GENOTYPE BY ENVIRONMENT INTERACTION AND STABILITY ANALYSIS OF TEF (*Eragrostis tef* (Zucc.) Trotter) VARIETIES FOR YIELD AND YIELD RELATED TRAITS IN SOUTH AND SOUTH WESTERN ETHIOPIA

MSC. THESIS

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NOVEMBER, 2019

JIMMA, ETHIOPIA

Genotype by Environment Interaction and Stability Analysis of Tef (*Eragrostis tef* (Zucc.) Trotter) Varieties for Yield and Yield Related Traits in South and South Western Ethiopia

A Thesis

Submitted to School of Graduate Studies, Jimma University College of Agriculure and Veterinary Medicine in Partial Fulifilment of the Requirement for the Degree of Master of Science in Plant Breeding

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November, 2019
Jimma, Ethiopia

DEDICATION

This work is dedicated to my beloved father Belete Baza and my mother Birhanesh Tanto for their hospitability and special care.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this thesis is my own work. I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of this thesis. Any scholarly matter that is included in the thesis has been given recognition through citation.

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BIOGRAPHIC SKETCH

The author was born in April 13, 1982 E.C/1990 G.C in Koysha Gola Kebele, Humbbo Wereda, Wolaita Zone, SNNP Regional State from father Belete Baza and his mother Birhanesh Tanto. He attended his education at Shochora Gola Primary and High School at Humbbo and completed in 1998 E.C. Then he attended his Senior Secondary and Preparatory School at Soddo Comprehensive and Preparatory School in 1999 E.C and completed since 2000 E.C.Later after he completed his senior secondary and preparatory school, he joined Jimma University and graduated in 2003 with BSc. degree in Plant Sciences. Soon after graduation, the author joined Rubber tree National Nucleus Project and worked as Agronomist for two and half years. Then, joined Ethiopian Institute Agricultural Research (EIAR) Jimma Agriculture Research Centre (JARC) in May 4, 2006 E.C and served as a junior researcher in plant breeding for cereal crops breeding program. Then he joined the School of Graduate Studies, Jimma University in 2010 E.C to pursue Msc studies in plant breeding.

ACKNOWLEDGEMENTS

I thank the Almighty God for helping me in all circumstances to complete the course work and my thesis research successfully. I am grateful to my major advisor, Kebebewu Assefa (Dr.) for his keen support, his insightful and constructive comments, continues follow in the progress of this study. In spite of his task of tef program leader, research work and other responsibilities at Debre Zeit Agricultural Research Center, he has made himself available and shared his due time and gave me a lot of knowledge throughout the completion of the thesis. I would like also to thank my instructor and Co-advisor Sentayehu Alamerew (Professor) he has devoted much of his time in critically reading and commenting on the manuscript starting from proposal to end of the thesis, in spite of his busy schedule and practically visited my experiment. I also greatly appreciate and thank Tsion Fikire (Msc) for her immense contribution and technical staff of tef program particularly Negussie Hussein and Kidist Tefera who directly or indirectly involved in support of research work. Words cannot express my indebtedness to Leta Tulu (Dr) former my case team leader and now at Holetta Agricultural Research Center for his unreserved and immeasurable advice and support throughout the course of this work.

I extend my sincere gratitude to my sponsor, Ethiopian Institute of Agricultural Research (EIAR) financial support provided for my study and for allowing me to continue my Msc. Programme and giving me study leave. I would also like to thank and appreciate all workers of Jimma, Ambo, Areka and Bako research centers for their collaborations. I also thank my colleagues in the cereal case team of Jimma Agricultural Research Centre (JARC).

I would like to thank my friends Mudin Biya (Msc), Afework Legesse (Msc and Spices breeder), Addis Alemayehu (PhD candidate), Kifle Belachewu (PhD candidate), Eshetu Yadete, Yechalew Sileshi (Msc), Ute Guja (Msc candidate), Desalegn Chalichissa (Msc), Mohammedsanni Zakir (Msc), Wakuma Merga (Msc) Tepi Agricultural Research Center and Getachewu Etana (Msc), Addishiwot Wondimu (Msc) at Jinka University and Tesafye Megersa for the contribution during my thesis writing.

It is my great pleasure to express my sincere appreciation to my father Belete Baza and My mother Birhanesh Tanto for their strength as well as self-managing capability to follow my education at different levels. Furthermore, my great appreciation also goes to my families and relatives: Bergene Belete, Workinesh Naasa, Deginesh Belete, Ephrem Amaru, Zeleke Chorfo,

Fisseha Mantuta and Alemu Habte for their unreserved support. I am indebted to all my friends whose names are not mentioned here.

It is my pleasure to acknowledge Jimma University for hosting my study and facilitating all the academic processes. I extend my gratefulness to my instructors in the School of Plant Sciences at the University, and indispensable guest lecturers for their genuine guidance that I benefited much from their endeavor. I would also like to sincerely appreciate the School of Graduate Studies for supporting me to the best of its capacity.

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LIST OF ACRYNOMYS AND ABBREVIATIONS

AEC	Average Environment Coordinate
AMMI	Additive Main effects and Multiplicative Interaction
ANOVA	Analysis of Variance
ASV	AMMI Stability Value
bi	Regression Coefficient
CSA	Central Statistical Agency
CV	Coefficient of Variation
DZARC	Debre zeit Agricultural Research Center
GEA-R	Genotype by Environment Analysis with R-software
GED	Genotype by Environment Data
GEI	Genotype by Environment Interaction
GGE	Genotype Main Effect and Genotype by Environment Interaction
GLM	General Linear Model
IPCA	Interaction Principal Component Analysis
JARC	Jimma Agricultural Research Center
LSD	Least Significant Difference
METs	Multi Environment Trials
Pi	Cultivar Superiority Index
RCBD	Randomized Complete Block Design
S^2di	Deviation from Regression
SAS	Statistical Analysis System Institute
Wi	Wricke's Ecovalence
YSI	Kang's Yield Stability Index

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ABSTRACT

Tef is the most important staple cereal crop in Ethiopia. However, its productivity is low due to several biotic and abiotic constraints. The diverse and dynamic environmental condition of Ethiopia needs detailed and sustainable study of genotype by environment interaction (GEI) for developed tef varieties. The objective of this study was to evaluate the genotype by environment interaction for grain yield of different tef varieties and to identify stable and/or high yielding genotypes across locations. Twenty-one tef varieties were tested at six environments/locations (Jimma/Melko, Omonada, Bedele, Arjo, Areka and Ambo) in South and Southwestern Ethiopia during the 2018 main cropping season using Randomized Complete Block Design (folded RCBD) with three replications. Grain yield and other related traits were recorded and mean performances of these traits and grain yield stability were evaluated using different statistical procedures. The results showed significant differences among tef varieties for grain yield and yield related traits. Combined mean grain yield of the tef varieties varied from 1084.3kg/ha for variety Dukem, to 662.8kg/ha for variety Kena.The proportions of total sum of squares for environment, genotype and GEI for grain yield were 69.4% 8% and 17.5%, respectively. Having the largest proportion of sum of squares, the environment had the highest impact on genotype performance followed by GEI and genotype. The Additive Main Effect and Multiplicative Interaction (AMMI) model also demonstrated the presence of GEI. The first and second interaction principal components axes (IPCA) highly significant ($p<0.01$) and cumulatively explained 63.4% of the total variation due to GEI.Stability parameters such as Cultivar superiority measure, Stability variance, Yield stability index,AMMI stability value, AMMI and GGE on average identified Heber-1 ,Quncho and Dukem as high yielding and the most stable tef varieties.Whereas, Variety Kena, Wellenkomi, Negus, Felagot and Guduru as low yielding and unstable varieties. Similar result was obtained from GGE biplots analysis showed that Dukem as an ideal variety, while variety Heber-1 and Abola were desirable varieties as they were closer to the ideal variety. Conversely, varieties Kena and Guduru were *the least desirable varieties based on GGE biplot. In general, the result of different stability parameters were differs in the selection of the best performing and stable varieties. The results from this study gave valuable information for researchers who were interested to examine the effect of G x E interactions on the performance of tef varieties in the South and Southwest Ethiopian condition. The study used data collected for only one season, which may limit the strength of its recommendation. However, the results are crucial in directing the breeding decision following additional season evaluation of the varieties in the same locations.*

***Keywords**:* AMMI Model, *Eragrostis tef*, Mega-Environmnet, Yield Stability

1. INTRODUCTION

Tef, *Eragrostis tef* (Zucc.) Trotter is a member of the grass family *Poaceae* and genus *Eragrostis.* The genus *Eragrostis* constitutes about 350 species of which only tef is cultivated for human consumption (Watson & Dallwitz, 1992). Fifty-four *Eragrostis* species are found in Ethiopia, out of which fourteen are known to be endemic. Worldwide, Africa contributes 43% of the genus, while South America contributes 18%. Likewise, 12%, 10%, 9%, 6% and 2% of the genus *Eragrostis*is from Asia, Australia, Central America, North America, and Europe, respectively (Costanza *et al.*,1979).Tef is an allotetraploid species with a base chromosome number of 10 (2n=4x=40) with genome size of 730 Mbp (Mulu *et al.*,1996). It is self-pollinated with chasmogamous and hermaphroditic flowers. It has very low degree of out-crossing, that ranges from 0.2% - 1.0% (Seyfu, 1997).

Tef (*Eragrostis tef* (Zucc.) Trotter) is a crop for which Ethiopia is the center of origin and diversity (Vavilov, 1951). Tef is endemic to Ethiopia and its major diversity is found only in that country. As with several other crops, the exact date and location for the domestication of tef is unknown. However, there is no doubt that it is a very ancient crop in Ethiopia, where domestication took place before the birth of Christ (Seyfu, 1997). It was probably cultivated in Ethiopia even before the ancient introduction of wheat and barley (Shaw, 1976).

According to Ethiopian flora, tef grows up to 2500 m.a.s.l. However, the Ethiopian biodiversity institute expedition and collection database indicates that tef is collected from the altitudinal range of 800 to 3200 m.a.s.l. (Alganesh,2013). Maximum production occurs at altitudes between 1800 and 2100 m, annual rainfall of 750 to 850 mm with growing season rainfall of 450 to 550 mm and a temperature range of 10 to 27°C. A very good result can also be obtained at an altitude range of 1700 to 2200 m and growing season rainfall of 300 mm (Seyfu, 1993). The temperature range of 10 to 27°C is most suitable to avoid frost (Seyfu, 1997), and soil temperature range of 18 to 27°C and above was recommended in US (Miller, 2008)

Tef is the most preferred crop as source of food and feed in Ethiopia. Besides, it is tolerant to drought, water logging and pests particularly against storage pests. Now a day, tef has become a globally popular crop for its gluten free property that makes it conducive for people suffering

from celiac disease and diabetic because of its slow release of carbohydrates. Hence, it is regarded as a promising alternative food replacing gluten containing cereals like wheat, barley and rye in products such as pasta, bread, beer, cookies and pancakes (Spaenij *et al*., 2005). Recently, Gina *et al*., (2014) supported this fact with results from the genome sequence initiative. Tef has high iron content that makes it appropriate for pregnancy related anemia (Alaunyte *et al*.,2012). The iron content mainly seems to play an essential role in Ethiopia, as there is absence of anemia in areas of tef consumption (BoSTID, 1996).

Tef [*Eragrostis tef* (Zucc.) Trotter] is the major cereal crop in Ethiopia where it is staple food for about 50 million people (Kebebew *et al.,* 2015). Its resilience to extreme environmental conditions and high in nutrition makes tef the preferred crop among both farmers and consumers (Plaza *et al*., 2015). Among the food crops grown in Ethiopia, tef is cultivated on about 3 million hectare producing 5.02 million tons (CSA, 2017). In spite of the low productivity, tef is widely cultivated by over six million small-scale farmers' households in Ethiopia. It is considered to be an orphan crop because it has benefited little from international agricultural research system (Kebebew *et al.,* 2015)

The low national tef productivity is mainly attributed to susceptibility to lodging, low yield potential of landraces under widespread cultivation, poor agronomic management practices, biotic and abiotic stresses (Kebebew *et al.,*2011).Nevertheless, it is possible to increase the yield up to 4.5 ton per hectare by using improved varieties and proper management practices (Likyelesh, 2013).Determining the magnitude and nature of the production environment is also the most important strategy to maximize grain yield and ensure stable performance of tef varieties across varying environments (Tiruneh,2000).

Cultivar performance is a function of the genotype and the production environment where it grows. Environmental factors have great influence on qualitative and quantitative traits. Consequently, performance tests of potential varieties are conducted in multiple years and locations (Bernardo, 2002). This is because, besides the genotype and environment main effects, performance of cultivars is also determined by the GEI (genotype x environment interaction) Genotype x environment interaction refers to the differential response of cultivars to environmental changes (Hallauer and Miranda,1988).Various causes have been described as sources of GEI in Sub-saharan Africa varieties growing environments; for instance,

temperature, rainfall, drought, length of growing season, sub-soil pH and socio-economic (sub-optimal input application) (Banziger *et al*., 2004).The relative magnitude of GEI provides information concerning the likely area of adaptation of a given genotype. It is also useful in determining efficient methods of using time and resources in a breeding program (Ceccarelli, 1989). Crop breeders have been striving to develop genotypes with superior grain yield, quality and other desirable characteristics over a wide range of different environmental conditions. Genotype x environment (G x E) interaction is one of the main complications in the selection of broad adaptation in most breeding programmes. The phenotype of an organism is determined by the combined effect of the environment and the genotype which interact with one another.

The main purpose of evaluating genotypes across environments is to estimate or predict genotype performance in future years, based on past performance data, and to develop or recommend superior ones. In almost all multi-location trials, there exists interaction and noise (Purchase, 1997). If there were no interactions, one variety would have been good enough for all environments and variety trials would have been conducted only at one location to provide universal results. If there was no noise, results would be exact and there would be no need for replications. But, the reality is quite different, two options are available to deal with these problems. The first one targets the genotypes, while the second aims at the environment. The first option is to search for high yielding and widely adapted cultivars that are successful across the growing environment of interest. The second alternative is to sub-divide the target regions into several relatively homogeneous macro-environments, then to develop and recommend suitable genotypes for specific regions. Tef is grown under high variation in climatic and edaphic factors that lead to GxE interaction even within a small geographic area (Hailu and Getachew, 2006).

Few studies (Tiruneh, 1999; Fufa *et al*., 2000; Mathewos and Getachew, 2012; Tiringo, 2012) analyzed the effect of GxE interaction on tef genotypes in Ethiopia. Those authors reported that the multi-location variety trials play a decisive role in the effort to develop high yielding varieties adapted to a wide range of environments.

According to the agricultural sample survey on crop area and production reported by by the Central Statistics Agency (CSA,2006), Southwestern and Southern part of Ethiopia are the high potential area for cereal production.Altogether they account for 89.8% of the total national area

planted to cereals and contribute 90.9% of the total annual production.Among cereals,maize,sorghum and tef are grown widely in the regions because of suitable environmental conditions.Despite broad area coverage of the crop,the progress made in tef productivity was low due to lodging and disease problems.Local varieties have been very competent with the improved varieties almost at all stages of evaluation.Very discouaraging aspect of the improved varieties is their instable yield potential.Even in uniform environment,there is high variation in yielding ability (Leta and Habte,2008).The major challenge of tef in South and Sourhwestern part of Ethiopia was lack of varieties which were high yielding and stable,tolerant/resistant to lodging and diseases.

Even though, there has been some studies made on the G x E interaction of tef in other parts of the country, there is a little information on the interaction of varieties in diverse environmental conditions of South and Southwestern Ethiopia. Keeping in view, the importance of GEI in reference to its application for identifying stable genotype, this research project was undertaken with the following objectives.

1.2 Objectives

1.2.1. General objective

- To determine the magnitude and nature of genotype by environment (location) interaction in tef in South and Southwestern Ethiopia

1.2.2. Specific objectives

The specific objectives were:

- To identify the pattern of interaction of genotype and environment on yield and yield related traits of tef varieties grown at different locations
- To identify high yielding and stable tef varieities using different stability models

2. LITERATURE REVIEW

2.1 The Origin and taxonomy of tef

Ethiopia is the centre of both the origin and diversity of tef (Vavilov, 1951), and over the years the crop species has co-evolved with Ethiopians. This is because Ethiopia harbours not only a wealth of diversity in the crop species, but also it is believed to be the centre of origin for its domestication, including the existence of the possible wild progenitors. As one of the biggest genus in the grass family, the genus *Eragrostis* contains over 350 species (Watson and Dallwitz, 1992). Of these species, about 43% are considered to have originated in Africa, 18% in South America, 12% in Asia, 10% in Australia, 9% in Central America, 6% in North America and 2% in Europe (Costanza *et al*., 1979). Among the 54 species found in Ethiopia, 14 are endemic to the country (Cufodontis, 1974).

Globally, the fact that tef originated in Ethiopia is not debatable; however, the exact location where it was first domesticated in Ethiopia yet remains unknown. Many maintain that tef originated in the northern highlands of Ethiopia, particularly in Tigray, where it is still an important crop. Based on the archaeological remains from northern Ethiopia, D'Andrea (D'Andrea, 2008) suggested that the earliest-known cultivation of tef was during the pre-Axumite period from 800 to 400 BC in the northern part of the country. According to the author, Ona Nagast, a location near Axum showed the first indication of tef cultivation. Over the years, several techniques involving morphological and cytogenetic methods (Jones *et al.,* 1978), biochemical methods (Endashew and Lester, 1981) and phylogenetic analysis using ribosomal DNA and transcription factor genes (Espelund *et al*., 2000) or nuclear and plastid genes were used in order to decipher the putative ancestral species for tef.

Using morphological and cytological evidence, Ponti (Ponti, 1978) and Tavassoli (Tavassoli, 1986) suggested *Eragrostis aethopica*, (2x), *E. pilosa* (4x), *E. mexicana* (6x), *E. barrelieri* (6x), *E. minor* (2x, 4x) and *E. cilianensis* (2x, 4x, 6x) to be closely related to tef. Analysis of genetic relationships among accessions of *E. tef, E. pilosa and E. curvula* which were collected from Ethiopia and the United States based on amplified fragment length polymorphism (AFLP) (Mulu *et al*., 1999; Mulu and Nguyen, 2000) and random amplified polymorphic DNA (RAPD) markers (Bai *et al*., 2000) depicted relatively low levels (18%) of polymorphism within *E. tef*,

and high similarity between *E. tef* and *E. pilosa*. Using two molecular markers, *E. pilosa* was found to be closely related to tef while *E. heteromera* and *E. cilianesis* are distantly related (Ingram and Doyle, 2003). While similar conclusions were reached using biochemical methods (Endashew and Lester, 1981), the close relationship between tef and *E. pilosa* was also evidenced by successful hybridisation between the two (Hailu *et al*., 2003). This hybridization generated viable offspring and ultimately resulted in the release of a variety called Simada (DZ-Cr-285 RIL295) from the inter-specific hybrid of tef [DZ-01-2785 × *E. pilosa* (line 30-5) (MoA, 2014). The compatibility between tef and *E. pilosa* was also observed in the F1-hybrid between the two species in which regular meiotic division and significantly high pollen or seed fertility was observed (Admas and Dagne, 2008). This suggests closeness of tef to *E. pilosa*. However, since the present *E. pilosa* is a tetraploid plant like tef, the diploid ancestor of tef has yet remained unknown.

Various nomenclatures names given to tef by various authorities at different times. However, presently the most accepted binomial nomenclature is *Eragrostis tef* (Zucc.) Trotter. This name which is based on the specific epithet '*tef*' previously used by Zuccagni was proposed by Trotter in 1918. Tef belongs to the Grass or *Poaceae* family (formerly *Gramineae*), sub-family Chloridoideae, tribe Eragrostideae and genus *Eragrostis*. Together with finger millet (*Eleusine coracana* Gaertn.), tef constitute the sole species in the sub-family Chloridoideae cultivated as a cereal crop. At a molecular level, the relationship of tef to other millets and major cereal crops.

Most millets are grouped under the subfamily Panicoideae, except for finger millet and tef, which belong to the subfamily Chloridoideae. Due to the absence of a waxy gene sequence in the NCBI database, three millets from the subfamily Panicoideae, namely kodo millet (*Paspalum scrobiculatum* L.), barnyard millet (*Echinochloa frumentacea* Link) and Fonio or Acha (*Digitaria exilis Stpf* and *D. iburua Stapf*), are not shown and the related species from the same genera are included for the first two.

2.2. Tef production, Constraints and Nutritional importance in Ethiopia

2.2.1 Tef production in Ethiopia

In Ethiopia, tef, maize, sorghum and wheat took up 24.02% (about 3,016,053.75 hectares), 16.80% (about 2,110,209.61 hectares), 14.58% (1,831,600.45 hectares) and 13.25%

(1,663,837.58 hectares) of the grain crop area, respectively. As to production, maize, tef, wheat and sorghum made up 27.02% (7.84 million tons), 17.29% (5.02 million tons), 15.63% (4.54 million tons) and 16.36% (4.75 million tons) of the grain production, in the same order. Tef is cultivated annually on about 3.01 million hectares and occupies a premier position in area coverage among the various food crops cultivated in the country. With regard to estimated crop yield, average national yield of tef is about 1.66-ton ha^{-1} (CSA,2017). This crop is the most important cereal crop in the country accounting for about 28% of the total acreage and 21% of the gross grain production of all cereals. It is grown by over 6.99 million farmers' households, and constitutes the major staple food grain for over 50 million Ethiopian people (CSA,2017). This implies that tef is very important in the overall national food security of the country (Kebebew *et al.*, 2013).

Tef can be grown from low to high altitude, indicating that the crop has great flexibility and plasticity in growing over a wide range of agronomic and edaphic conditions and under various rainfall, temperature and soil regimes (Ayalneh *et al*., 2012). In Ethiopia, tef can grow under wide and diverse agro-ecologies. It is mainly produced in Amhara and Oromia, with smaller quantities in the Tigray and SNNP regions. There are 19 major tef producing zones in the country. The Central and South Tigray zones are the major tef producing zones in Tigray. Within the Amhara region, East Gojjam, West Gojjam, North Gondar, South Gondar, North Wollo, South Wollo, North Shewa and Awi Zones are the major producers of tef. In Oromia region, the major tef producing zones include the East Shewa, West Shewa, South West Shewa, North Shewa, East Wollega, Horo Guduroo Wollega, Jimma, Illubabor and Arsi (CSA, 2017).

2.2.2 Constraints of Tef production

2.2.2.1 Technical Constraints

The national average grain yield of tef is 1.5 t ha^{-1} in 2013 (CSA, 2014). This among others is due to the widespread use of low-yielding varieties by majority of the tef-growing farming community coupled with unimproved traditional practices. According to the Central Statistical Agency, only 2.4% of the total tef farmers in Ethiopia grew improved varieties on 17% of the total land area (2.6 million ha) allocated for tef in 2009 cropping season (CSA, 2010; Setotaw, 2013). Furthermore, most of the tef growing farmers still use age-old traditional practices in all

pre- and post-harvest husbandry operations coupled with minimal and utmost suboptimal inputs as indicated in a recent review (Setotaw, 2013).

Lodging is defined as an anomally manifested as a displacement of the aerial parts of plants from the upright position, and it is induced by factors both extrinsic and intrinsic to the plant, and also by the interactions among the plant's external and internal factors (Seyfu, 1983, 1993). The causes for lodging in cereals comprise complex of factors including high rates of nitrogen fertilization, wind and heavy rain splashes, fungal crop damage, inadequate development of root system, high seeding rates, lack of phosphorus and potassium fertilization and insufficient strengthening of sclerenchyma tissue in the culms (Hamilton, 1951; Pinthus, 1973).

The direct and indirect deleterious effects of lodging on crops can be summarised as follows (Pinthus, 1973; Seyfu, 1983, 1993):i) Inflicts losses in yield and quality of both grains and straw harvested;ii) Creates favourable conditions for the development and spread of diseases and insect pests;iii) Imposes restrictions on the use of growth and yield promoting high input husbandry technologies such as high rates of nitrogen fertilizers;iv) Poses difficulties in manual and mechanical crop-harvesting operations. While studying the lodging phenomenon with tef, Seyfu identified the following major types of lodging (Seyfu, 1983): i) Transient lodging is a temporary situation occurring before heading with the plants often capable of recovering into the upright position. ii) Permanent lodging is a permanent displacement from the upright position often manifested after heading. It comprises three sub-categories: a) Root lodging involves uprooting of the whole plant while the stems still appear intact. b) Break lodging involves breakage of the stem usually near the base of the peduncle.c) Bend lodging is characterized by loss of plant elasticity leading to bending of stems while the roots are still secure in the soil. In practical husbandry, bend lodging is by far the commonest, most prevalent and economically most important type of lodging in tef (Seyfu, 1983, 1993). While bend lodging is the most significant, break lodging is of minor concern, and root lodging is relatively unimportant.

