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**ORIGINAL ARTICLE** **OPEN ACCESS**

# Genotype x Environment Interaction in Tef varieties [ *Eragrostis tef (Zucc) Trotter)]* in West Shewa Zone, Ethiopia

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**ABSTRACT**
*Tef [Eragrostis tef (Zucc) Trotter] is the major staple food crop for the Ethiopians. Tef is cultivated for a wide range of environmental conditions. Genotype x is an environmental interaction between the environment and genotypes, which resulting that an improved varieties of Tef across different environmental conditions. Hence, 10 tef genotypes were evaluated to understand the improved variety and estimate the magnitude of genotype x environment interactions. Data were collected on 13 quantitative traits on plot basis from randomly selected 5 tef plants from the central rows of each plot. Combined analysis of variance revealed that significant (P < 0.05) differences among genotypes, locations and genotype by environment interaction for all studied traits. The AMMI analysis partitioned the G x E variances into three principal component (PC) axes. The first and second interaction principal components explained for 84.6% (IPCA1=49.9% and IPCA2 = 34.7%) of the total variation. Meti and Babich were high yielding environments while Olonkomi and Guder were low yielding environments. The maximum days to maturity were 111.2 days for the genotype Guduru and the least were 93.5 days for genotype Felagot. High grain yield variation was observed among the genotypes, which is ranged from 11.6 q/ha Guduru to 15.7 q/ ha Felagot. The results of ASV and yield stability index reveal that Quncho and Dagim are suitable for wide production across the four environments while the 10 genotypes were divided into four genotypic groups. The huge variability was recorded in the grain yield among the 10 tef varieties at the four environments might be due to wide variability in climatic and soil conditions.*
***Keywords:*** *AMMI analysis: ASV: Combined analysis of variance: Genotype x Environment Interaction; Multivariate analysis: Yield stability index*

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## INTRODUCTION

Tef [*Eragrostis tef (Zucc)Trotter*] is the major staple food crop for the Ethiopians. The tef is an allotetraploid species with a base chromosome number of 10 (2n=4x=40) with genome size of 730 Mbp [10]. It is self-pollinated with chasmogamous and hermaphroditic flowers. Among yield and other traits, grain yield is highly affected by biotic and abiotic stresses as the effect of GEI. Therefore, the knowledge of magnitude of genotype by environment and stability of genotypes might have crucial role to confidentially scaling up the varieties. Crop performance is a function of genotype, environment, and genotype by environment interactions (GEI). The increase in crop production and productivity is, therefore, attained with advanced understanding of the crop management and growing environments [64].

Tef is a $C_4$ plant which allows it to more efficiently fix carbon in drought and high temperatures, and is an intermediate between a tropical and temperate grass[60]. The name tef is thought to originate from the Amharic word Teffa, which means "lost" [62]. Tef is grown for its tiny seeds and also for its straw to feed the cattle [32]. The seeds are very small, about 1 mm in length, and a thousand grains weigh approximately 0.3 g [59]. They can have a colour from a white to a deep reddish brown [60]. Tef is similar to millet and quinoa in cooking, but the seed is much smaller and cooks faster, thus using less fuel (Gonzales and Sasha, 2015). This probably refers to its tiny seeds, which have a diameter smaller than 1 mm .Tef is a fine-stemmed, tufted grass with large crowns and many tillers. Its roots are shallow, but develop a massive fibrous rooting system [32].

The total carbohydrate is the total of monosaccharaides, oligosaccharides, polysaccharides and total dietary fibre [1]. The total carbohydrate content of tef ranges from 57 to 86 g/100 g. However, relatively low total carbohydrate content was reported as (57 g/100 g) [31]. Generally, the total carbohydrate content of tef varieties was determined at 83--86 g/100 g [2]. Glycaemic index of tef is also lower than that of white rice, because of the slow digestion of the starch it contains [56]. Due to this property, it is particularly useful for diabetes patients [42].

Fatty acids have important effects for growth, development and future health problems. For example, the intake of omega-3 fatty acids (a-linoleic acid) has been found to reduce biological markers associated with cardiovascular disease, cancer, inflammatory and autoimmune diseases [18]. Teflipid content is higher than wheat and rice, but lower than corn.

There are wide ranges of mineral content among the varieties of tef and red tef has higher iron and calcium content than mixed or white tef. On the other hand, white tef has a higher copper content than red and mixed [3]. The mineral contents of tef grain includes Ca (180 mg/100 g), Fe (7.63 mg/100 g), Mg (184 mg/100 g), P (429 mg/100 g), K (427 mg/100 g), Na (12 mg/100 g), and Zn (3.63 mg/100 g) (wet basis) were reported. Another study showed that the Fe, Zn, and Ca contents of whole grain tef were 31.6, 2.31, and 78.8 mg/100 g (dry basis), respectively (Baye *et al.*, 2014). The Vitamin content of tef includes niacin: 3.363 mg/100 g, vitamin B6: 0.482 mg/100 g, thiamine: 0.39 mg/100 g, riboflavin: 0.27 mg/100 g, vitamin K: (phyllo Quinone) 1.9 mg/100 g, vitamin A: 9 IU, and a-tocopherol: 0.08 mg/100 g [65].

In Ethiopia, tef breeding program is coordinated by Debre Zeit Agricultural Research Center (DZARC) of Ethiopian Agricultural Research Institute (EIAR). Debre Zeit Agricultural Research Center (DZARC) is the center of excellence for tef research improvement. Under the umbrella of this institutional framework, the activities, particularly multi-location variety trials, of the tef breeding program is carried out at various federal and regional research centres and testing sites, higher learning institutions, and on farmers' fields [8]. Scientific tef improvement research in Ethiopia was started in the late 1950s. The period in the late 1950's marked the beginning of tef improvement research at Jimma Agricultural Technical School and later moved to Debre Zeit. Selection of lines from land races was the first attempt made to improve tef. In the years that followed the quest for a hybridization technique continued for several years with five inter-related phases without success.

In Ethiopia, crop production constituted an average 68% of agricultural GDP [30]. Small holders generated about 95% of the total production of the main crops (cereals, pulses, oil seeds, vegetables, root crops, fruits and cash crops) in the country [7]. Tef is an endemic tropical cereal crop of Ethiopia and it has been cultivated for thousands of years in Ethiopian high lands. Tef has been introduced to different parts of the world through various institutions and individuals since 1866 [4]. Due to its advantage to farmers, the cultivation of tef is increased from year to year. High market value and many other desirable characteristics, including higher nutritional value, low incidence of damage by insects, better adaptation to drought, adaptive to poor drainage, and high straw value have made tef attractive for cultivation [11].

The productivity of tef depends on weather conditions condition and appropriate technologies (fertilizer, improved seed, and herbicide) with the recommended rate and time. In the production year 2000, 2001 to 2014, 2015, tef showed an increasing rate in all area cultivated accounting production and productivity of 3.5%, 8.8%, and 5.1% respectively. Bezabeh, Nisrane [16; 55] reported that, tef output grows at 9.3% annually. Part of this tef growth was resulted from increments of cultivated area. In addition to this the increase in productivity of tef could be the result of good weather conditions [33]. Besides, high domestic demand, improved policy environment, enhanced investment and relatively high prices in the local market have encouraged tef farmers to produce in large amount and it increase tef productivity. According to Benson[15], significant increases in tef production provided the greatest benefits for urban consumers particularly poor urban households.

Tef is an important cereal crop which contributes 17.57% in area coverage and second next to maize in terms of total grain production [23] This area coverage of tef is increased to 27.37% in 2015/16 production season but, regarding to total production, it takes the third rank next to maize and sorghum. It indicates, as compared to 2014/15 production season, tef is decreased by one rank in 2015/16 production season which accounts 17.98% from total grain production [21. Tef is widely grown in East and West Gojam in Amhara and East and West Shoa in Oromia are known particularly as tef producer areas of the country [71]. A smaller quantity of it also produced in Tigray and SNNP regions [34].In line with this idea [33] Engdawork identified surplus and deficit areas in relation to tef production. According to Engdawork [33] finding, indicated that entire Shoa of Oromia region and entire Gojam of Amhara region are the major tef surplus producer areas of the country. On the other hand, entire Wollo, Tigray region, Harar, and Dire Dawa regions in Eastern Ethiopia and most of the pastoral's area of the country are considered as deficit tef producer areas of the country.

