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GENOTYPE-ENVIRONMENT INTERACTION AND STABILITY OF TEF [*Eragrostis tef* (Zucc.) Trotter] VARIETIES IN NORTHEAST ETHIOPIA

Fisseha WOREDE[1]*

[1]Ethiopian Institute of Agricultural Research, Fogera Rice Research and Training Center, Bahir Dar, Ethiopia

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Abstract

Analyzing Genotype-Environment interaction (GxE) is useful for exploring the opportunities and limiting the drawbacks of the effects. An investigation was conducted on 12 environments (six locations and two years) to study GxE and stability of 18 tef varieties, and to identify desirable environments. The experiment was laid in a randomized complete block design with three replications. The result of AMMI analysis of variance showed that tef grain yield was significantly ($P < 0.001$) affected by environments (E), genotypes (G) and GxE. Environment, G and GxE explained about 90.23%, 1.03% and 8.74% of the total sum of squares of treatments, respectively. The partitioning of the GxE by AMMI analysis showed that two of the Interaction Principal Component Axes (IPCAs) were highly significant ($P < 0.001$). The two IPCAs explained 66.06% of the total GxE in grain yield of the tef genotypes. AMMI1 showed that genotypes G and D had small interaction effects. Likewise, environments MR06 and KB07 had the highest interaction effects whereas SR06, KB06, JM06 and JM07 had smaller interaction effects. AMMI2 also showed that environments MR06, KB07 and CH07 exerted higher interaction effects; however, KB06, JM06 and JM07 exerted lower interaction effects. The GGE biplot identified three mega-environments: The first mega-environment is composed of environments Kobo, Jari and SR07 with genotype *Tseday* as a winner; genotype *Ziquala* represented the second mega-environment containing Jamma, Chefa and SR06; the third environment, made up of Mersa, was represented by genotype *Asgori*. *Tseday* was the most desirable variety; while Mersa was the least desirable environment.

Keywords: Adaptability, AMMI, *Eragrostis tef*, G x E, GGE, Stability

***Corresponding author:** Ethiopian Institute of Agricultural Research, Fogera Rice Research and Training Center, Bahir Dar, Ethiopia
E mail: fisseha1@yahoo.com (F. WOREDE)
Fisseha WOREDE https://orcid.org/0000-0001-8828-5028
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1. Introduction

The tiny-seeded cereal, tef [*Eragrostis tef* (Zucc.) Trotter], which is originated and diversified in the highlands of Ethiopia (Vavilov, 1951), has a great deal of importance and unique qualities as compared to other crops. Apart from its large area coverage and production in the country, both the grain and the straw are preferred by the people and by livestock, as food and as feed, respectively. The grain is packed with a number important nutrients (Mengesha et al., 1965), and now a days, it is regarded as one of the healthy food stuffs as it is gluten free (Spaenij-Dekking et al., 2005).

Until recently, the crop was not much known in the outside world as food crop and it was cultivated in Ethiopia. It is adapted to different temperature and altitudinal ranges (Ketema, 1997), different water regimes, and adapted to mild water stress, both deficit and excess. About 37 tef varieties have been developed (MoANR, 2016), mostly from the naturally existing variability and some by cross breeding, for different agro-ecological zones (AEZs) of Ethiopia. However, the yield of those varieties is not stable across different AEZs of Ethiopia.

