Genotype x Environment Interaction and Grain Yield Stability of Improved Teff [*Eragrostis tef* (Zucc.) Trotter] Varieties in Northwestern Ethiopia

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Abstract

Background: Teff is an important staple cereal crop in northwestern Ethiopia. However, the yield of the crop is very low due to, among others, lack of stable and high yielding varieties under varying environmental conditions because of genotype x environment interaction effect.

Objective: The study was conducted to assess the effect of genotype by environment interaction, identify mega environments, and select high yielding and stable teff genotypes that interact less with the changing environment.

Materials and Methods: Twenty improved teff varieties were evaluated using a randomized complete block design with three replications at Adet, Motta, Bichena, Debre-Tabor and Takussa districts for two consecutive years. Data were collected on days to heading and maturity, plant height, grain filling period, panicle and culm length, dry plant biomass and grain yield. The data were analyzed using a combined analysis of variance and genotype main effect plus genotype by environment interaction biplot.

Results: The combined analysis of variance for grain yield revealed highly significant ($P < 0.001$) effects for genotype (16%), environment (54%) and genotype **x** environment interaction (23%). The effect of environment was three times higher than that of genotype, indicating significant and undesirable influence of the environment on genotype stability. The mean grain yield across the environments ranged from 1.65 to 2.77 tons ha^{-1} for Debre-Tabor and Takussa, respectively. The genotype mean yield ranged from 1.68 to 2.51 tons ha^{-1} for Simada and Hiber-1, respectively. Genotype by environment interaction biplot analysis grouped the ten test environments and twenty genotypes into three mega-environments and four genotype groups. Besides, Adet district and Bichena district had relatively the longest vector length and the smallest angles with the average environmental axis, thus being the most representative of all environments. Regarding genotypes, Hiber -1 followed by Kora, Etsub and Dukem were identified as the best yielding and relatively stable genotypes to increase teff productivity in the region.

Conclusion: The biplot analysis of the genotype by environment interaction resulted in the identification of Adet and Bichena districts as the most favorable locations for teff production and as well as Hiber-1 as the most productive teff variety for cultivation in the study area. This implies that farmers in the two districts could be advised to take up this variety for enhancing yield of the crop and income from its production.

Keywords: Combined analysis; Environmental axis; Genotypes; Genotype main effect; Genotype x environment interaction; Grain yield stability

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ISSN 1993-8195 (Online), ISSN 1992-0407(Print)

1. Introduction

Teff is an important staple cereal crop in Ethiopia as well as in Amhara National Regional State, particularly in northwestern Ethiopia. In Ethiopia, the crop covers 3.02 million hectares per year and accounts for 30% of the total land allotted to cereals. It is second in total production (5.28 million tons) accounting for 20% of grain production among all cereals grown, while its national average productivity is 1.75 tons ha^{-1} (Central Statistical Agency (CSA), 2018). In Amhara National Regional State (ANRS), teff productivity (1.8 tons ha^{-1}) is slightly more than the national average (CSA, 2018).

Amhara region (northwestern part of Ethiopia) is one of the major teff growing areas in the country. According to CSA (2018), the contribution of the region in terms of area coverage and total production is about 38% and 39%, respectively. In spite of the importance of the crop, both the national and regional average yields are very low as compared to other cereals grown in Ethiopia as well as the crop's genetic potential. A study conducted under non-lodging condition has demonstrated that yield potential of the crop can further be increased up to 4.6 tons ha^{-1} (Yifru Teklu and Hailu Tefera, 2005). This shows there is higher difference between the potential of the crop and the actual yield, which is less than half. Some of the factors contributing to the low yield of teff include low soil fertility, lack of high yielding and widely adaptable varieties, weeds, erratic rainfall distribution in lower altitudes, lodging, waterlogging, and low moisture (Fufa Hundera, 1998). Among these factors, scarcity of stable and high yielding teff varieties under varying environmental conditions due to GEI effect is the main factor. The occurrence of genotype by environment interaction is the basic cause for differences among genotypes in terms of grain yield stability. Stability analysis can help to characterize the response of varieties to the changing environments and to determine the best and representative locations of the environmental diversity (Mohammed *et al.,* 2008). Hence, conducting experiments in several locations and seasons are needed to determine stable and high yielding varieties of the crop.

Multi-Environment Trials (MET) are carried out to evaluate grain yield stability performance of genetic materials under varying environmental conditions (Delacy *et al.,* 1996; Farshadfar *et al.,* 2012). Consequently, genotype x environment effects can be revealed by multi-environment trial experiments. The presence of a significant genotype x environment interaction for quantitative traits such as grain yield can lead to the failure of genotypes to achieve the same relative performance in different environments (Fekadu Gurmu *et al.,* 2009).

Information on genotype x environment interaction (GEI) leads to successful identification of stable genotypes, which could be used for wider cultivation. Yield is a complex quantitative character greatly influenced by environmental fluctuations; hence, the selection of superior genotypes based on grain yield performance at a single location in a year would not be very effective (Shrestha *et al.,* 2012). Thus, evaluation of genotypes for stability of performance under varying environmental conditions for yield has become an essential part of any plant breeding program. Moreover, understanding of genotype x environment interaction enables us to effectively allocate resources and to characterize genotypic responses to diverse crop productivity levels (Tiruneh Kefyalew *et al.,* 2000). Thus, it enables to eliminate unnecessary spatial and temporal replications of yield trails as well as to establish additional testing environments when the existing ones are under-represented (Basford and Cooper, 1998).

Even though some studies have been conducted to elucidate the G x E interaction of teff in other parts of the country, there is little information on the G x E interaction of teff varieties in diverse environmental conditions of north western Ethiopia. The importance of conducting more studies across major teff growing environments has been suggested by Mathewos Ashamo and Getachew Belay (2012), so as to enable breeders to identify adaptable, stable, and high yielding teff genotypes. Therefore, the objectives of the present study were to assess the effect of GEI and identify mega-environments, and to select high yielding and stable teff genotypes that interact less with the changing environment in northwestern Ethiopia.