In contrast, Van Delden and co-workers (van Delden *et al*., 2010), using biomechanical models with two tef cultivars in field trials in the Netherlands, reported that tef is most sensitive to root lodging and that given its current morphology, lodging of free-standing plants is inevitable in the tested environments. If the root lodging that the latter workers meant is similar to that

described earlier, it may not be unexpected especially on the sandy soil conditions and particularly under low plant density. But under Ethiopian conditions, tef is predominantly a heavy clay soil crop, and even on light soils the crop is grown in densest and such that root lodging is not the most important type of lodging. In tef, lodging reduces grain yield by 11–22% (average = 17%), 1000-kernel weight by 35%, grain yield per panicle by 51%, and percentage and rate of seed germination by 41 and 44%, respectively (Seyfu, 1983). This, therefore, indicates the economic significance of the problem of lodging in tef, and the urgent need for finding means for combating the problem.

2.2.2.2 Biotic and Abiotic Constraints

The foregoing technical constraints involving low yield potential, lodging, and culture demanding and labor-intensive husbandry requirements are mainly associated with the nature of the tef crop. Apart from these, however, other factors constraining tef production and productivity in different parts of Ethiopia include biotic stresses such as weeds, diseases and insect pests, and abiotic stresses like drought, water-logging, soil acidity and salinity and cold. However, significant variations were observed among tef accessions towards tolerance to soil acidity (Abate *et al.*, 2013) and salinity (Asfaw and Dano, 2011).

2.2.3. Nutritional importance of tef

Tef is a very nutritious cereal grain. Its nutritional content is generally comparable to that of the major world cereals like wheat, rice, barley and millets (USDA, 2015). Tef is superior in many aspects particularly in minerals such as calcium, iron, magnesium, phosphorus and potassium. The grains of tef are also rich in essential amino acids particularly in alanine, methionine, threonine and tyrosine (USDA, 2015). In recent years, tef has become popular as a health and performance food in the global market. Since the grains are gluten-free, it is useful as food for humans suffering from gluten protein allergy ailments known as celiac disease (Spaenij *et al*., 2005). Its low glycemic index characterised by slow release type starches, makes it particularly suitable for diabetic people (Baye, 2014). Moreover, its high iron content is associated with the low prevalence of hookworm (ENS, 1959) and pregnancy-related anemia in people consuming tef as staple food.

2.3 Historical Development of Tef Breeding and Research in Ethiopia

The period in the late 1950's marked the beginning of tef improvement research at Jimma Technical and Agricultural School and later moved to Debre Zeit (Likyelesh, 2005). In the overall history of tef breeding since then, five inter-related phases can be distinguished: (1) first phase (1956-1974) was characterized by an emphasis on germplasm enhancement (collection/acquisition, characterization and evaluation, systematics and conservation), genetic improvement relying entirely upon mass and/or pure-line selection directly from the existing germplasm and initiation of induced mutation techniques; (2) second phase (1975-1995) marked by the incorporation of intra-specific hybridization into the already pre-existing breeding methods following the discovery of the chasmogamous floral opening behavior of tef flowers (from about 6:45-7:30 AM) and thereby the artificial crossing technique by Tareke (1975); (3) third phase (1995-1998) featuring initiation of molecular approaches, including development of molecular markers and genetic linkage maps, and analyses of molecular genetic diversity; (4) fourth phase (1998-2003) marked by further incorporation of *in vitro* culture techniques and inter-specific hybridization (Hailu *et al.*,2003) along with re-appraisal of induced mutagenesis particularly for lodging and leaf rust disease resistance; and (5) fifth phase (from 2003 till present) featuring introduction of participatory breeding approaches in the pre-existing overall tef genetic improvement ventures (Getachew *et al.*,2006) and continued extensive molecular and genomic research approaches (Kebebew *et al.*, 2013).

2.4. Genotype x Environment Interaction in Tef

In studying GEI, it is important to describe the basic components of phenotypic variability, the genotype, the environment, and the interaction of the genotype and the environment. Genotype refers to any of pure-line variety, Clone, inbred-line, hybrid variety, open-pollinated variety, Composite variety, Synthetic variety, Elite breeding lines and others on which the breeder collects performance and trait information. Environment refers to the combination of physical attributes of a location and the climatic and other attributes of a specific season (*i.e*. soil type, fertility, topography, temperature, rainfall, pest/disease challenge) that affect the plant growth in the growing season. The genotype and environment interaction refers to the deviation in performance of any attributes of genotypes within the growing environments. The most important thing in GEI is that in the conditions where the different traits under consideration

show a change in rank in different environments. Such changes of rank in the genotypes which is called crossover GEI (Becker *Leon* 1988) creates inconvenience in plant breeding.

Information on the adaptation and stability of the genotypes over seasons and over sites is useful for recommending the varieties that should be grown under particular environments and predicting the yield expectations of the test varieties. A Genotype is considered the most stable one if it has a high mean yield, but a low degree of fluctuation in yielding ability when grown over diverse environments (Arshad *et al*., 2003). Knowledge of the extent of GEI and stability and performance of genotypes across environment is essential to the plant breeder; the former will help breeders to decide whether he will aim at widely adapted varieties or specifically adapted ones in recommending the final release (Mosisa, 1999).

Genotype x environment (G x E) interactions are of interest to plant breeders in the process of development of improved genotype. Baker (2002) defined genotype by environment interaction from biological and statistical point of view. The phenotype of an individual plant or animal is a consequence of the interaction between its genotype and the environment in which it exists. An interaction occurs when two genotypes differ in their response to a change in environments. Change in ranks of cultivar through environments indicates G x E interaction and lack of stability in the trait under study. Genotype by enivromnet is studied in order to answer a number of questions related to varietals adaptation and stability. Understanding GEI is useful, amongst other for developing different agro-ecologies, effective allocation of resources and for the characterization of genotype responses to variable productivity levels (Tiruneh, 2000).

Studies of genotype by enivironmnet interaction are relevant for determining breeding strategies. Varieties of tef developed through hybridization and/or selection show good adaptation in several regions of Ethiopia. However, there is a necessity of further research to take into account the realities of different agro-ecological zones in order to tap the genetic potential of the varieties (Hailu *et al*., 1995). Multi-location variety trials play a decisive role in the effort to develop high yielding varieties adapted to a wide range of environments. Tef is grown under high variation in climatic and edaphic factors that lead to GxE interaction even within a small geographic area (Hailu and Getachew, 2006). Various studies have been conducted to analyze the effect of GEI on different crops in Ethiopia.

Mathewos and Getachew (2012) evaluated best genotype according to yield parameter in Ethopia. They were estimated genotype and interaction identify stable genotype and assess the interaction pattern of the testing location, and statistical method used by Additive Main Effect and Multiplicative Interaction Model.

Habte *et al*., (2019) studied GEI in tef using 35 tef genotypes across nine locations and identified four mega environments for tef production in Ethiopia.Dagnachew (2014) studied about 30 advanced finger millet genotypes were evaluated against two standard checks (Gute and Taddese) across four locations (Arsi Negele, Assosa, Bako and Gute) in 2012 and 2013 main cropping seasons assess the stability and yield performance. Additive Main effect and Multiplicative Interaction (AMMI), Genotype and Genotype by Environment interaction (GGE) biplot analysis and, Eberhart and Russell model revealed that Acc. 203544 is stable high yielding (3.16 ton ha^{-1}) with a yield advantage of 13.7% over the best standard check, Gute (2.78 ton ha^{-1}), and thus should be recommended for possible release with wider environmental adaptability. Acc. 242111 (3.08 ton ha^{-1}), Acc. BKFM0051 (3.07 ton ha^{-1}) and Acc.229738 (2.99 ton ha^{-1}) were also high yielding, but showed narrow stability and thus should be recommended for verification and possible release for specific environments.

Workie *et al.* (2013) studied the assessment of genotype x environment interaction on maize crop across the North Western Ethiopia during 2010. Fifteen maize genotypes were evaluated at four locations that differ in soil type, attitude and mean annual rainfall. The experiment was laid out in a randomized block design with three replications. Single site analysis of variance for grain yield was done in SAS software different stability models such as Shukla's stability and Wricke's ecovalence were performed.

Fentaw (2011) conducted an experiment with the objectives of examining the magnitude of environmental effect on yield, stability and adaptability of thirteen durum wheat varieties under different agro ecological conditions in north western Ethiopia. The combined analysis of variance for grain yield indicated that environments, genotypes and GEI, contributed 65.91%, 8.18% and 10.92%, respectively. This indicates that the test environments were highly variable and have big influence on the yield performance of durum wheat genotypes. The GEI sum of squares is relatively higher than the genotype sum of squares, indicating that the influence of

GEI on durum wheat genotypes recommendation for specific growing condition should be considered.

Letta (2007) compared the several biometrical methods for analysis of GE interaction and yield stability. The study was assessed the nature and magnitude of GEI and the correlation among some stability parameter of grain yield. The stability analysis of identified genotypes 3 and 4 as more stable genotypes and recommended for commercial production in the South East Ethiopia. Stability analyses were performed using MSTAT-C and IRRI stat computer programs (IRRI Stat), Spearmen's coefficient of rank correlation was computed for each pair of the possible pair-wise comparison of the stability parameter by Minitab and AMMI was calculated by PURCHASE.

Domitruk *et al*. (2001) indicated that the analysis of variance procedure is a useful tool for estimating the existence and magnitude of GEI. In the multi environment trial (MET), the combined analysis of variance is useful for estimating variance components related to different sources of variation, including genotypes, environment and GEI (Yan and Hunt,2002)

An experiment was done on sorghum grain using 15 sorghum genotypes grown for three consecutive years (2003–2005) at three different environments in southern Ethiopia to investigate the effect of GEI on sorghum yield performance in the drought stressed parts of Ethiopia (Asfaw, 2007). The performance of genotypes in the various environments was different. The contribution of genotypes, environments and GEI were 5.9 %, 73.8 % and 20.3 % of the total sum of squares, respectively. The large sum of squares for environments indicated that the environments were diverse, with large differences among environmental means, causing most of the variation in grain yield. The magnitude of the GEI sum of squares was 3.41 times larger than that of the genotypes, indicating, that there were substantial differences in genotype response across environments.

The phenotype of an individual is determined by both the genotype and the environment; these two effects are not always additive which indicates that GEI, are present. The GEI result in inconsistent performances between the genotypes across environments. Significant GxE results from the changes in the magnitude of differences between genotypes in different environments or changes in the relative ranking of the genotypes (Falconer, 1952 and Fernandez (1991).

According to Baker (1990) and Cornelius *et al*. (1996), genotype by environmnet interaction have been grouped in to crossover and non-crossover interactions. The differential response of cultivars to diverse environments is referred to as a crossover interaction when cultivar ranks change from one environment to another. A main feature of crossover interaction is intersecting lines in a graphical representation. If the lines do not intersect, there is no crossover interaction (Kang, 1998).

Non-crossover (quantitative) interactions represent changes in magnitude of genotype performance, but rank order of genotypes across environments remains unchanged, i.e., genotypes that are superior in one environment maintain their superiority in other environments. Non-crossover interactions may mean that genotypes are genetically heterogeneous but test environments are more or less homogeneous or that genotypes are genetically homogeneous but environments are heterogeneous. In crop breeding, the crossover interaction is more important than non-crossover interaction (Baker, 1990). Since, the presence of a crossover interaction has strong implications for breeding for specific adaptation, it is important to assess the frequency of crossover interactions (Singh *et al*., 1999).

To be able to understand GEI and utilize it effectively in breeding programmes, information is needed on the factors responsible for the differential response of genotypes to variable environments. A factor may be present at optimal, suboptimal or superoptimal levels. When present at a level other than optimal, it represents a stress. According to Baker (1988), differences in the rate of increase in response of genotypes at suboptimal levels would reflect differences in efficiency, and differences in the rate of decrease at superoptimal levels would reflect differences in tolerance. Without the presence of stresses, genotype attributes, such as efficiency and tolerance, cannot be identified and investigated. In this section, the effects of environmental stress on the plant genome in general and biotic and abiotic factors that may be responsible for GEI are considered.

2.4.1.1 Genes and environment

Organisms are determined neither by their genes nor by their environment; they are the consequence of the interaction of genes and environment (Suzuki *et al*., 1981). 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 phenotype changes continually and the direction of that change is a function of the sequence of environments that the individual experiences (Suzuki *et al*., 1981).

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. Comstock and Moll (1963) classified environments into two categories, (i) Macro-environment, i.e. the environment which is associated with a given location or area at a particular period of time. (ii) Micro-environment, i.e. the environment of a single organism as opposed to that of another organism growing at the same time and in almost the same place. It includes physical and chemical attributes of soil, climatic variables, solar radiation, insect pests and disease. The macro-environments reflect a collection of micro-environments which are more alike within each macro-environment with the result that macro-environments substantially differ from each other.

The terms 'predictable and unpredictable environments' were coined by Allard and Bradshaw (1964) to define and classify environments. The predictable environment includes the regular and more or less permanent features of the environment such as climate as determined by its longitude and latitude, soil type, rainfall and day length. It also includes what are called controllable variables (Perkins and Jinks, 1971) e.g. the level of fertilizer applied, sowing date and sowing density, amount of irrigation and others that can be artificially created. The unpredictable or uncontrollable environments, on the other hand, include weather fluctuations such as differences between seasons in terms of amount and distribution of rainfall and the prevailing temperature during the crop growth. The absence or low level of interaction will be useful for uncontrollable variables, whereas for the controllable variables a high level of interaction in the favourable direction is desirable to obtain maximal performance (Chahal and Gosal, 2002).

2.5 Significance of Genotype x Environment Interaction in tef

What breeders can do to overcome the problem of G x E interaction depends upon the relative importance of variance components. Moreover, breeding programmes aimed to develop stable genotypes also depend upon whether a breeder is dealing with predictable or unpredictable environmental variation. Whenever dealing with predictable environmental variation, the first step that should be taken is to identify the differences. There is no difficulty when differences are recognizable, for example, differences in the seasons such as varieties to be developed for the rainy season or post-rainy season. Breeders can develop varieties suitable for both these seasons because environmental variation is defined.

For variety trials, which are tested in the same locations (L) and genotypes (G) and over years (Y), G x E analysis of variance may be partitioned into components due to G x L, G x Y and G x L x Y. Significance of mean square for G x L generally suggests that the region for which genotypes are being bred comprises of a number of special environments. In such circumstances the geographic region could be subdivided into sub regions which are relatively homogeneous. If interaction is very high, varieties should be bred which are specifically adapted to these ecotypes. Implication of G x Y different from G x L interaction. This is so because year-to-year fluctuations cannot be predicted in advance and breeders can hardly aim their programmes to develop varieties suited to particular years (Dabholkar, 1999).

In some situations, environmental variation is predictable, but can also be corrected. For example, saline soils can be corrected by certain agronomic practices or by addition of some amendments. This is easier and quicker than evolving varieties suitable for such situations. However, breeding of varieties suitable for saline or acidic soils is low cost input and also a relatively permanent solution to the problem. It is relatively easier to develop varieties specifically adapted to predictable environmental situations than to breed for unpredictable environmental variations. The aim of the breeding programme should, therefore be to develop genotypes that can withstand unpredictable transient environmental fluctuations. In other words, breed widely adapted genotypes (Dabholkar, 1999).

According to Allard and Bradshaw (1964) “a variety which can adjust its genotypic or phenotypic state in response to transient fluctuations in environment in such a way that it gives

high and stable economic returns for place and year, is termed as well buffered". Plant breeders generally agree that the new variety must show a high degree of stability in performance. The existence of G x E interactions complicates the identification of superior genotypes for a range of environments. G x E interactions can be an outcome of genotype rank changes from one environment to another, a difference in scale among environments, or a combination of these phenomena. According to Becker and Léon (1988), cultivar rank changes are of greater importance than scale change interactions in cultivar trials conducted over a series of environments. Hence, G x E interaction is critical only if it involves significant crossover interactions (significant reversal in genotypic rank across environments) (Becker and Léon, 1988).

2.6. Concepts of Mega-Environment

Mega-environments were first defined as environments with similar "biotic and abiotic stresses, cropping system requirements, consumer preferences, and volume of production" (Braun *et al.*, 1996). A cluster of environments or locations, which constantly share the same best cultivar, are called mega-environments (Yan and Rajcan,2002). Different environments with similar climatic, edaphic and other characteristics can be described by using different data of the environments and METs data to group under homogenous sub regions. Division of the target environments into meaningful mega-environments and deploying different cultivars for different mega-environments is the only way to utilize positive GEI and avoid negative GEI and sole purpose for GEI analysis (Yan *et al*., 2000).

2.7 Concept of Stability

Stability is a central keyword for plant breeders analysing GE data. A simple corresponding statistical term is 'dispersion around a central value' (Denis *et al*., 1996). There are two concepts of stability: static and dynamic. The static concept means that a genotype has a stable performance across environments and there is no among environment variance. This would mean that a genotype would not respond to high levels of inputs, such as fertilizer. This type of stability would not be beneficial for the farmer, and it has been referred to as the biological concept of stability (Becker,

1981), which is equivalent to Lin *et al*.'s (1986) type 1 stability. In type 1 stability, a genotype is regarded as stable if its among environment variance is small.

The dynamic concept means that a genotype has a stable performance, but, for each environment, its performance corresponds to the estimated level or predicted level. There would be agreement between the estimated or predicted level and the level of actual performance (Becker and Leon, 1988). This concept has been referred to as the agronomic concept (Becker, 1981), which is equivalent to Lin *et al.*'s (1986) type 2 stability. In type 2, a genotype is regarded as stable if its response to environments is parallel to the mean response of all genotypes in a test.

2.8 Adaptation of Genotype

Adaptability of a given cultivar or hybrid is defined as inherent genetic ability of a cultivar to be stable and high yielding in various environments (Zivanovic *et al*., 2004). Living organisms are capable of adjusting to the normal functions of their environment, which enable them to cope with situations within their surroundings. Moreover, adaptability refers to the manner in which an organism adjusts to its environment. For example, certain genotypes may produce high yields under certain environmental conditions but poor yields in others conditions (Balzarini *et al*., 2005).

2.9 Correlations Among Parameters

Correlation analysis is a technique which helps to explain the degree of relationship among quantitative traits of a given genotype (Malik *et al.,* 2005). Grain yield is a complex quantitative trait that depends on a number of environmental and genetic factors (Bocanski *et al*., 2009). Because of this during selection for grain yield, it is important to confirm relationship between traits that contribute to improved grain yield (Hallauer and Mirand, 1988).

2.10 Statistical Methods to Measure G x E Interaction and Stability Analysis in tef

2.10.1 Conventional Analysis of Variance

The classic model for analyzing the total yield variation contained in GEI observations is the analysis of variance (Fisher, 1918). The within-environment residual mean square measures the

error in estimating the genotype means due to differences in soil fertility and other factors, such as shading and competition from one plot to another. After removing the replicate effect when combining the data, the GEI observations are partitioned into two sources: (a) additive main effect for genotypes and environments and (b) non-additive effects due to GEI.

The analysis of variance of the combined data expresses the observed (*Yij*) mean yield of the i^{th} genotype at the j^{th} environment as

$$\mathbf{Yij = \mu + Gi + Ej + GEij + \varepsilon ij}$$

Where, μ is the general mean;

Gi, *Ej*, and *GEij* represent the effect of the genotype, environment, and

the GEI, respectively; and

εij is the average of the random errors associated with the r^{th} plot that receives the i^{th} genotype in the j^{th} environment.

The non-additive interaction as defined in implies that the expected value of the i^{th} genotype in the j^{th} environment (*Yij*) depends not only on the levels of G and separately, but also on the particular combination of levels of G and E (Crossa, 1990). A combined analysis of variance procedure is the most common method used to identify the existence of GEI from replicated multi-location trials. If the GEI variance is found to be significant, one or more of the various methods for measuring the stability of genotypes can be used to identify the stable genotype (s). Analysis of variance of multi location trials is useful for estimating variance components related to different sources of variation, including genotypes and GEI. In general, variance component methodology is important in multi location trials, since errors in measuring the yield performance of a genotype arise largely from GEI. Therefore, knowledge of the size of this interaction is required to (a) obtain efficient estimates of the genotypic effects and (b) determine optimum resource allocations, that is the number of plots and locations to be included in future trials.

2.10.2 Stability Analysis in tef

Stability analysis provides a general summary of the response patterns of genotypes to environmental change. Methods of determining genotype stability based on the GEI is available. The more important and frequently used methodologies are discussed as follow.

2.10.2.1 Wricke's Ecovalence (Wi)

Wrick (1962) as cited in Dia (2012) defined the concept of ecovalence as the contribution of each genotype to the GEI sum of squares. The ecovalence (Wi) or stability of the i^{th} genotype is its interaction with the environments, squared and summed across environments. Genotypes with a low (Wi) value have smaller deviations from the overall mean across environments and are thus more stable. According to the meaning of ecovalence, the stable genotype possesses a low ecovalence. Hence, genotypes with a low (Wi) value have smaller deviations from the mean across environments and are thus more stable.

2.10.2.2 Cultivar Performance Measure (Pi)

The method of Lin and Binns (1988) has the great advantage of a directed recommendation of more stable and adapted genotypes, due to the uniqueness of the parameter, the evaluation of genotype performance according to the environmental variation and the fact that the genotypes identified among the most stable and adapted are generally the most productive. The most stable genotype is the one with least deviation from the maximum yield of each environment, *i.e.*, with the lowest (Pi) value. It measures mean performance and stability simultaneously. Fiseha *et al*., (2015) used this method.

2.10.2.3 Shukla's Stability Variance (σ^2)

Shukla's stability variance (σ^2i) is the contribution of a genotype to the GEI sums of squares after adjusting for the average genotypic contribution to the GEI sums of squares. Shukla (1972) developed a modified version of the ecovalence in order to give unbiased estimate of the G X E variance for every genotype using the stability variance (σ^2i). A genotype is called stable, if its stability variance (σ^2i) is equal to the environmental variance (σ^2e) which means that σ^2i = 0.A relatively large value of σ^2i will thus indicate greater instability of genotypes.Shukla (1972) also proposed criteria for testing the significance of the stability variance of each genotype and

extended the model to allow the removal of the linear effects due to covariates. The analysis was done by using GEA-R (Genotype by Environment Analysis with R) software (Pacheco *et al*., 2015).

2.10.2.4 Eberhart and Russell's Joint Regression Model

Eberhart and Russell (1966) stressed that the most important stability parameters appeared to be the deviation from linear regression mean square because all types of gene action were involved in this parameter. They use the regression coefficient (bi) and the deviation from regression (S^2di). The (bi) values greater and less than one, if associated with relatively high mean yield, result in specific adaptation to high yielding (favorable) and low yielding (unfavorable) locations, respectively. Conversely, bi values around one indicate wide adaptation if combined with high mean yield.

In a genotype x environment interaction study on tef, the genotypes x environment interactions plus environmental linear effects were found to be significant for grain yield and identified stable genotypes from eighteen genotypes, by using regression model (Tiruneh,1999). Highly significant mean squares due to environments (linear) indicated differences between environments. The variance due to G x E (linear) was significant indicating that the stability parameter "bi" estimated by linear response to change in environment was not the same for all genotypes. This model is popular and has been used widely in stability analysis of different crop Firew (2003) in common beans and Brikti (2018) in tef used this stability parameter for the genotype evaluation.

2.10.2.5 AMMI Stability Value (ASV)

The ASV is the distance from the coordinate point to the origin in a two-dimensional scatter gram of IPCA1 scores against IPCA2 scores in the AMMI model (Purchase *et al*., 1997). Because the IPCA1 score contributes more to the GEI sum of squares, a weighted value is needed. This weight is calculated for each genotype and each environment according to the relative contribution of IPCA1 to IPCA2 to the interaction sum square. The genotypes with larger IPCA score, either negative or positive, are the more specifically adapted to certain environments and those with smaller IPCA scores indicate a more stable genotype across environments. Brikti (2018) used this stability parameter for genotypes evaluation in tef.

2.10.2.6 Yield Stability Index (YSI)

Farshadfar *et al*., (2011) developed yield stability index (YSI) which is similar to genotype selection index developed by Farshadfar *et al*., (2008) is recommended as a measure of stability.YSI is calculated by summing the rank of mean seed yield across environments and rank of AMMI stability value of genotypes. The lowest AMMI stability value takes the rank one, while the highest yield mean takes the rank one and then the ranks are summed in a single simultaneous selection index of yield and yield stability. The genotypes with lowest value of this parameter are desirable genotypes with high mean yield and stability.

2.10.3 Multivariate Analysis Methods in tef

According to Crossa (1990) multivariate analysis has three main purposes: (a) to eliminate noise from the data pattern (*i.e.* to distinguish systematic from nonsystematic variation); (b) to summarize the data; and (c) to reveal a structure in the data. In contrast with classic statistical methods, the function of multivariate analysis is to elucidate the internal structure of the data from which hypotheses can be generated and later tested by statistical methods (Gauch, 1982a & b). Multivariate analysis is appropriate for analysing two-way matrices of genotypes G and E environments. The response of any genotype in environments may be conceived as a pattern in E-dimensional space, with the coordinate of an individual axis being the yield or other metric of the genotype in one environment.