The basic cause of differences among genotypes in terms of yield stability is the incidence of genotype-environment interaction (GxE). This interaction can be partly understood as a result of differential reaction of cultivars to environmental factors (Becker and Leon, 1988). Analyzing the GxE, rather than ignoring, is useful for exploring the opportunities and limiting the drawbacks of the effects (Annicchiarico, 2002). The importance of GxE and stability has been documented by many workers in wheat (Farshadfar et al., 2011; Hagos and Abay, 2013; Ferede and Worede, 2016), barley (Voltas et al., 2002; Bantayehu, 2013; Mehari et al., 2014), rice (Samonte et al., 2005; Ouk et al., 2007; Akter et al., 2014; Dessie et al., 2018), finger millet (Fentie et al., 2013; Lule et al., 2014; Mamo et al., 2018), sorghum (Adugna, 2007; Almeida et al., 2014) and many other crops. Multivariate algorithms, Additive Main-effect and Multiplicative Interaction (AMMI), and genotype main effect and genotype-environment interaction (GGE), have been used to assess GxE in order to enable breeders to delineate mega-environments and target superior varieties on mega-environments (Gauch and Zobel, 1997; Yan and Hunt, 2002). The objectives of the present study were to assess GxE and stability of tef varieties, and to identify desirable environments in Northeastern part of Ethiopia.

2. Materials and Methods

2.1. Experimental materials and place of study

The field experiment was conducted at six locations in 2006 and 2007 main cropping seasons. The locations were Kobo (12^{0}8’21’’N/39^{0}18’21’’E, 1450m), Sirinka (11^{o}45’00’’N/39^{o}36’36’’E, 1850m), Mersa (11^{o}40’N/39^{o}39.5’E, 1850m), Jari (11^{0}21’N/39^{0}38’E, 1680m), Cheffa (10^{0}57’N/39^{0}47’E, 1600m) and Jamma (10^{0}40’N/39^{0}10’E, 2600m). All these locations represent the moisture stressed tef growing areas of Northeast Ethiopia. The first five locations experience moisture deficit, while Jamma experiences excess moisture at vegetative stage of the crop and deficit at later stages. The materials used were 18 tef varieties released by three agricultural research centers for different agro-ecological zones in Ethiopia (Table 1).

Table 1. Description of the 18 tef varieties used in the study

Variety	Name	Code	Year of release	Releasing research center
DZ-01-99	Asgori	A	1970	Debre Zeit
DZ-01-1681	Key Tena	B	2002	Debre Zeit
DZ-Cr-82	Melko	C	1982	Debre Zeit
DZ-01-787	Wellenkomi	D	1978	Debre Zeit
DZ-01-1281	Gerado	E	2002	Debre Zeit
DZ-Cr-358	Ziquala	F	1995	Debre Zeit
DZ-Cr-44	Menagesha	G	1982	Debre Zeit
DZ-01-1821	Zobel	H	2005	Sirinka
DZ-01-2054	Gola	I	2003	Sirinka
DZ-01-196	Magna	J	1970	Debre Zeit
DZ-01-974	Dukem	K	1995	Debre Zeit
DZ-Cr-37	Tseday	L	1984	Debre Zeit
DZ-01-1278	Ambo Toke	M	2000	Holetta
DZ-01-1285	Koye	N	2002	Debre Zeit
DZ-Cr-255	Gibe	O	1993	Debre Zeit
DZ-01-354	Enatit	P	1970	Debre Zeit
DZ-01-146	Genete	Q	2005	Sirinka
DZ-01-2053	Holetta Key	R	1999	Holetta

2.2. Experimental design and management

The experiment was laid-out in a randomized complete block design (RCBD) with three replications. A 2m x 2m plot was used for each variety. Inter-plot and between block distances of 1m and 1.5m were left. Sowing was done at the third week of July by broadcasting 10gm seed of each tef variety per plot. Fertilizer was applied at the rate of 41 N and 46 P_2O_5 kg ha^{-1}. Urea and DAP were used as sources of N and P, respectively. Plots were kept weed-free throughout the growth period.

2.3. Data collection and analyses

Data for grain yield (ton ha^{-1}) were collected. AMMI and GGE analyses were computed by using GenStat (16th edition) computer program.

3. Results and Discussion

The AMMI analysis of variance of grain yield (ton ha^{-1}) of 18 tef genotypes evaluated in 12 environments (six locations and two years) is presented in Table 2.