Despite its major importance in Ethiopia as a source of food, feed, cash, and as a rescue crop, tef is reported to have several production constraints. Hence, its national average yield is only about 1.64 tons per hectare [23]. The major reasons for such low yield of tef has been summarized by [8] as follows: low yield potential of the widely cultivated farmers' varieties; susceptibility to lodging especially under growth and yield promoting conditions; biotic stresses (diseases, insects, etc.); abiotic stress; the labour-intensive

husbandry and the weak seed and extension system. Thus, the poor extension linkage has hampered the penetration of improved varieties and production package to reach the desired level. As a result, most farmers in the larger parts of the country are still using local land-races or traditional agronomic practices. Such wide gap between using improved production package and using local land-races and cultural practices, is therefore, seriously affecting the national productivity of tef. The fact that tef production is a labour-intensive husbandry (requires up to five ploughing) and the difficulty of farmers to fulfil such requirement is another factor affecting the productivity of tef [8]. Last but not least, inadequate research investment allocated to tef improvement at national level and lack of global attention due to its localized importance has been considered as another critical constraint of tef [8].
Organisms are determined neither by their genes nor by their environment; they are the consequence of the interaction of genes and environment [63]. Genotype describes the complete set of genes inherited by an individual that is important for the expression of a trait under investigation. Phenotype describes all aspects of the individual's morphology, physiology and ecological relationships. The genotype is essentially a fixed character of the organism; it remains constant throughout life and is unchanged by environmental effects. The sum total of the effects of physical, chemical and biological factors of an individual other than its genotype is known as the environment. The individuals or populations of plants do not live in a vacuum but are surrounded and influenced by these factors.
Genotype X Environment Interaction is of major consequence to breeders in the process of developing improved varieties. When varieties are grown at several locations for testing their performance and relative rankings usually do not remain the same. This causes difficulty in demonstrating significant superiority of any variety. GEI is present whether varieties are pure lines, single crosses, double crosses, top crosses, S1 lines or any other material with which the breeder is working [24]. An understanding of environmental and genotypic causes of G x E interaction is important at all stages of plant breeding, including ideotype design, parent selection based on traits, and selection based on yield [40] Understanding of the causes of GEI can be used to establish breeding objectives, to identify ideal test conditions, and to formulate recommendations for areas of optimal cultivar adaptation. It can also help to reduce the cost of extensive genotype evaluation by eliminating unnecessary testing sites and by fine tuning the breeding programme. The presence of large GEI may necessitate establishment of additional testing sites, thus increasing the cost of developing commercially important varieties [43].
The concept stability of genotypes is central to all types of analyses of G x E interactions especially with reference to plant breeding. Stability has been described in many different ways over the years and there have also been different concepts of stability [50] One of the objectives of plant breeder is to develop cultivars that are high yielding across extensive ranges of environmental conditions. However, the presence of genotype by environment interactions (GEI) might complicate this labour [44]. For example, the GEI of a cross-over type causes changes in ranking performance across environments, complicating the breeder's task of selecting best candidate parents for next improvement cycle, and/or what to release as new cultivars for a given area or large region. When significant, GEI has an important role in accounting for the phenotypic variation of quantitative traits and can be accommodated in statistical models designed for multi environmental trials [19]. Stable genotypic performance is highly desirable in improved cultivars, which are important for food security and industrial uses [17]. The behaviour of cultivars in distinct environments is of special interest in breeding efforts targeting complex traits, such as grain yield, which are controlled by a large number of alleles, mostly presenting small effects, but which are very responsive to the environment [28].

## MATERIAL And Methods

### Description of the study area

The field experiment was conducted in the year 2019-2020, which is the main crop season in Babich, Guder, Olonkomi and Meti sub sites of the West Showa Zone. Since the maximum number of locations required to conduct GEI study is six, but due to the budget constraints, the experiments were conducted at four locations only. The West Showa site is located at 110 km West of Addis Ababa, the Babich site is located at 155 km from Addis Ababa and the soil type is Loam soil. Similarly, the Guder site is located at 115 km from Addis Ababa and the soil type is Nitosols. The Meti site is located at 107 km from Addis Ababa and the soil type is Loam soil and finally the Olonkomi site is located at 95 km from Addis Ababa and the soil type is Verti soil. All the locations come under the West Showa Zone.

### Experimental material

A total of 10 tef varieties were considered in this study. The list of test materials is mentioned in Table 1.

**Table 1:** Area cultivated and total production of tef by regions (2015/2016 production year (CSA, 2016)

| Region | Area cultivated (million ha) | % Share of total area planted | Production (Million Qt) | % Share of total production |
|---|---|---|---|---|
| Tigray | 0.162 | 5.66 | 1.899 | 4.25 |
| Amhara | 1.093 | 38.18 | 17.570 | 39.30 |
| Oromia | 1.369 | 47.82 | 22.156 | 49.55 |
| SNNPR | 0.212 | 7.40 | 2.773 | 6.20 |
| Benishangul | 0.027 | 0.94 | 0.315 | 0.70 |
| Total | 2.863 | 100 | 44.713 | 100 |

**Table 2:** Test locations Considered for study (West Showa Zone Agricultural Office, 2017).

| Locations | Mean-annual Rain fall (mm) | Altitude (m.a.s.l) | Temperature | | Soil type |
|---|---|---|---|---|---|
| | | | Min | Max | |
| | | | | | |
| Babich | 900-1800 | 1100-2000 | 16 oC | 28 oC | Loam soil |
| Guder | 800 -1100 | 1800 -3194 | 10 oC | 30 oC | Nitosols |
| Meti | 500-1600 | 1380-3130 | 10 oC | 28 oC | Loam soil |
| Olonkomi | 750-1170 | 2000-3288 | 9.3 oC | 23.8 oC | Verti soil |

**Table 3: Tef Genotypes used in the experiments**

| No | Local name | Variety name | Source | Year of release | Maintainer | Adaptation |
|---|---|---|---|---|---|---|
| 1 | Boset | DZ-cr-409 | Hybridization | 2012 | DZARC | _ |
| 2 | Dagim | DZ-cr-438 | Hybridization | 2016 | DZARC | _ |
| 3 | Tsedey | DZ-cr-37 | Hybridization | 1984 | DZARC | 1600-2400 |
| 4 | Felagot | DZcr-442 | _ | 2017 | _ | _ |
| 5 | Guduru | DZ-cr-1880 | Selection | 2006 | BARC | 1850-2500 |
| 6 | Kora | DZ-cr-438 | Hybridization | 2014 | DZARC | _ |
| 7 | Quncho | DZ-cr-387 | Hybridization | 2006 | DZARC | 1800-2400 |
| 8 | Nigus | DZ-cr-429 | _ | 2017 | _ | _ |
| 9 | Tesfa | DZ-cr-457 | _ | 2017 | _ | _ |
| 10 | Wedessa | DZ-01-1278 | Selection | 1999 | HARC | 2200-2400 |

**Key:** DZARC **=** BARC = Bako Agricultural Research Center; Debrezeit Agricultural Research Center; DZ-cr = Debrezeit cross

## Experimental design and field management

The experiment was conducted during the year of 2019/2020 in the main cropping season. The trials were carried out in randomized complete block design (RCBD). Each plot was 4 m long and 1 m wide consisted of 5 rows with spacing of 20 cm between rows and 40 cm between plot and 1m between blocks. Each variety was shown on 1 x 4 m and replicated trice under each test environment. Recommended agronomic package of the crop were uniformly applied to all plots using fertilizer sources and rates of NPS 100kg/ha, NPSB 100kg/ha, NPSBZn 100kg/ha and UREA 100kg/ha were applied. Similarly seed rate of 15kg/ha was used by drilling in rows **(Fig.1).**

## Data collection

Data was taken from 13 quantitative traits on plot basis and from randomly selected five (5) plants of tef from the central rows of each plot. The following data were collected on whole plot basis (**Fig.2**)

***Days to heading (DTH)****:* It was recorded as the number of days from sowing up to the emergence of the tips of panicle from the flag leaf sheath in 50% of the plot stands.

***Days to maturity (DTM)****:* It was recorded as the number of days from sowing up to 50% of the plants in the plot reaching physiological maturity stage (as evidenced by eye ball judgment of the plant stands when the color of the vegetative parts changed from green to colour of straw).

***Grain filling period (GFP)****:* It was recorded as the number of days from 50% heading to 50% maturity of the stands in each plot obtained by subtracting the former from the latter.


**Fig 1:** (a) Land preparation and layout of tef field under test locations, (b) During drilling of fertilizers under test location, (c) Tef data recording on the field and (d) Tef data recording on the field.


**Fig. 2:** (a) Tef data recording on the field, (b) Harvested tef from the field (Plot), (c) Separated (Cleaned) tef seed (Grain yield) from the straw, (d) Packed tef seed (Grain yield) from plot level.

***Lodging index (LOGI)**:* It was the value measured from the whole plot based on the product sum of the lodging degree taken on a scale of 0-5 and the lodging severity as % of the stand.
***Biomass yield (BY)**:* It was determined by weighting above ground total (shoot plus grain) biomass in gram for the entire plot.
***Grain yield (GY)**:* It was the weight of seeds harvested in gram from each plot.