2.10.3.1 Additive Main Effect and Multiplicative Interaction (AMMI) Model

AMMI is a combination of ANOVA for the main effects of the genotypes and the environments together with principal component Analysis (PCA) of the genotype by environment interaction (Gauch, 1988). The Additive Main effect and Multiplicative Interaction (AMMI) method proposed by Gauch (1992) is a statistical tool which leads to identification of stable genotypes with their adaptation behavior in a easy manner. The additive main effects and multiplicative interaction (AMMI) method integrates analysis of variance and principal components analysis into a unified approach (Gauch, 1988). According to Zobel *et al.*, (1988), it can be used to analysis METs.

The AMMI method is used for three main purposes. The first is model diagnoses, AMMI is more appropriate in the initial statistical analysis of yield trials, because it provides an analytical

tool of diagnosing other models as sub cases when these are better for particular data sets (Gauch, 1988). Secondly, AMMI clarifies the GEI and summarizes patterns and relationships of genotypes and environments (Zobel *et al.,* 1988). The third use is to improve the accuracy of yield estimates. Gains have been obtained in the accuracy of yield estimates that are equivalent to increasing the number of replicates by a factor of two to five (Zobel *et al.*, 1988; Crossa, 1990).

In multi-location trial of tef *(Eragrostis tef (*Zucc.)Trotter) several authors used AMMI analysis to partition the genotype x environment interaction matrix in to individual genotypic and environmental scores and came to the conclusion that AMMI-2 tends to be the best model for extracting patterns and rejecting noise from the data (Tiruneh 1999; Mathewos and Getachew, 2012; Brikti (2018).Tiruneh (2000) reported that the first IPCA alone captured 52% of the total G x E variance in only 21% of the interaction degrees of freedom.

2.10.3.2. Genotype Main Effect and Genotype by Environmnet Interaction (GGE) Bi-Plot

The term "GGE bi plot" first appeared in Yan *et al*., (2000). It refers to a bi plot that displays the G and GE of a genotype-by-environment data. GGE bi-plot is a data visualization tool, which graphically displays a GxE interaction in a two-way table (Yan, 2000).It is important to show the relationship between genotypes and environments for selected traits graphically by use of a genotype and genotype by environment interaction (GGE) biplot that allows visual assessment of genotype by environment interaction (GEI) pattern of multi-locational or multi-environment data (Yan *et al*., 2000).GGE is the most recent approach for analysis of GEI and increasingly being used in GEI studies in plant breeding research.

The model was proposed by Yan *et al*.,(2000) and has shown extensive usefulness and a more comprehensive tool in quantitative genetics and plant breeding. The model covers very critical areas in the study of stability of multi-locational trials, like the which-won-where pattern mean performance and stability of genotypes, discriminating ability, mega-environment investigation, and representativeness of environments.The GGE method emphasizes on two concepts, whereby in the first concept, it clearly points out that even though the measured yield is a result of combination effect by Genotype (G), Environment (E) and genotype x environment interaction (GEI), only G and GEI are relevant and must be considered simultaneously when

evaluating genotypes, thus the name GGE. The second concept is based on the biplot technique which was developed by Gabriel (1971) which is used to estimate and show the GGE of MEYT; hence the name GGE biplot.

The GGE biplot is made by the first two principal components (PC), PC1 and PC2 also known as the primary and secondary effects, respectively. This is derived from subjecting the environment centered yield data (due to GGE) to singular value decomposition. This now makes it very easy for one to see which genotype won in which environments, thus facilitating mega-environment (ME) identification (Yan *et al*., 2000). This is facilitated in the form of a polygon to visualize the interaction patterns between genotypes and environments (Yan and Kang, 2003), whereby furthest genotypes are connected from the biplot origin such that all genotypes are contained in the polygon (Kaya *et al*., 2006).

Some genotypes will be located on the vertices of the polygon and they are either the best or the poorest in one or more environments (Yan and Rajcan, 2002). The rays are drawn perpendicular to the sides of the polygon dividing it into sectors, such that the vertex genotypes in each sector is also the best genotype for sites whose markers fall into respective sector so that sites within the same sector share the same winning genotype (Yan *et al*., 2000).GGE biplot is a visual display of the G + GE of multi-environmental data where groups of locations with similar cultivar responses are presented and it identifies the highest yielding varieties for each group. PC1 tend to correlate highly with the genotype means, the ideal cultivar is the one which possess large scores for PC1, thus indicating high average yield and small PC2 scores indicating less GEI and greater stability.GGE bi-plot 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 (Yan, 2003), 2).Genotype evaluation (the mean performance and stability), and 3) Environmental evaluation (the power to discriminate among genotypes in target environments).Brikti (2018) in tef are among the many authors who used GGE bi-plot to identify mega environments, to evaluate the genotypes and to test the environments.

2.10.4 Spearman Rank Order Correlation Coefficient

To compare the different stability analysis procedures that undertaken in this study, spearman's coefficient of rank correlation was used (Steel and Torrie, 1980). Spearman rank order correlation coefficient is a non-parametric measure of association based on the rank of the data values. Spearman rank order correlation coefficient was computed by using SAS (2014) versions 9.3 software.

3. MATERIALS AND METHODS

3.1. Description of the Study Sites

The experiment was conducted during the 2018 main cropping season at six locations, namely: Melko, Bedele, Omonada, Arjo, Ambo and Areka. These locations represent the varying agro-ecologies with stressful nature and the major tef growing areas of Ethiopia in South and South-Western Ethiopia (Table 1)

Table 1: Location and descriptions of weather condition for six locations

Location	Geographic position		Altitude (m.a.s.l)	Soil type	Temp (^{0}C)	Rainfall (mm)
	Latitude (N)	Longitude (E)				
Ambo	$8^0$57′	$38^0$07′	2175	Vertisol	18	1018
Areka	$7^0$09′	$37^0$41′	1830	Alfisol	27	1539
Arjo	$8^0$74′	$36^0$50′	2457	Nitosol	18	1850
Bedele	$8^0$27′	$36^0$21′	2087	Nitosol	18	1700
Melko	$7^0$47′	36^0 47′	1753	Nitosol	22	1639
Omonada	$7^0$41′	$37^0$12′	1975	Nitosol	20	1600

Source: Research Centers and Agricultural Offices of the Respective Woredas

3.2. Experimental Materials

Twenty-one nationally released tef varieties were included in the study (Table 2). They were obtained from Debre Zeit Agricultural Research Center (DZARC)

Table 2 : Description of the tef varieties used in the experiment

No.	Variety name	Local name	Altitude	Source	Year of release	Maintainer	Productivity (t/ha)	
							On farm	On station
1	DZ-Cr-387 RIL355)	Quncho	1500-2500	Hybridization	2006	DZARC	2.0-2.2	2.4-2.8
2	DZ-01-1880	Guduru	1850-2500	Selection	2006	Bako	1.4-2.0	1.5-2.3
3	23-Tafi Adi-72	Kena	1850-2400	Selection	2008	Bako	1.3-2.3	1.7-2.7
4	DZ-01-3186	Etsub	1800-2600	Selection	2008	Adet	1.6-2.2	1.9-2.7
5	DZ-Cr-37	Tsedey	1500-2200	Hybridization	1984	DZARC	1.4-1.9	1.8-2.8
6	DZ-Cr-419 (DZ-Cr-974 X PI 222988)	Heber -1	1200-2000	Hybridization	2017	Adet	1.7-2.7	1.5-2.0
7	DZ-01-99	Asgori	1500-2400	Selection	1970	DZARC	1.7-2.2	2.4-3
8	DZ-01-974	Dukem	1400-2400	Selection	1995	DZARC	2-2.5	2.4-3.4
9	DZ-01-1285	Koye	1900-2200	Selection	2002	DZARC	1.8-2.5	2.4-3.6
10	DZ-Cr- 438 RIL7	Abola	1700-2400	Hybridization	2016	Adet	1.5-1.7	2.0- 2.8
11	DZ-01-196	Magna	1500-2400	Selection	1970	DZARC	1.4-1.6	1.8-2.2
12	DZ-01-354	Enatite	1600-2400	Selection	1970	DZARC	1.7-2.2	2.4-3.2
13	DZ-01-787	Wellenkomi	2800-2500	Selection	1978	DZARC	NA	NA
14	DZ-Cr-255	Gibe	1700-2000	Hybridization	1993	DZARC	NA	NA
15	DZ-01-2053	Holetta Key	1900-2700	Selection	1998/99	Holetta	NA	NA
16	DZ-CR-409 (sel. 50D)	Boset	NA	Hybridization	2012	DZARC	1.4-1.8	1.8-2.0
17	DZ-Cr-438 RIL133 B	Kora	NA	Hybridization	2014	DZARC	2.0 – 2.8	2.5 – 3.2
18	DZ-Cr-438 RIL91A	Dagim	NA	Hybridization	2016	DZARC	NA	NA
19	DZ-Cr-457 RIL181	Tesfa	NA	Hybridization	2017	DZARC	2.0 -2.4	2.5
20	DZ-Cr-442 RIL77C	Felagot	NA	NA	2017	DZARC	NA	NA
21	DZ-Cr-429 RIL125	Negus	NA	NA	2017	DZARC	NA	NA

Source: Debre Zeit Agricultural Research Center Tef Breeding Program DZARC =Debre Zeit Agricultural Research Center *NA =Not available

3.3. Experimental Design and Management

The trial was conducted using randomized complete block design (folded RCBD) with three replications at all locations under rain-fed conditions. Sowing was done manually in rows and the spacing between rows and plants was 20cm and 10cm, respectively. Spacing between plots was 1 m, whereas that between replications was 1.5 m and the total plot size was 2mx2m.Seed rates was based on the recommendation which was 15kg/ha. Planting was done on the onset of rain in the respective locations. As per the recommendations, plots were fertilized with 40 kg of N and 60 kg of P_2O_5per hectare for light soils and 60 kg N and 60kg P_2O_5 per hectare for black soils (Vertisols). All DAP was applied at planting, while urea was applied in split half at planting and the remaining half at tillering stage. All other relevant field trial management practices were carried out throughout the experimentation period across all locations as per the recommendations for the respective locations.

3.4. Data Collection

Data were recorded on plot and single plant basis and taken from the central eight rows of the plot. Individual plant based data were taken from five plants in each plot taken randomly from the central eight rows of each plot.

3.4.1 Data Collected on Plot Basis

Days to heading (DH): The number of days from 50% of the plots showing emergence of seedlings up to the emergence of the tips of the panicles from the flag leaf sheath in 50% of the plot stands

Days to maturity (DM): The number of days from 50% of the plots showing seedling emergence up to 90% of the plants in the plot reaching phenological maturity stage (as evidenced by eye-ball judgment of the plant stands when the color is changed from green to yellow color of straw)

Grain filling period (GFP): The number of days from 50% heading to 90% maturity of the stands in each plot

Lodging index (X): The value recorded following the method of Caldicott and Nuttall (1979) who defined lodging index as the sum of product of each scale or degree of lodging (0-5) and their respective severity percentage divided by five, where 0 value is fully upright (90^o), 1 = 0-

15^o lodging, 2=15-30^o lodging 3 = 30-45^o lodging, 4 = 45-60^o lodging and 5 = 60-90^o lodging and the plants become completely flat

Total biomass yield (g/plot): The weight of all the central row plants including tillers harvested at the level of the ground

Grain yield (g/plot): The weight of grain for all the central row plants including tillers harvested at the level of the ground

Straw yield (g/plot): The weight of straw plus chaff of all the central row plants including tillers harvested at the level of the ground

Thousand seed weight (g) : It is the weight of thousand seeds at 12.5% moisture content

Harvest index: The value computed as the ratio of grain yield to the total (grain plus straw) biomass multiplied by 100.

3.4.2 Data collected on plant basis

Plant Height (cm): Measured as the distance from the base of the stem of the main tiller to the tip of the panicle at maturity

Panicle Length (cm) : The length from the node where the first panicle branch starts up to the tip of the main panicle at maturity

Culm Length (cm) : The length of the main shoot node from the ground level up to the point of emergence of the panicle branches

Fertile Tillers : The number of panicle-bearing fertile tillers produced per plant

3.5. Statistical Analysis

Analysis of variance (ANOVA) was conducted separately for individual environments according to Gomez and Gomez (1984). Bartlett's test (1947) was used to assess the homogeneity of error variance between environments to determine the validity of the combined analysis of variance across environments. Analysis of variance for grain yield and related traits for each location and the combined analysis of variance over environments were performed with the PROC GLM procedure using SAS (2014) versions 9.3 software. Comparision of of treatment means was done using Fischer's least significant difference (LSD) test at 5% probability levels.

The following statistical model used for ANOVA of data of the individual environments:

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

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,

ϵ_{ij}= Error effect of genotype i in block j

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

$Y_{ijk} = \mu + G_i + E_j + GE_{ij} + Bk_{(j)} + \epsilon_{ijk}$

Where:

Y_{ijk} = Observed value of genotype i in block k of environment (location) j,

μ = Grand mean, capitalize the first letters, like this

G_i = Effect of genotype i,

E_j= Environment or location effect,

GE_{ij} = The interaction effect of genotype i with environment j,

$Bk_{(j)}$ = The effect of block k in location (environment) j,

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 effects of environment, genotype and GEI. Significance levels of these components were determined using F- test. The outline of the analysis of variance at individual and over location was indicated on Tables 3 and 4, respectively.

Table 3: Outline of analysis of variance for individual location

Source of variation	Df	SS	MS	F ratio
Replications (r)	r-1	SSr	SSr/r-1	
Genotypes (g)	g-1	SSg	SSg/g-1	MSg/MSe
Error	(r-1)(g-1)	SSe	SSe/(r-1)(g-1)	
Total	rt-1	TSS		

DF = degrees of freedom, r = replication, g = genotypes, e= error, SS=Sum squares, MS = mean squares, MSr = mean squares due to replications, MSg = mean squares due to genotypes, MSe = mean squares due to error.

Table 4: Outline of combined analysis of variance of overall locations

Source of variation	Df	MS	Expected MS	F ratio
Environment (E)	e-1	MSE	$s^2e + gs^2r(e) + rg\ s^2e$	MSE/ME
Replication within E	E(r-1)	MSr/E	$s^2e + g\ s^2r(e)$	MSr/e/Me
Genotypes (g)	g-1	MSg	$s^2e + gs^2ge + ers2g$	MS3/MSe
GEI	(e-1)(g-1)	MSgei	$s^2e + gs^2ge$	MS4/MSe
Error	e(g-1)(r-1)	MSe		
Total	Erg-1			

DF = degree of freedom, MS = Mean squares, r = replication, g = genotypes= environments, MSE = mean squares due to environments, MSr/E= mean squares due to replication (Environments), MSg = Mean squares due to genotypes, MSGEI= Mean squares due to GEI and MSe= Mean squares due to residual.

3.5.1 Stability Analysis

3.5.1.1. AMMI Stability Value (ASV)

Because AMMI model does not make provision for a quantitative stability measure, AMMI stability value (ASV) (Purchase, 1997) would be essential in order to quantify and rank genotypes according to their yield stability. AMMI's stability value (ASV) was calculated using the following formula with Microsoft excel (2010).

$$ASV = \frac{\sqrt{[IPCA1\ sumofsquares(IPCA1\ score)]^2}}{IPCA2\ sumofsquare} + (IPCA2\ score)^2$$

Where:

ASV = AMMI's stability value, SS = sum of squares, IPCA1 = interaction of principal component analysis one and IPCA2 = interaction principal component analysis two.

3.5.1.2. Cultivar Superiority Measure (Pi)

The underlying estimate of parameter P_i, measures the deviation from the yield of a given genotype in relation to the maximum in each one of the environments. The ideal genotype is the one with the lowest Pi value and the lowest contribution to the genotype by environment interaction. The data set was analyzed according to the procedure recommended by Lin and Binns (1988).The values estimated are the square of the difference between genotype mean and the maximum genotype mean at a location, summed and divided by twice the number of environments. The computation was performed with the aid of Genstat version 16th software.

According to Lin and Binns (1988) for cultivar superiority measure (Pi) analysis, the genotype with low or small (Pi) value is considered to be more stable.

Mathematically:

$$P_i = \sum_{j=1}^{n} \frac{(X_{ij} - M_j)^2}{2n}$$

Where, *Xij* is the average response of the i^{th} genotype in the j^{th} environment, *Xi* is the mean deviation of i^{th} genotype, *Mj* is the genotype with maximum response among all genotypes in the j^{th} location, and *n* is the number of locations. The first term of the equation represents the genotype sum of squares and the second part the GE sum of squares. The smaller the value of *Pi*, the less is the distance to the genotype with maximum yield and the better the genotype. A pair wise GEI mean square between the maximum and each genotype is also calculated.

3.5.1.3. Yield Stability Index (YSI)

Farshadfar *et al.*,(2011), developed this new approach as a measure of genotype stability. YSI incorporates both mean yield and stability in a single criterion. Low value of this parameters shows desirable genotypes with high mean yield and stability. YSI was calculated as:

YSI = RASV + RY

Where:

RASV is the rank of AMMI stability value and

RY is the rank of mean yield of genotypes across environments.

3.5.1.4 Wricke's Ecovalence

Wricke's ecovalence (Wi) expresses the stability of genotype i, as the interaction of this genotype with the environment, squared and summed across environments. The analysis was done by using Genstat version 16th software. Wricke's ecovalence can be expressed as:

$Wi = \Sigma (\bar{Y}_{ij}. - \bar{Y}_{i}.- \bar{Y}_{.j} + \bar{Y}..)^2$

Where:

$\bar{Y}ij.$ = The mean yield of the ith genotype in the jth environment,

$\bar{Y}i.$ = The mean yield of the ith genotype,

$\bar{Y}.j$ = The mean yield of the jth environment and

$\bar{Y}.$= Grand mean

3.5.1.5 Shukla's Stability Variance (σ^2)

Shukla's stability variance (σ^2i) is the contribution of a genotype to the GEI sums of squares after adjusting for the average genotypic contribution to the GEI sums of squares. Shukla (1972) developed a modified version of the ecovalence in order to give unbiased estimate of the G X E variance for every genotype using the stability variance (σ^2i). A genotype is called stable if its stability variance (σ^2i) is equal to the environmental variance (σ^2e) which means that σ^2i = 0.A relatively large value of σ^2i will thus indicate greater instability of genotype i.e Shukla (1972) also proposed criteria for testing the significance of the stability variance of each genotype and extended the model to allow the removal of the linear effects due to covariates.

The analysis was done by using GEA-R (Genotype by Environment Analysis with R) software (Pacheco *et al*., 2015). Shukla's stability variance (σ^2i) is the contribution of a genotype to the GEI sums of squares after adjusting for the average genotypic contribution to the GEI sums of squares.

$$\sigma_i^2 = \frac{1}{(G-1)(G-2)(E-1)}[(G(G-1) \quad \sum_j (Y_{ij} - Y_i - Y_J + Y_{...})^2 - \sum_i \sum_j (Y_{ij} - Y_i - Y_j + Y_{...})^2]$$

Where, Yij is the mean of the ith genotype in the jth environment, Y.j is the mean of all genotypes in the jth environments and $\bar{Y}$.. is the mean of all genotypes in all environments. A genotype is called stable if its stability variance (σ^2) is equal to environmental variance $\sigma^2 e$.

3.5.1.6 Eberhart and Russell's joint regression model

Eberhart and Russell's (1966) joint regression model was used for stability analysis of grain yield. They proposed an assessment of cultivar response to environmental changes using a linear regression coefficient and the variance of the regression deviations. The linear regression coefficients (βi) of the relationship between cultivars yield at each location and the mean location yield is measure of the linear responses to environmental change. The mean square for deviation from the regression (δ^2di) measures the consistency of this response.

The behavior of the genotype was assessed by the model:

$$Y = \mu + \beta I + \delta$$

Where: Yij = the mean of the ith genotype in the jth environment
μ =the grand mean

βi= the regression coefficient of the i_{th} genotype on environmental index

Ij=the environmental index obtained by the difference between the mean of each environment and the grand mean

$$I = (X - \mu)$$

δij=the regression deviation of the i_{th} genotype in the j_{th} environment.

The two stability parameters were calculated.

The first stability parameter was regression coefficient (βi) estimated as

βi= $\frac{\sum y_i I_j}{\sum I_j^2}$ where:$\sum y_i I_j$=is the sum of the product of the ith observation in the jth environment with its environmental index, $\sum I_j^2$ = is the sum of the squares of each environmental index

Therefore, the performance of each variety could be predicted by using the estimates of the parameters, Ȳij = xi+ bi Ii where xi is the estimate of μ.

The second stability parameter is the mean square deviation from linear regression and could be estimated first by squaring the deviation.The deviations $[\delta_{ij} = (Y_{ij} - \gamma_{ij})]$can be squared and summed to provide an estimate of another stability parameter (δ²di) that could be calculated as

$\delta^2 d_j = \left[\frac{\sum \delta^2 ij}{n-2}\right] - \frac{s_e^2}{r}$ where, $\frac{s_e^2}{r}$ =the estimate of the pooled error or the variance of a genotype mean at the jth location, n-2 = the degrees of freedom, r=number of replications

$$\sum_j \delta_i^2 = \left[\sum_j y_i^2 - \frac{y_i^2}{n}\right] - \left(\sum_j y\right) 2 / \sum_i I_j^2$$

3.5.1.7. Additive Main Effect and Multiplicative Interaction (AMMI) Model

Additive Main Effect and Multiplicative Interaction (AMMI) is one of most widely used model to explain G×E interaction of multi-environment genotype trial for categorizing the genotypes into narrow or wider adaptation (Crossa *et al*., 1990). It integrates ANOVA and PCA in to a unified approach, clarifies GEI, and summarizes patterns and relationship of genotypes and environments. Moreover, graphical representation can be used to easily interpret results using AMMI biplot that shows main effects and GEI (Zobel *et al*., 1988; Gauch, 1988). AMMI analysis was done by using Genstat version 18thsoftware according to the model suggested by Crossa *et al*., (1990).

The AMMI Model Equation is:

$$\boldsymbol{Yij} = \mu + \boldsymbol{gj} + \boldsymbol{ej} + \sum \boldsymbol{x\ k\ \lambda k\ ajk\gamma jk} + \varepsilon \boldsymbol{ij}$$

Where, Yij is the mean of the genotype in the environment,

μ is the grand mean,

gj is the genotype effect,

ej =is the environment effect, is the singular value for principal component, is

the eigenvector score for genotype i and component k, is the eigenvector score for genotype i

and component k and is the error for genotype i and environment j.

From the equation of the AMMI model analysis were interpreted by a biplot between Principal Component (PC) Axis 1 versus PC Axis 2. A genotype or an environment with a PC score close to zero shows the small interaction effect and considered as stable.

3.5.2.8 Genotype Main Effect and Genotype by Environment Interaction Effect (GGE) biplot analysis

The GGE biplot was constructed by using Genstat version 16th software.GGE biplot methodology, which is composed of two concepts, the biplot concept (Gabriel, 1971) and the GGE concept (Yan *et al.*, 2000), was used to graphically analyze the performance of the wheat genotypes at different environments. This methodology uses a biplot to show the factors (G and GE) that are important in genotype evaluation and that are also the sources of variation in GE interaction analysis of MET data (Yan, 2001). The general model for GGE Biplot is as follow:

Y_{ij} -μ-βj = λ1Ɛi1ηj1 + λ2Ɛi2ηj2 + $Ɛ_{ij}$ where:

Y_{ij}= the performance of the i^{th} genotype in the j^{th} environment;

μ = the grand mean;

β_j = The main effect of the environment j:

λl and λ2 = Singular value for IPCA1 and IPCA2 respectively:

Ɛi1 and Ɛi2 = Eigen vectors of genotype i IPCA1 and IPCA2 respectively:

ηj1 and ηj2 = Eigen vectors of environment j for IPCA1 and IPCA2 respectively and

$Ɛ_{ij}$ = Residual associated with genotype i and environment j.

3.5.2.9 Spearman Rank Order Correlation Coefficient

To compare the different stability analysis procedures that were undertaken in this study, spearman's coefficient of rank correlation was used (Steel and Torrie,1980). Spearman rank order correlation coefficient is a non-parametric measure of association based on the rank of

the data values. Spearman rank order correlation coefficient was computed by using SAS (2014) versions 9.3 software.

$$r_s = 1 - \frac{6\sum D^2}{n\left(n^2 - 1\right)}$$

Where, r_s = Spearman rank order correlation coefficient, d_i = the difference between the rank of corresponding values of Xi and Yi, n = number of value in each set

4. RESULTS AND DISCUSSION

4.1. ANOVA and Grain Yield Mean Performance of tef varieties at Individual locations

Analysis of variance revealed the presence of significant ($P<0.01$) differences in tef grain yield among tef varieties tested at Omonda, Melko, Bedele, Arjo, Ambo and Areka 2018 cropping season (Appendix Table 1). This indicated the presence of performance variation among the tested varieties for grain yield and it is possible to identify high yielder varieties for possible use in these locations.