Table 2. The AMM1 analysis of variance table for grain yield of 18 tef varieties on 12 environments

Source	d.f.	SS	MS	G x E explained (%)
Treatments	215	289.62	1.347	
Genotypes	17	2.99	0.176**	
Environments	11	261.32	23.757**	
Interactions	187	25.31	0.135**	
IPCA 1	27	10.29	0.381**	40.66
IPCA 2	25	6.43	0.257**	25.40
Residuals	135	8.58	0.064	
Error	408	26.79	0.066	

**= significant at 0.001 probability level

The analysis showed that tef grain yield was significantly (P < 0.001) affected by environments (E), genotypes (G) and GxE. Significant effects of G, E and GxE were reported in tef (Kefyalew, 1999; Debusho et al., 2006; Ashamo and Belay, 2012). Environment explained about 90.23% of the total sum of squares of treatments signifying that the environments considered in the study were so diverse to cause most of the variation in grain yield. Environmental mean grain yield ranged from 0.546 tons ha^{-1} at Mersa in 2007 to 2.681 tons ha^{-1} at Sirinka in 2007 (Table 3).

Table 3. Mean grain yield (ton ha-1) of 18 tef varieties across 12 environments

Variety Name	Code	Environment												Genotype mean
		SR06	KB06	MR06	JR06	CH06	JM06	SR07	KB07	MR07	JR07	CH07	JM07	
Asgori	A	1.188	1.165	1.872	0.907	0.639	0.634	2.716	1.530	0.860	1.375	1.784	0.688	1.280
Key Tena	B	1.134	1.231	2.110	0.646	0.615	0.549	2.428	1.347	0.618	1.176	2.387	0.491	1.228
Melko	C	1.319	1.538	1.287	1.230	1.032	0.645	2.943	1.911	0.560	1.614	2.078	0.712	1.406
Wellenkomi	D	1.245	1.058	0.918	0.985	0.895	0.572	2.309	1.470	0.383	1.324	2.375	0.523	1.171
Gerado	E	1.400	1.227	1.204	1.347	0.820	0.472	3.349	2.031	0.567	1.677	2.079	0.447	1.385
Ziquala	F	1.470	1.247	0.969	1.429	1.199	0.855	2.445	1.808	0.545	1.262	2.526	0.729	1.374
Menagesha	G	1.377	1.478	1.237	1.449	0.840	0.639	2.550	1.785	0.548	1.346	2.526	0.471	1.354
Zobel	H	1.471	1.299	1.050	1.084	0.923	0.412	2.445	1.926	0.331	1.229	2.397	0.645	1.268
Gola	I	1.678	1.450	1.152	1.267	1.130	0.559	2.801	1.892	0.244	1.567	2.383	0.530	1.388
Magna	J	1.471	1.345	1.086	1.138	0.964	0.597	2.580	1.903	0.487	1.372	2.149	0.550	1.303
Dukem	K	1.444	1.180	1.201	1.169	1.105	0.609	2.772	2.162	0.439	1.397	2.197	0.574	1.354
Tseday	L	1.191	1.371	1.338	1.451	1.023	0.665	2.809	2.825	0.424	1.443	1.932	0.639	1.426
Ambo Toke	M	1.281	1.441	1.235	1.123	0.978	0.625	2.960	2.151	0.449	1.457	2.449	0.739	1.407
Koye	N	1.352	1.464	1.616	1.081	0.681	0.519	2.461	1.597	0.484	1.200	2.498	0.572	1.294
Gibe	O	1.406	1.103	1.231	1.383	1.005	0.646	2.562	2.179	0.593	1.342	2.117	0.653	1.352
Enatit	P	1.592	1.526	0.946	1.112	0.987	0.761	2.679	1.274	0.660	0.991	2.302	0.704	1.294
Genete	Q	1.513	1.023	1.665	0.984	1.001	0.534	2.769	1.486	0.646	1.418	2.587	0.694	1.360
Holetta Key	R	1.366	1.501	1.528	1.461	0.873	0.497	2.678	1.822	0.990	1.371	2.245	0.606	1.412
Environment mean		1.383	1.314	1.314	1.180	0.928	0.600	2.681	1.839	0.546	1.365	2.279	0.609	1.336