***Harvest index (HI)****:* The ratio of grain yield to shoot biomass sampled from the entire plot expressed in percentage.
Data collected on plant basis from 5 (five) randomly selected plants from the three central rows of each plot include: -
***Plant height (PH)****:* It was measured from the base of the stem of the main tiller to the tip of the main shoot panicle at maturity recorded as the average of five plants per plot and measured in centimetre.
***Panicle length (PaL)****:* It was measured from the base of the main shoot panicle where the first branch emerges to the tip of the panicle at maturity recorded as the average of five plants per plot and measured in centimetre.
***Culm length (CL)****:* The length of the main shoot Culm from the ground level to the point of emergence of the panicle branches at maturity were recorded as the average on five plants per plot and measured in centimetre.
***Peduncle length (PDL)****:* It was measured from the last Culm node to the base of the panicle recorded as the average on five plants per plot and measured in centimetres.
***Number of total tillers per plant (TT)****:* It was recorded as the number of all tillers produced per plant assessed as the mean of five random plants per plot.
***Number of nodes (NN)****:* It was recorded as the number of nodes produced per plant assessed as the mean of five random plants per plot.

**Data analysis**

**Statistical methods to measure G x E interaction**

**Parametric approach**

Number of approaches have been proposed to understand GEI [66]. The common method is to estimate the environment component of the GEI and characterize the environments by the average yield of the genotypes [26]. The classical parametric approaches for analysis of genotype x environment interaction are based on several assumptions: normality of the distribution, homogeneity of variances and additive nature of effects (Khalili and Pour Aboughadareh, 2016). By use of non-parametric methods, which are simple and easy for analysis, all of the mentioned assumptions are avoided [61].

**Regression coefficient ($b_i$) and deviation mean square ($S^2d_i$)**

According to Ramagosa and Fox [58] simple linear regression provides a conceptual model for genotypic stability and is the most widely used statistical technique in plant breeding. This model is also called the Finlay and Wilkinson [36] approach. The regression of each genotypes mean yield against the mean yields of an environment is determined and the stability range is determined by the main effects multiplied by the regression coefficients of genotypes. The GEI is divided into two segments i) a component due to linear regression ($b_i$) of the i$^{th}$ genotype on the environment mean and ii) a deviation ($d_{ij}$): $GE_{ij}= b_i E_j + d_{ij}$ Therefore $Y_{ij}= \mu + G_i + E_j + (b_i E_j + d_{ij}) + e_{ij}$ where, Yij is the yield of the i$^{th}$ genotype in the j$^{th}$ environment, μ is grand mean, Gi is genotype deviation from the grand mean and $e_{ij}$ is the error mean.

**Ecovalence ($W_i$)**

The contribution of each genotype to the GEI sum of squares as a stability measure and defined this concept or statistics as Eco-valence ($W_i$). Eco-valence is simple to calculate and is expressed as: $W_i = \Sigma_j (Y_{ij} - \bar{Y}_{i.} - \bar{Y}_{.j} + \bar{Y}_{..})^2$ where $Y_{ij}$ is the mean performance of genotype iin the j$^{th}$ environment and $Y_{i.}$ and $Y_{.j}$ is the genotype and environment mean deviations respectively, and *Y* is the overall mean. For this reason, genotypes with a low $W_i$ value have smaller deviations from the overall mean across environments and are thus more stable. According to Becker and Leon [12] the eco-valence measures the contribution of a genotype to the GEI; a genotype with zero eco-valence is regarded as stable.

**Cultivar performance measure**

Cultivars performance largely depends on their genetic make-up, environment and their interaction. Fluctuating response of genotypes across test environment is a usual phenomenon, known as GEI [33]. According to the reports of Lin and Binns [50], the superiority measure ($P_i$) of the i$^{th}$ genotype as the mean square of distance between the i$^{th}$ genotype and the genotype with the maximum response as:

$$P_i = \frac{[n (Y_{i.} - M_{...})2 + (Y_{ij} - Y_i + M_{j.} + M_{...})2]}{2n} \quad (1)$$

Where $Y_{ij}$is the average response of the i$^{th}$ genotype in the j$^{th}$ environment, $Y_i$ is the mean deviation of genotype i, Mj is the genotype with maximum response among all the genotypes in the j$^{th}$ locations, and n is the number of locations. The smaller the value of $P_i$, the less is the distance to the genotype with maximum yield and the better the genotype.

**Multivariate analysis techniques**

Multivariate techniques are widely applied in stability analysis to provide further information on real multivariate response of genotypes to environments. According to Becker and Leon [12] multivariate analysis has three main purposes: (1): to eliminate the noise from the data pattern, (2): to summarize the data, (3): to reveal the structure in the data. Through multivariate analysis, genotypes with similar responses can be clustered, hypothesized, and later tested, and their data can be easily summarized and analysed [38].

**Principal component analysis (PCA)**

According to Purchase [57], PCA is efficient in multivariate method of stability analysis and describing GEI. Principal component analysis is used to find out the characters which accounted more for the total variation.

**Principal coordinate analysis (PCOA)**

Principal coordinate analysis (PCOA) permits the use of all types of variables, provided that a coefficient of appropriate type has been used to compute the resemblance hemi-matrix. Principal coordinates analysis helpful to permit the positioning of objects in a space of reduced dimension while preserving their distance relationships as well as possible [20].

**Cluster analysis**

Clustering the genotypes into different groups based on only information found in the data that describes the objects and their relationships. The importance of clustering is grouping similar (or related) to one another and different from (or unrelated) to the objects in other groups. The greater the similarity (or homogeneity) within a group and the greater the difference between the groups [20].

**Additive main effects and multiplicative interaction method (AMMI)**

Degree and direction of G x E interaction help breeders to reduce the cost of genotypes evaluation by avoiding uninformative testing locations [5]. Sufficient understanding of GEI and its exploitation can contribute significantly to genotype improvement [6]. Under multi environment trials genotypes are evaluated at many locations as stable performance accompanied with higher yield are more important as compared to yield at specific environment [9].

Plant breeders explore for genotypes with consistent yield performance across environments [14]. Numbers of statistical methods such as ANOVA, joint linear regression model, principal component analysis have been observed in studying GEI [25]. AMMI method is a combination of ANOVA and multiplicative GEI obtained from a singular value decomposition of the matrix of residues [54]. This analytic tool has an edge over joint linear regression as well as principal component analysis [49]. AMMI combines analysis of variance (ANOVA) into a single model with additive and multiplicative parameters. The model equation is: $Y_{ij} = \mu + G_i + E_j + \sum^{n}_{k=1\, \lambda k}$ αik γjk + eijWhere, $Y_{ij}$ is the yield of the $i^{th}$ genotype in the $j^{th}$ environment; μ is the grand mean; $G_i$ and $E_i$ are the genotype and environment deviations from the grand mean, respectively λk is the Eigen value of the PCA analysis axis k; αik and γjk are the genotype and environment principal component scores for axis k; n is the number of principal components retained in the model and eij is the error term.

**GGE-Bi-plot**

AGE-Bi-plot is a data visualization tool, which graphically displays a GEI in a two- way table. It is an effective tool for: 1: - Mega-environment analysis (e.g., "which won-where" pattern), whereby specific genotypes can be recommended to specific mega-environments; 2: - Genotype evaluation (the mean performance and stability), and 3: - Test-environmental evaluation. GGE-Bi-plot analysis is increasingly being used in GEI data analysis in agriculture [45]. The phenotypic expression of a genotype is a mixture of genotype (g) and environment (e) components, and interactions (gxe) between them. GEI complicates the process of selection of genotypes with superior performance. Multi-environment trials are widely used by plant breeders to evaluate the relative performance of genotypes for environments [27].

**Analysis of Variance (ANOVA)**

Analysis of variance (ANOVA) was made for yield and its component traits per each environment. After testing homogeneity of error variance, combined analysis of variance was made for grain yield. SAS software version 9.2 was used to analyse the stability of varieties and to know the magnitude of genotype x environment interaction. Additive main effect and multiplicative interaction (AMMI) model were used to combine the conventional analysis of variance for additive main effects with principal component analysis [37]. Adjusted means of 10 varieties from 4 environments were pooled to compute the AMMI analyses using SAS version 9.2 Software. AMMI stability values (ASVs) were calculated and ranked to assess stability of the hybrids across different environments. The ASV was used to know the distance from zero in a two-dimensional scatter gram of $IPCA_1$ scores against $IPCA_2$ scores. Thus, ASVs were calculated as follows:

$$ASV = \sqrt{\left[\frac{\text{IPC1Sum of Square}}{\text{IPCA2Sum of Sqare}}\left(IPCA1score\right)\right]^2 + [\text{IPCA2score})^2} \qquad - (2)$$

Where, ASV=AMI stability value;

SS = sum of squares for IPCAs,

$IPCA_1$=the first interaction principal component analysis

$IPCA_2$ = the second interaction principal component analysis, and thus hybrid with lower ASV is considered more stable than those with higher ASV values. Yield stability index (YSI) were calculated by adding the ranks of ASV values and the ranks of mean grain yield of each hybrid, where lower ASV and YSI represented better stability. Genotype x environment analysis will also be analysed using R package (GEAR-R with a set of R programs) to compute AMMI value, GGE- bi-plot and stability parameters. Graphical procedures of GGE- biplot methods were used to display locations' yield data in the form of genotype main effect (G) and the (GEI) in two-way data.