2. Materials and Methods

2.1. Description of the Study Area

A field experiment was conducted in five locations during the 2018 and 2019 main cropping seasons under rain-fed condition. The test locations were Adet (Yilmana-Densa), Motta (Hulet-Eju-enesie), Bichena (Enemay), Debre-Tabor, and Takusa districts (Figure 1). The climatic, edaphic and geographic descriptions of the locations are different and presented in Table 1.

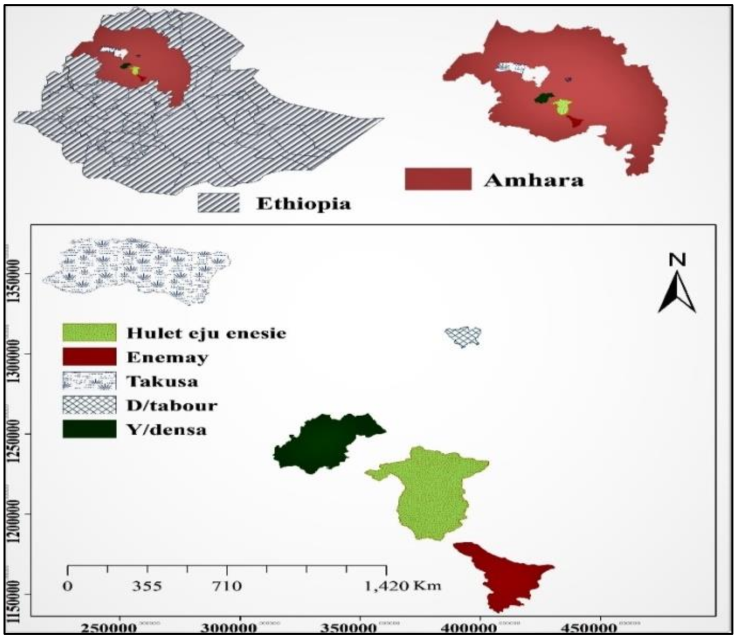

Figure 1. Map of Amhara National Regional State showing the testing sites.

Table 1. Description of the locations and seasons.

Test environments		Altitude	Geographical location		Soil type	Weather data		
Code	Name	(m.a.s.l.)	Latitude	Longitude		Rainfall (mm)	Temperature (°C)	
							Max.	Min.
E1	Debre-Tabor-2018	2591	11^{0}51'N	38^{0}01'E	Luvisol	1609.5	22.5	9.5
E2	Adet –2018	2240	11^{0}16' N	37^{0}29' E	Nitosol	1432.0	25.6	10.8
E3	Motta–2018	2470	11^{0}20'N	37^{0}88' E	Nitosol	1334.0	23.8	10.5
E4	Bichena–2018	2541	10^{0}46'N	38^{0}19'E	Vertisol	1186.0	24.4	11.1
E5	Takussa–2018	1840	12^{0}10'N	37^{0}06' E	Vertisol	870.0	15.0	28.0
E6	Debre–Tabor-2019	2591	11^{0}51'N	38^{0}01'E	Luvisol	1926.1	22.7	10.0
E7	Adet–2019	2240	11^{0}16' N	37^{0}29' E	Nitosol	1591.8	25.9	11.1
E8	Motta–2019	2470	11^{0}20'N	37^{0}88' E	Nitosol	1457.5	24.1	11.4
E9	Bichena–2019	2541	10^{0}46'N	38^{0}19'E	Vertisol	1126.4	23.5	10.7
E10	Takussa–2019	1840	12^{0}16'N	37^{0}06' E	Vertisol	Na	Na	Na

Note: *m.a.s.l. = meter above sea level; E = East; N = North; Max. = Maximum; Min. = Minimum; and Na = Not available for the specified periods. Weather data were collected from West Amhara Meteorological Cervices Center (2018 and 2019), and edaphic information's were obtained from the respective research centers.*

2.2. Plant Materials

Twenty teff varieties released for cultivation in Ethiopia were used in this study (Table 2). The varieties were deliberately collected based on their phenology, adaptation, yield performance, and seed color, to select high yielding and stable teff genotypes that interact less with the changing environment in north western Ethiopia (Table 2).

2.3. Treatments and Experimental Management

The treatments consisted of 20 genotypes (Table 2) and ten environments (locations) (Table 1). The experiment was laid out as a Randomized complete block design and replicated three times per treatment. Each plot consisted of six rows with 2 m length and 0.2 m spacing between rows. The spacing between blocks and plots were 1.5 m and 1 m, respectively. Land was prepared according to the conventional practice. It was ploughed five times using oxen before planting and the plot after the last ploughing was used for sowing. Planting was done from the beginning to end of July depending on the recommendations for the different test locations. Sowing was done by hand drilling using seeding rate of 15 kg ha^{-1}. A blanket recommendation rate of Urea and Di ammonium Phosphate (DAP) were applied to the plots at the rate of 40/60 N/P_2O_5 ha^{-1} for Nitisols and Luvisols and 60/60 N/P_2O_5 ha^{-1} for vertisols. All of the DAP was applied at planting but Urea was top dressed at tillering stage. All other pre-and post-planting management practices were made as per the recommendations for teff husbandry in all test locations.

2.4. Data Collection

Data were collected on plant, row and plot basis. Five randomly taken plants were selected from the central four rows for plant-based parameters. The entire six rows in the plot were used for plot-based data scoring whereas four central rows were used for row-based data scoring. Plant height, panicle length, and culm length were recorded on plant basis. Shoot dry biomass and grain yield were recorded on row basis whereas days to heading and days to maturity, grain filling period were recorded on whole-plot basis.

Table 2. Descriptions of teff genotypes used for the study.

