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Evaluation of Yield Performance and Stability of Early Maturing Tef [*Eragrostis tef (Zucc) Trotter]* Genotypes in Tigray, Ethiopia

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Tef, a staple food crop in Ethiopia, is well-adapted to diverse climatic conditions and soil types. Despite its resilience, tef's national yield remains low at 1900kg/ha due to moisture stress, lodging, soil fertility, and poor agronomic practices etc. With a potential yield of 6000kg/ha, there is

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significant gap to bridge. This study assessed the yield performance and stability of early maturing tef genotypes across three locations over two years in moisture-stressed areas of Tigray. Data was collected on grain yield (kg/ha) on the recombinant inbred lines of tef. The ANOVA was used to estimate the effect of environment, genotypes and genotype by environment interaction. Whereas, the genotype stability was analyzed by GGE biplot and AMMI ANOVA. Analysis of variance showed significant differences (P<0.01) among genotypes, environments, and genotype by environment interaction (GEI). Environments accounted for 85.23% of yield variation, genotypes for 3.37%, and GEI for 11.38%. The highest yield was from genotype KaymurriX3774-13(RIL-99) at Alamata 2019 (4320.3 kg/ha), with a grand mean yield of 2066.5 kg/ha across all environments. The study identified a crossover type GEI, with yield variation attributed to climatic factors and soil fertility. The AMMI and GGE biplot analyses explained 73.02% and 89.40% of the GEI effect, respectively, with KaymurriX3774-13(RIL-99) consistently performing best. This study highlighted the importance of selecting high-yielding, stable tef genotypes and classifying tef growing locations for better evaluation and recommendation, considering the impact of uneven rainfall and other yield-limiting factors.

Keywords: Stable tef genotypes; moisture stress; multi yield trials; additive main effect and multiplicative interaction model (AMMI); genotype plus genotype by environment interaction (GGE-biplot).

1. INTRODUCTION

Tef *(Eragrostis tef)* is a staple food crop in Ethiopia, known for its genetic variability and adaptability to diverse climates and soil types [1]. It grows best at altitudes of 1700 -2200 meters above sea level (masl) with 300 mm of rainfall during the growing season [2]. Tef offers numerous benefits: resilience to erratic climates, income generation from grain and straw, nutritional value [3], gluten-free properties [4], and relatively minimal disease issues [5].

Despite these advantages, tef yields remains low at 1900 kilogram per hectare (kg/ha) (CSA,2022) due to factors such as moisture stress, lodging, poor soil fertility, inadequate agronomic practices, low- yielding cultivars, and pests (mainly tef shoot fly). Research shows tef yields can reach 2800kg/ha, whith a potential of 6000kg/ha [6]. Bridging the gap between national yields and potential productivity is crucial for improving food security. This becomes increasingly relevant, as the price of tef in Tigray regional state has risen from 3,000 to 14,000 Birr per quintal in the last six years.

Crop performance is influenced by genotype, environment, and their interaction [7]. Understanding these interactions is vital for crop production [8,9]. Multi-environment trials (MET) helps address selection challenges caused by genotype-environment interactions [10]. Evaluating offspring of selected tef parents, particularly recombinant inbred lines, is ideal for assessing yield and stability. Studies show significant yield variation due to genotype, environment, and their interaction [11,7,12].

Identifying superior genotypes through multi-location trials is essential. Higher yielding, stable genotypes across environments are crucial for variety development [13]. However, developing widely adaptable varieties is challenging due to genotype-environment interactions [11]. Ethiopia's agro-ecological diversity necessitates selecting tef genotypes adaptable to specific environments. Yield variation due to environments ranges from 55 to 91%, with genotype variance from 1.8% to 28.5% and genotype-environment interaction accounts for 7.3% to 15.1% of yield [14].

Common statistical methods for selecting crop genotypes include additive main effects and multiplicative interaction (AMMI) and genotype main effects and genotype-environment interaction (GGE) biplot analysis [8]. Mean variance component (θi) is also used for tef stability analysis [12]. Grain yield variability is examined using stability and GGE biplot analysis [15,16].