## RESULTS AND DISCUSSION

### Analysis of variance (ANOVA) and Estimates of Variance Component

Combined analysis of variance for grain yield of the 10 improved tef varieties tested across four testing environments revealed presence of significant ($P < 0.05$) variations for genotypes, environments and genotype by environment interactions (Table 2). The significant variability among the tef varieties in the present study is in line with the previous reports in tef [48]. The significant GXE interaction in the present study indicated unstable performance of tef varieties across the test environments (Appendix Table A). While, E3 (Meti) and E1 (Babich) were high yielding environments; E4 (Olonkomi) and E2 (Guder) were low yielding environments.

Although not at all locations, variety of Felagot (G4) performed better than others at least at two low yielding environments E4, (Olonkomi), E2, (Guder) and one high yielding environment E3, (Meti). Apart from this, tef varieties with higher productivity at specific tested environment (sites) were at Meti (Boset, Felagot,Dagim and DZ-cr-37), at Babich (Boset, Dagim, Felagot and Wedessa), at Guder (Boset, Nigus, Kora and Guduru), at Olonkomi (Felagot, Kora and Quncho (Table 3). Interestingly, the three top yielding varieties at Meti (Boset, Felagot and Dagim) have very close kinship. The huge variability in the grain yield among the 10 tef varieties at the four environments might be due to wide variability in climatic and soil conditions. Earlier works also reported similar inconsistencies in yield performance which complicated the selection and recommendation of stable genotype across environments [39: 47].

### Regression analysis based on Eberhart and Russell model

Mean square due to genotypes and interaction of genotype x environment (linear) were found to be significant ($P < 0.05$). The significance of genotypes x environments (linear) showed difference in yield performance among the genotypes under different environments. The mean performance, regression coefficient ($b_i$) and squared deviation ($S^2d_i$) from the regression values are presented in (**Appendix Table B**). According to Eberhart and Russell [29] genotypes with high mean yield and regression coefficient ($b_i$) equal to unity and deviation from regression ($S^2d_i$) approach to zero. The genotypes Felagot, Boset and Dagimhave mean yields higher than the average with, ($b_i$) values that did not differ significantly from unity and ($S^2d_i$) approaching zero. This implied that these genotypes were stable and widely adapted. However, Guduru performed poorly in all of the environments except in Guder (E2) because its mean grain yield was lower than the average and its ($b_i$) value was significantly less than unity. Any improvement in environment or agronomic practice will not bring change in grain yield increment in such variety. On the other hand, the genotypes Boset, Tsedey and Dagim had significantly higher ($b_i$) value showing that these genotypes were sensitive to changes in environmental conditions and tend to give high yield at a favourable environment (**Table 4**).

### AMMI Analysis of Variance for Grain Yield

AMMI model revealed significant ($P < 0.05$) differences for grain yield (q/ha) of 10 tef varieties due to genotypes, environments and their interaction. This is in-line with the previous works [47]. The AMMI analysis partitioned the G x E variance into three principal component (PC) axes as presented in (**Table 5**). Based on this, the first and second interaction principal components explained for 84.6% (IPCA1= 49.9% and IPCA2 = 34.7%) of the total variation. However, previously, Jifar [41] who reported 72.5% (IPCA1 = 53.04% and IPCA2 = 19.49%) of the total variation to be captured by the first and second IPCAs.

In the present study, the variation explained by the environment was higher than that of genotype and GE interaction in line with the earlier findings of other scholars [64]. The first two IPCAs that contributed for over 70% of the G x E interaction were used to create a biplot as being employed previously reported [47] (**Table 6**).

### Mean Grain Yield and AMMI stability value (ASV)

The mean grain yield of the four environments ranged from 9.1 q/ha at environment Olonkomi (E4) to 22.45 q/ ha at environment Meti (E3) with a mean of 13.7q/ha. The grain yield at Meti was followed by those at Babich, Guder and Olonkomi in descending order **(Table 7)**. On the other hand, among the 10 tef varieties tested across four environments, the mean grain yield ranged from 11.6q/ha for Guduru(G5) to 15.7q/ha for Felagot (G4). The five top yielding varieties were Felagot (15.7 q/ha), Boset (15.3 q/ha), Dagim (15.0 q/ha), Kora (13.7q/ha) and Quncho (13.7q/ha). The AMMI stability values (ASV), in the present study ranged from 0.22 for Quncho to 1.46 for Felagot **(Table 8)**. Thus, Quncho had the lowest ASV (0.22) and moderately higher grain yield (13.7 q/ha) whereas Felagot had the highest yield (15.7 q/ha) with relatively larger ASV (1.46) followed by Boset which had the next highest yield (15.3q/ha) with ASV (0.44).Hence, when considering higher grain yield, varieties such as Felagot, Boset and Dagimwith high grain yield and relatively more stable could be selected instead of varieties such as Kora and Quncho which were more stable but with moderately low yield.(**Table 9**)

**Mean performances of tef yield component traits**

The mean yield performance of the 10 tef varieties at four environments is shown in (**Table 10**). The maximum day to maturity is 111.2 days for the genotype Guduru and the least was 93.5 days for genotype Felagot. The overall evaluated genotypes at this area are relatively early matured. The range of days to maturity was longer as compared to the previous study of [46] who reported 84 to 100 days to maturity of 320 tef germplasms collected from diverse agro-ecology of Ethiopia and evaluated at Debrezait and Alem Tena. Hence the climatic conditions of one area adversely affect the maturity period of crop and thus most of the materials evaluated in this area were forced too early. The shorter phenelogy of the genotypes evaluated at this area might be due to the low altitude of the area. Thus, knowing of the phonological features of crop is important to adjusting the time of planting and may be reduces the adverse effects of weather condition [13] (**Table 11**).

There was significant difference among genotypes for plant height; which was ranged from 89.8 cm for Nigusto 118.6 cm for Tsedey with an average mean value of 103 cm. Genotype (Tseday) was the tallest height of 118.6 cm followed by variety Guduru113.4 cm, Quncho (112.7 cm), and Kora (111.1 cm), while the shortest plant height was found for Negus (89.8 cm). The length of panicle was ranged between 30.9cm for Felagot to 45.3 cm for Guduru with an average mean value of 37.5 cm. The maximum panicle length is for Guduru (45.3cm) and the least one is for Felagot (30.9cm). Culm length is the difference of plant height and panicle length. Maximum culm length was found for Tsedey (72.4 cm) while the least culm length was for Nigus (60.5 cm). Most of the time, these four traits have strong positive association with each other's [51;52]. Consideration of such plant growth characters during selection is very important as it is helpful to selecting the genotype with relatively withstand lodging. High grain yield variation was observed among the genotypes, which is ranged from 11.6 q/ha Guduru to 15.7 q/ha Felagot. This big variation among genotypes might be mainly due to the genetic potential of the genotypes. The variety, Quncho gave 13.7q/ha. The top genotype Felagot (G4) has a yield advantage over Quncho. Boset (G1) have relatively better harvest index (27.1 %). **(Table 12).** Based on the mean value, overall genotypes which have minimum yield advantage over Quncho variety were selected and advanced to the next breeding step which is a regional variety trail.

**Analysis of GGE–Bi-plot**

GGE bi-plot is visualized on the basis of results explained for the first two principal components [68]. In the present study, the first two principal components of GGE bi-plot explained 82.72% (PC1= 58.26% and PC2= 24.45%) of the total variations (**Fig. 3**). In the polygon view, genotypes found farthest away from the origin are the vertex genotypes having the highest yield in their respective sector [35]. In the present study, these genotypes include Felagot, Guduru, Tsedey, Nigus and Boset they all have the highest yield in their respective sector. In GGE bi-plot graph, various lines emanating from the origin and become perpendicular to the line connecting the vertex genotypes are useful to divide the testing environments and genotypes into different sectors. Therefore, the four testing environments were divided into three mega environments while the 10 genotypes were divided into four genotypic groups. The three mega environments consisted of Group-I Babich (E1) and Meti (E3), Group-II Guder (E2), and Group-III Olonkomi (E4). Variety Tsedey (G3) was the vertex and highest yielding genotype at environment namely Guder (E2). Similarly, Boset (G1) was the vertex and highest yielding genotype in Babich (E1) while, Felagot (G4) was the highest yielding at Olonkomi (E4). The other vertex genotypes (Guduru (G5), Negus (G8) however, had no corresponding environment and hence are the poorest yielding in all the testing environments. Sector four which consisted of Guduru (G5), Kora (G6), Nigus (G8) and Tesfa (G9) had no vertex genotype, though their mean yields were substantially higher than the grand mean and they were also among the top yielding genotypes in their neighbouring environments.