Mean yields of varieties across environments ranged from 330 to 1250kg/ha at Omonada,420 to 1013kg/ha at Melko,208 to 790kg/ha at Bedele,930 to 1490kg/ha at Areka,330 to 940kg/ha at Arjo and 882 to 1690kg/ha at Ambo (Table 5). Mean yields of varieties across environments ranged from 662.8kg/ha to 1084.3kg/ha with mean grain yield of 826.8kg/ha. The popular variety Quncho, ranked first by mean grain yield at Omonada, seventh at Melko, Areka and Arjo eighth at Bedele and fifth at Ambo. This rank change of the same variety over locations by the same trait is the consequence of the highly significant GxE interaction. The varieties exhibited highest mean grain yield (1264.5kg/ha) at Ambo while lowest at Bedele (459.4kg/ha).

The variety Dukem, was found to be the best variety with average mean grain yield of 1084.3kg/ha followed by Heber-1 (1032.3kg/ha) and the popular variety Quncho with mean grain yield of 957.3kg/ha.At Omonada,the varieties that equally recorded the highest mean performance were Quncho,Dukem and Negus (recently released variety) with the mean of 1250kg/ha.The lowest performance was exhibited by both the variety Guduru and Felagot with the mean of 330kg/ha.The varieties Guduru (1013kg/ha),Kora (799kg/ha) and Kena (741kg/ha) exhibited the highest mean performance at Melko.On the other hand,Abola(791.6kg/ha),Koye (675kg/ha) and Dukem (625kg/ha) exhibited highest mean yield at Bedele.At Areka,the varieties Negus,Heber-1 and Dukem exhibited highest mean yield with 1496kg/ha,1467kg/ha and 1427kg/ha respectively.The varieties Felagot (942kg/ha) and Dukem (1692kg/ha) exhibited the highest mean grain yield at Arjo and Ambo respectively.The finding was in line with the Kebebew *et al*.,(2001b) reported the grain yield of tef varieties ranged from 1058kg/ha to 4599kg/kg/ha.

The ranking of varieties was different from one environment to another. This indicates that varieties may not express the same phenotypic performance under different environmental conditions or different varieties may respond differently to a specific environment. The three highest mean yields across the different environments were recorded by Dukem, Heber-1 and Quncho with the overall mean of 1084.3, 1032.2 and 957.3kg/ha respectively. On the other hand, the varieties Kena, Felagot and Wellenkomi exhibited the lowest overall mean grain yield of 662.8,703.3 and 712.5kg/ha respectively.

In general, ranking of genotypes changes from one environment to another and this is also an indication for the existence of G x E interaction due to variation among the testing locations. Change in performance of yield with environments was also reported by Fiseha *et al.* (2015) in sesame. Brikit (2018) reported genotypes vary on their performance for grain yield in different environments. Genotypes Menagesha, Dima and Gerado possessed the highest grain yield in E1; Genete, Koye and Dima in E2; Pop8R61, Pop7R36 and Melko in E3; Gola, Genete and Ajora in E4; Dima, Koye and Melko in E5; Pop9R24, Gerado and Koye in E6, and Pop7R36, Gola and Pop6R45 in E7

Generally, most of the varieties at Ambo exhibited the best performance with average grain yield of 1264.5kg/ha and Bedele zone exhibited the lowest average yield of 459.5kg/ha, the varieties were found to have lower average grain yield as compared to other testing environments (Table 5), while there were significant variations among varieties performance. The best performance of tef varieties at Ambo (highland) was due to the suitable weather conditions, which favors vegetative growth and increased grain yield. On the other hand, location Bedele, the performance of varieties was low as compared to other locations. This may be due to unfavorable environments where either edaphic or climatic conditions.

Table 5: Mean of grain yield (kg/ha) of tested varieties across different locations during the 2018 cropping season

Varieties	Locations						Mean	Rank
	Omonada	Melko	Bedele	Areka	Arjo	Ambo		
Quncho	1250^{a}	521^{e-g}	525^{ed}	1330^{ab}	608^{c-f}	1510^{a-d}	957.3	3
Guduru	330^{j}	1013^{a}	580^{c-e}	1108^{c-e}	430^{f-i}	1120^{e-h}	763.5	16
Kena	500^{i}	740^{cb}	390^{gf}	1040^{c-f}	425^{f-i}	882^{h}	662.8	21
Etsub	540^{i}	680^{b-d}	360^{gh}	1330^{ab}	540^{e-h}	1250^{c-g}	783.3	14
Kora	790^{fg}	790^{b}	208^{ji}	1220^{bc}	580^{d-f}	1260^{c-f}	808	10
Dagim	790^{fg}	713^{cb}	330^{gh}	1340^{ab}	660^{b-f}	1360^{a-e}	865.5	7
Abola	916^{c-e}	528^{e-g}	790^{a}	1330^{ab}	560^{e-g}	1520^{a-c}	940.7	4
Negus	1250^{a}	420^{g}	225^{ij}	1490^{a}	460^{f-i}	908^{hg}	792.2	11
Felagot	330^{j}	530^{e-g}	275^{hi}	1140^{c-e}	940^{a}	1005^{f-h}	703.3	20
Tesfa	660^{h}	730^{bc}	350^{gh}	1130^{c-e}	350^{hi}	1101^{e-h}	720.2	18
Heber -1	1000^{bc}	720^{bc}	580^{c-e}	1460^{a}	808^{ab}	1625^{ab}	1032.2	2
Wellenkomi	708^{hg}	707^{c-d}	300^{g-i}	1060^{c-f}	330^{i}	1170^{e-h}	712.5	19
Gibe	790^{fg}	480^{e-g}	280^{hi}	1080^{c-f}	416^{f-i}	1340^{b-f}	731	17
Asgori	1083^{b}	574^{d-f}	508^{e}	1120^{c-e}	850^{ab}	1250^{c-f}	897.5	5
Dukem	1250^{a}	715^{bc}	641^{bc}	1420^{a}	790^{a-c}	1690^{a}	1084.3	1
Koye	958^{cd}	658^{b-d}	675^{b}	1080^{c-f}	416^{f-i}	1250^{c-f}	839.5	9
Holetta Key	875^{d-f}	460^{fg}	340^{gh}	1030^{d-f}	480^{e-i}	1520^{a-d}	784.2	12
Tsedey	916^{c-e}	520^{e-g}	625^{b-d}	1101^{c-f}	760^{a-d}	1310^{b-f}	872	6
Boset	958^{cd}	678^{b-d}	625^{b-d}	1210^{b-d}	470^{e-i}	1170^{e-h}	851.8	8
Magna	1000^{bc}	604^{c-e}	560^{c-e}	930^{f}	370^{g-i}	1210^{e-h}	784	13
Enatite	830^{ef}	679^{b-d}	480^{ef}	968^{ef}	540^{e-h}	1104^{e-h}	765.5	15
Mean	844	641	459.4	1187.6	561.1	1264.5	**826.4**	
LSD at (5%)	113	138	107	188	192	343		
CV (%)	8.8	13	17.4	9.6	20.6	9.9		

Means followed by a common letter with in a column are not significantly different from each other at $P \leq 0.05$,LSD = Least Significant Difference,CV =Coefficient of Variation

4.2. ANOVA and mean performance for yield related traits at Individual Locations

ANOVA revealed highly significant difference ($p< 0.001$) among the twenty-one tef varieties in phenology traits such as days to heading, days to maturity and grain filling period at both Omonada and Ambo locations. At both locations (Areka and Arjo) there was highly significant difference ($p <0.001$) in both days to maturity and heading, but significant difference in days to heading ($P <0.05$).At Bedele, there were highly significant differences in days to heading and grain filling period, but non-significant difference in days to maturity ($P>0.05$).At Melko, all phenology traits did not show significant variations among the tested varieties (Appendix, Table 1).

Many studies have indicated the presence of substantial variation among tef genotypes for different traits of tef. Habte *et al.,* (2011) reported highly significant genotype variation for days to panicle emergence and maturity, plant height, culm and panicle length, shoot biomass, grain yield, harvest index, lodging index and thousand seed weight. Similarly, highly significant ($P <0.01$) genotype differences for days to panicle emergence, lodging percentage, thousands kernel weight, grain yield per plant and grain yield per hectare were also reported by Ayalneh *et al.*,(2012).

Variety Heber -1 followed by Quncho exhibited longest plant height with the respective values of 126cm, 104.3cm and 118cm at Areka, Melko and Omonada locations respectively. The mean plant height was ranged from 93.3 to 126.6cm at Areka, 88.2 to 118.1cm at Omonada, 73.6 to 104.3cm at Melko, 65.2 to 95.4cm at Arjo, 65.8 to 90.2cm at Ambo and 69.8 to 81.2cm at Bedele. Tseday (65.2 cm) at Arjo, Boset (65.8cm) at Ambo, Abola (69.8cm) at Bedele and Holetta Key (73.6 cm) at Melko showed the shortest plant height (Appendix, Table 3). However; these varietes were not situated as their rank position in other environments. Therefore, the presence of genotype by environment interaction was clearly evident on plant height the tested genotypes across environment. The longest plant height was recorded at Areka and Omonada with mean values of 107.6cm and 104.8cm while the shortest plant height was recorded at Bedele (75.5cm) and Ambo (77.3).

Panicle length ranged from 38 to 45.8cm at Omonada, 33.7 to 45.9cm at Melko, 33.2 to 40.7cm at Bedele, 32.2 to 45.8cm at Areka, 24.5 to 37.4cm at Arjo and 25.4 to 35.2cm at Ambo. Variety Guduru had longest panicle length at Omonada (45.8cm), Melko (45.9 cm) and Ambo (35.2

cm). The longest panicle length was recorded at Omonada (41.6 cm) and Melko (38.9cm), while the shortest panicle length was recorded at Arjo (30.4cm) and Ambo (30.5 cm). From twenty-one varieties, Guduru have the longest panicle length (40.3 cm), while Holetta Key recorded the shortest (32.8 cm) panicle length (Appendix Table 3).

Culm length ranged from 48.6 to 73cm at Omonada, 38.8 to 61.2cm at Melko, 34.2 to 42.7cm at Bedele,58 to 82.7cm at Areka,37.7 to 62.9cm at Arjo and 40 to 55.4cm at Ambo (Appendix Table 3). The varieties Heber-1 and Guduru had the longest culm lengh with mean values of 58.72 cm and 58.42, respectively, while the variety Holetta key showed the shortest culm length of 46. 8cm.The longest culm length was recorded at Areka (63.1cm) and shortest was at Bedele (38cm).

Number of tillers per plant (NTP) refers to the number of shoots that emerge at the base of the main stem excluding the main shoot. Number of fertile tillers per plant ranged from 2.2 to 6 at Omonada, 1.6 to 3.6 at Melko, 1.6 to 2.3 at Bedele, 4.3 to 6.2 at Areka, 3.2 to 4.8 at Arjo and 3.8 to 5.9 at Ambo (Appendix Table 3). The mean number of fertile tillers per plant was highest at Areka and Ambo. At Bedele, the varieties had low mean tiller number per plant.

Lodging index ranged from 47.3 to 75.3 at Omonada, 52 to 66.3 at Melko, 59.6 to 69.3 at Bedele,43.3 to 71.3 at Areka,56.6 to 71.3 at Arjo and 49.6 to 68.6 at Ambo (Appendix Table 4).The highest lodging index was recorded at Bedele,Omonada and Arjo while lowest at Areka.Straw yield ranged from 750 to 3667 kg/ha at Omonada,196 to 1217 kg/ha at Melko,155 to 1618 kg/ha at Bedele,2179 to 4542 kg/ha at Areka,920 to 3220 kg/ha at Arjo and 3040 to 5160 kg/ha at Ambo (Appendix table 5).The highest straw yield recorded at Ambo (4179.1kg/ha) and lowest at Melko (688kg/ha).

The varieties exhibited different biomass yield per hectare that ranged from 1080 to 4750 kg/ha at Omonada, 770 to 2230 kg/ha at Melko, 780 to 2408 kg/ha at Bedele, 3209 to 5650 kg/ha at Areka, 1500 to 4160kg/ha at Arjo, and 4250 to 6660 kg/ha at Ambo. The varieties Dukem and Negus exhibited the highest and lowest overall mean biomass yield with means of 3845kg/ha and 2563kg/ha, respectively (Appendix Table 5). The recently released varieties had relatively low average mean biomass yield compared to Quncho and Kora.Harvest index showed significant ($p < 0.05$) effects of varieties at almost all locations and non-significant at Melko (Appendix table 1). Harvest index exhibited difference among varieties having a range from

17.6 to 53.65% at Omonada, 38.6 to 74.5% at Melko, 17.6 to 80.1% at Bedele, 19.6 to 38% at Areka,16.44 to 38.67% at Arjo and 18.5 to 28.5% at Ambo. The varieties had different harvest indices at different locations with an overall mean of 30.3%. The varieties Tseday and Kora exhibited highest and lowest overall harvest index with 35.5% to 25.4%, respectively. Quncho (28.6%) (popular variety) and Kora (25.4%) had low harvest index compared to the recently released varieties such as Dagim (30.1%), Abola (33.2%), Negus (33.6%), Felagot (30%), Tesfa (28%) and Heber-1(33.8%).

Most of the tested varieties had harvest index below 35.5%. These low values could be explained by the low grain yields obtained by the improved varieties with an intermediate shoot biomass. The harvest index values obtained for all varieties varied from 25.4 to 35.5%. This is in a similar range of 5 to 39%, reported in other studies on tef (Kebebew *et al.*, 1999, 2001; Seyfu, 1993), but relatively low compared to other crops such as maize, rice and barley which have more than 50% (Yang and Zhang, 2010).

Thousand seed weight ranged from 0.2 to 0.6 g at Omonada, 0.33 to 0.7 g at Melko, 0.36 to 0.6 g at Bedele, 0.2 to 0.6 g at Areka, 0.2 to 0.4 g at Arjo and 0.2 to 0.5 g at Ambo (Appendix Table 5). The varieties exhibited different seed weight at different locations. At both Omonada and Melko, the variety Kora had high seed weight and weighed 0.6 and 0.7 g, respectively. At Bedele, the variety Kena, at Areka Guduru, at Arjo Etsub and at Ambo Dagim weighed 0.6, 0.55, 0.43 and 0.48 g, respectively. Varieties provided low mean of days to heading of 40.3 and 43.3 both at Ambo and Areka and took the longest period at Arjo with mean of 75 days. At location Bedele, varieties were maturity early and late matured at Arjo with the mean of 78.6 and 145 days respectively. Grain filling period is an important trait in tef that ultimately affects the overall grain yield by increasing grain yield. Grain filling period ranged from 34.3 to 44.6 at Omonada,34 to 43.3 at Melko,18.3 to 30 at Bedele,55.3 to 65.6 at Areka,68.6 to 73 at Arjo and 29.3 to 65.6 at Ambo.

The results of the current investigation were in agreement with the range values reported previously in other tef studies (Kebebew *et al.*, 2001b). Nevertheless, the range values for the three phenologic traits are relatively low as compared to those reported by Kebebew *et al.*,(2001b). This might be due to differences in the experimental plant materials and locations used in the different studies.

4.3. Combined ANOVA for Grain Yield and Yield Related Traits Across Locations

Combined analysis of variance was performed to determine the effects of environment, genotype, and GE interaction on grain yield of tef varieties regarding to result of Bartlett's (1947) homogeneity test. Combined analysis of variance for grain yield showed that main effects of genotypes and environments,as well as GEI were significant at $p<0.01$ (Table 6).The significance of the GEI effects suggests that there were significant difference in response of genotypes to environments and hence sensitivity and instability (Akcura *et al*.,2006).Genotypic rank differences over environments showed the existence of crossover GEIs (Crossa,1990),which showed the necessity to assess the response of the genotypes to environmental variation.

Grain yield is a quantitative trait, which its expression is the result of genotype, environmental factors and GE interaction. The large magnitude of GE interaction, cause to the more dissimilar genetic systems, which controlling the physiological processes conferring yield stability to different environments (Cooper *et al*., 2001).

All varieties showed inconsistent performances across the tested environments. For example, variety Quncho, ranked 1st in location Omonada, but it ranked 14th in location Melko for mean grain yield. In general, the ranking of genotypes changes from one environment to another and this is an indication for the existence of G x E interaction due to variation among the testing locations. Means across environments are adequate indicators of genotypic performance only in the absence of genotype by environment interaction. If G x E interaction is present, means across environments does not tell us how genotypes differ in relative performance over environments. Thus, such inconsistence yield ranking of genotypes from environment to environment revealed that the GEI effect was cross over type as described by Matus *et al.*,(2003). The total variation explained was 69.4 % for environment, 7.94% for genotype and 17.5% for GXE interaction (Table 6). The high percentage of the environment sum square is an indication that the major factor that influence yield performance of tef varieties was the environment. The relatively large percentage of the genotype x environment interaction sum square when compared to that of genotypes as a main effect is a very important consequence. The G x E interaction is highly significant ($p<0.01$) accounting for 17.5% of the sum of squares

implying the need for investigating the nature of differential response of the genotypes to environments.

In general, from the combined ANOVA (Table 6), superiority of genotypes across environments cannot be identified by considering their mean yield and yield related traits performance because G x E interaction is highly significant. Because of the interactions between genotypes and environments, yield of genotypes tested across vary and it is a problem for breeders to identify varieties that consistently gave high yields in locations with diverse environmental conditions. Pham and Kang (1988) indicated that since G x E interactions minimize the usefulness of genotypes, it was thus imperative that yield levels, adaptation and stability are taken into account in multi-location trials.

Crossa (1990), elaborated that only qualitative or crossover interactions are relevant in agriculture, and appropriate statistical analyses were required for quantifying them. Furthermore, the traditional analysis of variance determines the values of each variance source and the significance of the contribution of each component, but it does not partition the interaction into several components and thus other types of analyses should be performed. Hence, such multi-location trial data along with a highly significant G x E interaction requires measures of stability analysis techniques that will help to get more information on the G x E interaction as well as to assess the adaptation regions of the genotypes according to their favorable interaction. However, the findings of these trials were in accordance with other workers of Tirngo (2012) in tef

The main effects of environment, genotype and genotype x environment interaction were highly significant ($P \leq 0.01$) for plant height, panicle length, culm length, biomass yield, thousand seed weigth, straw yield, lodging index, fertile tillers, days to heading, grain filling period and days to maturity (Table 6).

Table 6: Combined Analysis of Variance for all 13 yield and yield related traits across locations

Traits	Source of variation						
	Environment (5)	Rep (Env) (12)	Genotype (20)	GXE(100)	Error (240)	Mean	CV%
BY	162184188.3**	611904.8	2096345.2**	1064040.1**	88805.2	3044.646	9.78
SY	105297213.3**	514795.7	1238932.4**	780677**	101360	2220.438	14.3
PH	12493.6*	144.4	606.8**	85**	23.1	89	5.4
PL	1474.9**	45.5	96.3**	19.5**	8.6	36.4	8.1
CL	7688.5**	30	324.3**	58.6**	13.1	52.5	6.9
DH	10070.9**	62.51	45.5**	17.5**	9.11	52.08	5.8
DM	39480.6**	41.3	17.2**	28.5**	6.14	97.7	2.53
FT	106.4**	0.37	0.56**	0.52*	0.1	3.3	9.2
GFP	17854.9**	19.3	65.1*	31.9**	9.4	45.6	6.72
LI	461.36**	33.12	258.6**	52.3**	16.11	60.8	6.6
TSW	0.59**	0.0047	0.02**	0.021**	0.0032	0.41	13.55
HI	6916.44**	110.22	122.15**	126.48**	42.02	30.30	13.97
GY	7382685.8**	17357.41	211165.97**	93774.9**	10130.3	826.4	12.2

*,** significant ($p < 0.05$) and highly significant ($p < 0.01$) respectively,ns = non significant ,CV=Coefficient of Variation BY=Biomass Yield, SY= Straw Yield, PH =Plant Height,PL =Panicle Length,CL=Culm Length,DH =Days to Heading, DM=Days to Maturity,FT-Fertile Tillers,GFP=Grain filling period, LI=Lodging Index, TSW=Thousand Seed Weight,HI =Harvest Index and,GY =Grain yield,GxEI=Genotype by Environment Interactio

The environment contributed more than 88% to total treatment sum square in phenology (days to heading, days to maturity and grain filling period and Similar finding was reported by Gadissa (2018) in bread wheat),environment contribution to total variation of 80 to 86% in biomass yield, straw yield and fertile tillers,65 to 72% in plant height ,grain yield,culm length and harvest index.These traits were determined mainly by the environment.Genotype contributed less than 10% to total treatment sum square in all traits except in lodging index (30.5%),panicle length (13.9%),plant height (13.4%) and culm length (11.9%).Genotype contributed less than 10% to total treatment sum square in all traits except in culm length (11.9%),plant height (13.42%),panicle length (13.9%) and lodging index (30.46%)(Table 7).

Genotype by environment interaction contributed less than 10% to total treatment sum square of six traits involving straw yield (8.61%),plant height (9.4%),days to heading (3.13%),days to maturity (1.4%),fertile tillers (8.4%) and grain filling period (3.32%).It contributed 10 to 20% in grain yield (17.6%),panicle length (14.04% and harvest index (18.4%).30 to 40% in thousand seed weight (33.3%) and lodging index (31.2%).Both G and GxE interaction had moderate contribution to the determination of different traits, although the environment contributed more than 50% to total treatment sum square of these traits.Genotype by environment was more important in the determination of agronomic traits; and its contribution was always higher than the contribution of the genotype.Similar report was made by Tiruneh (2001) and Tiringo (2012) in tef who reported significant G x E interaction effect and has recommended the need for further G x E interaction studies in the various tef-growing regions of the country for a better understanding of its magnitude and nature.

Table 7: Percent contribution of each variance component to total sum of squares for different agronomic traits of tef varieties

Traits	Genotype	Environment	G x E interaction
Biomass Yield	3.92	82.63	10.9
Straw Yield	3.01	85.95	8.61
Plant Height	13.42	69.12	9.4
Panicle Length	13.9	53.23	14
Culm Length	11.9	70.8	10.8
Days to Heading	1.62	89.9	3.1
Days to Maturity	0.17	97.4	1.4
Fertile Tillers	1.82	85.5	8.4
Grain Filling Period	1.35	92.7	3.3
Lodging Index	30.46	13.58	31.2
Thousand Seed Weight	6.35	46.03	33.3
Harvest Index	3.3	68.63	18.4
Grain Yield	7.94	69.4	17.6

4.4. Stability Analysis for Grain Yield

There were numerous methods to evaluate yield stability. In this study, the stability parameters of Wricke's ecovalence, cultivar superiority measure, stability variance, Eberhart and Russel joint regressions analysis, AMMI stability value, yield stability index, AMMI model and GGE biplot was used to evaluate the yield stability of 21 tef varieties tested across six environments

4.4.1 Wricke's Ecovalence Analysis (Wi)

Wricke (1962) defined the concept of eco-valence, to describe the stability of a genotype, as the contribution of genotype stability of the i^{th} genotype is its interaction with environments, squared and summed across environments to the GEI sum of squares. The lower the Wi value of a genotype, the smaller is its fluctuations from the predictable response in different environments so that the genotype with the least ecovalence is considered to be ideal from the point of view of yield stability.

The five most stable tef varieties according to the eco-valence method of Wricke's (1962) were Gibe, Wellenkomi, Dagim, Heber-1 and Tesfa.The varieties ranked for mean yield 17^{th},19^{th},7^{th},2^{nd} and 18^{th} respectively (Table 9). This observation means that these varieties showed lower differential responses to the changes in the growing environment. Except the varieties, Dagim and Heber-1, the top ranked varieties in terms of this stability value had overall mean yields below the grand mean. The varieties Heber-1 and Kora, which ranked 2^{nd} and 9^{th} in grain yield also ranked 4^{th} and 7^{th} in Wricke's ecovalence values and they were the only varieties that were found to be relatively promising as high yielder and stable.

The most interactive and unstable varieties based on the ecovalence method were Negus (V21), Guduru (V20), Felagot (V19), Kena (V18) and Quncho (V17). These varieties were ranked for mean yield as 10^{th}, 16^{th}, 20^{th}, 21^{th} and 3^{rd} respectively (Table 8). Desalegn (2019) identified three maize hybrids using wrieck ecovalence stability parameter.