Genotype	ID	Year of release	Suitable environment	Seed color	Breeding center	Grain yield (tons ha^{-1})	
						Research station	Farmers' field
WellenKomi (DZ-01-787)	G1	1978	HP	Pale white	Debre-Zeit	2.4-3.0	2.0-2.4
Tsedey (DZ-Cr-37)	G2	1984	LW	White	Debre-Zeit	1.8-2.5	1.4-2.2
Dukem (DZ-01-974)	G3	1995	HP	Pale white	Debre-Zeit	2.4-3.4	2.6-2.7
Ziquala (DZ-Cr-358)	G4	1995	HP	White	Debre-Zeit	17-24	16-22
Ambo Toke (DZ-01-1278)	G5	2000	HP	White	Holeta	2.4-3.5	Na
Dega-Tef (DZ-01-2675)	G7	2005	HP	Pale white	Debre-Zeit	1.5-2.2	1.6-2.0
Quncho (DZ-Cr-387RIL355)	G8	2006	HP	Very white	Debre-Zeit	2.0-3.2	1.8-2.6
Etsub (DZ-Cr-3186)	G9	2008	HP	White	Adet	1.9-2.7	1.6-2.2
Simada (DZ-Cr-285RIL295)	G10	2009	LW	White	Debre-Zeit	1.9-2.8	1.6-2.5
Boset (DZ-Cr-40RIL-50d)	G11	2012	LW	Very white	Debre-Zeit	1.8-2.0	1.4-1.8
Kora (DZ-Cr-438RIL-133B)	G12	2014	HP	Very white	Debre-Zeit	2.5-2.8	1.8-2.2
Were-Kiyu (Acc.21476A)	G13	2014	LW	White	Sirinka	2.22	Na
Abola (DZ-Cr-438(RIL7)	G14	2015	HP	White	Adet	2.0-2.8	1.46-1.68
Dagim (DZ-Cr-438-RIL91A)	G15	2015	HP	White	Debre-Zeit	2.5-2.8	1.8-2.3
Areka-1(DZ-01-974*DZ-012788)	G6	2017	LW	White	Areka	1.6-1.87	1.6-1.75
Negus (DZ-Cr-429RIL125)	G16	2017	HP	Very white	Debre-Zeit	2.8	Na
Felagot (DZ-Cr-442RIL77C)	G17	2017	HP	Brown	Debre-Zeit	2.54	Na
Tesfa (DZ-Cr-457-RIL181)	G18	2017	HP	Very white	Debre-Zeit	2.5	Na
Hiber-1 (DZ-Cr-419)	G19	2017	LW	White	Adet	1.7-2.7	1.46-2.08
Abay (Acc#225931)	G20	2018	HP	White	Adet	2.5-3.5	1.8-2.2

Note: *ID = identification; HP = High potential; LW = Low moisture; and MoA = Ministry of Agriculture. Na = not available. Genotypes were obtained from MoA (2006–2018) and variety releasing centers.*

2.5. Data Analysis

Analysis of variance for grain yield and yield related traits was carried out for each location separately using PROC GLM model of SAS computer program (SAS Institute, 2002). Duncan's Multiple Range Tested was used for mean separation. The combined analysis of variance across locations was done using PROC GLM with MIXED procedure of SAS software which corresponds to the statistical model. Genotype effects were assumed to be fixed and environmental effects as random. To determine the validity of the combined analysis of variance, the homogeneity of error variance between environments were performed based on the ratio of the larger mean square of error (MSE) from the separate analysis of variance to the smallest mean square of error as:

$$\text{F–ratio} = \frac{\text{Large MSE}}{\text{Small MSE}}$$

If the larger error mean square was not three-fold larger than the smaller error mean square, the error variance was considered homogeneous (Gomez and Gomez, 1984). Genotype by environment interaction was quantified using pooled analysis of variance, which partitions the total in to its component parts (genotype, environment, genotype **x** environment interaction and pooled error). The following statistical model was used for ANOVA of data of the individual environments:

$$Y_{ij} = \mu + G_i + B_j + \varepsilon_{ij}$$

Where, Y_{ij} = observed value of genotype i in block j; μ = grand mean of the experiment; G_i = effect of genotype I; B_j = the effect of block j; and, ε_{ij} = error effect of genotype i in block j.

In performing the combined analysis of variance, genotypes were assumed to be fixed while replications with in environments were assumed random. The following statistical model was used for combined analysis of variance over locations:

$$Y_{ijk} = \mu + G_i + E_j + GE_{ij} + B_{kj} + \varepsilon_{ijk}$$

Where, Y_{ijk} = observed value of genotype i in block k of environment (location) j, μ = grand mean, G_i = effect of genotype i, E_j= environment or location effect, GE_{ij} = the interaction effect of genotype i with environment j, B_{kj} = the effect of block k in location (environment) j, and ε_{ijk} = error (residual) effect of genotype i in block k of environment j.

The combined analysis of variance was carried out to estimate the additive main effects of environment, genotype and GEI. Significance levels of these components were determined by using F-tests. Whenever the F-test was found significant, genotype x environment interaction was described using GGE biplot analysis (Yan *et al.,* 2000) using GENSTAT analytical software version 18 (VSN International, 2015). Genotype main effect plus genotype x environment interaction biplot model (Yan *et al.,* 2000) is the most commonly used and more efficient in determining the most stable and high yielding genotypes in multi-environment trials as compared to the earlier procedure (Eberhart and Russell, 1966; AMMI model, Guach and Zobel, 1988). The GGE biplot allows visual examination of the relationships among the test environments, genotypes and genotype x environment interactions. Thus, the first two principal components (PC1 and PC2) were used to graphically represent the GEI, and to identify the rank of the test genotypes and environments (Yan *et al.,* 2000).

GGE biplot analysis was based on the simplified model with two principal components (Yan *et al.,* 2000). The model was:

$$Y_{ij}–y_{ij} + l_1x_{i1}h_{j1} + l_2x_{i2}h_{j2} + \varepsilon_{ij}$$

In which, Y_{ij} is the productivity mean of cultivar i in environment j, y_{ij} is the general mean of the cultivars in environment j, l_1 x_{i1} $h_{j1}$is the first principal component (PCA1), l_2 x_{i2} h_{j2} is the second principal component (PCA2), l_1 and l_2 are the eigenvalues associated with PCA1 and PCA2, respectively, $x_{i1}$and x_{i2} are the values of the first and second principal components, respectively, for cultivar I, h_{j1} and h_{j2} are the values of the first and second principal components, respectively, for environment j, and ε_{ij} is the error ij associated with the model.