**Relationship among Environments and Discriminative Vs. Representativeness**

The angle between the vectors of two environments has a meaningful relation with the correlation coefficient between them Yan [69] used to group the test environments. The relationships among the four test environments in the present study were presented in (**Fig. 4**). Based on this graph, the angle between Babich (E1), Guder (E2) and Meti (E3) was less than $90^o$ indicating the existence of positive correlation between them. On the other hand, the angle between Meti (E3) and Olonkomi (E4) is nearly ($90^o$) showing that these environments are not correlated. Furthermore, Olonkomi (E4) had obtuse angle (>$90^o$) with Meti

(E3), Babich (E1) and Guder (E2) showing that it has negative correlation with these environments. Thus, if environments are negatively correlated, genotypes performing best in one environment would perform less in the other environment and vice versa. However, if environments are positively correlated genotypes performing best in one environment will have the same performance in the other environment.

**Table 4: Analysis of variance for grain yield (q/ha) of 10 tef varieties evaluated at four environments in West Showa in 2019/2020.**

| Sources of Variation | DF | SS | MS |
|---|---|---|---|
| Treatments | 39 | 3656.553 | |
| Environment (E) | 3 | 3170.334 | 1056.8** |
| Genotype (G) | 9 | 174.2197 | 19.4** |
| G*E | 27 | 311.9997 | 11.6** |
| Residuals | 80 | 367.8267 | 4.6 |
| Total | 119 | | |

**Key:** DF= Degree of Freedom, E = Environment, G = Genotype, G x E = Genotype by Environment interaction, MS = Mean of Squares, SS= Sum of squares.

**Table 5: The first four AMMI selection per environment**

| Number | Environments | Mean | Varieties | | | |
|---|---|---|---|---|---|---|
| | | | G1 | G2 | G3 | G4 |
| | | | | | | |
| 1 | Babich (E1) | 11.72 | G1 | G2 | G4 | G10 |
| 2 | Guder (E2) | 11.47 | G1 | G8 | G6 | G5 |
| 3 | Meti (E3) | 22.45 | G1 | G4 | G2 | G3 |
| 4 | Olonkomi(E4) | 9.08 | G4 | G6 | G7 | G2 |
| Grand Mean | | 13.68 | | | | |

**Key:** G1 = Boset, G2 = Dagim, G3 = DZ- cr- 37, G4 = Felagot, G5 = Guduru, G6 = Kora, G7 = Quncho, G8 =Nigus, G9 = Tesfa and G10 =Wedessa, E1 = Babich, E2 = Guder, E3 = Meti and E4 = Olonkomi.

Table 6: Stability analysis in tef varieties grown in West Shewa in 2019/2020

| Genotype | Regression coefficient ($b_i$) | Squared deviation from regression ($S^2d_i$) | Grain yield(q/ha) |
|---|---|---|---|
| Boset | 1.3095 | 0.6462 | 15.3 |
| Dagim | 1.1783 | -0.6278 | 15.0 |
| Tsedey | 1.1988 | 5.0409 | 13.2 |
| Felagot | 0.9514 | 16.1327 | 15.7 |
| Guduru | 0.7208 | 4.781 | 11.6 |
| Kora | 0.8411 | 0.4646 | 13.7 |
| Quncho | 0.9607 | 0.1733 | 13.7 |
| Nigus | 0.7664 | 1.0468 | 13.0 |
| Tesfa | 0.9739 | 0.3318 | 12.5 |
| Wedessa(Ambo Toke) | 1.0992 | 0.1375 | 13.3 |
| Mean | | | 13.7 |

**Key:** q/ha = Quintal per Hectare; *, ** = significant at 5% probability and significant at 5% probability level

**Table 7: Analysis of variance for grain yield using the Eberhart-Russell Model.**

| Source of variation | Degree of freedom | Mean square |
|---|---|---|
| Genotype | 9 | 19.4** |
| Environment in linear | 3 | 1056.8** |
| Genotype x Environment(linear) | 27 | 11.6** |
| Residual | 190.5 | |

Grand mean = 13.7; CV = 11.4; ** = significant at 5% probability

**Table 8: Analysis of variance for additive main effect and multiplicative interaction (AMMI) model for grain yield (q/ha) of 10 tef varieties across four environments in West Shewa, Ethiopia.**

| Sources of Variation | DF | SS | MS | Total Variation explained (%) | GxE explained (%) | GxE cumulative (%) |
|---|---|---|---|---|---|---|
| Treatments | 39 | 3656.553 | | | | |
| ENV(E) | 3 | 3170.334 | 1056.8** | 86.7 | | |
| GEN(G) | 9 | 174.2197 | 19.4** | 4.8 | | |
| G x E | 27 | 311.9997 | 11.6** | 8.5 | | |
| PC1 | 11 | 155.6291 | 14.1** | | 49.9 | 49.9 |
| PC2 | 9 | 108.1139 | 12.0** | | 34.7 | 84.5 |
| PC3 | 7 | 48.25664 | 6.9 ns | | 15.5 | 100.0 |
| Residuals | 80 | 367.8267 | 4.6 | | | |
| Total | 119 | | | | | |

**Key:** ENV= environment; GEN= genotype; ENV*GEN= environment by genotype interaction; PC1= principal component - 1; PC2= principal component -2; MS = Mean of Squares; SS= Sum of Squares; DF= Degree of Freedom

Table 9: AMMI stability values and grain yield stability index along with principal components (PCs) for 10 tef varieties evaluated across four environments in West Shewa in 2019/2020.

| SN | TYPE | NAME | YLD (q/ha) | Yield rank | PC1 Score | PC2 Score | ASV | ASV Rank | YSI |
|---|---|---|---|---|---|---|---|---|---|
| 1 | GEN | Boset | 15.3 | 2 | 0.139 | -0.398 | 0.44 | 6 | 2 |
| 2 | GEN | Dagim | 15.0 | 3 | -0.025 | -0.297 | 0.30 | 2 | 1 |
| 3 | GEN | Tsedey | 13.2 | 6 | 0.046 | -0.657 | 0.66 | 8 | 5 |
| 4 | GEN | Felagot | 15.7 | 1 | -1.000 | 0.242 | 1.46 | 10 | 4 |
| 5 | GEN | Guduru | 11.6 | 9 | 0.645 | 0.344 | 0.99 | 9 | 6 |
| 6 | GEN | Kora | 13.7 | 4 | 0.103 | 0.389 | 0.42 | 5 | 3 |
| 7 | GEN | Quncho | 13.7 | 4 | -0.154 | 0.006 | 0.22 | 1 | 1 |
| 8 | GEN | Nigus | 13.0 | 7 | 0.269 | 0.495 | 0.63 | 7 | 5 |
| 9 | GEN | Tesfa | 12.5 | 8 | -0.195 | 0.144 | 0.32 | 3 | 4 |
| 10 | GEN | Wedessa | 13.3 | 5 | 0.171 | -0.268 | 0.36 | 4 | 3 |
| 11 | ENV | Babich | 11.7 | 2 | 0.408 | -0.294 | 0.66 | 1 | 1 |
| 12 | ENV | Guder | 11.5 | 3 | 1.000 | 0.461 | 1.51 | 3 | 3 |
| 13 | ENV | Meti | 22.45 | 1 | -0.448 | -0.976 | 1.17 | 2 | 1 |
| 14 | ENV | Olankomi | 9.1 | 4 | -0.960 | 0.810 | 1.60 | 4 | 4 |

**Key:** ENV= environment; PC= principal component; ASV= AMMI stability value; YSI= yield stability index; GEN = genotype

**Table 10: Mean performance of tef grain yield and some yield component traits across four sites in West Shewa during 2019/2020 main cropping season.**

| Varieties | Grain Yield (q/ha) | HIP | DM | PH | Panicle Length | Culm Length |
|---|---|---|---|---|---|---|
| Boset | 15.3 | 27.1 | 94.6 | 94.2 | 31.8 | 64.2 |
| Dagim | 15.0 | 22.9 | 97.8 | 107.9 | 37.2 | 71.6 |
| Tsedey | 13.2 | 22.3 | 102.2 | 118.6 | 45.1 | 72.4 |
| Felagot | 15.7 | 25.6 | 93.5 | 91.3 | 30.9 | 60.9 |
| Guduru | 11.6 | 18.6 | 111.2 | 113.4 | 45.3 | 69.3 |
| Kora | 13.7 | 21.0 | 97.9 | 111.1 | 39.1 | 71.2 |
| Quncho | 13.7 | 21.3 | 99.4 | 112.7 | 44.9 | 70.3 |
| Nigus | 13.0 | 22.1 | 98.3 | 89.8 | 33.8 | 60.5 |
| Tesfa | 12.5 | 21.8 | 94.3 | 92.4 | 32.9 | 61.3 |
| Wedessa | 13.3 | 23.5 | 98.3 | 98.3 | 33.6 | 66.5 |
| Significance | ** | ** | ** | ** | ** | ** |
| Minimum | 11.6 | 18.6 | 93.5 | 89.8 | 30.9 | 60.5 |
| Maximum | 15.7 | 27.1 | 111.2 | 118.6 | 45.3 | 72.4 |
| Mean | 13.7 | 22.6 | 98.7 | 103 | 37.5 | 66.8 |
| LSD ($_{0.05}$) | 1.3 | 1.4 | 1.9 | 3.5 | 1.5 | 2.3 |
| CV (%) | 11.4 | 11.6 | 3.8 | 6.5 | 7.7 | 6.6 |

**Key**: GY= grain yield (q/ha); HI= harvest index (%); DM = days to maturity (№ of days); PH= plant height (cm); PL= panicle length (cm); CL= Culm length (cm); LSD=least significant difference; CV= coefficient of variation.