CH06= Chefa 2006, CH07= Chefa 2007, JM06= Jamma 2006, JM07= Jamma 2007, JR06= Jari 2006, JR07= Jari 2007, KB06= Kobo 2006, KB07= Kobo 2007, MR06= Mersa 2006, MR07= Mersa 2007, SR06= Sirinka 2006, SR07= Sirinka 2007

Only a small portion, 1.03% of the total sum of squares of the treatments, was attributed to genotypic effects. Genotype grain yield (averaged across environments) ranged from 1.171 tons ha^{-1} for *Wellenkomi* to 1.426 tons ha $^{-1}$ for *Tseday* (Table 3). GxE explained 8.74% of the treatment variation in grain yield. The magnitude of the GxE sum of squares was about 8 times larger than that of genotypes, indicating the presence of substantial differences in genotypic response across environments. Kefyalew (1999) explained the largest proportion of the total sum of squares (SS) due to environments (70%) followed by the GxE source of variation (22%) for grain yield; the genotype source contributed the lowest proportion (7%).

Genotype *Gerado* had the highest yield of 3.349 ton ha^{-1} at the highest yielding environment (Sirinka in 2007) whereas *Holetta Key* was the highest yielder (0.990 ton ha^{-1}) at the lowest yielding environment (Mersa in 2007) (Table 3).

The partitioning of the GxE by employing AMMI model analysis showed that two of the Interaction Principal Component Axes (IPCAs) were highly significant ($P < 0.001$). The first IPCA captured 40.66% of the interaction SS. Similarly, the second IPCA captured 25.40% of the interaction SS. The two IPCAs explained 66.06% of the total GxE in grain yield of the tef genotypes. Ashamo and Belay (2012) reported 49% of the GxE variance to be captured by the first significant ($P < 0.05$) IPCA. Kefyalew (1999) also explained 58.82% of the total GxE by the first (21.57%), second (19.61%) and third (17.65%) significant IPCAs.

The AMMI biplot showing the main and IPCA1 effects of both genotypes and environments on tef grain yield is depicted in Figure 1.

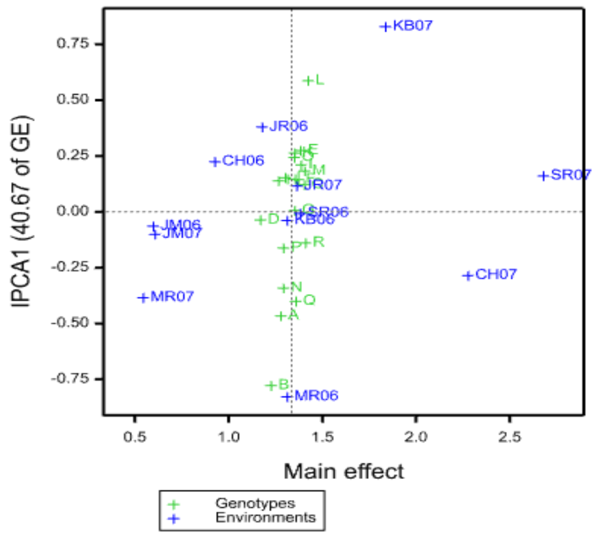

Figure 1. AMMI biplot of main effects of tef genotypes and environments, and IPCA1 using symmetrical scaling. CH06= Chefa 2006, CH07= Chefa 2007, JM06= Jamma 2006, JM07= Jamma 2007, JR06= Jari 2006, JR07= Jari 2007, KB06= Kobo 2006, KB07= Kobo 2007, MR06= Mersa 2006, MR07= Mersa 2007, SR06= Sirinka 2006, SR07= Sirinka 2007.