3. Results and Discussion

3.1. Analysis of Variance

Variance of homogeneity from results of the quick Bartlett test revealed that the mean squares of individual locations were homogenous for grain yield. Thus, the combined analysis of variance for gain yield of 20 improved teff varieties at ten environments showed highly significant ($P < 0.001$) effects of genotypes, environments and genotype x environment interaction (Table 3). Environments accounted for 54% of the total variation followed by the GEI (23%) whereas the genotype alone accounted 16% (Table 3). Habte Jifar *et al.* (2019) reported similar findings in teff multi-environment trials, where the largest proportion of total variation was attributed to locations and relatively smaller effects were noted due to genotype and genotype and environment interaction (GEI). Sewagegne Tariku *et al.* (2018) also found similar results in which environments contributed about 91% of the total variation in grain yield of teff, while genotypes and GEI accounted for about 0.87% and 3.63%, respectively. The high percentage of the environment sum squares is an indication that the major factor that influence yield performance of teff genotypes is the environment. Besides, the environmental effect was found to be highly significant. This may indicate presence of significant differences among testing locations due to variation in temperature, soil type, rainfall, and other environmental factors as also reported by Legesse Kassa *et al.* (2006).

Table 3. Combined ANOVA for grain yield (ton ha^{-1}) of genotypes tested at five environments during 2018 and 2019 cropping seasons.

Source of variation	Degrees of freedom	Sum of squares	Percent of total explained	Mean squares	Pr > F
Blocks (Environments)	20	1.4323	0.925	0.072	<.0001
Environment	9	82.75	53.47	9.194	<.0001
Genotype	19	25.39	16.41	1.336	<.0001
Genotype × Environment	171	35.58	22.99	0.20807	<.0001
Residuals	380	9.61	6.21	0.02529	
Total	599	154.76	100		
Mean			2.16		
Coefficient of determination (R^2)			0.94		
Coefficient of variation (%)			7.36		

The large sums of squares associated with the environment in the present study indicate that the selected test environments were agro-ecologically diverse. This signifies the importance of site selection for teff cultivation. The mean grain yield across environments ranged from 1.65 tons ha^{-1} for Debre-Tabor to 2.77 tons ha^{-1} for Takussa. On the other hand, the grain yield means of the genotypes ranged from 1.68 to 2.51 tons ha^{-1} for Simada and Hiber-1, respectively. Takusa and Bichena were relatively high yielding environments compared to Debre-Tabor, Motta and Adet. The variety Hiber-1 performed best in most of the environments (locations) followed by the varieties Etsub and Kora. Apart from this, the teff varieties with higher grain yield at specific location respectively, were: Hiber-1, Dagim and Etsub at Adet; Kora, Hiber-1 and Dukem at Bichena; Etsub, Hiber-1 and Kora at Takussa; Worekiyu, Wellenkomi and Filagot at Motta; and Etsub, Dukem and Wellenkomi at Debre-Tabor (Table 4). The high variability in grain yield among the twenty teff varieties at the ten environments might be due to wide variability in climatic and soil conditions. Similarly, inconsistent grain yield performances of teff varieties have been found across locations (Solomon Chanyalew *et al.,* 2009; Ayalneh Tilahun *et al.,* 2012; Mathewos Ashamo and Getachew Belay, 2012; Wendwosen Shiferaw *et al.,* 2012; Sewagegne Tariku *et al.,* 2018; Habte Jifar *et al.,* 2019).

Table 4. Mean grain yield ton ha^{-1} of twenty teff genotypes for individual environments during the 2018 and 2019 main cropping seasons.