Effective variety development requires selecting appropriate parents, using optimal breeding methods, evaluating promising tef materials, designing controlled experiments, and accurate data analysis. The main purpose of MET is to identify superior cultivars for farmer recommendation [17]. Evaluating tef recombinant inbred lines across locations and years assesses their adaptability and stability. GGE biplot analysis help interpret MET data, providing insights into genotypic main effects and genotype-environment interaction [18]. Plant breeders favor crossover for variety selection, influenced by superiority, noise, unpredicted environmental factors [19].

The national tef research program has released over 50 varieties, yet significant yield gaps persist. Ethiopia's diverse agro ecologies contribute lower yield in tef varieties. This study aimed to assess the yield performance and stability of early maturing tef genotypes over two years across three locations during the 2018 and 2019 cropping seasons in moisture stressed areas of Tigray. Addressing these yield gaps by identifying superior, stable tef genotypes adapted to specific environments is critical for enhancing tef productivity and ensuring food security in Ethiopia.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The experiment was conducted at three locations over two consecutive years (2018 and 2019). Details of the locations are in Table 1.

2.2 Experimental Materials and Design

The trial included four recombinant inbred lines and two checks: Boset (standard) and Zagurey (local). The lines were developed at Debre Zeit Agricultural Research Center, by hybridizing Keymurri and 3774-13 for early maturity, higher yield, and stability in moisture-stressed areas.

The experimental design was a randomized complete block design (RCBD) with four replications. Blocks, plots, and row spacing 1 m, 0.5 m and 0.2 m, respectively. Seed were sown at 15 kg/ha by rows, with 100 kg/ha of urea and blended fertilizer(Chanyalew et al., 2015). Urea was applied in two phases: at tillering and before heading.

2.3 Data Analysis

Grain yield data was collected per plot (m^2) and converted to kg/ha. Normality was assessed using Shapiro's test in R software. Homogeneity of residual variance (MSE) was checked as per Cruz et al. [20]. ANOVA was used to analyze the effects of environments (E), genotypes (G), and genotype-environment interaction (GEI) on yield (α = 0.05), with mean differences compared using the least significant difference (LSD) test.

Genotype stability was analyzed using GGE biplot and AMMI ANOVA. GGE biplot analysis employed a linear mixed-effects model, with genotype as a random effect and environment a fixed effect, using the lme4 package [21]. Principal component analysis (PCA) was used assessed stability, with longer vectors perpendicular to the average line indicating greater GEI and lower stability [22,23]. Stability was further analyzed using mean variance component (θi) via an online tool (https://manzik.com/stabilitysoft/ [24]).

Table 1. The list of locations and their description

S.no	Locations name	Latitude	Longitude	Altitude	Soil type
1	Ahiferom (debdbo)	$14^0$16'57.12''N	$39^0$04'6.78''E	2021 masl	Loam
2	Alamata	$12^0$40'48''N	$39^0$41'06''E	1550 masl	Loam
3	Adwa (Maytium)	$14^0$9'4.64''N	$38^0$50'57.24''E	1887 masl	Loam

Table 2. list of six pedigree tested tef genotypes and their sources

S.no	Genotypes	Sources	Remark
1	Boset(DZ-Cr-409(RIL#50d)	DZARC	Standard check
2	KaymurriX3774-13(RIL-99)	''	
3	KaymurriX3774-13(RIL-62)	''	
4	KaymurriX3774-13(RIL-141)	''	
5	GA-10-3XKaymurri(RIL-244)	''	
6	Local /zagure	Axum ARC	

DZARC= debre zeit agricultural research center, Axum ARC=Axum Agricultural Research Center

Variance explained by each source (genotypes, environments, and interaction) was calculated by dividing the sum squares by the total, multiplied by 100. The magnitude of GxE interaction was estimated using variance components [25], genetic correlation between environments quantified the GxE influence [26].