In the Figure, distances along the abscissa shows main effect differences, whereas the ordinate shows differences in interaction. The tef genotypes more or less had similar pattern in genotypic main effect, as they are arranged in a vertical line, but had sizable differences in the interaction effects. Genotypes A, B, D, H, J, N and P had below average genotypic main effect. In contrast, C, E, F, G, I, K, L, M, O, Q and R had above average genotypic main effect. Genotypes B, L, A and Q had higher interaction effect. However, G and D had small interaction effect (Figure 1).

On the contrary, the environments did not show any pattern. Environments SR07, CH07 and KB07 had higher environmental main effects, while MR07, JM06 and JM07 had smaller main effects. Environments KB06 and MR06 had similar main effects but they differ in interaction effects. MR06 and KB07 had the highest interaction effect; SR06 followed by KB06, JM06 and JM07 had smaller interaction effects. The rest of the environments, however, had moderate interaction effects (Figure 1).

Figure 2 shows the interaction pattern of the 18 tef genotypes with the 12 environments. The distances from the origin indicate the magnitude of interaction exerted by environments on genotypes, or vice versa (Voltas et al., 2002). Accordingly, environments MR06, KB07 and CH07 exerted higher interaction effects, signifying that they are more discriminating than the others; however, KB06, JM06 and JM07 exerted lower interaction effects. Likewise, genotypes L, A and B had higher interaction, showing that they are more responsive to environmental changes, and hence they are specifically adapted. On the contrary, genotypes C, M, J, G and R had least contribution to the interaction component indicating their wider adaptability.

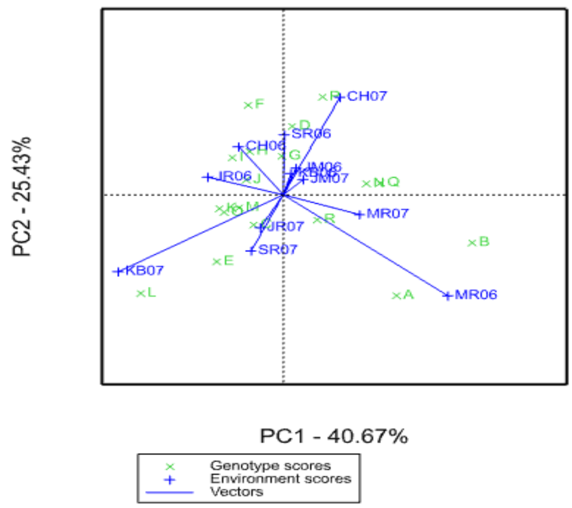

Figure 2. AMMI biplot of tef genotypes and environments plotted against PCA1 and PCA2 using symmetrical scaling. CH06= Chefa 2006, CH07= Chefa 2007, JM06= Jamma 2006, JM07= Jamma 2007, JR06= Jari 2006, JR07= Jari 2007, KB06= Kobo 2006, KB07= Kobo 2007, MR06= Mersa 2006, MR07= Mersa 2007, SR06= Sirinka 2006, SR07= Sirinka 2007.

The GGE biplot is useful for identification of mega-environments, superior (high-yielding and stable) genotype and best test-environments (representative and discriminating), among other things (Yan and Tinker, 2006).

In the which-won-where view of the GGE biplot, a polygon is drawn on genotypes that are furthest from the biplot origin circumscribing all other genotypes. Genotypes located on the vertices of the polygon performed either the best or the poorest in one or more environments. The equality lines, perpendicular lines drawn to each side of the polygon, divide the biplot into sectors (Yan and Tinker, 2006). The pattern in Figure 3 suggests that the target environment could be divided into four different mega-environments.