Variety	2018					2019					Overall mean	Rank
	D/T	Adet	Motta	Bichena	Takusa	D/T	Adet	Motta	Bichena	Takusa		
Wellenkomi	2.18^{bc}	2.38^{cde}	2.12^{a}	2.93^{bc}	2.36^{de}	1.99^{bc}	1.77^{fg}	2.21^{ab}	2.53^{abc}	2.31^{defg}	2.28	5
Tsedey	1.25^{h}	1.95^{fg}	1.98^{abc}	2.35^{e}	2.55^{cd}	1.32^{j}	2.03^{cde}	1.94^{cdef}	1.72^{f}	2.29^{defg}	1.94	17
Dukem	2.29^{b}	2.29^{cde}	1.78^{cde}	3.13^{b}	3.03^{ab}	2.10^{ab}	2.21^{abcd}	1.78^{efg}	2.85^{a}	2.33^{def}	2.38	4
Ziquala	1.62^{efg}	2.24^{def}	1.59^{e}	2.53^{de}	2.46^{cde}	1.48^{fghi}	2.00^{de}	1.70^{g}	1.92^{ef}	2.28^{defg}	1.98	15
Ambotoke	1.85^{de}	2.59^{bc}	1.94^{abcd}	2.80^{bcd}	3.05^{ab}	1.53^{fgh}	2.02^{de}	2.01^{cbd}	2.34^{bcd}	2.22^{efg}	2.24	7
Areka-1	1.72^{ef}	2.12^{efg}	1.67^{de}	1.75^{f}	2.90^{ab}	1.89^{c}	1.73^{gh}	1.71^{g}	1.86^{f}	2.36^{cde}	1.97	16
Dega-Tef	2.18^{bc}	2.19^{ef}	1.94^{abcd}	2.82^{bcd}	1.87^{f}	1.93^{c}	2.08^{cde}	1.96^{cdef}	2.72^{ab}	1.89^{i}	2.16	9
Quncho	1.96^{cd}	2.53^{bcd}	1.80^{bcde}	2.96^{bc}	3.03^{ab}	1.60^{def}	2.11^{bcd}	1.89^{cdefg}	2.61^{abc}	2.10^{ghi}	2.26	6
Etsub	2.52^{a}	2.81^{ab}	1.79^{bcde}	2.94^{bc}	3.20^{a}	2.23^{a}	2.20^{abcd}	1.87^{cdef}	2.60^{abc}	2.64^{a}	2.48	2
Simada	1.27^{h}	1.57^{h}	1.65^{e}	1.96^{f}	2.93^{ab}	1.36^{ij}	1.63^{gh}	1.24^{h}	1.08^{g}	2.12^{fgh}	1.68	19
Boset	1.49^{fgh}	2.29^{cde}	1.93^{abcd}	2.88^{bc}	2.88^{ab}	1.39^{hij}	2.00^{de}	1.74^{fg}	2.35^{bcd}	2.57^{abc}	2.15	10
Kora	1.99^{cd}	2.56^{bcd}	1.97^{abc}	3.46^{a}	3.03^{ab}	1.70^{de}	2.26^{abc}	1.96^{cdef}	2.91^{a}	2.46^{abcd}	2.43	3
Werekiyu	1.71^{ef}	2.38^{cde}	2.16^{a}	2.77^{cd}	2.13^{ef}	1.56^{ef}	2.00^{def}	2.27^{a}	2.36^{bcd}	2.15^{efgh}	2.15	11
Abola	1.68^{ef}	2.29^{cde}	1.97^{abc}	2.88^{bc}	2.37^{de}	1.41^{ghij}	1.99^{def}	1.83^{defg}	2.62^{abc}	2.11^{fghi}	2.12	13
Dagim	1.58^{fg}	2.80^{ab}	1.74^{cde}	2.72^{cd}	2.72^{bc}	1.55^{fg}	2.32^{ab}	1.89^{cdefg}	2.58^{abc}	2.45^{abcd}	2.24	7
Negus	1.52^{fg}	2.82^{ab}	2.00^{abc}	2.91^{bc}	2.39^{cde}	1.52^{fgh}	2.15^{bcd}	2.02^{bcd}	1.86^{f}	2.17^{efgh}	2.13	12
Felagot	1.39^{gh}	2.12^{efg}	2.06^{ab}	2.93^{bc}	3.12^{a}	1.72^{d}	2.20^{abcd}	1.88^{cdefg}	2.26^{cde}	2.37^{bcde}	2.21	8
Tesfa	1.27^{h}	1.86^{g}	1.82^{bcde}	2.29^{e}	3.08^{ab}	1.34^{ij}	1.51^{h}	1.81^{defg}	1.32^{g}	1.99^{hi}	1.83	18
Hibir-1	1.97^{cd}	2.94^{a}	1.99^{abc}	3.15^{b}	3.17^{a}	1.97^{bc}	2.39^{a}	2.08^{abc}	2.89^{a}	2.58^{ab}	2.51	1
Abay	1.41^{gh}	2.11^{efg}	1.98^{abc}	2.86^{bcd}	3.07^{ab}	1.36^{ij}	1.84^{efg}	1.97^{cde}	2.02^{def}	2.21^{efgh}	2.08	14
Mean	1.74	2.34	1.89	2.75	2.77	1.65	2.02	1.89	2.27	2.28	2.16	
SEM (±)	0.076	0.098	0.084	0.105	0.108	0.0523	0.082	0.078	0.133	0.244		
CV (%)	7.59	7.23	7.71	6.63	6.73	5.49	703	7.15	10.17	5.85		

Note: *Means in the same column followed by the same letters are not significantly different at P ≤ 0.05 using Duncan's Multiple Range Test. D/T = Debre-Tabor. CV = Coefficient of variation and SEM =Standard error of the mean.*

3.3. Stability Analysis and Mega-Environment Classification Using GGE Biplot

3.2.1. The "Which-won-where" pattern

The analysis of variance showed the presence of highly significant G x E mean squares for grain yield across the test environments. This result indicates that the use of the GGE biplot would be pertinent to decompose the G x GEI effects. The Principal Component axis1 (PC1) and axis 2 (PC2), are cumulatively, explained 68% of the total variation for grain yield (Figure 2). This result suggests that the biplot graphics explained most of the sums of squares for genotype by environment interaction. This outcome made it possible to have a safe genotype selection based on the multivariate analysis as per the suggestions of Yan (2001).

The varieties and the environments found inside the polygon were less responsive to environment stimuli (Figure 2). Environments grouped inside the same polygon had similar influence on the genotypes. Environment groups deriving from the ten assessed environments revealed three mega-environments. The first one encompassed Takusa and Debre-Tabor areas with genotypes Etsub and Hiber-1 presented in the vertex. The second mega-environment contains Adet and Bichena areas and the third mega-environment contains only one location which is Motta with the vertex genotype Werkiyu (Figure 2). Related to this result, Karimizadeh *et al.* (2013), Yirga Belay (2016) and Sewagegne Tariku *et al.* (2018) identified different lentil, sesame and tef varieties, respectively, growing on mega environments. In the polygon view of the biplot analysis, the genotypes and test environments fell into four and three sectors, respectively. Varieties from the polygon vertex that did not group in any one of the environments were not fit varieties for the tested environment. The vertex variety Simada (G10) and Tesfa (G18) had no corresponding environment and hence have the lowest mean grain yield across environments (Figure 2). Habte Jifar *et al.* (2019) similarly reported non fit varieties for the tested environments in teff GGE biplot analysis.