Table 8: Wricke's Ecovalence (Wi) value for 21 tef varieties at tested six environments

Variety Code	Common Names	Wi	Rank	Grain yield (kg/ha)	Rank
V1	Quncho	162990	17	957.3	3
V2	Guduru	443429	20	763.5	16
V3	Kena	164396	18	662.8	21
V4	Etsub	112032	12	783.3	14
V5	Kora	80724	7	808	10
V6	Dagim	50982	3	865.5	7
V7	Abola	155808	16	940.7	4
V8	Negus	483095	21	792.2	11
V9	Felagot	428392	19	703.3	20
V10	Tesfa	58377	5	720.2	18
V11	Heber -1	52263	4	1032.2	2
V12	Wellenkomi	46639	2	712.5	19
V13	Gibe	41399	1	731	17
V14	Asgori	118900	13	897.5	5
V15	Dukem	88266	8	1084.3	1
V16	Koye	103723	11	839.5	9
V17	Holetta Key	130044	14	784.2	12
V18	Tsedey	91931	9	872	6
V19	Boset	99695	10	851.8	8
V20	Magna	136323	15	784	13
V21	Enatite	60909	6	765.5	15

4.4.2. Lin and Binns Cultivar Superiority Measure (Pi)

According to Lin and Binns (1988) for cultivar superiority measure (Pi) analysis, the genotype with low or small Pi value is considered to be the more stable. Accordingly, the high yielding varieties, namely Dukem, Quncho and Heber-1 showed low cultivar superiority value and highest yield performance indicating stability of those varieties. On the other hand, the varieties Enatite, Kena and Guduru which showed high Pi value and lowest mean yield were considered to be unstable (Table 9). Similar results were reported by other researchers about the ability of Pi to classify genotypes based on their stability Desalegn *et al.,* 2012 in bread wheat; Wosene *et al*.,2015 in barley; Abate, 2011 in Durum wheat

Table 9: Cultivar Superiority Index (Pi) 21 tef varieties tested across six environments

Variety Code	Common Names	Pi	Rank	Grain yield (Kg/ha)	Rank
V1	Quncho	40180	3	957.3	3
V2	Guduru	134620	19	763.5	16
V3	Kena	160102	20	662.8	21
V4	Etsub	97594	13	783.3	14
V5	Kora	81456	9	808	10
V6	Dagim	59542	7	865.5	7
V7	Abola	44234	4	940.7	4
V8	Negus	125344	18	792.2	11
V9	Felagot	161378	21	703.3	20
V10	Tesfa	119684	16	720.2	18
V11	Heber -1	17903	2	1032.2	2
V12	Wellenkomi	121529	17	712.5	19
V13	Gibe	109126	15	731	17
V14	Asgori	52955	5	897.5	5
V15	Dukem	11564	1	1084.3	1
V16	Koye	72140	8	839.5	9
V17	Holetta Key	91333	10	784.2	12
V18	Tsedey	59271	6	872	6
V19	Boset	98156	14	851.8	8
V20	Magna	95904	11	784	13
V21	Enatite	97002	21	765.5	15

4.4.3. Shukla's Stability Variance (σ^2)

Shukla (1972) developed a modified version of the ecovalence in order to give unbiased estimate of the genotype by enviromnet interaction variance for every genotype using the stability variance (σ^2**).** A genotype is called stable if its stability variance is equal to the environmental variance. Therefore, a genotype is considered as stable genotype when its contribution to the total genotype by environment interaction sum of squares is small as compared to the contribution of other genotypes in a given test. A relatively large value of σ^2 will thus indicate greater instability of genotype i. According to this stability parameter the most stable varieties were Dukem, Dagim and Heber-1 (Table 10). This means that these varieties showed lower differential responses to the changes in the growing environment and contributed minimally to the sum of squares of the interaction effect regardless of their low yielding ability.

This result suggests that selection for genotypic performance stability based on (σ^2) parameters favours below average yielding over high yielding tef varieties. Similarly, the most unstable varieties were Kena, Wellenkomi, Felagot and Tesfa (Table 10).Gadissa (2018) reported the breadwheat genotypes ETBW8078 (#3), ETBW8459 (#8), ETBW8311 (#5), ETBW8427 (#7) and ETBW8084 (#4) were stable according to Shukla's stability variance using the stability parameter.

Table 10: Mean grain yield (kg/ha) and Shukla's stability variance (σ^2) for 21 tef varieties tested across six environments

Variety Code	Common Names	Mean yield	Rank	σ^2	Rank
V1	Quncho	957.3	3	34392.4	17
V2	Guduru	763.5	16	96384.2	20
V3	Kena	662.8	21	34703.2	18
V4	Etsub	783.3	14	23127.9	12
V5	Kora	808	10	16207.3	7
V6	Dagim	865.5	7	9632.67	3
V7	Abola	940.7	4	32804.8	16
V8	Negus	792.2	11	105153	21
V9	Felagot	703.3	20	93060.1	19
V10	Tesfa	720.2	18	11267.3	5
V11	Heber -1	1032.2	2	9915.82	4
V12	Wellenkomi	712.5	19	8672.69	2
V13	Gibe	731	17	7514.29	1
V14	Asgori	897.5	5	24646.2	13
V15	Dukem	1084.3	1	17874.5	8
V16	Koye	839.5	9	21291.3	11
V17	Holetta Key	784.2	12	27109.6	14
V18	Tsedey	872	6	18684.5	9
V19	Boset	851.8	8	20400.8	10
V20	Magna	784	13	28497.6	15
V21	Enatite	765.5	15	11827	6

4.4.4. Eberhart and Russell's Joint Regression Analysis

The Eberhart & Russell (1966) procedure involves the use of joint linear regression where the yield of each genotype is regressed on the environmental mean yield. The sums of squares due to environments and genotype x environment interaction are partitioned into environments

(linear), genotype x environment (linear) and deviations from the regression model. The genotype's performance was generally expressed in terms of three parameters, mean yield (*x*), regression coefficient (*bi*) and the deviation (S^2di) from the regression. According to this model a stable genotype should have a high mean yield, b=1.0 and S^2di =0. It is however specifically the deviation from the regression (S^2di) which is used as a measure of a genotype's stability across environments.According to the estimated coefficient of regression values,the tef varieties Kena,Guduru,Enatite, Felagot and Koye had the value near to unity, and thus considered as stable varieties, while the varieties Holetta Key,Quncho,Dukem,Heber-1 and Gibe had estimated regression coefficient values greater than unity and hence, they are considered as unstable for grain yield (Table 11).This result is in line with the findings of Desalegn (2019) in maize.

Table 11: Eberhart and Russell (1966) stability value of regression coefficient (bi) and deviation from regression (S^2di) of mean grain yield (Kg/ha) of tef varieties

Variety Code	Common Names	Mean yield	Rank	bi	Rank	S^2di	Rank
V1	Quncho	957.3	3	1.2544	20	26532.6	17
V2	Guduru	763.5	16	0.6673	2	89965.8	19
V3	Kena	662.8	21	0.6667	1	20156.8	14
V4	Etsub	783.3	14	1.1136	11	21314.2	15
V5	Kora	808	10	1.1171	13	13370.3	9
V6	Dagim	865.5	7	1.1731	15	3575.17	4
V7	Abola	940.7	4	1.1158	12	32184.5	18
V8	Negus	792.2	11	1.186	16	110930	21
V9	Felagot	703.3	20	0.7272	4	91474.3	20
V10	Tesfa	720.2	18	0.955	9	9478.49	6
V11	Heber -1	1032.2	2	1.2216	18	1114.61	3
V12	Wellenkomi	712.5	19	1.017	10	6795.61	5
V13	Gibe	731	17	1.208	17	-753.61	2
V14	Asgori	897.5	5	0.8063	7	19459.7	13
V15	Dukem	1084.3	1	1.2264	19	9804.08	7
V16	Koye	839.5	9	0.8033	5	15494.2	10
V17	Holetta Key	784.2	12	1.2556	21	18204.5	12
V18	Tsedey	872	6	0.8045	6	12614.9	8
V19	Boset	851.8	8	1.1662	14	16092.6	11
V20	Magna	784	13	0.811	8	24076.6	16
V21	Enatite	765.5	15	0.7038	3	-2331.4	1

4.4.5 The AMMI Stability Value (ASV)

ASV is the distance from the vertex of IPCA 1 and IPCA 2 to the genotypes or environments that fall in the AMMI2 biplot graph. This value is finally used to measure the grain yield stability of the genotypes and cluster the genotypes and environments into different groups (Purchase, 2000). Genotypes or environments which are very close to the vertex are more stable than those genotypes or environments away from the vertex. In other words, genotypes or environments that have less value of ASV score tend to be more stable than those genotypes or environments having high ASV scores.

The difference in stability measurement of the two principal components can be compensated by proportional difference between the IPCAs (1:2) then determined by Pythagoras theorem in effect of AMMI stability value. Purchase, (1997) noted that AMMI stability value (ASV) does not offer quantitative stability measure, but it rather quantities and ranks genotypes according to their yield stability.Varities with lower ASV values are considered more stable than varieties with higher ASV.Based on ASV, therefore, Quncho (V1) ranked first followed by Heber-1 (V11), Tseday (V18) ,Wellenkomi (V12) and Enatite (V21) which have high stability, whereas Guduru (V2),Negus (V8),Felagot (V9),Kena (V3) and Magna (V20) were observed to be the most unstable genotypes (Table 12).Similar results were reported by Brikti (2018) in tef and Desalegn (2019) in maize.

Table 12: Mean of tef grain yield (kg/ha), AMMI Stability Value (ASV), and interaction principal component axis (IPCA 1 and IPCA 2) scores of the 21 tef varieties tested across six environments.

Variety Code	Common Names	Mean yield (kg/ha)	Rank	IPCA1	IPCA2	ASV	Rank
V1	Quncho	957.3	3	11.72017	0.91431	0.914	1
V2	Guduru	763.5	16	-18.41441	6.19024	23.747	21
V3	Kena	662.8	21	-10.30785	-0.4103	12.840	18
V4	Etsub	783.3	14	-7.15025	-3.7107	9.644	15
V5	Kora	808	10	-2.93699	-5.68153	6.756	10
V6	Dagim	865.5	7	-2.00917	-5.35971	5.915	7
V7	Abola	940.7	4	3.39740	8.25994	9.280	14
V8	Negus	792.2	11	12.27249	-14.47816	21.049	20
V9	Felagot	703.3	20	-12.03633	-11.37004	18.811	19
V10	Tesfa	720.2	18	-4.79134	0.65248	6.001	8
V11	Heber -1	1032.2	2	1.89577	-1.43696	2.763	2
V12	Wellenkomi	712.5	19	-2.71755	2.13736	4.002	4
V13	Gibe	731	17	3.39269	1.81092	4.596	6
V14	Asgori	897.5	5	4.64516	-2.29621	6.222	9
V15	Dukem	1084.3	1	7.73895	1.34574	9.729	16
V16	Koye	839.5	9	1.38064	8.91280	9.077	13
V17	Holetta Key	784.2	12	5.99426	5.09714	9.037	12
V18	Tsedey	872.0	6	2.06209	2.88825	3.864	3
V19	Boset	851.8	8	3.20633	-6.63713	7.745	11
V20	Magna	784.0	13	4.36553	9.64042	11.067	17
V21	Enatite	765.5	15	-1.70757	3.53127	4.122	5

4.4.6. Yield Stability Index (YSI)

Stability is not the only parameter for selection, because the most stable genotypes would not necessarily give the best yield performance (Mohammadi *et al*,. 2010), hence there is a need for approaches that incorporate both mean yield and stability in a single index, that is why various authors introduced different selection criteria for simultaneous selection of yield and stability: rank-sum, modified rank-sum and the statistics yield stability (Farshadfar, 2008). In this regard, ASV takes into account both IPCA1 and IPCA2 and justifies most of the variation in the GEI.

The least YSI is considered as the most stable with high yield mean. It was applied to identify high yielding stable genotypes in cereal crops like maize (Fan *et al*., 2007) and durum wheat (Mohammadi *et al*., 2010). By using these measures, suitable wheat genotype can be identified for varying existing environmental conditions. Based on YSI, variety Quncho, Heber-1 and Tseday were the most stable varieties and these varieties exhibited mean grain yield above grand mean. Conversely, the varieties Kena, Felagota and Guduru were the most unstable ones or adapted to specific environments (Table 13). Yield Stability index was efficient in identifying high yielder and stable genotypes. Gadissa (2018) identified five bread wheat genotypes according to the yield stability index parameter.

Table 13: Mean grain yield (kg/ha) and yield stability index (YSI) of the 21 tef varieties tested across six environments

Varieties code	Varieties	Mean yield	Rank	Yield Stability Index	Rank
V1	Quncho	957.3	3	4	1
V2	Guduru	763.5	16	37	19
V3	Kena	662.8	21	39	20
V4	Etsub	783.3	14	29	16
V5	Kora	808	10	20	9
V6	Dagim	865.5	7	14	4
V7	Abola	940.7	4	18	7
V8	Negus	792.2	11	31	18
V9	Felagot	703.3	20	39	20
V10	Tesfa	720.2	18	26	15
V11	Heber -1	1032.2	2	4	1
V12	Wellenkomi	712.5	19	23	12
V13	Gibe	731	17	23	12
V14	Asgori	897.5	5	14	4
V15	Dukem	1084.3	1	17	6
V16	Koye	839.5	9	22	11
V17	Holetta Key	784.2	12	24	14
V18	Tsedey	872.0	6	9	3
V19	Boset	851.8	8	19	8
V20	Magna	784.0	13	30	17
V21	Enatite	765.5	15	20	9

4.4.7. Additive Main Effects and Multiplicative Interaction (AMMI) Model

AMMI analysis of 21 tef varieties tested across the six environments showed that environments (E) and genotypes (G) and genotype × environment interaction (GEI) were highly significant ($P \leq 0.01$) (Table 14), indicating the presence of genetic variation and possible selection of stable genotypes. Asrat *et al*.,(2009) stated that the significance exhibited by GEI indicates that each of the variety interacted differently at each location. The Gollob's test (1968) discovered that the first five IPCAs were significant ($P<0.01$), indicating that the total information contained in GEI can be explained using these IPCAs.The IPCA are ordered according to decreasing importance.

The AMMI analysis showed that 64.7% of the total sum of squares attributed due to environmental fluctuations exhibiting that the environments were diverse, with large differences among environmental means causing most of the variation in grain yield. Tiruneh (2000) reported the largest proportion of the total sum of squares (SS) was due to environments (70%) followed by the G x E source of variance (22%) for grain yield. The genotype source contributed the lowest proportion (7%) to the total treatment SS.In the present study the total sum of squares of the model attributed due to genotypes and genotype by environment interaction was 8.02 and 17.2%, respectively. Only a small portion of the total sum of squares was attributed to genotypic effects.

The magnitude of GEI was two times greater than that of genotypes, indicating that substantial difference in genotypic response across environments. The AMMI analysis of variance of the sum of squares due to GEI was further partitioned into principal component analysis (Table 12). The first principal component (IPCA1) captured 42.8% of the interaction sum of squares, the second principal component (IPCA2) explained 24.54% of the interaction sum of square, the third principal component, the third principal component (IPCA3) explained 17.6%,the fourth principal component (IPCA4) and cumulatively the first two principal components explained 63.4%. All the interaction principal components of mean square were highly significant ($P \leq 0.01$).

This suggested that the AMMI model with first and second multiplicative terms was adequate for cross-validation of the yield variation explained by GEI in the present data. Therefore, the

first two interaction principal components were highly important in explaining the interaction sum of squares. The result of the current study was in agreement with Farshadfar and Mojgan (2014). The Authors recommended that the first two interaction principal components can explained the genotype by environment interaction in multi-location trials, whereas the remaining interaction principal component does not help in the accurate prediction and is not interpretable. The most accurate model for AMMI can be predicted using the first two IPCAs. Agyeman *et al.*,(2015) illustrated that most of the interaction occurs in the first few axes. Tiruneh (2000) reported that the three IPCA axes together explained 84% of the total interaction variance. The first IPCA alone captured 52% of the total G x E variance in only 21% of the interaction degrees of freedom. On the contrary, Farshadfar *et al*.,(2008), recommended an AMMI model with the first four IPCAs predicates the genotype by environment interaction

Table 14: Results of AMMI analysis of variance for grain yield of 21 tef varieties tested across six locations.

Source of Variation	Df	SS	MS	GxEI Explained (%)	Cumulative Variance explained (%)	Precent of total variation Explained (%)
Total	377	54236321	143863			
Environments	5	36573950	7314790***			67.4
Reps with Env.	12	506073	42173			
Genotype	20	4353373	217669***			8.02
Gen. x Env.	100	9330951	93310***			17.2
IPCA1	24	4000566	166690**	42.8	42.8	
IPCA2	22	1928952	87680**	20.6	63.4	
IPCA3	20	1648343	82417**	17.66	81.06	
IPCA4	18	1168163	64898**	12.5	93.56	
IPCA5	16	584927	36558*	6.26	99.82	
Error	240	3471973	14467			

** =Significant at 0.01. ns= non Significant, Reps=Replication; Loc=Location; gen.=Genotype; df=degree freedom;SS=Sums Square,MS=Mean Square GXEI=Genotype by Environment Interaction,IPCA=Interaction Principal Component Analysis

The proportion of variance explained by the first two IPCA axis was greater than 60% in all traits. Eigen values of the first two axes were greater than the mean of all Eigen values. Hence, much of the variability was accounted by the first two IPCA components. The environment revealed a high variability for both the main and interaction effects (Table 14). Therefore, it was necessary to classify the environments to identify and recommend target genotypes according to adaptation. Romogosa and Fox (1993), in triticale and Eberhart and Russell (1966) in maize, Tiruneh, (2000) in tef, have also reported grouping of environment and genotypes based on the G x E patterns.

4.4.7.1 AMMI 1 Biplot Analysis for Yield

The AMMI1 model biplot is presented in Figure 1. AMMI bi-plot analysis represents graphical representation (bi-plot) to summarize information on main and interaction effect of both varietes and environment simultaneously. The IPC1 is represented by y-axis, whereas genotype and environment mean were represented in x-axis (Figure 1). Genotypes or location placed in the right side of the original (above grand mean) were high yielding genotypes or locations where as genotypes or locations are placed in the left side (below grand mean) were low yielding. The IPCA score of genotypes in the AMMI analysis were indications of stability of genotypes over the environments (Gauch and Zobel, 1997). The greater the IPCA score (-ve or +ve), the more specifically adapted a genotype was to a specific environment. The closer the IPCA score to zero, the more stable the genotypes over the tested locations.

The varieties Dagim (T6), Koye (T16), Tseday (T18),Kora (T5) and Heber-1 (T11) with high yield and variety Enatite (T21) and Wellenkomi (T12) with low yield exhibited score near to zero. Therefore, these varieties were stable varieties or widely adapted varieties across diverse locations and contribute less to the G x E interaction. Simiraly Desalegn (2019) in maize reported stable genotypes were adaptive to wider areas and give consistency mean yield across the test locations. The varieties T1, T7, T2, T3, T6, T9 and T16 were found nearly closer to the origin and the most stable with little responsive to the GEI.Varieties far from the origin are sensitive to environmental changes.

The varieties Kena (T3) and Felagot (T9) were with mean yields less than the overall mean and with negative highest IPC1 score, whereas the variety Guduru (T2) was with mean yield less

than average mean and with negative highest IPC 1 score. The variety Dukem (T15) and Quncho (T1) with mean yield more than average mean and with positive IPCA 1 score tended to contribute less to GE interaction and accordingly can be regarded as the most stable varieties. Similar to the varieties, the locations Bedele (E3),Arjo (E5) and Melko (E2) were low yielding locations during the experimental year as well as unfavorable environments and contributed highly to G x E interaction. The location Omonada and Areka were high yielding environments and contribute to high G x E interaction since these locations had high principal component 1 axis, these were unstable locations. Ambo was the high yielding location and relatively contributes to low G x E interaction and located on the bi plot graph nearest to the origin relative to the other locations. Therefore, the location was considered as favorable location relative to the others. Similar result was reported by Adugna and Labuschagne, (2002).

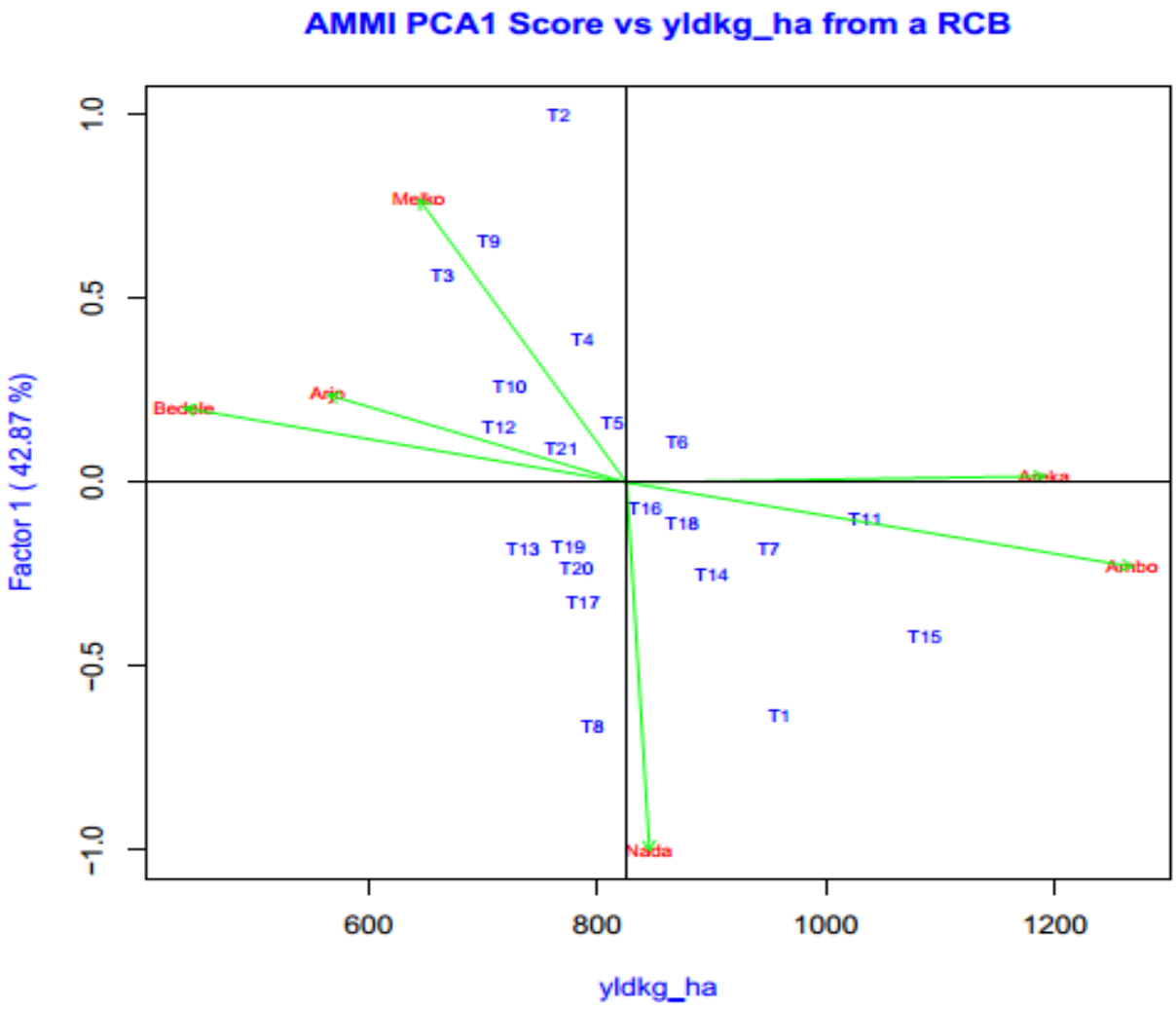

Figure 1: AMMI 1 Biplot of IPCA 1 against grain yield of 21 tef varieties across six enviroments

T1=Quncho,T2=Guduru,T3=Kena,T4=Etsub,T5=Kora,T6=Dagim,T7=Abola T8=Negus,T9=Felagot,T10=Tesfa,T11=Heber1,T12=Wellenkomi,T13=Gibe,T14=Asgori,T15=Dukem,T16=Koye,T17=Holetta Key,T18=Tseday,T19=Boset,T20=Magna and T21=Enatite

The variety Dukem was identified as specifically adapted to the environments Omonada and Ambo and these two environments were considered as the wide range suitable environments for these varieties, whereas variety Negus (T8) and Quncho (T1) had similar performance and the best at Omonada (E1) for yield. The varieties Quncho and Boset showed positive IPCA1 score, while variety Enatite and Wellenkomi showed negative IPCA1 score with below average yield and IPCA1 score near zero. Other varieties showed below average yield and negative

IPCA1 score. On the other hand, the environments E1 had large positive IPCA1 score with high mean value, while E6 showed small positive IPCA1 score near zero with high mean value. In the AMMI 1 biplot, the varieties that group together (i.e. T1, T15, T14, T7, T11, T18 and T16) have similar adaptation, while environments, which group together influences the varieties in the same way (Kempton R A, 1984).