3. RESULTS AND DISCUSSION

3.1 Analysis of Variance

The combined mean analysis of variance for grain yield (kg/ha) tef genotypes showed significant differences at (P<0.001) for genotypes, environment and genotype by environment interaction (GEI) (Table 3). GEI is the relative performance of genotypes varies from one environment to others [27]. The significance of GEI makes difficulty in selection of superior genotypes across environments [28,23]. [29] and [13] suggested for the minimization of GEI in selection of genotypes, creating homogeneous environment and development of stable genotypes. Yield variations among genotypes across different environments can be attributed to factors like climatic fluctuations (rainfall, temperature, relative humidity); for example, the yield differences were significant at Alamata 2018 and Alamata 2019 (Table 4 and Fig. 1). Environmental factors explained 85.23% of the total yield variation, while genotypes and interaction accounted for 3.37% and 11.38 %, respectively (Table 3). This aligns with research suggesting that grain yield is more influenced by environment than by genotypes or their interaction [30,14,7,19,8].

Higher yielding tef genotypes with relative stability are better for selection. Environmental variation is heightened by unpredicted weather conditions (rain fall, temperature), soil type and others factors. Soil fertility at Alamata is better than at Adwa and Ahiferom, with altitudes ranging from 1555 to 2021 meter above sea level. Significant environment effects and high variance components can be attributed differences in fertility and rainfall distribution [31].

The average environment grain yield across genotypes ranged from the lowest of 1289 kg/ha for the local check at Ahiferom 2018 to 4320kg/ha for KaymurriX3774-13(RIL-99) at Alamata 2019, with a grand mean of 2066kg/ha (Table 4). The average grain yield of genotypes ranged from 1932 kg/ha for the local check to 2283 kg/ha for KaymurriX3774-13(RIL-99), with a grand mean 2111 kg/ha. The presence of grain yield ranking across the locations indicates a crossover type of GEI [9] (Fig. 2).

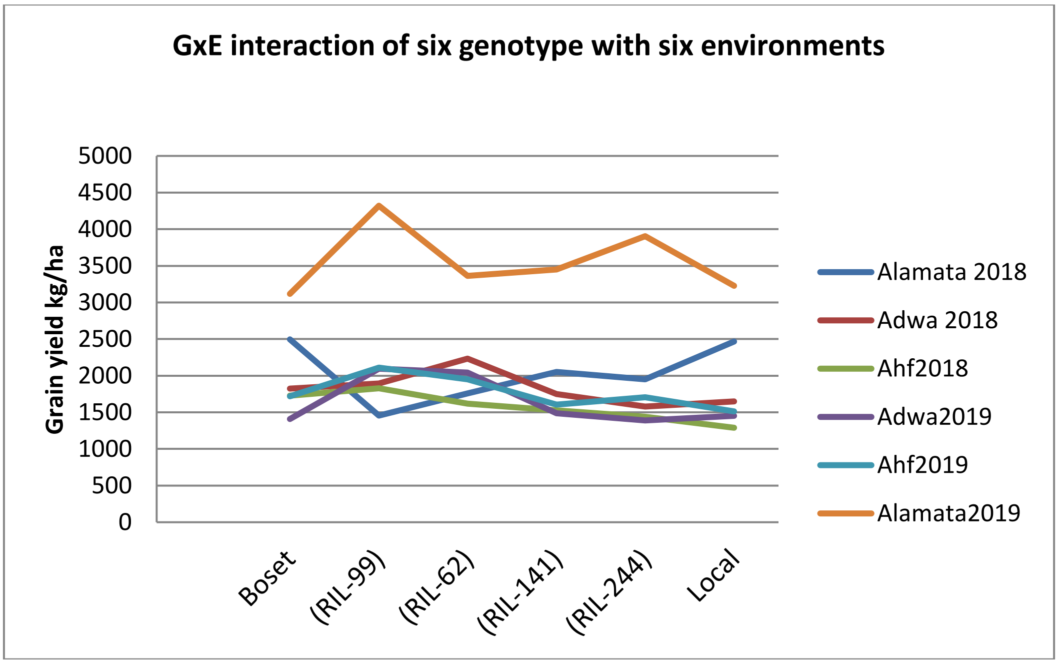

Fig. 1. Grain yield performances of six tef genotypes across six environments Alamata at 2018, Adwa at 2018, Ahf2018(Ahf=Ahferom), Adwa at 2019, Ahf2019 and Alamata at 2019 and two years showing the existence of relative changes in ranks (crossovers) due to genotype by environment interaction