**Table 11: ANOVA table for AMMI model (GenStat)**

| Source | DF | SS | MS | F | F- prob |
|---|---|---|---|---|---|
| Total | 119 | 3897 | | | |
| Treatments | 39 | 3706 | 95 | 43.5 | 0.00 |
| Genotypes | 9 | 181 | 20.1 | 9.18 | 0.00 |
| Environments | 3 | 3206 | 1068.5 | 261.05 | 0.00 |
| Block | 8 | 33 | 4.1 | 1.87 | 0.08 |
| Interactions | 27 | 320 | 11.9 | 5.43 | 0.00 |
| IPCA | 11 | 154 | 14 | 6.42 | 0.00 |
| IPCA | 9 | 115 | 12.8 | 5.86 | 0.00 |
| Residuals | 7 | 51 | 7.3 | 3.33 | 0.004 |
| Error | 72 | 157 | 2.2 | | |

**Key**: DF= degree of freedom; SS= sum of square; MS= mean of square; IPCA= Interaction principal component axis.

**Table12: Ranges of tef grain yield and component traits across four sites in West Showa in 2019/2020**

| Sites | Babich | | | Guder | | | Meti | | | Olonkomi | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Grain Yield (q/ha) | 9.5 | 13.7 | 11.7 | 9.1 | 13.8 | 11.5 | 17.4 | 26.7 | 22.5 | 5.8 | 15.5 | 9.1 |
| HI (%) | 17.9 | 27.8 | 22.7 | 16.9 | 24.8 | 18.8 | 20.3 | 30.7 | 26.3 | 20.8 | 124.0 | 37.2 |
| DM (№of days) | 92.0 | 128.3 | 100.2 | 73.7 | 83.7 | 77.4 | 101.3 | 112.0 | 104.6 | 105.0 | 120.7 | 112.9 |
| PH (cm) | 86.7 | 109.7 | 97.3 | 91.6 | 128.0 | 110.0 | 90.9 | 116.7 | 104.8 | 84.6 | 123.1 | 99.9 |
| Panicle Length(cm) | 29.0 | 42.4 | 35.5 | 33.3 | 49.7 | 40.3 | 30.5 | 46.3 | 37.8 | 29.0 | 46.7 | 36.2 |
| Culm Length(cm) | 48.4 | 67.8 | 60.9 | 64.5 | 80.8 | 72.5 | 58.9 | 72.4 | 67.1 | 52.0 | 76.4 | 61.9 |

**Key**: GY= grain yield (q/ha); HI= harvest index (%); DM= days to maturity (№ of days); PH= plant height (cm); PL= panicle length (cm); CL= Culm length (cm).

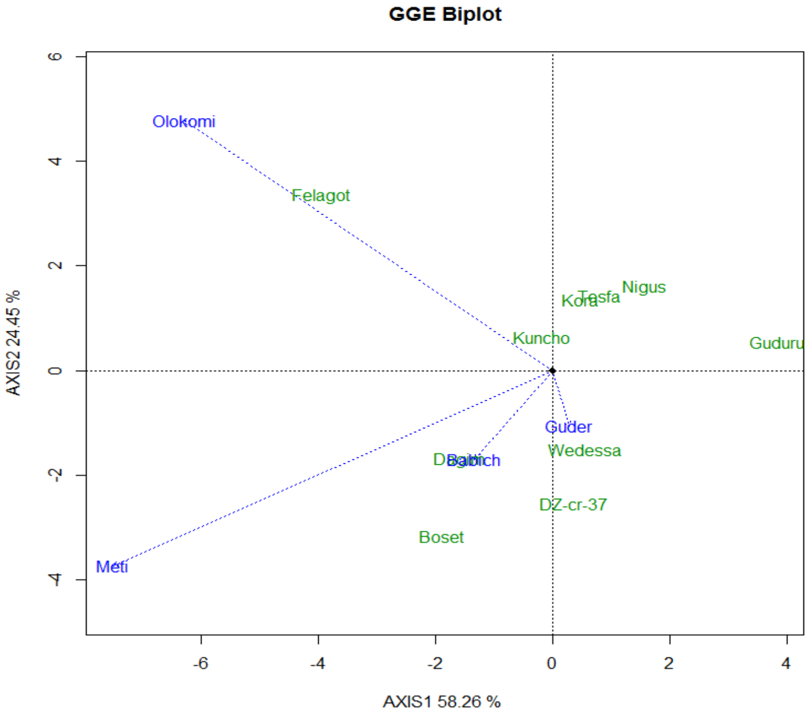


**Figure 3: Which Performed where view of the GGE bi-plot showing the grouping of genotypes and environments into various sectors.**

**Key:** G1 = Boset, G2 = Dagim, G3 = DZ- cr- 37, G4 = Felagot, G5 = Guduru, G6 = Kora, G7 = Quncho, G8 =Nigus, G9 = Tesfa and G10 =Wedessa, E1 = Babich, E2 = Guder, E3 = Meti and E4 = Olonkomi.

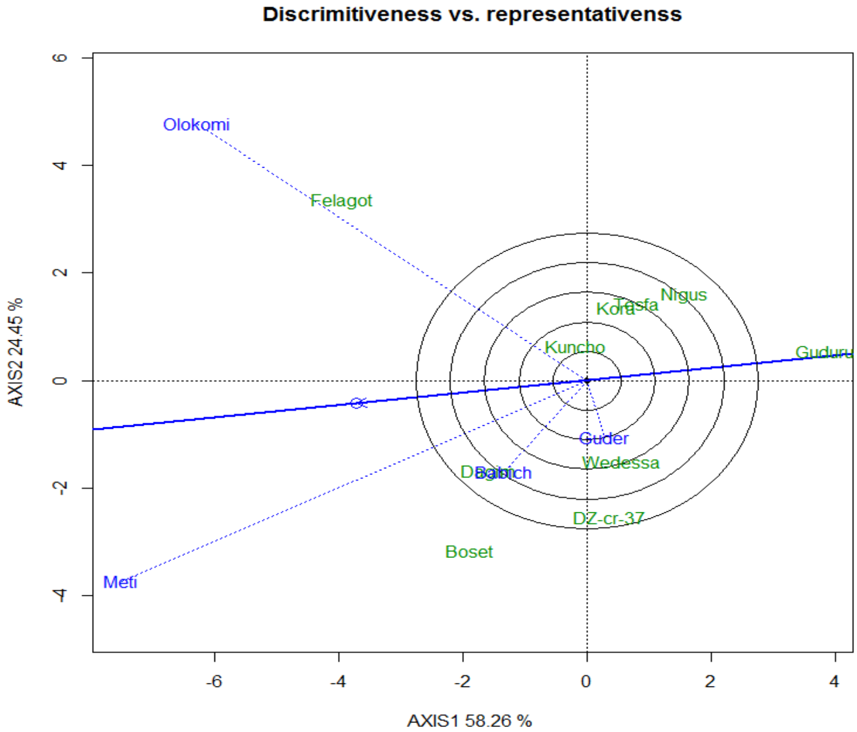


**Figure 4: GGE bi-plot showing the relationship among testing Environments and Discriminative Vs Representativeness.**
**Key:** G1 = Boset, G2 = Dagim, G3 = DZ- cr- 37, G4 = Felagot, G5 = Guduru, G6 = Kora, G7 = Quncho, G8 =Nigus, G9 = Tesfa and G10 =Wedessa, E1 = Babich, E2 = Guder, E3 = Meti and E4 = Olonkomi