Varieties and environments on the same parallel line, relative or ordinate have similar yields and a variety or environment on the right side of the midpoint of this axis has higher yields than those of left hand side. Although, the varietes T16, T18, T7 and T14 were considered as the favorable environments for Omonada and Ambo. Similar outcomes have reported by Das *et al*.,(2010).The variety T1 (Quncho) showed positive IPCA1 score and varieties T12 and T21 were showed negative IPCA1 score with below average yield and IPCA1 score near zero indicating that these varieties were stable and less influenced by the environments (Yau S K, 1995).Other varieties showed below average yield and negative IPCA1 score.

On the other hand, the environment Omonada have large positive IPCA1 score with high mean value and Ambo showed small positive IPCA1 score near zero with high mean value and hence, had small interaction effects indicating that all the varieties performed well in these locations. The environment, Melko has large negative IPCA1 scores, which interact positively with varieties having negative IPCA1 scores and negatively with the varieties that having positive IPCA1 scores. Similar findings and interpretation have been made by Adugna *et al*.,(2007). Finally, the AMMI 1 biplot statistical model has been used to diagnose the G × E interaction pattern of grain yield of tef. The varieties T16, T18, T17 and T14 were hardly affected by the G × E interaction and thus will perform well across a wide range of environments. Environmnets, such as Omonada and Ambo could be regarded as a good selection site for tef improvement due to stable yields.

4.4.7.2 AMMI 2 Biplot for Yield

The AMMI analysis for the first interaction principal component (IPCA1) captured 42.8% and the second interaction principal component (IPCA2) explained 20.6%, the two interaction principal components cumulatively captured 63.4% of the sum of squares (Table 9). From previous yield trial of genotype by environment interaction in tef, Brikti (2018) reported that,

the AMMI analysis for the first interaction principal component (IPCA1) captured 38.6% and the second interaction principal component (IPCA2) explained 24.54%, the two interaction principal components cumulatively captured 63.14% of the sum of squares. When IPCA1 was plotted against IPCA2, Purchase (1997) pointed out that the closer the genotypes score to the center of the biplot the more stable they are and the reverse.

Hence, varieties T13, T21, T18, T11, T14 and T12 were plotted relatively close to the origin in the AMMI 2 biplot indicating their related yielding potential to all environments. Among these stable varieties, only varieties T11, T18 and T14 were exhibited grain yield higher than grand mean. Therefore, the varieties were considered as a high yielding and widely adapted varieties indicating their minimum contribution to the total genotype by environment variance. On the contrary, tef varieties namely T2,T8,T1 and T9 were scattered away from the origin in the biplot indicating that the varieties were more sensitive (unstable) to environmental interaction (Figure 2).

The AMMI 2 bi-plot showed that location Omonada, Melko and Bedele were far from the origin indicating that these environments contributed higher amount of variation to the total genotype by environment interaction. However, due to their longest distance between its marker and the origin (high IPCA score), the varieties variability at this environment may not accurately reflect the average varieties performance across environments. On the other hand, location Ambo, Arjo and Areka located close to the origin indicating their lower contribution to the genotype by environment interaction variance. This indicates that they are stable environment and the least discriminating environment (Figure 2).

Varieties that are close to each other tend to have similar performance and those that are close to environment indicates their better adaptation to that particular environment. Hence, varieites T7, T17 and T20 were relatively adapted to environment Ambo.Varieties T6 and T5 were relatively adapted to environment Arjo. The varieties T3, T1 and T19 were specifically adapted to location Melko, Omonada and Areka respectively. Similar results were reported by Kempton R A, (1984); Brikti (2018).

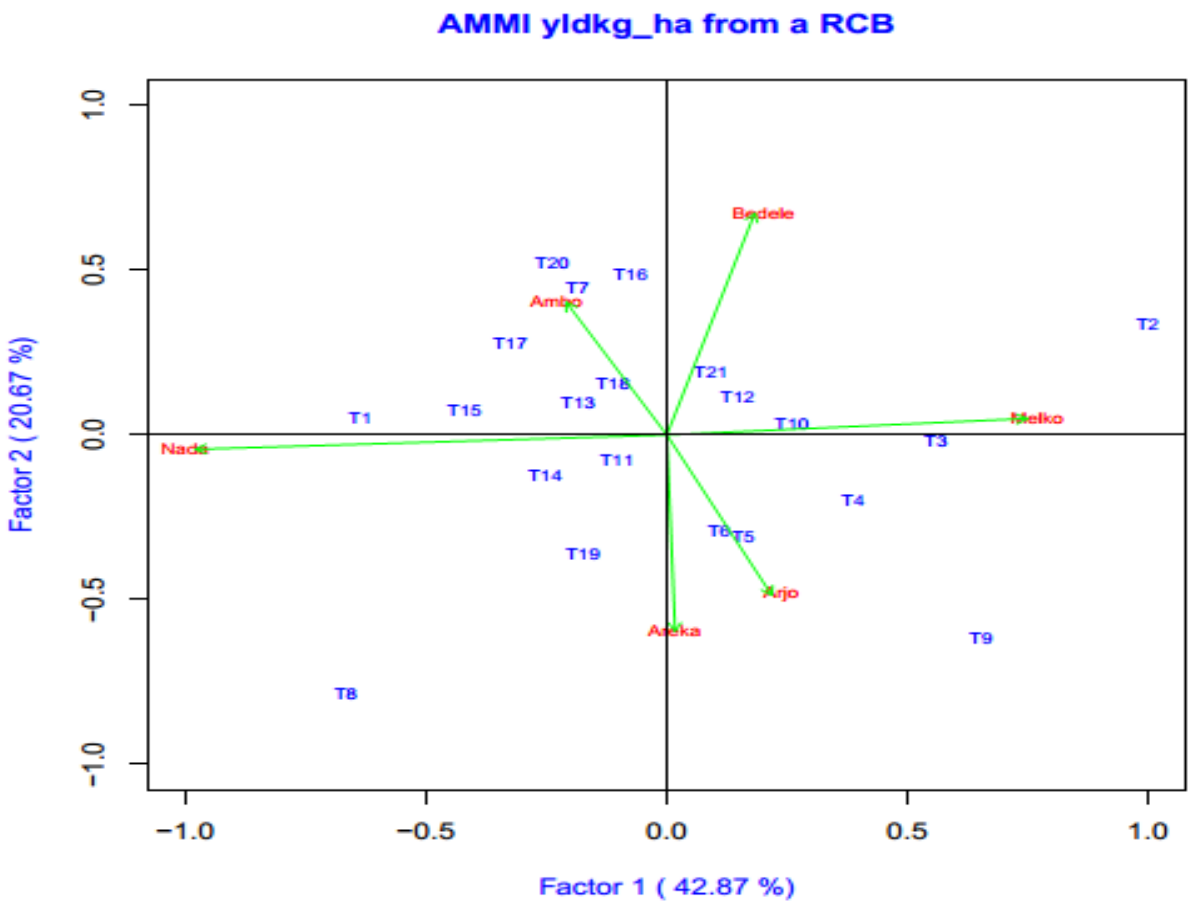

Figure 2: AMMI2 bi plot for grain yield of 21 tef varieties showing the plotting of IPCA1 and IPCA2 of varieties

T1=Quncho,T2=Guduru,T3=Kena,T4=Etsub,T5=Kora,T6=Dagim,T7=AbolaT8=Negus,T9=Felagot,T10=Tesfa,T11=Heber1,T12=Wellenkomi,T13=Gibe,T14=Asgori,T15=Dukem,T16=Koye,T17=Holetta Key,T18=Tseday,T19=Boset,T20=Magna and T21=Enatite

4.4.7.3 AMMI Selections for the highest five yielding varieties across six locations

The AMMI model selected five best varieties in each environment and illustrated in Table 15. Accordingly, variety Dukem was the best adapted at five environments among six environments and it was ranked first in E6 (Ambo), third at Omonada,Bedele and Areka and fourth at Arjo.The variety Heber-1 ranked second at both Areka and Ambo,third at Arjo and fifth at Omonada and Melko.The variety Quncho (popular variety) also adapted at three test locations and ranked first at Omonada and fifth at both Areka and Ambo.Generally, variety T15 (Dukem) and T11 (Heber-1) were the only two varieties that were best adapted with high mean yield

across five environments. Therefore, these varieities were recommended for each testing environments and other areas which have similar agro-ecology with this testing environments.

Table 15: The top performing tef varieties across six tested environments in 2018 main cropping season

Environment	Number	Mean	IPCA1 score	Rank				
				1	2	3	4	5
Ambo	1	1267.8	5.88452	T15	T11	T7	T17	T1
Areka	2	1191	-0.44803	T8	T11	T15	T6	T1
Bedele	3	438.5	-5.21627	T7	T16	T15	T18	T19
Arjo	4	564.3	-6.13698	T9	T14	T11	T15	T18
Melko	5	644.0	-19.81856	T2	T5	T3	T10	T11
Omonada	6	845.2	25.73532	T1	T8	T15	T14	T11

T1=Quncho,T2=Guduru,T3=Kena,T5=Kora,T6=Dagim,T7=Abola,T8=Negus,T9=Felagot,T10=Tesfa, T11=Heber1,T14=Asgori,T15=Dukem,GT16=Koye,T17=Holetta Key,T18=Tseday and T19=Boset

4.4.8. Genotype Main Effect and Genotype by Enivironmnet Bi-plot Analysis for Grain Yield

One of the most attractive features of a GGE biplot is its ability to show the which-won-where pattern of a GED.(Yan and Tinker (2006) reported that the use of a biplot is an intriguing, as it graphically addresses important concepts such as crossover GE, mega-environment differentiation and specific adaptation.GGE biplot is visualized on the basis of results explained for the first two principal components (Yan and Kang,2003).In the present study, the first two principal components of GGE biplot explained 66.67% (PC1=48.07% and PC2=18.6%) of the total variations (Fig. 3).GGE is effective in evaluating test environments, i.e., it has the power to discriminate among the genotypes (informative) in target environments and the representativeness (stable) of the test environments, which is not possible with AMMI analysis. In addition, it is effective in identifying superior cultivars ("which-won-where") and possible mega-environments (Kaya *et al*.,2006). The GGE biplot graphic analyses of the 21 tef varieties across the six environments are discussed on figure 3.

4.4.8.1 Which-Won-Where pattern of GGE biplot

According to Yan *et al*., (2002),the polygon view of GGE biplot indicates the best genotypes in each environment and group of environments. In this situation, the polygon is formed by connecting the signs of the varieites that are farthest away from the biplot origin, such that all

other varieties are contained in the polygon. In this case, the polygon connects all the farthest varieties and perpendicular lines divide the polygon into sectors. Sectors help to visualize the mega-environments. This means that winning varieties for each sector are placed at the vertex. The pattern on the environment in the above biplot suggests that the existence of three different mega-environments (Fig.3). But, this pattern may not be repeatable across years (Yan *et al*.,2000). To confirm the repeatability of the mega-environment result, there need to be multiyear data (Yan *et al*. 2005).

The vertex varieties were T8,T15,T11,T2 and T3.These varieties were the best or worst in some or all environments because they are furthest from the origin of the biplot (Yan and Kang, 2003).They are more responsive to environmental change and are considered as specifically adapted varieties. They are best in the environments lying within their respective sector in the polygon view of the GGE-biplot (Yan and Tinker, 2006).

The variety (T15) was high yielding variety at Areka and Ambo and the variety (T11) high yielder at both Bedele and Arjo. The vertex variety (T3) was the poorest at almost all of the test environments and ranked 19th at Omonada,21th at Ambo,18th at Areka and 16th at Arjo, since it had the longest distance from the origin of the biplot on the opposite side of the environments. The varieties T1, T11 and T15 are located near to the orgin implying that these varieties were broadly adapted (Abay and Bjornstad, 2009). It had also been observed that no environments fell into sectors where variety T3 was the vertex variety indicating that this variety was not the best in any of the test environments. Brikti (2018) used seven locations for the study and clustered into seven mega environments for the production of tef genotypes and winning genotypes for each mega environment for specific adaptation. Connecting the extreme varieties on a GGE biplot forms a polygon and the perpendicular lines to the sides of the polygon form sectors of varieties and locations (Kaya *et al.*,2006).The environments fall into three quadrants and the varieties also fall into four quadrants (Figure.3). The GGE biplot identified three different tef growing mega-environments.

The first quadrant consisted of only (Melko) and three varieties T4, T9 and T2 and with the latter being the vertex variety. The second quadrant contained Areka, Ambo, Bedele and Arjo and five varieties (T6,T18,T7,T11 and T15). Also quadrant two contained both high and low

yielding environment (Areka and Ambo and Bedele respectively) and high yielding variety (T15). The vertex varieties were T15 and T11. The third quadrant contained only one environment (E1, Omonada) and five varieties (T1, T14, T17,T16 and T8).The vertex varieties were (T1 and T8) and variety (T1) was high yielder in almost all environments. The location Omonada clustered in one mega environment (ME1) and Bedele, Ambo, Areka and Arjo were in second mega environment (ME2) and Melko were clustered in one sector and could be considered as third mega environment (ME3) for tef varieties evaluation and recommendation.

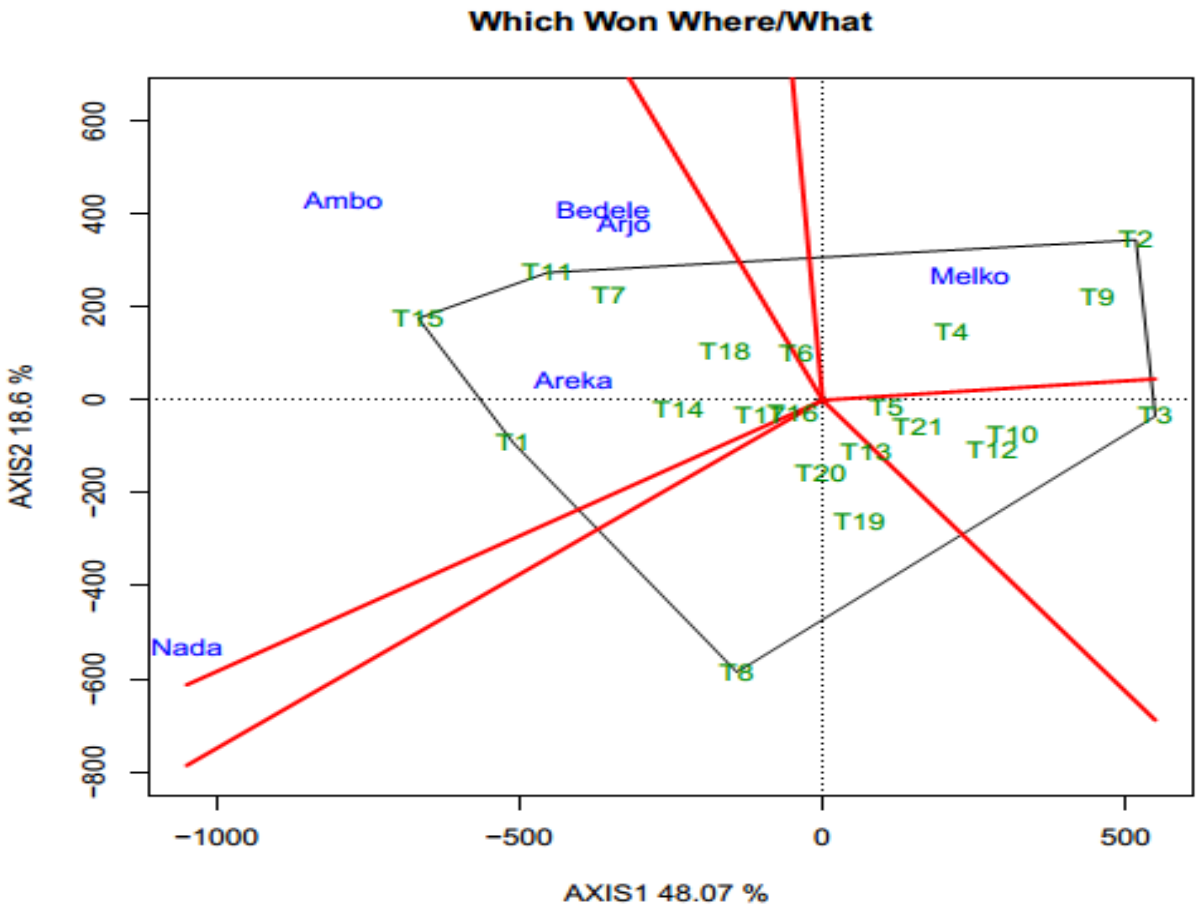

Figure 3: Polygon views of the GGE biplot based on symmetrical scaling for the which-won-where pattern of varieties and environments

T1=Quncho,T2=Guduru,T3=Kena,T4=Etsub,T5=Kora,T6=Dagim,T7=Abola,T8=Negus,T9=Felagot, T10=Tesfa,T11=Heber1,T12=Wellenkomi,T13=Gibe,T14=Asgori,T15=Dukem,T16=Koye.T17=Holetta Key,T18=Tseday,T19=Boset,T20=Magna and T21=Enatite

4.4.8.2. Ranking of varieties based on mean grain yield and stability performance

Mean yield and stability performance of varieties described in figure 4. The varieties on the right of the ordinate line had yields less than average mean yield. Accordingly, the varieties Kena (T3), Guduru (T2), Felagot (T9), Etsub (T4) and Tesfa (T10) had mean grain yield lower than the grand mean (Figure 4). The varieties on the left side of the line have yield performance greater than mean yield and according to this, the varieties Dukem (T15), Heber-1 (T11), Abola (T7), Tseday (T18) and Dagim (T6) gave mean yields which were higher than grand mean (826kg/ha). A longer projection to the AEC ordinate, regardless of the direction, represents a greater tendency of the GE interaction of a genotype, which means it is more variable and less stable across environments and viceversa. For instance, varieties Gibe (T13) and (Enatite) T21 were more stable as well as low yielding. Considering simultaneously yield and stability, variety Koye (T16), Quncho (T1) and Kora (T5) showed the best performances (Figure 4), suggesting their adaptation to a wide range of environments.

The variety Etsub (T4) and Magna (T20) were most desirable, with high yield but low stability. The variety Asgori (T14) had high yield, but was less stable. The variety Kena (T3) was found on the right side of the line and it is the least stable with low yield and had a large contribution to the genotype by environment interaction; it had the longest distance from the average environment.

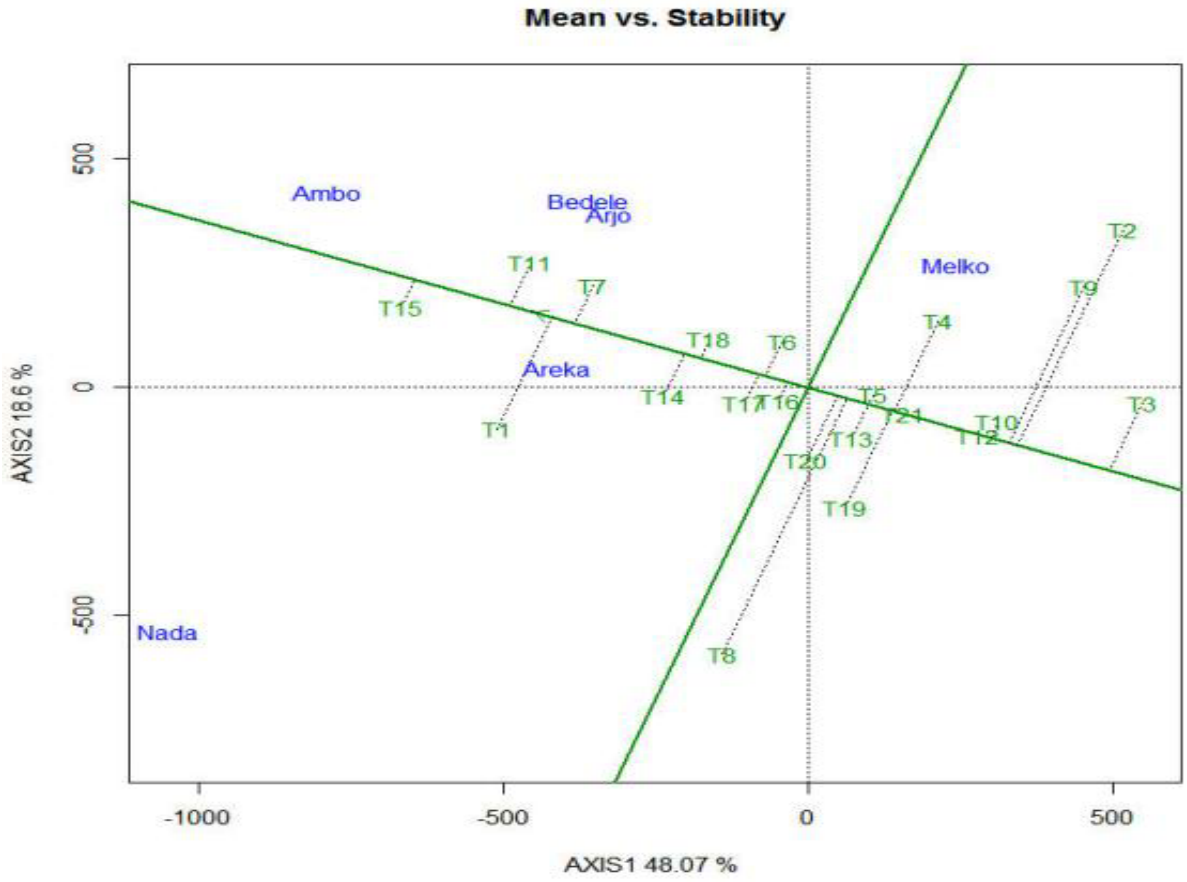

Figure 4: Mean yield and stability performance of varieties

T1=Quncho,T2=Guduru,T3=Kena,T4=Etsub,T5=Kora,T6=Dagim,T7=Abola,T8=Negus,T9=Felagot, T10=Tesfa,T11=Heber1,T12=Wellenkomi,T13=Gibe,T14=Asgori,T15=Dukem,T16=Koye.T17=Holetta Key,T18=Tseday,T19=Boset,T20=Magna and T21=Enatite

4.4.8.3. Evaluation of varieties based on ideal variety

An ideal genotype is expected to have the highest mean grain yield performance and stability in performance across environmnets (Farshadfar *et al.*,2012).Though such an ideal genotype may not exist in reality,it can be regarded as a reference for genotype evaluation (Kaya *et al.*,2006).The ideal genotype is located in the first concentric circle in the biplot.From this study T15 (variety Dukem) was the "ideal" variety with the highest mean grain yield followed by T11 and T7 which fall closer to the center of concentric circles, and they are desirable varieties in terms of high yield and stability, as compared to other varieties. The center of the concentric circles represents the position of an ideal genotype, which is defined by a projection onto the mean environment axis that equals the longest vector of the genotypes that had above average

mean yield and by a zero projection onto the perpendicular line (zero variability across environments).

Because the units of both IPCA1 and IPCA2 for the genotypes are the original unit of the yield in the genotype focused scaling, the units of the AEC abscissa (mean yield) and ordinate (stability) should also be the original unit of the yield. The unit of the distance between genotype and the ideal genotype, in turn is the original unit of yield. Therefore, the ranking based on the genotype-focused scaling assumes that stability and mean grain yield are equally important (Yan and Rajcan, 2002). On the other hand, the varieties T2, T3, T9, T8, T10, T12, T19 and T20 which are located distant from the first concentric circle were undesirable varieties (Figure 5). Similar result was reported by Habte (2019) tef genotype (T6) with the highest average yield was identified to be the ideal genotype to evaluate the test genotypes relative to it.