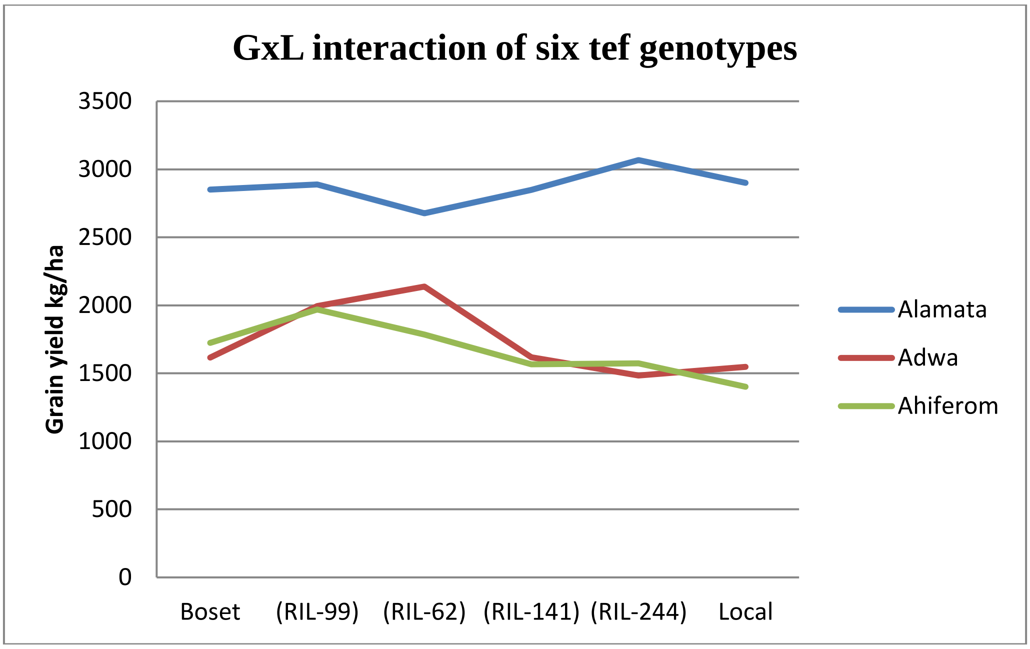

Fig. 2. Grain yield performances of six tef genotypes across three locations Alamata, Adwa and Ahferom and two years showing the existence of relative changes in ranks (crossovers) due to genotype by location interaction