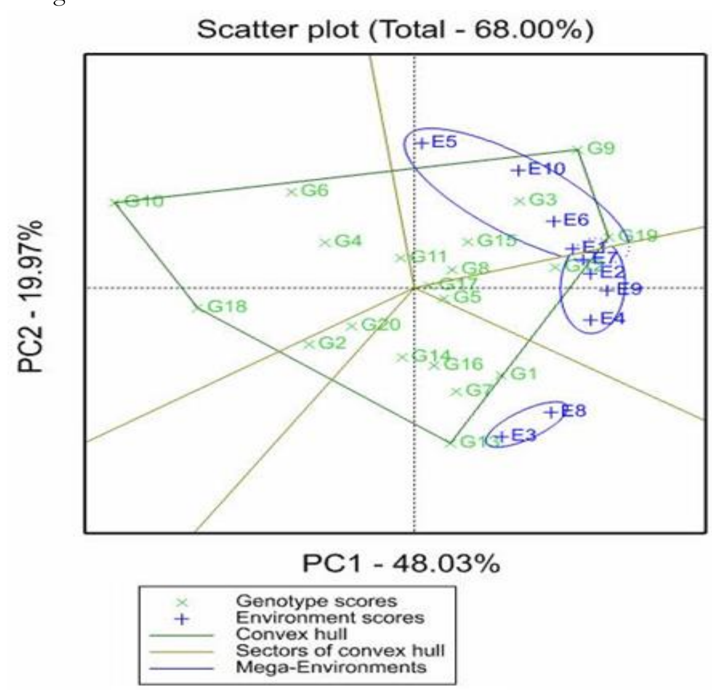

Figure 2. Polygon views of the GGE-biplot based on symmetrical scaling for the Which-won-where pattern analysis for varieties and environments (E1 = Debre-Tabor year-1, E2 = Adet year-1, E3 = Motta year-1, E4 = Bichena year-1, E5 = Takusa year-1, E6 = Debre-Tabor year-2, E7 = Adet year-2, E8 = Motta year-2, E9 = Bichena year-2, E10 = Takusa year-2, G1 = Wellenkomi, G2 = Tseday, G3 = Dukem, G4 = Ziquala, G5 = Ambotoke, G6 = Areka-1, G7 = Dega-Tef, G8 = Quncho, G9 = Etsub, G10 = Simada, G11 = Boset, G12 = Kora, G13 = Werekiyu, G14 = Abola, G15 = Dagim, G16 = Negus, G17 = Flagot, G18 = Tesfa, G19 = Hiber-1, and G20 = Abay).

3.2.2. Evaluation of genotypes relative to ideal genotypes

A genotype which is found at the center of the concentric circle is considered as an ideal genotype for teff grain production with its high mean yield and consequently stable characteristics, and genotypes that are close to the ideal genotype are considered as good genotypes (Figure 3). Accordingly, Hiber-1 (G19) being at the center of the concentric circle can be considered as an ideal genotype for teff grain production with high mean yield and stable characteristics. Likewise, Kora (G12), Etsub (G9) and Dukem (G3) that were close to the ideal genotypes are considered as good genotypes based on their yield performance as well as stability. On the other hand, Simada (G10), Tesfa (G18), Tseday (G2) and Areka-1(G6) which are located farther from the first concentric circle are undesirable and low yielding genotypes (Figure 3). These results are confirmed by the mean separation test discussed earlier in Table 4. Similarly, Sewagegne Tariku *et al.* (2020) identified variety Hebir-1 is the most ideal genotype for teff grain production in teff variety verification trials. The relative contribution of stability and grain yield for identifying desirable genotype found in this study by the ideal genotype procedure of GGE biplot were also similar to Fan *et al.* (2007) maize hybrids stability studies.

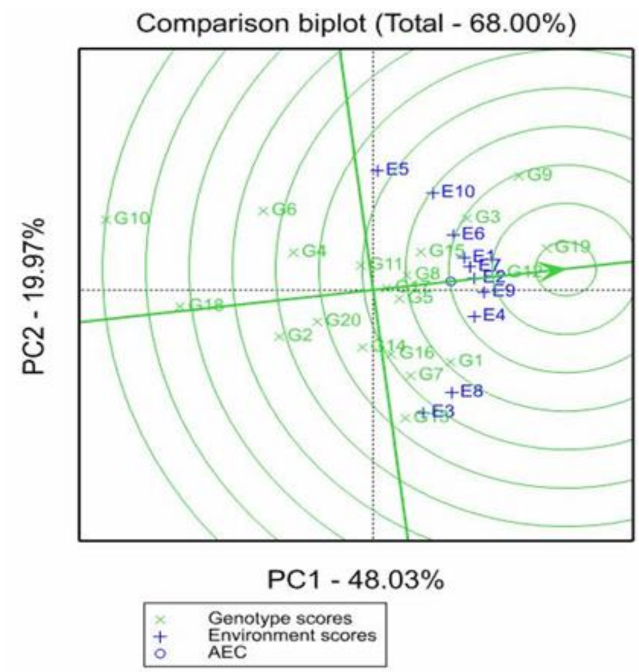

Figure 3. GGE-biplot based on genotype-focused scaling for comparison the genotypes with the ideal genotype (E1 = Debre-Tabor year-1, E2 = Adet year-1, E3 = Motta year-1, E4 = Bichena year-1, E5 = Takusa year-1, E6 = Debre-Tabor year-2, E7 = Adet year-2, E8 = Motta year-2, E9 = Bichena year-2, E10 = Takusa year-2, G1 = Wellenkomi, G2 = Tseday, G3 = Dukem, G4 = Ziquala, G5 = Ambotoke, G6 = Areka-1, G7 = Dega-Tef, G8 = Quncho, G9 = Etsub, G10 = Simada, G11 = Boset, G12 = Kora, G13 = Werekiyu. G14 = Abola, G15 = Dagim, G16 = Negus, G17 = Flagot, G18 = Tesfa, G19 = Hiber-1, and G20 = Abay).

3.2.3. Interrelationship among environment

In GGE biplot, the cosine of the angle between any environment vectors stands for correlation intensity. Less than 90° indicates a positive correlation, more than 90° indicates a negative correlation and close to 90° indicates no correlation (Yan and Kang, 2003). The angle between the vectors of two environments has a meaningful relation with the correlation coefficient between them (Yan, 2002; Yan and Kang, 2003) and such a relationship is used to group the test environments. Thus, if two environments are positively correlated, the best yielding genotypes in one environment will perform best in the other environments. In contrast, if two environments are negatively correlated, the best yielding genotypes in one environment perform the least in the other environment and vice versa (Yan, 2002; Yan and Kang, 2003). In the present study, as shown on Figure 4, Adet, Debretabor and Bichena with an angle less than 90° are positively correlated with each other. On the other hand, Takussa and Motta environments had greater than 90° angle and hence have negative correlations.