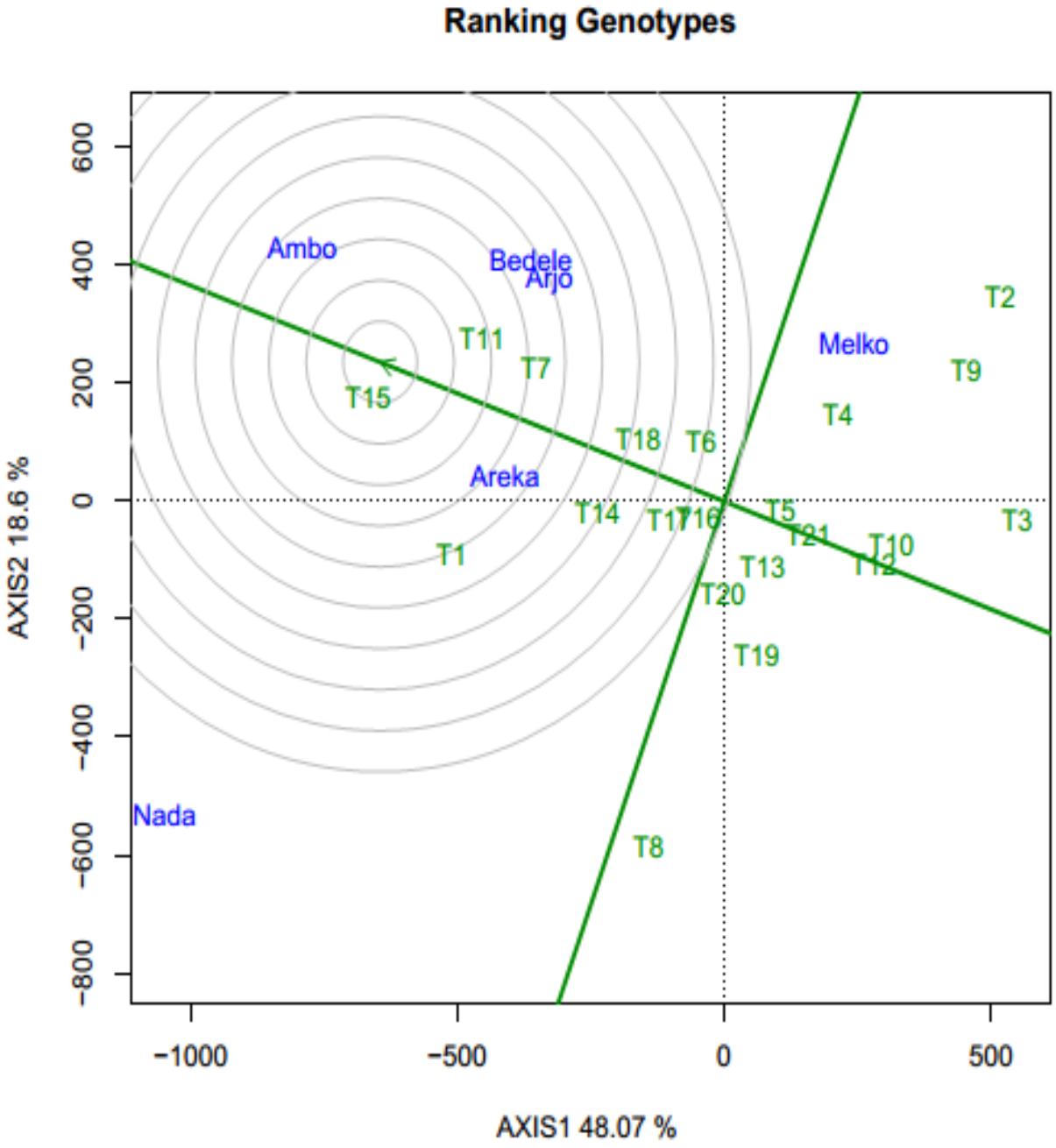

Figure 5: Evaluation of varieties relative to ideal varieties

T1=Quncho,T2=Guduru,T3=Kena,T4=Etsub,T5=Kora,T6=Dagim,T7=Abola T8=Negus,T9=Felagot,T10=Tesfa,T11=Heber1,T12=Wellenkomi,T13=Gibe,T14=Asgori,T15=Dukem,T16=Koye.T17=Holetta Key,T18=Tseday,T19=Boset,T20=Magna and T21=Enatite

4.4.8.4. Evaluation of environments relative to ideal environment

In figure 6, the ideal environment is located in the first concentric circle in the environment focused biplot, and desirable environments are close to the ideal environment. Nearest to the first concentric circle, environment Ambo, followed by Bedele and Arjo were close to the ideal environment. According to Yan (2001), discriminating ability and representativeness are important properties of a test location. An ideal location should be highly differentiating (discriminating) for the tested genotypes and at the same time be representative of the target locations (Yan and Kang,2003). The ideal environment is representative and has the highest discriminating power (Yan and Tinker 2006).

This result in line with (Brikit 2018) reported among the test environments, Mehoni which fell into the center of concentric circles was an ideal test environment in terms of being the most representative of the overall environments and the most powerful to discriminate the performance of the tested genotypes. Yan and Rajcan (2002) and Naroui *et al*. (2013) reported that by assuming an ideal environment as the center, concentric circles it is possible to identify desirable environments which are found closer to the ideal environment. Hence, among the testing environments Bedele and Arjo, which fell relatively near to this ideal environment were identified as the desirable testing environments in terms of being the most representative of the environments and powerful to discriminate genotypes. Mahdieh *et al*. (2016) 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

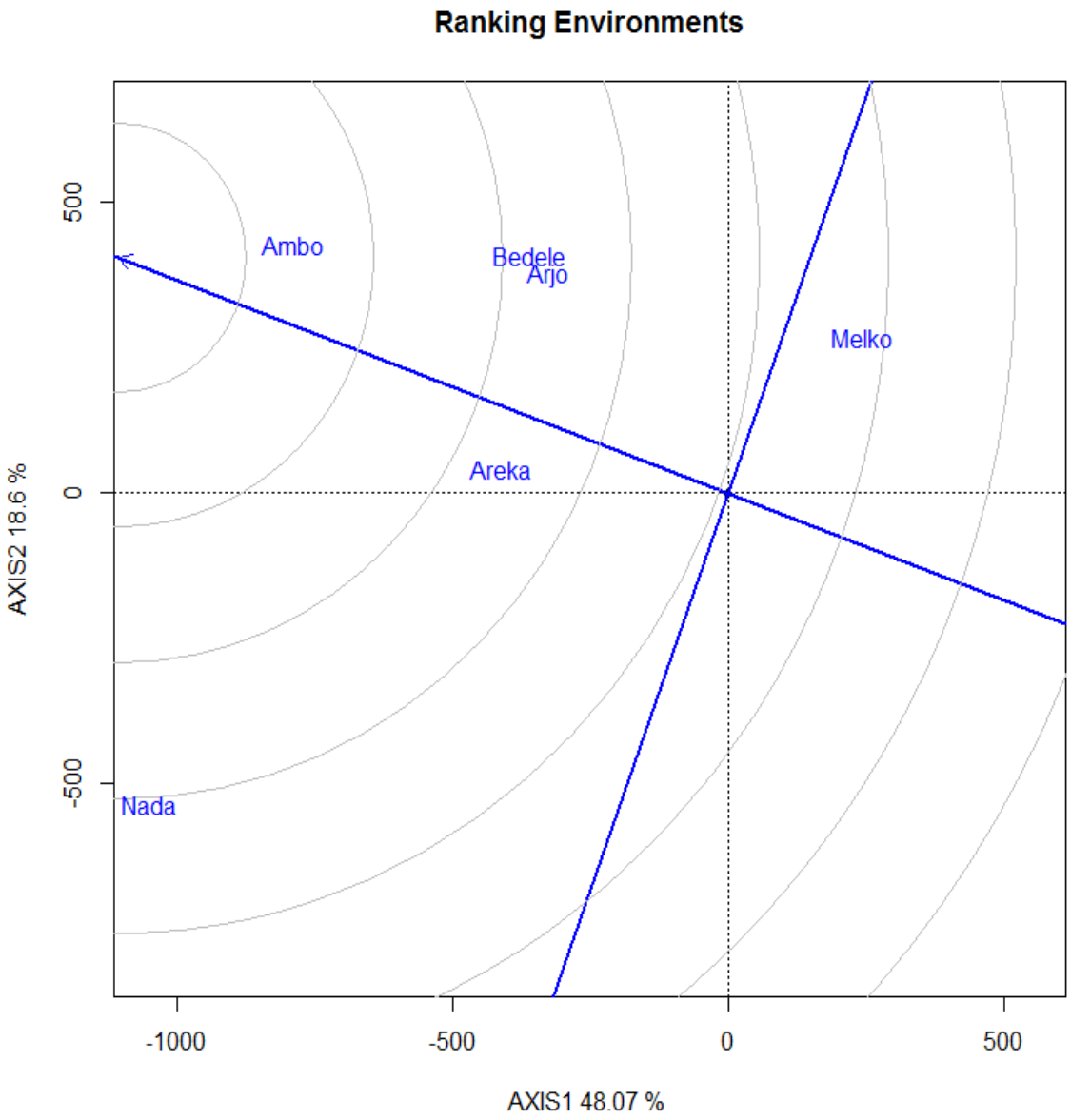

Figure 6: Evaluation of environments relative to ideal environments

4.4.8.5 Relationship among Environments

The summary of the interrelationships among the environments was earlier given on Figure.7. The lines that connect the biplot origin and the markers for the environments are environment vectors, and the angle between the vectors of two environments is related to the correlation coefficient between them. The cosine of the angle between the vectors of two environments approximates the correlation coefficient between them (Yan 2002).

According to the angles between test location vectors, the six locations are grouped into three major groups.Group one includes Melko, group two includes Bedele, Arjo,Ambo and Areka and group three include Omonada.The smallest angle is between environments Bedele and Ambo, implying that there is very high correlation between them (r=0.99** between predicted yield by GGE2).Ambo is also closer to Areka, was highly significant indicating close correlation between them (r = 0.94***).The correlation between Bedele and Areka was (r = 0.90***). Therefore, the first group Bedele, Arjo,Areka and Ambo were closely correlated (Figure.7) suggesting that these locations provide redundant information on their capacity in discriminating between the genotypes.

The second group included Melko and had a very short vector and is solitary. The third group included Omonada alone and it had with the longest vectors from the origin. The angle between Melko and Omonada was greater than 90^0, showing a negative correlation between them (r = -0.79***). The angle between Bedele and Omonada was less than 90^0 indicating that there was some positive correlation between them (r=0.25). All other locations had also positive correlation between themselves and with Bedele and Omonada.Obtaining reliable information on the similarity of environments and their subdivision into groups can enable breeders to use fewer test environments reducing the cost of testing and increasing breeding efficiency. With the longest vectors from the origin, environments Ambo and Omonada were the most discriminating environments.Arjo and Areka were moderately discriminating, while Melko was least discriminating location.

Discriminating ability and representativeness are the important properties of a test location. An ideal location should be highly differentiating for the tested genotypes and at the same time representative of the target location. Similar to ideal genotype, an ideal environment or location is defined and showed by the small circle with an arrow pointing to it. Meaning that the environment is more desirable and discriminating when located closer to the center circle or to an ideal environment. Gadissa (2018) reported the six locations are grouped into three major groups. The smallest angle is between environments KU (Kulumsa) and AR (Arsi robe), implying that there is very high correlation between them (r=0.99** between predicted yield by GGE2). AS (Asasa) is also closer to Arsi Robe, indicating close correlation between them (r = 0.94***). The correlation between KU and AS was (r = 0.90***). Therefore, the first group

KU (Kulumsa), AR (Arsi Robe) and AS (Asasa) were closely correlated and suggesting that these locations provide redundant information on their capacity in discriminating between the genotypes.

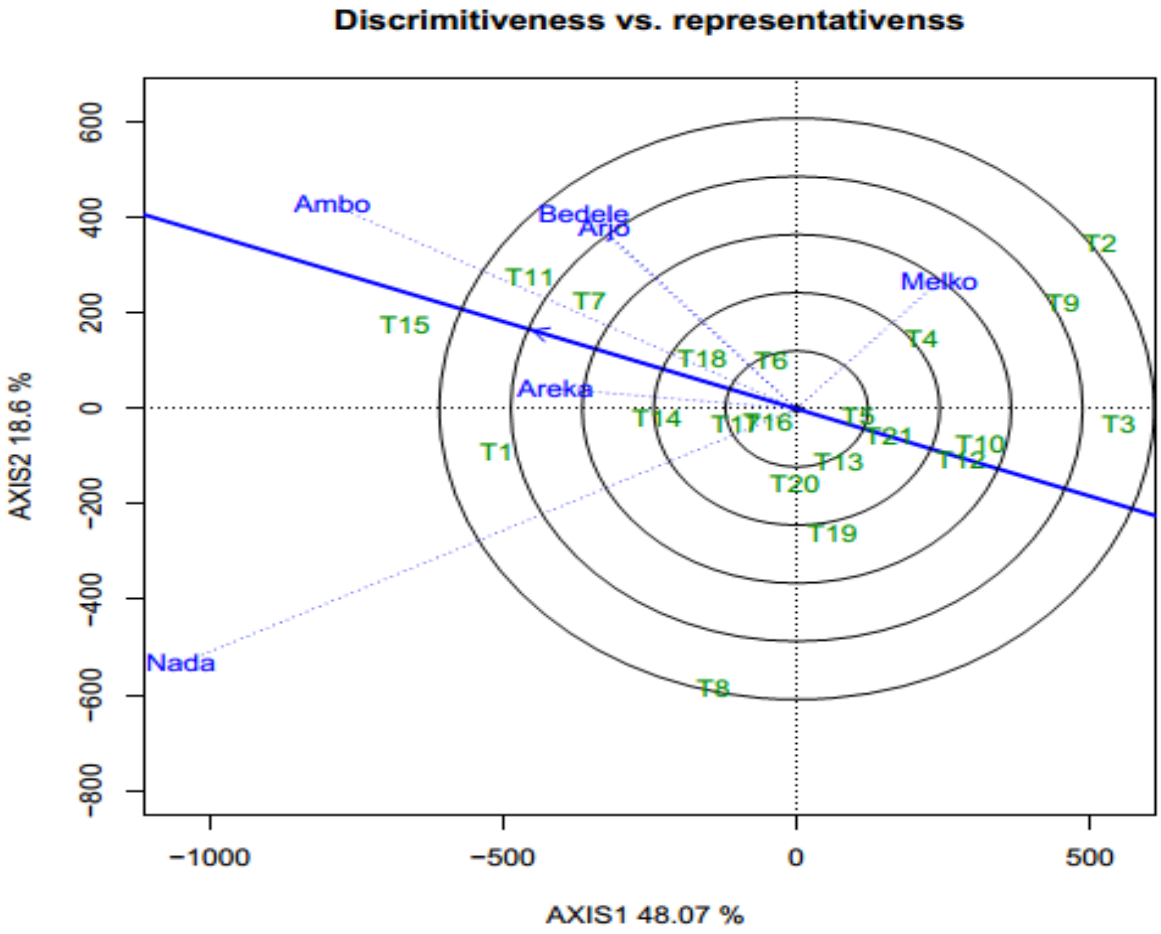

Figure 7: The discrimination and representativeness view of the GGE biplot to rank test environments relative to an ideal test environment

T1=Quncho,T2=Guduru,T3=Kena,T4=Etsub,T5=Kora,T6=Dagim,T7=Abola,T8=Negus,T9=Felagot, T10=Tesfa,T11=Heber1,T12=Wellenkomi,T13=Gibe,T14=Asgori,T15=Dukem,T16=Koye.T17=Hole tta Key,T18=Tseday,T19=Boset,T20=Magna and T21=Enatite

4.5. Correlation of Stability Parameters

Different stability parameters such as regression coefficient (bi **)**,deviation from regression (S^2di) ,AMMI stability value (ASV),Lin and Binns's (1988) cultivar superiority measure (Pi),Shukla's (1972) stability variance, ($\sigma^2 i$) and Wricke's (1962) ecovalence (Wi) used to compare the stability of 21 tef varieties across six locations.Spearman's coefficient of rank correlation (Steel and Torrie,1980) was determined for each of the possible pair wise comparision of the ranks of different stability static procedures.The degree of correlation among different stability parametrs represents whether one or more parameters should be used for genotype performance forcast,and also gives breeder the right to choose the best stability parameter(s) suitable for the stability.

From table 16,the mean grain yield had positive and significant correlation with bi,but negative and highly significant correlation with Pi and YSI and non-significant with Wi, $\sigma^{2,}$ASV and S^2di.The non-significant correlation among yield and stability statistics provide information that cannot be collected from average yield.The high positive correlation among mean grain yield and stability parameters indicates that selection for yield would change yield stability by increasing the parameter leading to development of genotypes that are specifically adapted to environmnets with optimal growing conditions.S^2di highly and positively correlated with Wi, σ^2,ASV and YSI and negatively correlated with bi,but non-significant correlated with Pi.

YSI positively correlated with Wi,Pi, σ^2 and ASV,but negatively correlated with bi.Positive correlation among stability parameter means they can gave similar pattern in ranking of the genotypes and this implying that they can be used interchangeably in the study of genotype by environment interaction of tef and the result was in agreement with (Muluken,2009).Mean grain yield was negatively correlated with most of the stability models implying that compatibility of high yield and stability of grain yield performance is an important, but difficult to achieve at the same time (Kang *et al*.,1991).Stability parameters that positively associated with grain yield seems the appropriate stability parameter that helps to identify both high yielding and relatively stable varieties Desalegn (2019) in maize reported grain yield is highly significant negatively correlated with Pi (r=-0.98) and Ysi (r=-0.85).Shuckal's stability variance was highly positively significant correlated with most stability parameter which ranged from (r=0.62) for both Si and

ysi to (r=0.99) for *wi* which indicate those stability parameter was suitable for the selection of genotypes in this particular study. *Wi* was highly significantly correlated with ASV (r=0.88) and Ysi (r=0.62) which indicate both the parameter was complement each other in the selection of genotypes as stable one. Pi was highly significantly correlated with ysi (r=0.86).

Table 16: Spearman's rank correlation coefficient for stability parameters of tef grain yield

	Yld	**Wi**	**Pi**	**σ^2**	**bi**	**ASV**	**YSI**	**S^2di**
Yld								
Wi	-0.11274^{ns}							
Pi	-0.88493**	0.1899^{ns}						
σ^2	-0.1127^{ns}	0.883**	0.1899^{ns}					
bi	0.5343*	-0.25065^{ns}	-0.54522*	-0.25065^{ns}				
ASV	-0.27493^{ns}	0.69610**	0.37982^{ns}	0.69610**	-0.31169^{ns}			
YSI	-0.7853**	0.45883*	0.79782**	0.45883*	-0.44079*	0.75522**		
S^2di	-0.11259^{ns}	0.94675**	0.13967^{ns}	0.94675**	-0.16104**	0.69221**	0.45754*	

ns,*,**=non-significant, significant at (P≤0.05) and significant at (p≤0.001) respectively bi =regression coefficient, S^2di =Deviation from regression, ASV=AMMI stability value, Pi=Lin and Binns's (1988) cultivar superiority measure, $\sigma^2 i$ =Shukla's (1972) stability variance; Wi=Wricke's (1962) ecovalence

5. SUMMARY AND CONCLUSION

The genotype by environment interaction makes it difficult to select the best performing as well as the most stable genotypes and so its efficient interpretation is important issue in plant improvement in Ethiopia. The study carried out with objectives of to identify stable and/or high yielding varieties and assess their performance across locations. Twenty-one tef varieties were tested at six locations in South and Southwestern Ethiopia during 2018 main cropping season. The experiment was laid out in randomized complete block design (folded RCBD) with three replications across all environments.

The varieties performed best at Ambo with mean grain yield of 1264.5kg/ha.Most varieties had however, low yield at Bedele with mean grain yield of 459.4kg/ha.Genotype by environment interaction was found to be highly significant ($P<0.01$) for genotypes, environment and their interaction. The combined analysis of variance revealed that environment contributed the greatest proportion 69.4% of the total variance component for grain yield, while genotype contributed 7.94% and G x E interaction contributed 17.5% respectively. The significant effects revealed that environmental conditions had major effects in selecting tef varieties for high grain yield, stability and wide adaptation.

The AMMI analysis showed that tef grain yield was significantly affected by environmental fluctuation where the major proportion of sum of squares was explained by environments (67.4%), followed by the GEI (17.2%) and the genotype effects (8.02%), which indicated more contribution of the environments to the variance in grain yield performance. The GEI sum square of the combined ANOVA for grain yield was further partitioned into different IPCAs by the AMMI analysis. The first two IPCAs were highly significant and explained 63.4% of the interaction sum of squares. Thus, the AMMI model with the first two IPCAs was adequate for cross-validation of the yield variation explained by GEI.

Stability parameters such as cultivar superiority measure, stability variance, yield stability index, AMMI stability value, AMMI and GGE on average identified Heber-1, Quncho and Dukem as the most stable tef varieties with mean yields greater than the grand mean. Whereas, variety Kena, Wellenkomi, Negus, Felagot and Guduru as low yielding and unstable varieties. Similar result was obtained from GGE biplots analysis showed that Dukem as an ideal variety,

while variety Heber-1 and Abola were desirable varieties as they were closer to the ideal variety. Conversely, the varieties Kena and Guduru were the least desirable varieties based on GGE biplot. Also GGE biplot identified location Ambo was the ideal environment for tef cultivation, while Bedele was the poor yielding and least representative environment.

The different stability measurements used in this study demonstrated association and disassociation among them in ranking of the varieites based on stability. The mean grain yield had positive and significant correlation with bi, but negative and highly significant correlation with Pi and YSI and non-significant with Wi, $\sigma^{2,}$ASV and S^2di. S^2di highly and positively correlated with Wi, σ^2, ASV and YSI and negatively correlated with bi,but non-significant correlated with Pi.YSI positively correlated with Wi,Pi, σ^2,and ASV,but negatively correlated with bi.Positive correlation among stability parameter means they can gave similar pattern in ranking of the genotypes and this implying that they can be used interchangeably in the study of genotype by environment of tef.

The results from this study gave valuable information for researchers who were interested to examine the effect of G x E interactions on the performance of tef varieties in the South and Southwest Ethiopian condition. The study used data collected for only one season, which may limit the strength of its recommendation. However, the results are crucial in directing the breeding decision following additional season evaluation of the varieties in the same locations.

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7. APPENDICES

Appendix Table 1: ANOVA for yield and yield related traits of 21 tef varieties in each location

Source of Variation	Grain Yield					
	Omonada	Melko	Bedele	Areka	Arjo	Ambo
Genotype (20)	214137**	55493 ***	88988 ***	80864***	93878 ***	146679.9 ***
Rep (2)	13958	7980	5786	12869.9	37232	26318
Error (40)	5542	7021	5702.7	13031.1	13628	15857
CV (%)	8.8	13	17.4	9.6	20.68	9.9
Biomass Yield						
Genotype (20)	2318611 ***	432154 ***	460084 ***	1062855***	1581052***	1561789 ***
Rep (2)	441111	235869	1509583.7	467881	571706	445277.7
Error (40)	39736	38041	56495	164199.7	53581	180777.7
CV (%)	6.8	14.6	15.2	9.26	8.8	7.8
Straw Yield						
Genotype (20)	1675664 ***	216402 ***	181961 **	1006895 ***	1059185 ***	1002208 ***
Rep (2)	322807	161911	1349579	328561	571617	354298
Error (40)	40287	45202	69247.7	168411	69617	215395
CV (%)	9.6	30.96	23.28	12.9	12.7	11.1
Plant Height						
Genotype (20)	187.8***	255.1***	39.8***	218.1***	220.9***	220.9***
Rep (2)	149.9	565.8	8.87	55.3	13.3	22.74
Error (40)	21.6	27.5	8.34	38.44	6.36	12.53
CV (%)	4.4	5.9	3.8	5.75	3.13	4.4
Panicle Length						
Genotype (20)	13.4***	43.7***	13.5*	59.26***	40.11***	40.11***
Rep (2)	23.5	159.48	22.2	35.9	11.84	11.8
Error (40)	4.13	13.8	6.3	7.68	6.42	6.4
CV (%)	4.8	9.5	6.7	6.97	8.34	8.34

Appendix Table 1 (*Continued)*

Culm Length						
Genotype (20)	125.8***	134.6***	17.11***	114.07***	177.15***	177.1***
Rep (2)	20.7	37.1	10.47	14.02	50.4	50.42
Error(40)	4.7	14.7	7	20.5	11.47	11.47
CV (%)	3.5	7.8	6.9	6.65	6.7	6.77
Days to Heading						
Genotype(20)	14.15***	21.4^{ns}	31.1***	6.9*	2.72*	56.7***
Rep (2)	64	285.4	5.3	5.7	0.39	7.63
Error (40)	5.8	15.4	13.01	2.94	1.46	15.75
CV (%)	5.06	7.5	6.57	3.8	1.61	10.4
Days to Maturity						
Genotype (20)	14.08***	2.54^{ns}	12.8^{ns}	5.8***	8.28***	113.8***
Rep (2)	20.4	189.2	29.3	8.87	32.25	0.58
Error (40)	3.25	22.2	12.8	3.5	2.88	1.15
CV (%)	2.1	5.2	4.5	1.8	1.16	1.3
Grain filling period						
Genotype (20)	18.9***	20.04^{ns}	30.8***	18.4***	4.5***	124.6***
Rep (2)	15.3	83.2	31.4	6.39	1.25	5.82
Error (40)	3.5	12.04	7.7	6.2	0.38	15.9
CV (%)	4.8	9.4	11.7	4.2	0.88	9
Lodging index (X)						
Genotype (20)	135.04***	34.52***	26.92***	208.7***	40.68*	74.6***
Rep (2)	87.92	2.545	0.44	5.761	87.34	14.7
Error (40)	22.89	3.812	1.24	36.9	21.06	10.68
CV (%)	7.64	3.38	1.75	10.59	7.28	5.35