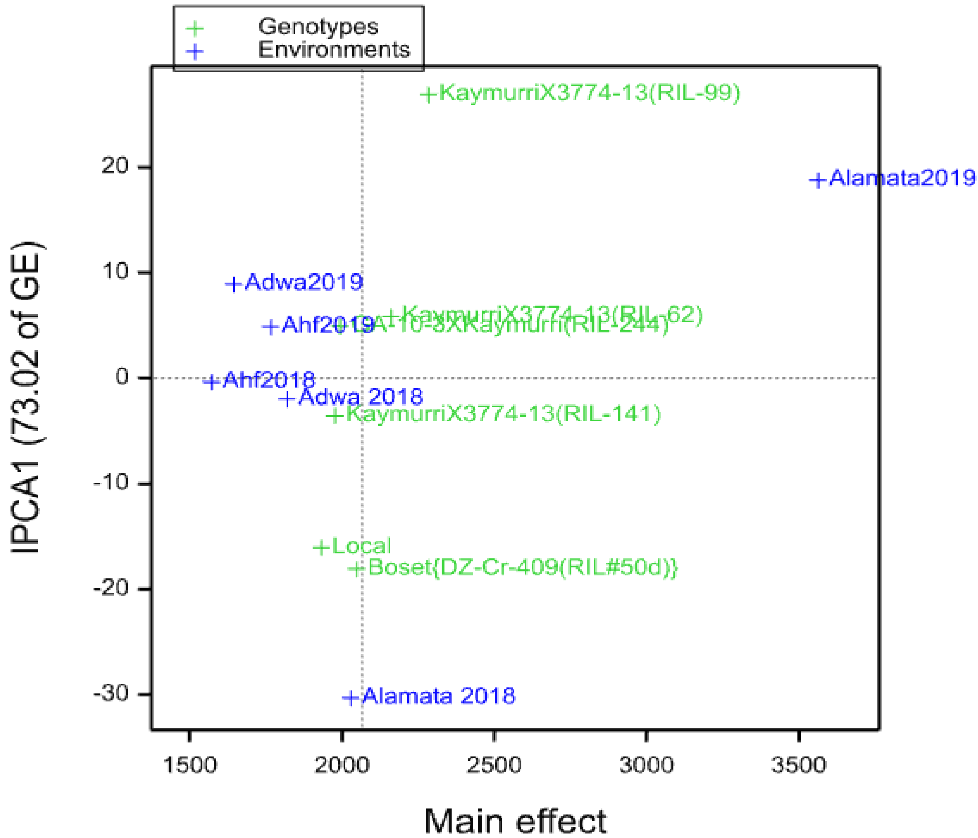

Fig. 3. Biplot of the yield means and the first principal component axis scores of 6 tef genotypes and 6 environments. Green and blue stands for genotypes and environments, respectively

The AMMI model revealed that two terms of AMMI were statistically significant, with the interaction of principal component axis (IPCA1) explaining 73.02% of the variation (Fig. 3), consistent with finding by Tolossa et al. [8]. The GGE biplot visualized the first two principal components, explaining 68.98% and 20.42% of the variation, for a total of 89.40% (Fig. 5). Genotypes located on the vertices of the polygon in the GGE biplot either performed the best or the poorest in one or more [22]. Genotype KaymurriX3774-13 (RIL-99) performed best across all environments. KaymurriX3774-13 (RIL-62) and Boset also performed well in certain environments, while the local check was the poorest yielding genotypes (Fig. 4).

Among the tested tef genotypes, Kaymurri X3774-13(RIL-99),KaymurriX3774-13(RIL-62), and GA-10-3XKaymurri (RIL-244) had yields above the grand mean and were selected out of the six populations. Their mean yields are similar, but their interactions with environments differed as reported by Crossa et al. [30]. Genotypes near the origin, like KaymurriX3774-13(RIL-62) and GA-10-3XKaymurri (RIL-244), were above the mean with stability, while the local and KaymurriX3774-13 (RIL-141) were below the grand mean but stable. Environmental variability was lower except at Alamata 2019 (Fig. 5). The single–arrowed line (AEC abscissa) points to higher mean yield across environments [22].

The slope regression (bi) indicates the genotype`s response to environmental index. A bi close to suggest adaptation to all environments, while a bi > 1 indicates sensitivity to environmental change and specific adaptability to high-yielding environments [32]. In this study, KaymurriX3774-13(RIL-99) and GA-10-3XKaymurri (RIL-244) had bi values near 1, making them suitable for the tested locations. The other genotypes scored less than 1, favoring low yielding environments (Table 5).