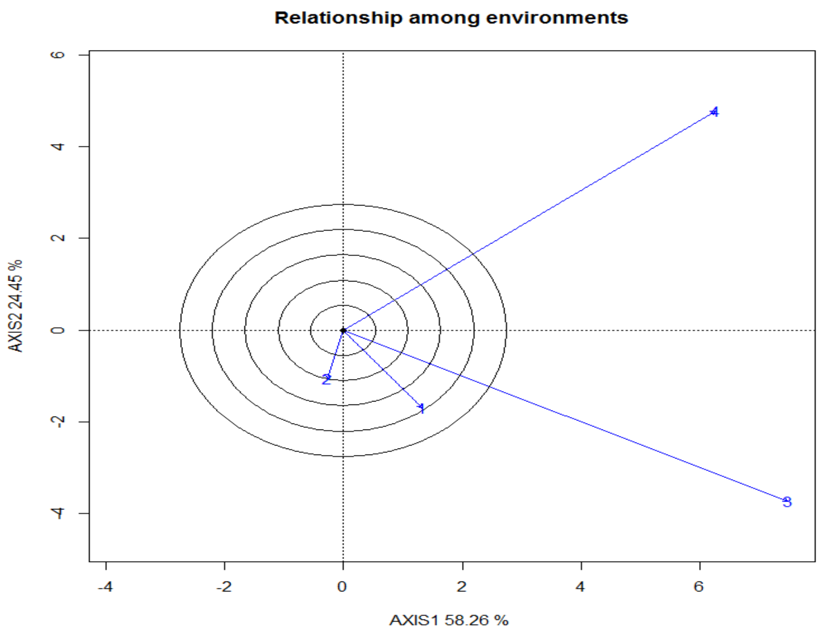


**Figure 5: GGE bi-plot showing the relationship among testing Environments.**
**Key:** 1 = Babich (E1), 2 = Guder (E2), 3 = Meti (E3), 4 = Olonkomi (E4) and E1- E4 represents the name of Environment.

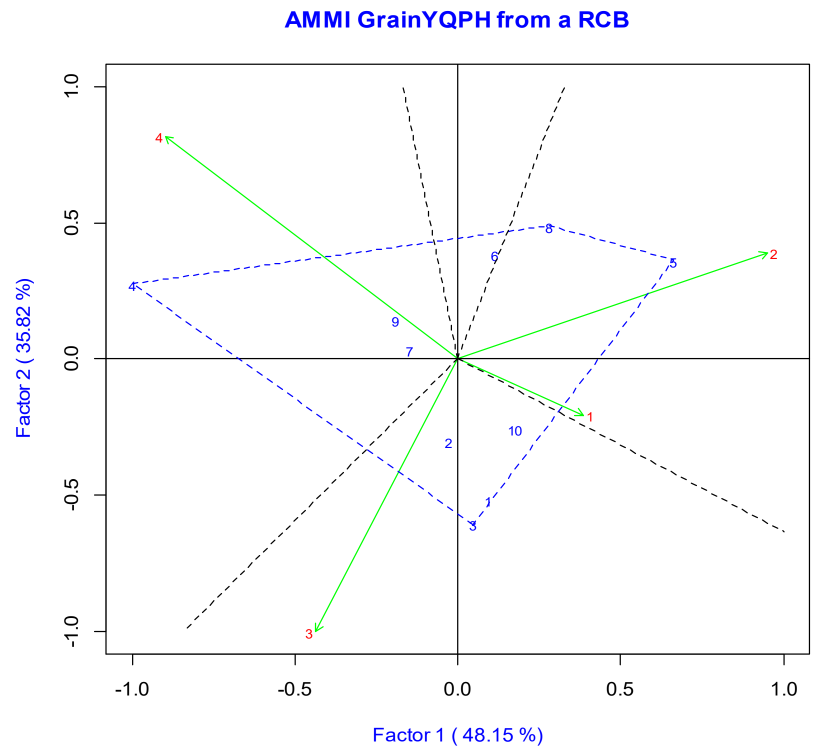


**Figure 6:** AMMI grain yield q/ha from RCBD.
**Key:** Number (1- 10) and (1- 4 red) represents the name of genotypes and environments respectively**.**

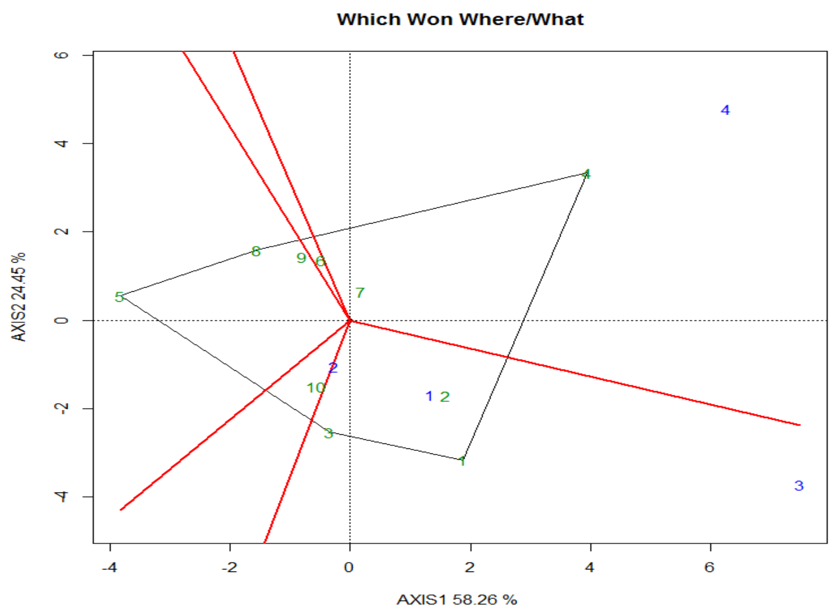


**Figure 7: Which-Won-Where view of GGE-bi-plot for grain yield of 10 tef varieties evaluated across four environments.**
**Key:** G1 = Boset, G2 = Dagim, G3 = DZ- cr- 37, G4 = Felagot, G5 = Guduru, G6 = Kora, G7 = Quncho, G8 =Nigus, G9 = Tesfa and G10 =Wedessa, E1 = Babich, E2 = Guder, E3 = Meti and E4 = Olonkomi.

### Which-won-where' patterns of genotypes and environments

The most attractive features of a GGE bi-plot are its ability to show the which-won where pattern of a genotype by environment data set **(Fig. 3**). The polygon view of a GGE- bi-plot clearly shows the which-won-where pattern, and thus arranged the genotypes in such a manner that some of them were on the vertex while the rest were inside the polygon. They were best in the environment lying within their respective sector in the polygon view of the GGE-bi-plot [70]. These genotypes were considered specifically adapted to that environment (**Appendix Table C**). Accordingly, the bi-plot showed that on the vertex varieties were, Boset, Tsedey, Felagot, Guduru, and Nigus was on the line of the polygon (**Appendix Table D**).

Environments within the same sector share the same winner genotypes, and environments in different sectors have different winning varieties. No genotypes close to the origin of the axes that have wider adaptation. Genotypes located on the vertex of the polygon performed either the best or the poorest in one or more locations since they had the longest distance from the origin of bi-plot [67].Therefore, among the vertex varieties Felagot and Boset were identified as the high yielding varieties, while Guduru and Niguswere considered as the low yielding varieties across the testing environments, as they had the longest distance from the origin (**Fig. 4**). Another interesting feature of the GGE- bi-plot is the identification of mega-environments as well as their winning genotypes, which are the best in the environment lying within their respective sector in the polygon view of the GGE-bi-plot [70].

The GGE- bi-plot view of grain yield of tef varieties based on genotype-focused scaling comparison is presented in (**Fig. 5)**. An ideal genotype is defined as the genotype having the greatest PC1 scores (high mean performance) and with zero G x E interaction thus, genotype was genotype Felagot. If a genotype is located closer to the ideal genotype, it becomes more desirable thus, genotype was genotype Quncho than other genotypes which are located far away from the ideal genotype. Thus, starting from the middle of concentric circle pointed with arrow concentric circles was drawn to help visualize the distance between genotypes and the ideal genotype [70].

Because the units of both IPCA1 and IPCA2 for the genotypes were the original unit of yield in the genotype focused scaling. The ideal genotype Felagot can be used as a benchmark for selection. The variety fell in the first circle, which shows the higher yielding ability and important for production. Variety, Felagot located on the second circle, the most preferred varieties. On the other hand, undesirable varieties were those with very distant position from the first circle; namely, Guduru, Tesfa and Wedessa.

**Ranking testing Environments Relative to the Ideal Environment and Genotype**

Average environmental axis (AEA) is a line passing through the origin and pointing to the positive direction with its distance equal to the longest vector. Besides, an ideal environment is a point on the AEA in the positive direction of the bi-plot origin and is equal to the longest vector of all environments [70]. Thus, the ranking of environments has identified (Olonkomi) as the most ideal environment followed by (Meti) whereas, (Babich) followed by (Guder) were the least ideal environments (**Fig. 6**). Ideal environments are generally, expected to have more power of discriminating genotypes and more representative of the overall environments [67]. On the other hand, the length of environmental projections appeared onto a genotype axis shows the performance of the best genotype at different environments relative to the other environments. Thus, Olonkomi followed byMeti had the longest projection from the axis where Felagot (G4) ranked first (**Fig. 7**). Hence, environments other than Babich (E1) and Guder (E2) were found to be best for the performance of Felagot (G4).