Appendix Table 1 (***Continued)***

Thousand seed weight						
Genotype (20)	0.04***	0.026***	0.016***	0.017***	0.015***	0.0158***
Rep (2)	0.003	0.0004	0.006	0.018	0.001	0.0011
Error (40)	0.007	0.003	0.005	0.0024	0.00077	0.00077
CV (%)	19.22	10.2	16	11.8	9.46	9.4
Harvest Index						
Genotype (20)	243.1 ***	206.78 ^{ns}	122.76 *	65.4 ***	92.4 *	24**
Rep (2)	23.4	175.1	381.8	4.29	70.9	5.52
Error (40)	13.1	113.2	61.5	14	40.2	9.8
CV (%)	12.1	20.9	28.1	13.5	28.7	13.4
Fertile Tillers						
Genotype (20)	0.23***	0.73***	0.11*	0.817***	0.41*	0.37***
Rep (2)	0.27	0.75	0.68	0.44	1.21	0.01
Error(40)	0.07	0.16	0.056	0.149	0.18	0.01
CV (%)	10.7	17.8	12.66	7.95	11.1	2.6

*=significant ($p<0.05$), ** =highly significant ($p<0.01$),***=Very highly significant ,ns=non-significant, CV=Coefficient of Variation

Appendix Table 2; Mean of phenology traits at each location

Varieties	Omonada			Melko			Bedele		
	DH	DM	GFP	DH	DM	GFP	DH	DM	GFP
Quncho	50	84	34	54	89	35	56	77	22
Guduru	52	89	37	56	90	34	59	75	20
Kena	49	88	40	52	90	37	58	81	22
Etsub	49	88	39	55	89	35	57	78.6	22
Kora	52	89	37	55	91	36	58	79.6	21
Dagim	51	88	37	53	87	34	58	78.3	21
Abola	50	84	34	54	89	35	55	82.3	27
Negus	45	86	36	52	90	36	52	77	18
Felagot	45	83	37	46	90	43	52	77.3	26
Tesfa	47	83	36	52	88	36	59	77.3	18
Heber -1	48	89	40	53	89	36	57	78.3	21
Wellenkomi	49	87	38	54	90	36	58	77	19
Gibe	48	86	38	52	89	37	54	77.6	24
Asgori	45	88	43	50	88	38	50	78	27
Dukem	47	87	40	56	91	35	58	82	24
Koye	45	84	39	54	88	34	50	80.9	30
Holetta Key	47	92	45	47	88	34	49	75	26
Tsedey	45	86	39	48	90	41	51	79.3	28
Boset	45	85	40	50	89	39	55	77.3	22
Magna	49	87	38	52	89	37	52	78	26
Enatite	47	86	40	51	90	39	54	81.3	27
Mean	48	86.6	38.4	52.2	89.2	36.6	54.8	78.5	23.4
LSD at 5%	3.9	2.9	3.1	6.4	4.27	5.72	5.95	5.9	4.59
CV (%)	5.1	2.1	4.8	7.5	2.9	9.4	6.57	4.55	11.7

DH=Days to Heading, DM= Days to Maturity, GFP=Grain filling period,LSD =Least Significant Difference, CV =Coefficient of Variation

Appendix Table 2.(Continued)

Varieties	Areka			Arjo			Ambo		
	DH	DM	GFP	DH	DM	GFP	DH	DM	GFP
Quncho	45	102	57	75	147	72	34	84	49
Guduru	44	106	62	77.3	148	71	38	67	29
Kena	46	106	59	76	147	71	48	83	46
Etsub	44	102	58	73	144	71	33	75	48
Kora	45	105	60	74.6	147	72	46	82	37
Dagim	46	102	57	75.3	147	71	34	77	43
Abola	46	102	55	75.6	145	71	39	84	46
Negus	43	103	59	74.6	147	70	43	92	40
Felagot	43	105	62	72.6	142	70	44	92	48
Tesfa	44	103	59	75.3	145	70	39	80	40
Heber -1	46	104	57	75.3	148	73	38	78	40
Wellenkomi	44	104	59	76	148	72	38	80	42
Gibe	45	104	59	75	148	70	35	87	53
Asgori	44	105	61	74	145	70	36	85	50
Dukem	45	103	58	76	147	71	37	75	36
Koye	40	106	66	74	145	71	33	82	50
Holetta Key	46	103	57	75.3	145	69	33	83	50
Tsedey	41	106	64	74.6	144	69	42	84	42
Boset	45	104	59	74.6	147	71	41	86	44
Magna	46	104	58	75.3	144	69	35	93	66
Enatite	45	103	58	74.3	145	72	35	81	46
Mean	44.5	103.8	59.2	74.9	146	70.7	38.1	82.4	44.9
LSD at 5%	2.83	1.6	4.11	2	2.8	1.02	6.5	1.7	6.6
CV (%)	3.8	0.93	4.2	1.61	1.16	0.88	10.4	1.3	9

DH = Days to Heading, DM=Days Maturity, GFP =Grain Filling Period,LSD =Least Significant Difference,CV =Coefficient of Variation

Appendix Table 3: Mean of growth character at each location

Varieties	Omonada				Melko				Bedele			
	PH	PL	CL	FT	PH	PL	CL	FT	PH	PL	CL	FT
Quncho	118	45	73	2.3	92	38	53	2	74	37	37	1.8
Guduru	117	46	71	2.5	103	46	57	2.2	74	37	38	1.6
Kena	104	41	63	2.3	95	37	58	1.8	74	37	38	1.8
Etsub	112	44	68	2.6	88	42	47	1.8	70	35	35	1.8
Kora	111	41	69	2.9	100	46	54	2.3	79	38	42	2.2
Dagim	110	41	69	6	95	43	51	2	71	35	36	1.8
Abola	108	42	67	2.7	89	38	51	2.4	70	33	35	1.6
Negus	100	41	59	2.5	78	39	39	1.6	80	39	41	1.8
Felagot	95	38	57	3.3	85	36	50	2	80	41	34	2.2
Tesfa	107	40	64	2.3	89	37	52	2.1	75	38	37	1.8
Heber -1	107	42	65	2.3	104	46	59	2.4	78	38	40	1.8
Wellenkomi	104	44	61	2.4	88	41	47	2.1	74	36	37	1.6
Gibe	105	43	62	2.6	77	36	41	2.1	77	35	42	1.6
Asgori	102	43	59	2.5	76	35	40	2.3	81	40	41	1.8
Dukem	114	42	72	2.2	101	40	61	2.5	78	39	38	1.7
Koye	99	41	58	2.3	83	40	44	2.8	77	39	39	1.8
Holetta Key	88	40	49	2.8	74	34	40	2.2	74	37	36	1.9
Tsedey	93	38	55	2.2	84	35	49	2.9	71	35	35	1.9
Boset	96	38	58	2.2	80	36	44	1.9	77	37	39	2
Magna	111	42	69	2.4	91	37	54	2.2	80	37	39	1.9
Enatite	99	42	57	2.8	80	36	42	3.6	70	35	35	2.3
Mean	105	41.6	63	2.67	88.2	38.9	49.2	2.2	75.5	37	38	1.8
LSDat 5%	7.6	3.35	3.6	0.44	8.6	6.13	6.34	0.65	4.76	4.1	4.4	0.4
CV (%)	4.4	4.8	3.46	10.7	5.95	9.57	7.8	17.8	3.8	6.7	6.9	12.6

PH=Plant height,PL=Panicle length,CL=Culm Length and FT=Fertile Tillers, LSD =Least Significant Difference,CV=Coefficient of Variation

Appendix Table 3:(Continued)

Varieties	Areka				Arjo				Ambo			
	PH	PL	CL	FT	PH	PL	CL	FT	PH	PL	CL	FT
Quncho	116	44	72	4.3	95	35	61	4.2	78	33	45	4.2
Guduru	115	46	69	4.6	91	32	60	3.2	90	35	55	4.5
Kena	113	38	75	4.7	89	30	63	3.6	71	26	45	5.6
Etsub	111	46	64	4.7	83	37	46	3.6	82	31	52	5.9
Kora	114	40	74	5.5	93	33	60	3.7	82	33	49	4.8
Dagim	112	39	72	4.7	84	27	57	4.3	79	31	48	4.6
Abola	113	42	71	5.4	74	29	44	4.8	76	27	48	4
Negus	108	37	72	5	70	27	42	4	70	29	43	4.8
Felagot	98	32	65	4.3	84	27	55	4.1	74	30	45	4.8
Tesfa	102	33	68	4.8	74	27	47	3.8	73	28	45	4.13
Heber -1	127	45	83	4.7	85	32	54	3.9	86	33	52	3.9
Wellenkomi	111	45	65	5.1	85	34	50	3.8	86	32	54	3.8
Gibe	107	43	64	5.1	76	35	38	3.8	76	31	44	3.8
Asgori	95	33	59	5.1	70	29	41	3.6	77	30	47	5
Dukem	115	44	71	4.4	91	33	58	3.2	79	31	47	4.5
Koye	103	38	66	4.8	76	30	46	4.1	71	30	42	5.2
Holetta Key	96	34	62	6.2	73	26	48	4.2	72	27	45	5
Tsedey	99	35	64	4.9	65	26	38	4	74	31	43	4.4
Boset	93	36	58	4.9	73	24	47	3.8	66	25	40	4.6
Magna	114	40	74	5.6	76	28	48	3.7	84	34	50	4.3
Enatite	100	45	58	4.3	80	34	44	3.5	77	33	44	5.2
Mean	107.6	39.8	68	4.9	80	30.4	49.9	3.9	77.3	30.5	46.9	4.6
LSD at 5%	10.2	6.9	7.4	0.67	4.16	4.18	5.58	0.7	5.8	4.2	5.6	0.2
CV (%)	5.75	4.57	6.6	7.9	3.13	8.3	6.7	11.1	7.05	12	9.6	7.4

PH = Plant Height,PL=Panicle Length,CL=Culm Length and FT =Fertile Tillers, LSD =Least Significant Difference,CV=Coefficient of Variation

Appendix Table 4: Means of lodging index at each test location

Varieties	Environments					
	Omonada	Melko	Bedele	Areka	Arjo	Ambo
Quncho	72	60	63	65	62	69
Guduru	75	66	61	63	71	65
Kena	66	59	69	64	64	63
Etsub	67	57	65	58	64	63
Kora	68	61	68	65	64	68
Dagim	68	57	61	58	61	63
Abola	63	59	61	60	64	59
Negus	60	54	64	60	58	59
Felagot	55	55	64	49	60	66
Tesfa	63	54	60	43	63	62
Heber-1	66	62	63	72	71	67
Wellenkomi	62	57	62	63	66	66
Gibe	65	56	62	59	61	58
Asgori	64	58	69	48	63	56
Dukem	68	62	63	65	60	64
Koye	57	58	64	54	57	59
Holetta Key	47	53	60	49	63	57
Tsedey	53	57	60	48	61	50
Boset	55	56	63	44	62	57
Magna	67	57	68	69	68	55
Enatite	57	52	62	51	60	56
Mean	62.8	57.7	63.4	57.4	62.97	61
LSD at 5%	7.9	3.22	1.84	10.37	7.57	5.4
CV (%)	7.	3.9	1.75	10.59	7.28	5.5

LSD =Least Significant Difference, CV =Coefficient of Variation

Appendix Table 5: Mean of grain yield related traits at each location

Varieties	Omonada				Melko				Bedele			
	BY	SY	TSW	HI	BY	SY	TSW	HI	BY	SY	TSW	HI
Quncho	3416	2166	0.33	36.6	1203	682	0.56	43.3	1730	1205	0.4	30.3
Guduru	1416	1086	0.33	23.3	2230	1217	0.54	45.4	1450	870	0.5	40.0
Kena	2660	2160	0.56	18.8	1593	853	0.6	46.5	1330	940	0.6	29.3
Etsub	2330	1790	0.33	23.2	1519	839	0.6	44.8	1410	1050	0.4	25.5
Kora	3410	2620	0.6	23.2	1946	1156	0.7	40.6	1125	917	0.5	18.5
Dagim	3410	2620	0.4	23.2	1490	777	0.56	47.9	1270	940	0.4	26.0
Abola	1916	1000	0.56	47.8	1221	693	0.53	43.2	2408	1618	0.4	32.8
Negus	2330	1080	0.36	53.6	870	450	0.63	48.3	1280	1055	0.5	17.6
Felagot	1080	750	0.5	30.6	948	418	0.66	55.9	1441	1166	0.4	19.1
Tesfa	3750	3090	0.43	17.6	1389	659	0.56	52.6	1403	1053	0.4	24.9
Heber -1	2580	1580	0.43	38.7	1465	745	0.63	49.1	1650	1070	0.46	35.2
Wellenkomi	2580	1872	0.2	27.4	1290	583	0.63	54.8	1416	1116	0.36	21.2
Gibe	2750	1960	0.2	28.7	930	450	0.46	51.6	1160	880	0.46	24.1
Asgori	4750	3667	0.53	22.8	770	196	0.66	74.5	1908	1400	0.4	26.6
Dukem	4330	3080	0.36	28.8	1690	975	0.33	42.3	2060	1419	0.46	31.1
Koye	3750	2792	0.5	25.5	1326	668	0.56	49.6	2066	1391	0.36	32.7
Holetta Key	2750	1875	0.56	31.8	965	505	0.56	47.7	1330	990	0.36	25.6
Tsedey	2500	1584	0.53	36.6	957	437	0.66	54.3	1900	1275	0.43	32.9
Boset	3250	2292	0.36	29.5	1040	362	0.48	65.2	780	155	0.5	80.1
Magna	3416	2416	0.46	29.3	1305	701	0.5	46.3	2075	1515	0.4	27.0
Enatite	3250	2420	0.56	25.5	1760	1081	0.4	38.6	1560	1080	0.5	30.8
Mean	2934	2090	0.43	29.6	1329	688	0.56	49.6	1560	1100	0.43	30.1
LSD at 5%	328.9	331.2	0.14	12.1	322	351	0.18	17.5	392	434	0.11	13
CV (%)	6.8	8.6	19.2	6	14.6	31	10.17	20.9	15.2	23.2	16	28.1

BY=Biomass yield,SY=Straw Yield ,TSW= Thousand Seed Weight,HI=Harvest Index,LSD=Least Significant Difference,CV=Coefficient of Variation

Appendix Table 5 (Continued)

Varieties	Areka				Arjo				Ambo			
	BY	SY	TSW	HI	BY	SY	TSW	HI	BY	SY	TSW	HI
Quncho	5130	3800	0.2	25.9	2830	2222	0.37	21.48	6660	5150	0.38	22.7
Guduru	5650	4542	0.55	19.6	2500	2070	0.26	17.20	4530	3410	0.38	24.7
Kena	4070	3030	0.46	25.6	2000	1575	0.2	21.25	4750	3868	0.33	18.6
Etsub	4090	2760	0.4	32.5	2160	1620	0.43	25	5416	4166	0.3	23.1
Kora	4630	3410	0.4	26.3	1500	920	0.3	38.67	5830	4570	0.25	21.6
Dagim	4070	2730	0.47	32.9	3000	2340	0.27	22	5416	4056	0.48	25.1
Abola	4860	3530	0.3	27.4	1660	1100	0.2	33.73	5560	4040	0.34	27.3
Negus	3920	2430	0.44	38.0	2500	2040	0.2	18.4	4660	3752	0.25	19.5
Felagot	4190	3050	0.49	27.2	4160	3220	0.27	22.6	4830	3825	0.37	20.8
Tesfa	3770	2640	0.4	30.0	2000	1650	0.3	17.5	4660	3559	0.37	23.6
Heber -1	5020	3560	0.33	29.1	3410	2602	0.23	23.7	6416	4791	0.35	25.3
Wellenkomi	4350	3290	0.47	24.4	2000	1670	0.37	16.5	6330	5160	0.34	18.5
Gibe	3560	2480	0.4	30.3	2160	1744	0.36	19.26	6000	4660	0.36	22.3
Asgori	4620	3500	0.32	24.2	3500	2650	0.2	24.29	5830	4580	0.24	21.4
Dukem	5060	3640	0.31	28.1	3316	2526	0.3	23.82	6416	4726	0.33	26.3
Koye	4580	3500	0.37	23.6	2500	2084	0.2	16.64	5416	4166	0.33	23.1
Holetta Key	3209	2179	0.37	32.1	2830	2350	0.2	16.96	6100	4580	0.33	24.9
Tsedey	4160	3059	0.43	26.5	3000	2240	0.3	25.33	5416	4106	0.34	24.2
Boset	3703	2493	0.5	32.7	2330	1860	0.36	20.17	4500	3330	0.27	26
Magna	4730	3800	0.53	19.7	2250	1880	0.37	16.44	4250	3040	0.31	28.5
Enatite	4280	3312	0.33	22.6	1830	1290	0.27	29.51	5330	4226	0.38	20.7
Mean	4364	3178	0.4	27.6	2545	1983	0.3	22.4	5444	4179	0.3	23.3
LSD at 5%	669	677	0.08	6.1	382	435	0.05	10.47	702	766	0.046	5.2
CV (%)	9.26	13	12	13.4	8.8	8.71	9.5	9.64	7.8	9.34	4.52	8.8

BY=Biomass yield,SY=Straw Yield ,TSW= Thousand Seed Weight,HI=Harvest Index,LSD=Least Significant Difference,CV=Coefficient of Variation

Appendix Table 6: Mean performance for morpho-phenologic, grain yield and yield related traits of 21 tef varieties evaluated across six environments during 2018 main cropping season

Varieties	Traits						
	DH	DM	GFP	PH	PL	CL	FT
Dukem	53.1^{a-d}	97.6^{b-f}	44.5^{d-f}	96.1^{a}	38.3^{b-d}	57.7^{a-c}	3.1^{hi}
Heber -1	52.9^{b-e}	97.6^{b-f}	44.5^{d-f}	97.8^{a}	39.5^{ab}	58.7^{a}	3.2^{f-i}
Quncho	52.3^{c-f}	97.1^{d-g}	44.8^{c-f}	95.5^{ab}	38.7^{a-d}	56.8^{a-c}	3.1^{hi}
Abola	53.2^{a-d}	97.7^{b-f}	44.3^{ef}	88.3^{de}	35.1^{f-i}	52.9^{d}	3.4^{d-g}
Asgori	49.9^{hg}	98.2^{a-d}	48.3^{a}	83.6^{fg}	35.5^{e-h}	47.9^{fg}	3.3^{d-g}
Tsedey	50.5^{f-h}	98.1^{a-e}	47.3^{ab}	81.1^{g}	33.5^{ij}	47.3^{fg}	3.4^{c-f}
Dagim	52.7^{c-e}	96.5^{e-g}	43.8^{f}	91.8^{c}	36.2^{e-g}	55.5^{c}	3.3^{e-h}
Koye	49.5^{h}	97.6^{c-f}	48.1^{a}	85.1^{f}	35.9^{e-g}	49.2^{e-g}	3.5^{b-e}
Kora	55^{a}	98.8^{a-c}	43.9^{f}	96.5^{a}	38.6^{a-d}	58.1^{ab}	3.4^{c-f}
Negus	51.8^{d-g}	99.1^{a-c}	47.2^{ab}	84.5^{f}	35.1^{f-i}	49.3^{ef}	3.3^{e-h}
Holetta Key	49.5^{h}	97.5^{c-g}	47.8^{ab}	79.4^{h}	32.8^{h}	46.8^{g}	3.7^{a}
Etsub	51.7^{d-g}	96.1^{gf}	44.3^{ef}	90.9^{dc}	39^{a-c}	51.9^{d}	3.5^{b-d}
Magna	51.3^{d-h}	99.2^{ab}	47.9^{ab}	92.6^{bc}	37^{d-f}	55.8^{bc}	3.4^{c-g}
Boset	51.8^{d-g}	97.8^{a-e}	46^{b-e}	80.9^{gh}	32.8^{j}	47.8^{fg}	3.3^{d-g}
Enatite	51^{e-h}	97.7^{b-f}	46.7^{a-c}	84.5^{f}	36.9^{d-f}	46.9^{g}	3.6^{ab}
Guduru	54.3^{a-c}	95.9^{g}	41.5^{g}	98.4^{a}	40.3^{a}	58.4^{a}	3.1^{hi}
Gibe	51.3^{d-h}	97.9^{a-e}	46.5^{a-d}	86.3^{ef}	37.2^{c-e}	48.8^{e-g}	3.3^{f-i}
Tesfa	52.7^{c-e}	96.1^{gf}	43.1^{fg}	86.7^{fe}	33.9^{h-j}	52.4^{d}	3^{i}
Wellenkomi	52.9^{b-e}	97.5^{c-g}	44.5^{d-f}	91.3^{cd}	38.7^{a-d}	52.4^{d}	3.2^{hi}
Felagot	50.7^{f-h}	98.1^{a-e}	47.4^{ab}	86.15^{ef}	33.9^{h-j}	50.9^{ed}	3.6^{bc}
Kena	54.8^{ab}	99.3^{a}	44.5^{d-f}	90.9^{dc}	34.5^{h-j}	56.8^{a-c}	3.2^{f-i}
Mean	52.1	98	46	89	36	52	3.3
CV (%)	5.8	2.5	6.7	5.4	8	7	9.2

Means followed by a common letter with in a column are not significantly different from each other at P≤0.05,DH=Days to Heading, DM=Days to Maturity,GFP=Grain Filling Period,PH=Plant Height,PL=Panicle Length,CL=Culm Length,FT=Fertile Tillers,TSW=Thousand Seed Weight, BY=Biomass Yield,SY=Straw Yield, LI=Lodging Index,HI=Harvest Index,CV=Coefficient of Variation ,LSD= Least Significant difference

Appendix Table 6 (Continued)

Varieties	Traits					
	LI	TSW	BY	SY	HI	GY
Dukem	64^{b-e}	0.35^{i}	3845^{a}	2767^{a}	29.8^{b-g}	1084.3^{a}
Heber -1	67^{a}	0.4^{e-h}	3431^{cb}	2396^{cd}	33.8^{ab}	1032.2^{a}
Quncho	65^{a-c}	0.39^{e-h}	3614^{b}	2666^{ab}	28.6^{c-h}	957^{b}
Abola	61^{e-g}	0.38^{h-i}	3217^{ed}	2267^{d-f}	33.2^{ab}	949^{b}
Asgori	60^{g-i}	0.39^{e-h}	3563^{b}	2663^{ab}	32.6^{a-d}	899^{bc}
Tsedey	55^{l}	0.45^{a-c}	2946^{f-h}	2071^{f-i}	35.5^{a}	874^{cd}
Dagim	61^{d-g}	0.42^{c-f}	3086^{ef}	2216^{d-f}	30.1^{b-g}	869^{cd}
Koye	58^{h-j}	0.39^{f-h}	3108^{c-f}	2266^{d-f}	30.6^{b-f}	842^{c-e}
Kora	66^{ab}	0.47^{a}	3298^{cd}	2485^{bc}	25.4^{h}	813^{d-f}
Negus	59^{g-i}	0.39^{f-h}	2563^{j}	1767^{j}	33.6^{ab}	796^{e-g}
Holetta Key	55^{lk}	0.4^{a-d}	2656^{ji}	1869^{ij}	35.5^{a-c}	787^{e-h}
Etsub	62^{d-f}	0.41^{d-g}	2741^{ji}	1757^{g-j}	30.6^{b-f}	785^{e-h}
Magna	64^{b-d}	0.43^{b-e}	2991^{fg}	2209^{d-f}	28.3^{d-h}	781^{e-h}
Boset	56^{j-l}	0.41^{d-g}	2685^{ji}	1911^{h-j}	31.9^{a-e}	774^{e-h}
Enatite	56^{j-l}	0.41^{d-h}	2970^{f-h}	2199^{d-f}	28.9^{c-h}	770^{f-j}
Guduru	67^{a}	0.46^{ab}	2975^{fg}	2209^{d-f}	28.9^{c-h}	766^{f-j}
Gibe	60^{f-h}	0.37^{hi}	2822^{g-i}	2086^{e-h}	29.7^{b-g}	735^{g-j}
Tesfa	57^{i-k}	0.41^{e-h}	2831^{g-i}	2108^{e-h}	28^{e-h}	723^{h-k}
Wellenkomi	62^{c-f}	0.39^{e-h}	2997^{gf}	2283^{c-e}	27.3^{f-h}	712.5^{i-k}
Felagot	58^{h-j}	0.45^{a-c}	2777^{hi}	2072^{f-i}	30^{b-g}	703.3^{jk}
Kena	63^{j-l}	0.47^{a}	2819^{hi}	2154^{e-g}	26.3^{hg}	662.8^{k}
Mean	61	0.4	3045	2220	30	826.4
CV (%)	6.6	13.5	9.8	14.3	21	12.2

Means followed by a common letter with in a column are not significantly different from each other at P ≤0.05,DH=Days to Heading,DM=Days to Maturity,GFP=Grain Filling Period,PH=Plant Height,PL=Panicle Length,CL=Culm Length,FT=Fertile Tillers,TSW=Thousand Seed Weight, BY=Biomass Yield,SY=Straw Yield, LI=Lodging Index,HI=Harvest Index,CV=Coefficient of Variation,LSD= Least Significant difference

Appendix figure 1. photos during field trial evaluation and data collection (A and B)

Appendix photo (A)

Photo B