10.85	38.75	11.39	13.03	15.9	18.29
G8	15.06	19.14	12.10	36.22	11.69	11.01	12.75	16.85
G9	20.81	19.36	17.19	40.32	11.28	14.11	13.64	19.53
G10	17.51	17.27	13.48	35.46	13.57	12.16	16.36	17.97
G11	19.45	15.74	15.60	37.79	8.63	12.82	15.4	17.9
G12	20.34	19.67	17.74	40.16	13.78	20.39	14.1	20.9
Means	18.16	18.62	15.64	37.21	11.98	14.38	14.50	18.64
CV (%)								18.27
LSD (0.05)								1.8

Where G1-G12 = Genotypes and Holeta, Ginchi, Adadi and Suba= testing Environments and Grain yield in quintal per hectare

3.1.2. Stability Analysis

The average environment coordination (AEC) approach is used to depict graphically the mean grain yield and stability performance of genotypes (Figure 2). Utilizing this method, the highest yielding and most stable genotypes can be determined by integrating grain yield and stability performance of genotypes. An ideal genotype is the one that exhibits the highest mean performance and is extremely stable

across all test conditions [28, 29]. A desirable genotype is one that is located closer to an ideal genotype, which is typically at the center of the concentric circles or arrows, according to AEC view comparison biplot. An ideal genotype is connected to the high-yielding genotypes with the greatest vector length.

The mean performance axis of genotypes is indicated by an arrow on the AEC X-axis (PC1), which crosses through the biplot origin in the average environmental coordinate (AEC)

system. The biplot origin and the ATC Y-axis are both perpendicular to one other. The stability axis (PC2) is indicated by this axis. The mean grain yield would be higher for genotypes that were farther from the origin on the positive side of the AEC abscissa and lower for genotypes that were farther from the origin on the negative side. Additionally, a genotype's projection becomes less stable the longer it is in absolute terms [30].

The genotypes were split into two groups for this study. The first group, G12, G5, G9, G2, and G3, has stable performance that is above average. The performance of the remaining genotype groups (G8, G1, G4, G6, G7, G10, and G11) was below average. An ideal genotype is one that is completely stable in a wide range of conditions and has the highest average performance of any genotype [15, 31]. Therefore, G12, G5, and G9 were more stable as well as relatively high yielding in terms of grain production when both grain yield and stability performance were taken into account. These genotypes might be thought of as the most advantageous ones. This outcome is consistent with earlier research [8, 16].
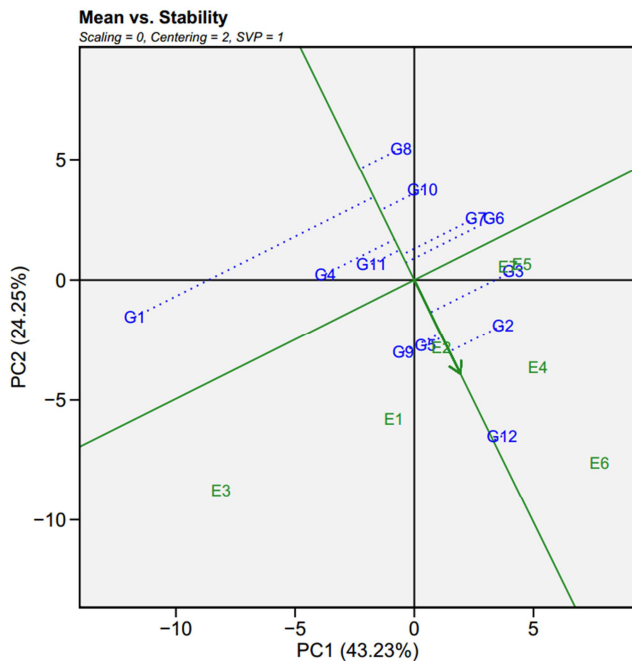

Figure 2. *The average-environment coordination (AEC) view to rank genotypes relative to an ideal genotype (the center of the concentric circles).*