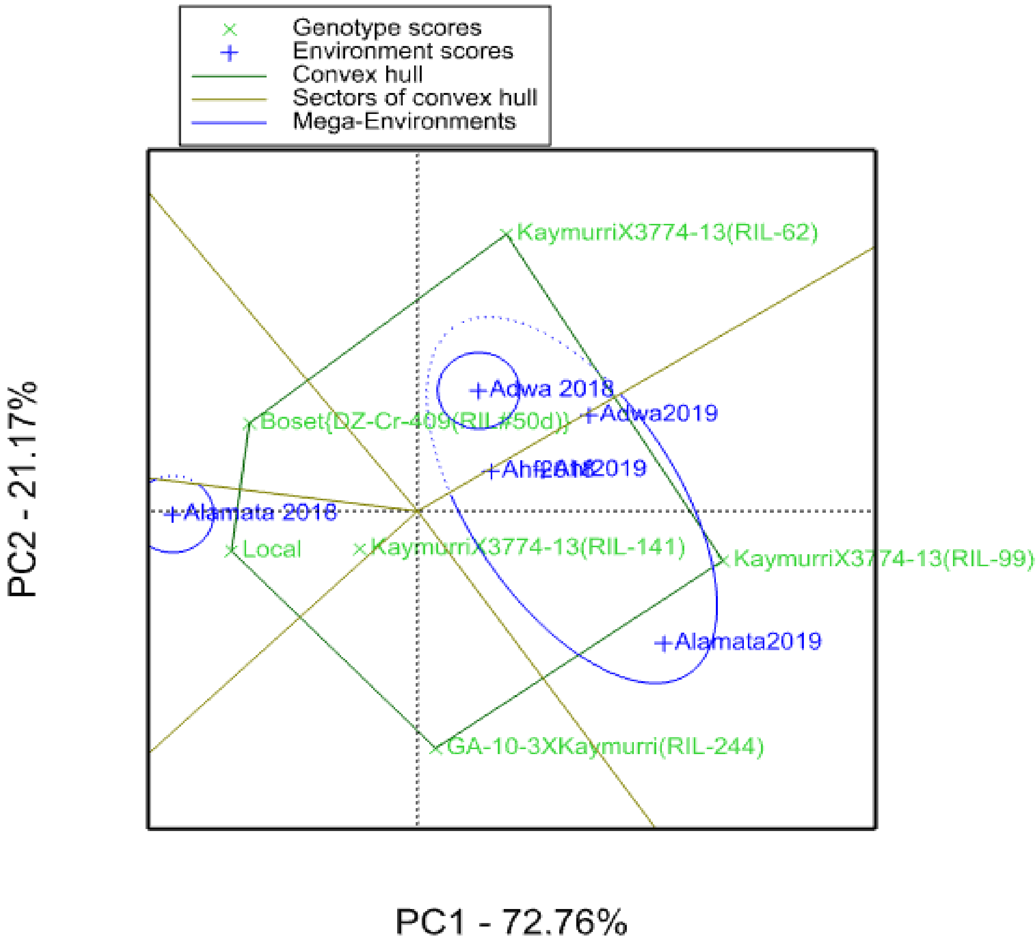

Fig. 4. The which-won-where view of the GGE biplot for the tef genotypes, Green and blue stands for genotypes and environments, respectively

Table 3. Combined analysis of variance for mean grain yield of six tef genotypes in two year and for three locations total six environments

Source of variation	Df	Sum Square	Mean square	F value	P-value	Explained SS (%)	Coefficient of variation (CV)
Genotypes	5	2677467	535493	7.157	0.000	3.37%	13.22%
Environments	5	67559624	13511925	180.6	0.000	85.23%	
Genotypes environments	25	9024090	360964	4.824	0.000	11.38%	
Residual	102	763100	74814				
Total	137	80024281					

Df=degree of freedom

Table 4. The mean performance of grain yield (kg/ha) at three locations (Adwa, Ahiferom and Almata) for 2018/19 and 2019/20

S.no	Genotypes	Grain Yield(kg/ha)					
		Ala2018	**Adw2018**	**Ahf2018**	**Adw2019**	**Ahf2019**	**Ala2019**
1	Boset{DZ-Cr-409(RIL#50d)}	2496	1822.96	1729.53	1408.67	1717.26	3117.1
2	KaymurriX3774-13(RIL-99)	**1455.75**	**1892.81**	**1828.43**	**2095.62**	**2110.30**	**4320.3**
3	KaymurriX3774-13(RIL-62)	1759.083	2233.04	1619.84	2042.73	1949	3364.5
4	KaymurriX3774-13(RIL-141)	2050.417	1750	1528.28	1485.15	1603.7	3447.8
5	GA-10-3XKaymurri(RIL-244)	1949.417	1578.82	1439.76	1389.21	1704.92	3906.2
6	Local	2467.167	1647.26	1289.53	1450.31	1512.77	3226.5
	GM	2030	1821	1573	1645	1766	3564
	CV%	16.36	16.948	15.30	9.662	10.68	8.682
	LSD@5%	604.21	465.102	362.64	239.59	284.51	466.35

Cv%=coefficient of variance percent, LSD%=last of significance difference at 5%. Ala2018=Alamata 2018, Adw2018=Adwa2018, Ahf2018=Ahferom2018

Table 5. The combined mean performance of tef genotypes for two years and three locations (Adwa,Ahiferom and Alamata)