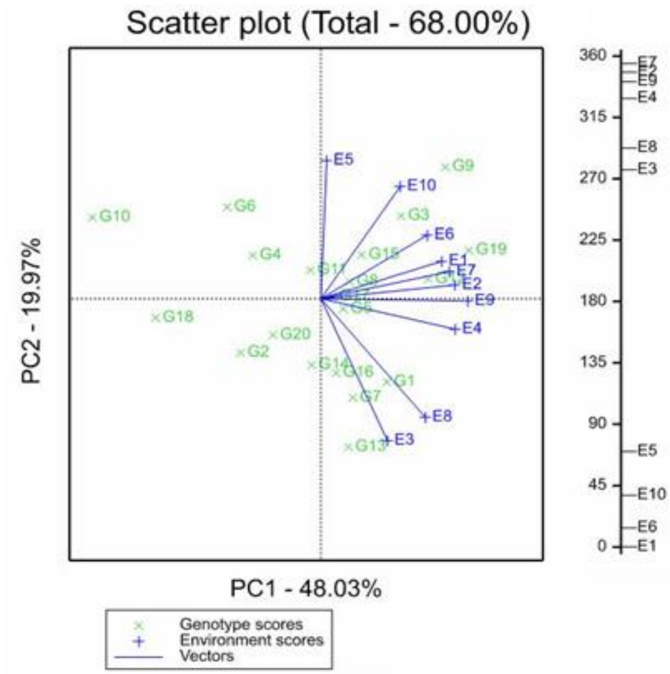

Figure 4. GGE-biplot based on environment-focused scaling for environments (E1 = Debre-Tabor year-1, E2 = Adet year-1, E3 = Motta year-1, E4 = Bichena year-1, E5 = Takusa year-1, E6 = Debre-Tabor year-2, E7 = Adet year-2, E8 = Motta year-2, E9 = Bichena year-2, E10 = Takusa year-2, G1 = Wellenkomi, G2 = Tseday, G3 = Dukem, G4 = Ziquala, G5 = Ambotoke, G6 = Areka-1, G7 = Dega-Tef, G8 = Quncho, G9 = Etsub, G10 = Simada, G11 = Boset, G12 = Kora, G13 = Werekiyu. G14 = Abola, G15 = Dagim, G16 = Negus, G17 = Flagot, G18 = Tesfa, G19 = Hiber-1, and G20 = Abay).

3.2.4. Evaluation of environments relative to ideal environments

An ideal environment should satisfy two conditions at the same time. These distinctly differentiate and discriminate the genotypes, and the representativeness for the target environments (Yan, 2010). Discriminating refers to an environment's ability to maximize the variance among candidate genotypes in a study (Blanche and Myers, 2006). An ideal trial site can effectively screen genotypes that have high and stable yields. In GGE biplot graph, the small circle stands for an ideal environment, which depends on the mean coordinates of all test environments. There has been a positive correlation between the environment vector length and the environment discriminating ability while there has been negative correlation between the angle existing in environment vector with the ideal environment and the environment's representativeness of the target environment (Yan, 2010). Accordingly, Figure 5 shows that the discriminating ability and the best representative environments for teff varieties was in declining order E2 (Adet year-1), followed by E7 (Adet year-2), E9 (Bichena year-2), E4 (Bichena year-1), E1 (Debre-Tabor year-1), E6 (Debre-Tabor year-2), E8 (Motta year-2), E3 (Motta year-2), E10 (Takusa year-2), and E5 (Takusa year-1). A test environment having a small angle with the average environmental axis is said to be more representative of other test environments (Yan and Tinker, 2006). In the present study, therefore, Adet (E2) which fell into the center of concentric circle and had the longest vector length and the smallest angle with the average environmental axis was identified to be the most representative of all test environments. Hence, Adet and Bichena are relatively ideal locations for teff cultivation among the test environments. In agreement with this finding, Habite Jifar *et al.* (2019) reported that Adet and Axum are relatively representative environments among test environments for teff production, but on the contrary, same researchers reported that they were not discriminative environments. Mahdieh *et al.* (2016) also reported that a testing environment has less power to discriminate genotypes when located far away from the center concentric circle or to an ideal environment. Hence, in connection to our result, Motta and Takusa testing locations, which are located far away from the center concentric circle, are considered as less powerful to discriminate genotypes.

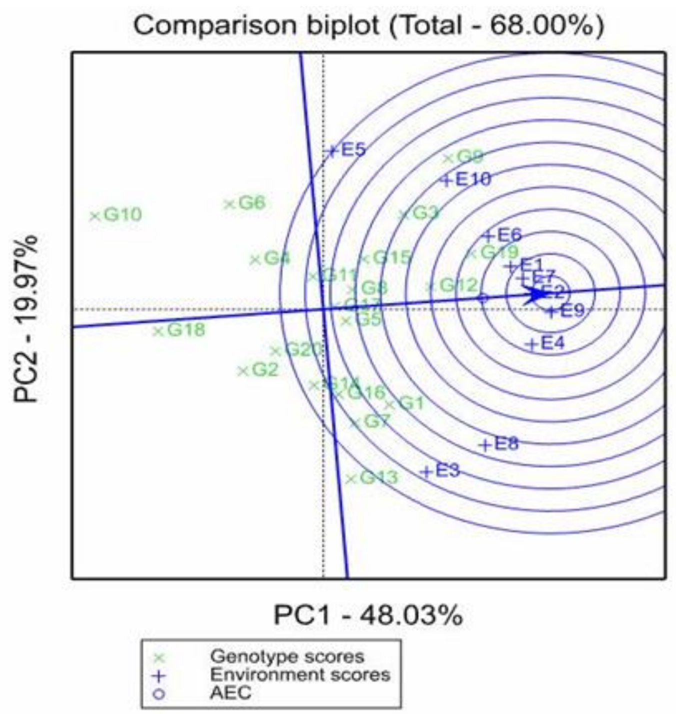

Figure 5. GGE-biplot based on environment-focused scaling for comparison of environment with the ideal environments (E1 = Debre-Tabor year-1, E2 = Adet year-1, E3 = Motta year-1, E4 = Bichena year-1, E5 = Takusa year-1, E6 = Debre-Tabor year-2, E7 = Adet year-2, E8 = Motta year-2, E9 = Bichena year-2, E10 = Takusa year-2, G1 = Wellenkomi, G2 = Tseday, G3 = Dukem, G4 = Ziquala, G5 = Ambotoke, G6 = Areka-1, G7 = Dega-Tef, G8 = Quncho, G9 = Etsub, G10 = Simada, G11 = Boset, G12 = Kora, G13 = Werekiyu. G14 = Abola, G15 = Dagim, G16 = Negus, G17 = Flagot, G18 = Tesfa, G19 = Hiber-1, and G20 = Abay).