Based on the findings for the first two principal components, a GGE biplot has been created [22]. In the current research, the first two GGE biplot principal components (PC1=43.23 and PC2=24.25%) explained 67.48% of the overall variations (Figure 3). According to Farshadfar and Yan, the vertex genotypes with the highest yield in a given sector are those found farthest from the origin in the polygon view. Vertex genotypes in the current investigation include G12, G3, G6, G8, and G1 [24, 25]. In each of their specialized fields, they all have the highest yield. To split the testing environments and genotypes in a GGE biplot graph, several lines that emerge from the origin and become perpendicular to the line linking the vertex genotypes are useful. Therefore, the seven testing

environments were divided into three mega environments while the 12 genotypes were divided into five genotypic groups (Figure 3). The three mega environments consisted of Group-I (E1, E2, E4 and E6), Group-II (E5 and E7) and Group-III (E3). Genotypes G6, G8 and G10 had no corresponding environment.

The GGE biplot approach successfully reveals genotype performance and stability by providing a graphic representation of the interactions between genotypes and environments [22]. To explore the adaptation of genotypes in the particular or across all test environments, the illustration of a "which won where" pattern in multi-environment trials is crucial [23]. Despite being the furthest from the biplot origin, the vertex genotypes were the most sensitive. Yan and Tinker [23] defined responsive genotypes as those that performed either best or worst in one or all situations. The relative performance of each genotype in a given environment was displayed using the GGE biplots of the graph results. A test environment that has a narrow angle with AEC i. e close to the center of concentric circles is the more representative/ideal of other test environments. The test environment Holeta-2014 (E2) was more representative environment. similar to the previous reports [16, 26].
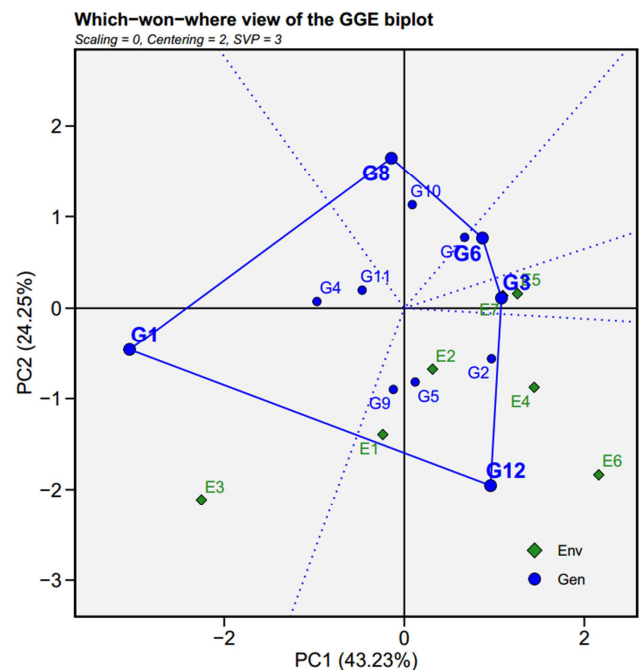

Figure 3. *Which won where the view of the GGE biplot to show which tef genotypes performed bets in which environments.*

4. Conclusion

Genotype-by-environment interaction (GEI) has a key effect on crop variety development. Understanding the structure and nature of GEI is important in plant breeding programs because a significant GEI can seriously harm exertions in choosing superior genotypes relative to new crop introductions and cultivar development programs. According to the results of AMMI analysis, environmental factors had the

greatest impact on tef grain yield performances, followed by genotype-environment interaction, with genotype having the least impact.

The AMMI and GGE biplot analysis showed best suited genotype for each specific environment. Considering simultaneous average yield and stability, G12 and G5 genotypes were the best genotypes across all tested environments. Genotype twelve (G12), while test environment Holeta-2014 (E2) was more representative environment. Therefore, after receiving approval, this genotype would be used as a commercial variety for possible tef growing places to increase tef productivity and production as well as used as parent material for tef breeding.

Acknowledgements

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