S.no	Genotypes	Yield(kg/ha)			mean (kg/ha)	Parametric stability	
		Alamata	**Ahiferom**	**Adwa**		**b_i**	**θ_i**
1	Boset{DZ-Cr-409(RIL#50d)}	2806.55	1723.395	1615.815	2048.587	0.894806	2
2	KaymurriX3774-13(RIL-99)	2888.025	1969.365	1994.215	2283.868	1.170231	1
3	KaymurriX3774-13(RIL-62)	2561.792	1784.42	2137.885	2161.366	0.927887	3
4	KaymurriX3774-13(RIL-141)	2749.109	1565.99	1617.575	1977.558	0.972786	6
5	GA-10-3XKaymurri(RIL-244)	2927.809	1572.34	1484.015	1994.721	1.098853	5

6	Local	2846.834	1401.15	1548.785	1932.256	0.935438	4
	GM	2796.687	1669.443	1733.048	2066.393		
	CV%	32.47	15.265	15.26			
	LSD@5%	1026.539	267.560	267.56			

GM=gran mean, CV=coefficient of variation LSD@5%=least significance difference at 5 probability level , b_i= regression coefficient, θi=mean variance component

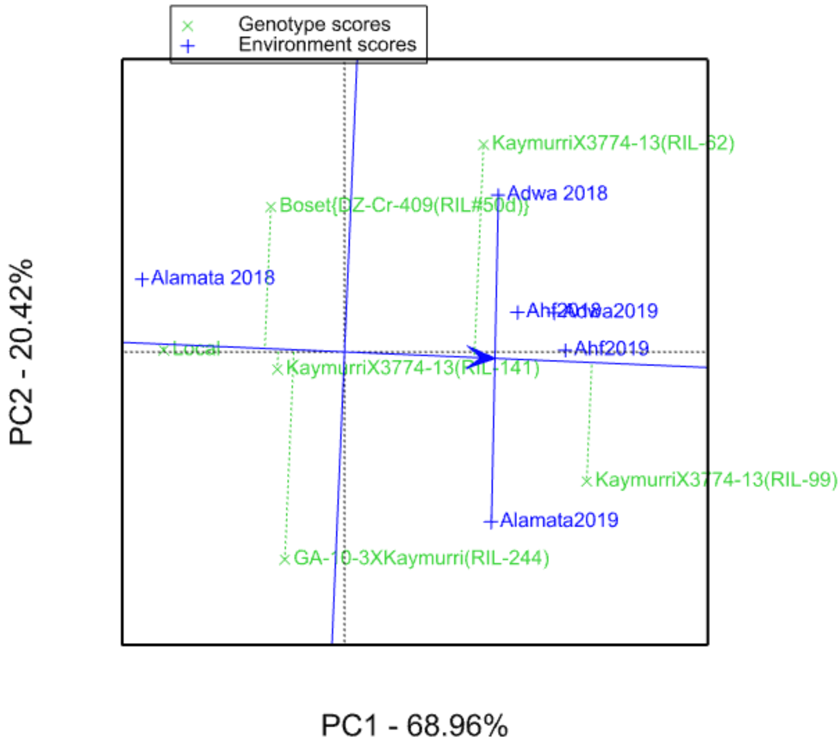

Fig. 5. Average environment coordination (AEC) views of the GGE-biplot based on environment focused scaling for the means performance and stability of genotype. Green and blue stands for genotypes and environments, respectively.

4. CONCLUSION

This study highlighted the significant genotype by environment interaction (GEI) in tef, emphasizing the need for multi-environment trials (MET). Environmental factors accounted for 85.23% of yield variability, while genotypes and their interactions contributed 3.37% and 11.38%, respectively. Genotype KaymurriX3774-13 (RIL-99) consistently performed well, indicating its potential for broader cultivation.

AMMI and GGE biplot analyses effectively highlighted GEI and identified stable genotypes. Targeted breeding programs using MET and advanced statistical methods are essential for improving tef yields and enhancing productivity. Classifying tef growing locations can further refine genotype evaluation and recommendations, considering the impact of uneven rainfall distribution and other yield-limiting factors.

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DISCLAIMER (ARTIFICIAL INTELLIGENCE)

NO, generative AI was not used for preparing the manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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