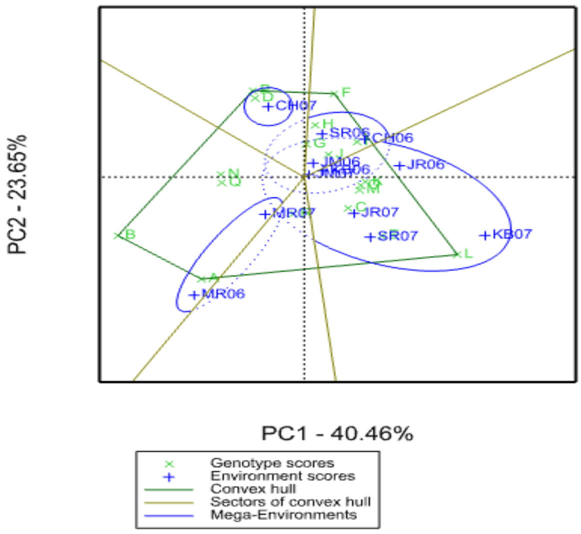

Figure 3. GGE biplot analysis showing the mega-environments and their respective high yielding genotypes. CH06= Chefa 2006, CH07= Chefa 2007, JM06= Jamma 2006, JM07= Jamma 2007, JR06= Jari 2006, JR07= Jari 2007, KB06= Kobo 2006, KB07= Kobo 2007, MR06= Mersa 2006, MR07= Mersa 2007, SR06= Sirinka 2006, SR07= Sirinka 2007.

The first mega-environment is composed of environments SR07, JR06, KB07, KB06 and JR07 with genotype L (*Tseday*) as a winner. Genotype F (*Ziquala*) represented the second mega-environment containing JM06, JM07, CH06 and SR06. The third environment, made up of MR07 and MR06, was represented by genotype A (*Asgori*); whereas genotype P (*Enatit*) represented environment CH07. However, as far as mega-environment CH07 is concerned, on the one hand, it is hardly possible to consider a location to be a mega-environment. On the other hand, in that environment, the highest yielding genotype was Q (Genete) not P (Enatit). This happened as a result of incomplete fitting of the GGE model to the original data (Voltas et al., 2005) as the which-won-where pattern is largely, not entirely, validated from the original data (Yan, 2002). Similar result was reported by Voltas *et al.* (2005) in barley. Besides, mega-environments are determined by the frequently winning genotypes (Gauch and Zobel, 1997), therefore, only three mega-environments instead of four would be possible in the present study. Similar result was reported by Samonte *et al.* (2005). As a result, the three possible mega-environments would be: mega-environment I composed of environments SR07, Jari (JR06 and JR07) and Kobo (KB07 and KB06) with genotype L (*Tseday*) as a winner; Genotype F (*Ziquala*) representing the second mega-environment containing Jamma (JM06 and JM07), Chefa (CH06 and CH07) and SR06; and the third environment, made up of Mersa (MR06 and MR07), was represented by genotype A (*Asgori*).

Ideal environments should be more representative of the entire set of environments and should have more genotype discriminating power, such environments should have small PC2 (absolute) and large PC1 scores (Yan et al., 2000; Yan and Rajcan, 2002). Figure 4 shows the average-environment coordination (AEC) view of ranking environments relative to an ideal environment. The center of the concentric circles pinpoints the ideal environment, more representative and highly discriminating. Thus, environments placed closer to the ideal environment are more desirable (Yan and Tinker, 2006). Accordingly, KB07 (Kobo 2007) is the most desirable environment than the others. However, Mersa (MR06 and MR07) and CH07 were the least desirable environments as they are located far away from the ideal environment.