3.3.5. Mean grain yield and stability performance of genotypes

Ranking of twenty teff varieties based on mean yield performance and stability is presented in Figure 6. The single arrow line passing through the biplot origin and the average environment indicated by the small circle is the average environments coordinate (AEC) axis, which is defined by the average PC1 and PC2 scores of all environments (Yan and Kang, 2003). This line points towards higher mean yield across environments. Hence, in the present biplot, G19 gave the highest mean yield followed by G9, G12, G3, G1, G8, G5, G15 and G17. The remaining genotypes had bellow grand mean yield (Figure 6). In lien with this result Sewagegne Tariku *et al.* (2020) reported that Hiber-1 is the highest mean grain yield and relatively stable variety in teff variety verification trial.

The line which passes through the biplot origin and perpendicular to the AEC axis shows the measure of stability. Either direction away from the biplot origin, on this axis, indicates greater Genotype **x** environment interaction and poor stability or vice versa (Kaya *et al.,* 2006). Thus, in terms of stability the genotypes ranked as G17 > G12 > G18 > G8 > G5 > G19 > G11 > G20 >

G2 > G15 > G4 > G14 > G3 > G16 > G1 > G7 > G9 > G6 > G10 > G13 (Figure 6). Stability was reported to have lower heritability than mean performance (Eskridge, 1996) hence; it is useful only when considered jointly with mean performance. Yan and Tinker (2006) also noted that stability refers to the relative performance of a genotype and it is meaningful only when associated with mean performance.

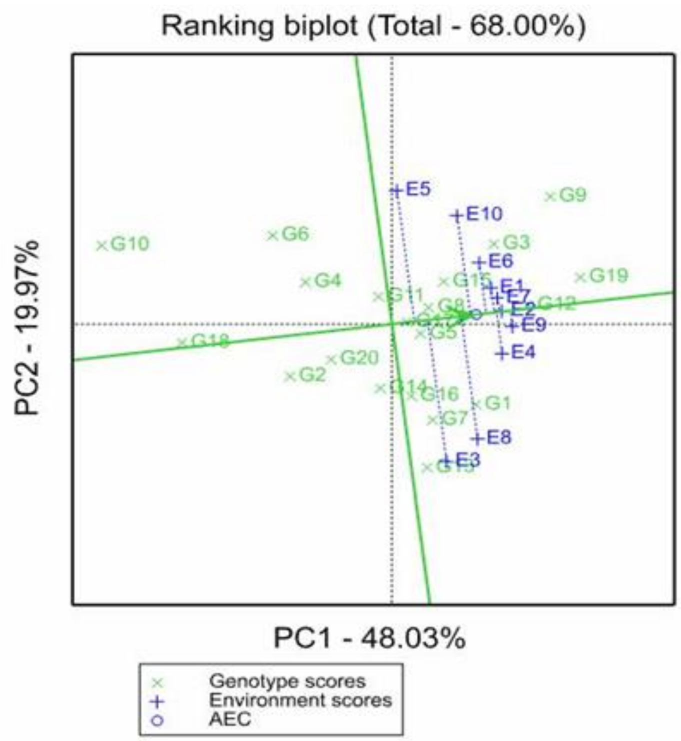

Figure 6. GGE-biplot based on environment-focused scaling for comparison of environment with the ideal environments (E1 = Debre-Tabor year-1, E2 = Adet year-1, E3 = Motta year-1, E4 = Bichena year-1, E5 = Takusa year-1, E6 = Debre-Tabor year-2, E7 = Adet year-2, E8 = Motta year-2, E9 = Bichena year-2, E10 = Takusa year-2, G1 = Wellenkomi, G2 = Tseday, G3 = Dukem, G4 = Ziquala, G5 = Ambotoke, G6 = Areka-1, G7 = Dega-Tef, G8 = Quncho, G9 = Etsub, G10 = Simada, G11 = Boset, G12 = Kora, G13 = Werekiyu. G14 = Abola, G15 = Dagim, G16 = Negus, G17 = Flagot, G18 = Tesfa, G19 = Hiber-1, and G20 = Abay).

4. Conclusions

Analysis of GEI is necessary to determine the stability and performance of varieties across different environments. The results of the combined analysis of variance in this study have demonstrated that teff grain yield and plant height, panicle length, dry biomas, days to heading and maturity were significantly affected by environment (E), followed by G x E interaction and genotype (G) effects, respectively. The results of the research revealed that the varieties Hiber-1 (G19), Kora (G12), Etsub (G9) and Dukem (G3) were found to be good genotypes based on their yield performance as well as stability. On the other hand, Simada (G10), Tesfa (G18), Tseday (G2) and Areka-1(G6) were found as unstable and low yielding genotypes. Thus, Hiber-1 could be recommended for wide cultivation across the areas of north western Ethiopia because of its high yield potential and yield stability. The results have also demonstrated that the variety Kora for Bichena, Etsub for Debre-Tabor and Takusa and Werekiyu for Motta could be potentially productive for specific adaptation to boost grain production of the crop. Furthermore, the present study revealed the existence of three mega-environments and four teff genotype groups in north western parts of Ethiopia. Environment, Adet, and Bichena have the longest vector length and the smallest angle with average environmental axis was the most discriminating and representative of all test environments, respectively. It could, thus, be concluded that Adet and Bichena districts are the best locations for teff production and Hiber-1 is the best teff variety to be produced in the region.

5. Acknowledgements

The authors are grateful to Adet Agricultural Research Center for providing financial supports and teff breeding staff of Adet and Debre-Tabor Research sub-center for technical supports.

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