**Ranking Genotypes Relative to the Ideal Genotypes and Environment**

The average environment coordination view of the GGE bi-plot shows the ranking of genotypes based on the performance of ideal genotypes. The relative adaptation of the ideal genotype is evaluated by drawing a line passing through the bi-plot origin and the best genotype marker. This line is called a genotype axis and is connected to the best genotype. Such ranking of genotypes based on performance of ideal genotype revealed that Felagot followed by Boset and Dagim respectively were among the top yielding genotypes. Thus, (Felagot) with the highest average yield was identified to be the ideal genotype to evaluate the performance of test genotypes relative to it. In ranking genotypes relative to the best environment, Olonkomi (E4) was identified to be the best environment to evaluate the performance of genotypes. Thus, the best environment axis was drawn towards Olonkomi (E4) and then a perpendicular line to this axis that passes through the biplot origin was also drawn to separate genotypes yielding above and below the mean in the ideal environment. Dagim, Tsedey, Wadessa, Nigus, Tesfa, and Korawhich appeared on the same direction with therefore, found to perform above average in the environment of Meti.

**Genotypes Mean Yield and Stability**

The average environment coordination (AEC) is a line that passes through the origin and points to the higher mean yield across environments and it shows the increase in rank of genotypes towards the positive end. This line was reported to be useful to evaluate mean grain yield and stability of genotypes [69]. According to such reports, genotypes considered to be stable are those appeared closer to the origin with the shortest vector from the AEC. Thus, the present study shows the mean performance and stability of the genotypes. Based on this, Dagim, Kora, Tesfa and Wadessa with the shortest vector from the AEC axis were identified as the most stable genotypes while Felagot, Boset, Tseday, Guduru and Nigus with the longest vector from AEC were the most unstable genotypes. On the other hand, Felagot followed by Boset, Dagim, Koraand Quncho scored moderate grain yield whereas Guduru, Tesfa, and Nigusattained inferior grain yield in all environments. An ideal genotype for a specific environment has the highest mean yield and responds best at that particular environment while it is less stable in the other environments and need to be recommended for a specific environment [68]. According to the same authors, ideal cultivars have large PC1 scores (high mean yield) and small PC2 scores (high stability). Thus, in the present study, Felagot, Boset, and Dagim, which had larger PC1 and smaller PC2 scores were identified to be high yielding and stable.

## CONCLUSIONS

Tef is major staple food crop of Ethiopians. Genotype x environment interaction (GEI) is an interaction between environment and the genotypes. A total 10 tef improved varieties were evaluated for grain yield in west showa zone for a period of one year across four locations using randomized complete block design. From the combined analysis of variance, the effects of environment, genotype and genotype x environment were significant for grain yield and accounted for 86.4 %, 4.8 % and 8.6 % of the total sum of squares. The high percentage of the environment sum of square indicates the major impact of environment on yield performance of tef in west Shewa and variability of the test environments as well. There was significant difference among genotypes for plant height; which was ranged from 89.8 cm for Nigus to 118.6 cm for T sedey with an average mean value of 103 cm. The GEI is significant ($p<0.05$) accounting for 8.6 % of the total sum of squares implying the need for suggesting different varieties for different test locations.
The presence of the GEI indicates that the phenotypic expression of one genotype might be superior to another genotype in one environment but inferior in a different environment. This may also suggest repeating the experiment to make conclusive recommendation. However, the results of AMMI stability value and yield stability index leads to recommend Quncho and Dagim across the four test environments. The four testing environments were divided into three mega environments while the 10 genotypes were divided into four genotypic groups. The ranking of environments has identified (Olonkomi) as the most ideal environment followed by (Meti) whereas, (Babich) followed by (Guder) were the least ideal environments. Ideal environments are generally, expected to have more power of discriminating genotypes and more representative of the overall environments. The huge variability in the grain yield among the 10 tef varieties at the four environments might be due to wide variability in climatic and soil conditions.

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## APPENDIX

**Appendix Table A: List of improved tef varieties released in Ethiopia by research centers (MoA, 2010) used in study**

| Genotype | Variety name | Year of release | Seed color | Breeding method | Suitable environment |
|---|---|---|---|---|---|
| Boset | DZ-Cr-409(RIL50d) | 2012 | Very white | Hybridization | Low moisture |
| Dagim | DZ-cr-438 | 2016 | White | Hybridization | - |
| Tsedey | DZ-cr-37 | 1984 | White | Hybridization | Low moisture |
| Felagot | DZ-cr-442 | 2017 | Red | - | - |
| Guduru | DZ-cr-1880 | 2006 | White | Selection | High potential |
| Kora | DZ-cr-438(RIL133B) | 2014 | Very white | Hybridizaton | High potential |
| Quncho | DZ-cr-387(RIL355) | 2006 | Very white | Hybridization | High potential |
| Negus | DZ-cr-429 | 2017 | White | - | - |
| Tesfa | DZ-cr-457 | 2017 | White | - | - |
| Wedessa | DZ-cr-1278 | 1999 | White | Selection | High potential |

**Key:** MoA = Ministry of Agriculture; DZ-cr = Debrezeit cross

**Appendix Table B: Mean grain yield, regression coefficients ($b_i$) and deviation from regression ($S^2d_i$) values for ten tef genotypes evaluated over four environments in West Shewa Zone**

| Genotypes | Yield q/ha | Yield rank | $b_i$ | $S^2d_i$ | Rank |
|---|---|---|---|---|---|
| Boset | 15.3 | 2 | 1.3095 | 0.6462 | 6 |
| Dagim | 15.0 | 3 | 1.1783 | -0.6278 | 5 |
| Tsedey | 13.2 | 6 | 1.1988 | 5.0409 | 9 |
| Felagot | 15.7 | 1 | 0.9514 | 16.1327 | 10 |
| Guduru | 11.6 | 9 | 0.7208 | 4.781 | 8 |
| Kora | 13.7 | 4 | 0.8411 | 0.4646 | 4 |
| Quncho | 13.7 | 4 | 0.9607 | 0.1733 | 2 |
| Negus | 13.0 | 7 | 0.7664 | 1.0468 | 7 |
| Tesfa | 12.5 | 8 | 0.9739 | 0.3318 | 3 |
| Wedessa | 13.3 | 5 | 1.0992 | 0.1375 | 1 |
| Grand mean | 13.7 | | | | |

**Key:** $b_i$ = Regression coefficient; $S^2d_i$ = Squared deviation from regression; q/ha = quintal per hectare

**Appendix Table C: Wricke's ($W_i$) ecovalence value for ten tef genotype evaluated over four Environments in West Shewa Zone**

| Genotypes | Yield q/ha | Yield rank | Wricke's ($W_i$)Ecovalence | Rank |
|---|---|---|---|---|
| Boset | 15.3 | 2 | 12.9911 | 7 |
| Dagim | 15.0 | 3 | 3.6014 | 4 |
| Tsedey | 13.2 | 6 | 15.7642 | 8 |
| Felagot | 15.7 | 1 | 33.9787 | 10 |
| Guduru | 11.6 | 9 | 19.355 | 9 |
| Kora | 13.7 | 4 | 5.0882 | 5 |
| Quncho | 13.7 | 4 | 1.9727 | 1 |
| Negus | 13.0 | 7 | 9.3868 | 6 |
| Tesfa | 12.5 | 8 | 2.1975 | 2 |
| Wedessa | 13.3 | 5 | 2.7882 | 3 |

 

**Appendix Table D: Nassar and Huehn non parametric measures of yield stability of tef varieties evaluated over four environments in West Shewa Zone**

| Genotype | S(1) | Rank | S(2) | Rank | Yield q/ha | Yield rank |
|---|---|---|---|---|---|---|
| Boset | 1.67 | 4 | 9.33 | 6 | 15.3 | 2 |
| Dagim | 0.83 | 2 | 1 | 1 | 15.0 | 3 |
| Tseday | 3.33 | 8 | 18 | 10 | 13.2 | 6 |
| Felagot | 2.5 | 5 | 13 | 9 | 15.7 | 1 |
| Guduru | 1.17 | 3 | 6 | 5 | 11.6 | 9 |
| Kora | 2.67 | 6 | 10.33 | 7 | 13.7 | 4 |
| Quncho | 1.17 | 3 | 3.33 | 3 | 13.7 | 4 |
| Negus | 2.83 | 7 | 11.33 | 8 | 13.0 | 7 |
| Tesfa | 0.83 | 2 | 4.67 | 4 | 12.5 | 8 |
| Wedessa | 0.67 | 1 | 1.67 | 2 | 13.3 | 5 |

**Key:** S (1) = Mean absolute rank difference: S (2) = Variance of rank

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