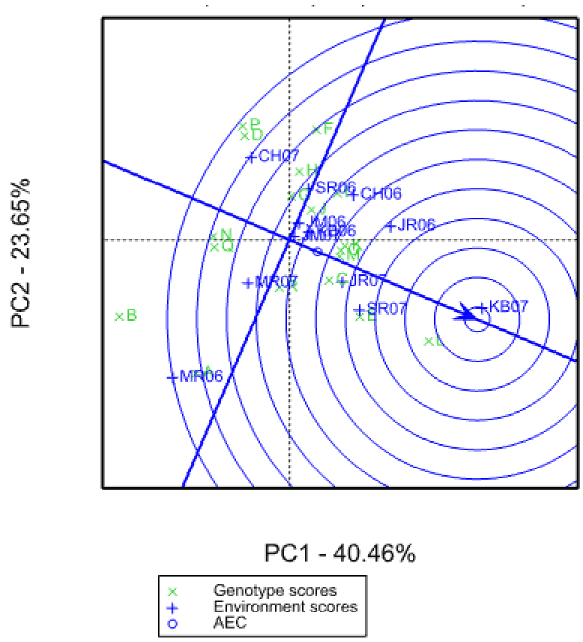

Figure 4. GGE biplot view to rank the 12 tef growing environments using environment-centered scaling. CH06= Chefa 2006, CH07= Chefa 2007, JM06= Jamma 2006, JM07= Jamma 2007, JR06= Jari 2006, JR07= Jari 2007, KB06= Kobo 2006, KB07= Kobo 2007, MR06= Mersa 2006, MR07= Mersa 2007, SR06= Sirinka 2006, SR07= Sirinka 2007.

According to Yan *et al.* (2000) and Yan and Rajcan (2002), ideal genotype is that having large PC1 score (high grain yield) and small absolute PC2 scores (high stability). Figure 5 shows the average-environment coordination (AEC) view of ranking genotypes relative to an ideal genotype.

The center of the concentric circles shows the ideal genotype, a genotype absolutely stable and highest yielder. Thus, genotypes situated closer to the ideal genotype are more desirable (Yan and Tinker, 2006). Accordingly, the genotype L (*Tseday*) is the most desirable variety than the others. Kefyalew (1999) also reported *Tseday* (DZ-Cr-37) to have had a yield comparable to the highest yielding genotype while having IPCA scores closer to zero. *Tseday* (DZ-Cr-37) has previously been recommended for its high grain yield and consistent performance on all the test locations except Jari and Jamma (Worede et al., 2007).

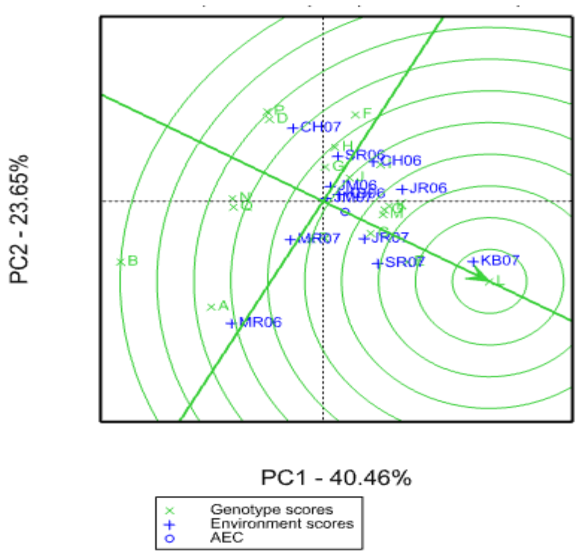

Figure 5. GGE biplot of tef genotypes on 12 environments using genotype-centered scaling. CH06= Chefa 2006, CH07= Chefa 2007, JM06= Jamma 2006, JM07= Jamma 2007, JR06= Jari 2006, JR07= Jari 2007, KB06= Kobo 2006, KB07= Kobo 2007, MR06= Mersa 2006, MR07= Mersa 2007, SR06= Sirinka 2006, SR07= Sirinka 2007.

4. Conclusion

The result demonstrated the importance of AMMI and GGE in identifying suitable environments and stable tef varieties for the Northeastern part of Ethiopia. On top of that, the finding also showed the importance of GGE in detecting mega-environments and the corresponding suitable genotypes. The three genotypes, *Tseday, Ziquala* and *Asgori*, could be recommended for large-scale production in the three mega-environments. However, Mersa should not be used as a representative test location for tef research.

Conflict of interest

The authors declare that there is no conflict of interest.

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