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Additive Main Effects and Multiplicative Interactions (AMMI) Analysis of Grain Yield in Tef (*Eragrostis tef (zucc.*) Varieties in South West Ethiopia

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Abstract

The study was carried out in south western Ethiopia across six test locations during the 2019 cropping season with objective of determining magnitude of GxE interaction and stability analysis of Tef varieties. A total of eight tef varieties were laid out randomized complete block design with three replicates at each site. AMMI analysis revealed that the effects of genotype, environment and genotype by environment interaction (GEI) were highly significant ($p < 0.01$), and their respective contribution to the treatment sum of squares was 7.50%, 69.22% and 20.19%. The AMMI model partitioned four significant IPCAs components and the first two IPCA1 (62.26%) and IPCA2 (27.74%) together contributed 90% of GEI sum of squares. AMMI model graphical interpretation identified varieties G-5 (Abola) and G-8 (Kora) as the most stable and high yielder across tested environments. The varieties G-5 (Abola) (7592 kg/ha) and G-8 (Kora) (8264 kg/ha) varieties had the average yield which was greater than the grand mean (7473 kg/ha). With respect to environment E-5 (Omonada) and E-3 (Somodo) located relatively near to the origin and they were less interacting environments, considered as favorable environments.

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AMMI, biplots analysis, GxE interaction, grain yield, IPCA, Stability.

Introduction

Tef (*Eragrostis tef* (zucc.) Trotter) is one the most important cereals crop belongs to the poaceae family. It is native to Ethiopia, which is centre of diversity for this important cereal crop (Vavlov, 1951). Tef is one of the major cereals in terms of area and volume of production among grain crops. It is cultivated on approximately about 3 million hectare of land producing 5.02 million tons (CSA, 2017).

Production and productivity of tef yield is low due to susceptibility to lodging, low yield potential of landraces under widespread cultivation, poor agronomic management practices, biotic and abiotic stresses (Kebebew *et al.*, 2015, Assefa *et al.*, 2011, Assefa *et al.*, 2015). 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). Genotype by environment interaction testing over diverse environment is very important to ensure that whether there is a need to develop a widely adapted cultivar for all environments of interest, or specifically adapted cultivars for specific target environments (Yan *et al*., 2007; Yan and Kang, 2003). In crop improvement programs multi-environment performance tests across a wide range of environments are conducted to reduce the effect of GEI and to ensure that the selected genotypes have a high and stable performance across several environments as it is easier and cost effective both in terms of variety evaluation and seed multiplication (Matus-Cadiz *et al*., 2003). However, the need to develop a stable variety across the environment is dependent up on the kind of interaction prevailing (Yan and Kang, 2003).

Different methods have been proposed to study the pattern of genotype by environment interaction, explore the performance of genotype in response to the environment and estimate yield (Van Eeuwijk, 1995; Naveed *et al.*, 2007). Among the statistical model used, the additive main effects and multiplicative interaction (AMMI) model is a preferred to analyze multi-environment varietal trials effectively and efficiently, where there is a usual occurrence of genotype by environment interaction. It is a model which combines analysis of variance (ANOVA) for additive main effects and uses the principal component analysis (PCA) to partition the multiplicative structure of the G× E interaction (Gauch, 1988; Zobel *et al.*, 1988; Gauch and Zobel, 1996; Gauch, 2007). The ANOVA model partitions the total sum of squares (SS) into the components environment, genotype and G× E interaction without further partitioning the interaction component, making interpretation difficult or complicated in terms of significance of genotypes across different environments.

On the other hand, AMMI 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 (Gauch and Zobel, 1988; Zobel *et al*, 1988 and Gauch, 1988).

The objectives of this study are therefore to assess the G× E interaction pattern of the multi-environment trials of tef varieties and model the data using appropriate AMMI model, and to select and recommend high yielding varieties with respect to yield potential and stability.

Materials and Methods

Plant Materials and Test Locations

A multi environment trial was conducted using eight tef varieties (Table 3) for each location during the 2019 main cropping seasons at, Gechi, Omonada, Gooma, Somodo, Melko and Kersa. Average weather data and geographical coordinates of the test sites are presented in table 1.

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

Experimental Design and Management

The trial was conducted using randomized complete block design (RCBD) with three replications at all locations under rain-fed conditions. Sowing was done manually. Fertilizer rate, seed rate, and crop cultivation were applied based on agronomic recommendations for each site. 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_5 per hectare for light soils and 60kg 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.

Data Collection

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

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- 15^0 lodging, 2=15-30^0 lodging 3 = 30-45^0 lodging, 4 = 45-60^0 lodging and 5 = 60-90^0 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 (gram)

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.

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

Statistical analysis

Combined analysis over years and locations was done separately for Gechi, Omonada, Gooma, Somodo, Melko and Kersa SAS software (SAS 9.0) after testing for homogeneity of variance. GGE biplot analysis was conducted on the mean best linear unbiased estimate (BLUE) values of eight Tef genotypes in the respective locations using GenStat 18 (VSN International, 2015).

Results and Discussion

A combined analysis of variance for grain yield of eight tef varieties tested across six locations revealed highly significant difference for environment, genotype and genotype by environment interaction (Table 3). Highly significant variation was observed for genotype by environment interaction of Tef grain yield, indicating that possibility of stability analysis. Large proportion of the variation was explained by the environmental effect (69.22%) followed by the GEI effect (20.19%). Genotypes accounted for (7.5%) of the overall variation. There still remains some proportion of variation left unexplained by the model pooled into the error term (3.08%). The high percentage of the environment sum square is an indication that the major factor that influence yield performance of Tef genotypes is 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 69.22% of the sum of squares implying the need for investigating the nature of differential response of the genotypes to environments.

Highly significant variations observed for most of the traits (Days to heading, days to maturity, plant height, Panicle length, culm length, lodging index, shoot biomass, grain yield, harvest index) tested among genotypes across all locations, indicating the existence of variability among the tested genotypes (Table 4).

AMMI Analysis

AMMI multiplicative component further partitioned the GE interaction into five interaction principal component axes (IPCAs). However, only the first three axes showed highly significant contribution to the GEI in the AMMI model. The remaining (fifth) principal components contributed insignificant portion of the variation. AMMI analysis showed that the effects of genotype, environment and genotype by environment interaction (GEI) were highly significant ($p < 0.01$), and their respective contribution to the treatment sum of squares was 7.50%, 69.22% and 20.19% (Table 5). The IPCA1 (62.26%) and IPCA2 (27.74%) together contributed 90% of GEI sum of squares. The first two IPCA scores were significant at ($P<0.01\%$) and cumulatively accounted for 90 % of the total GxE interaction. This indicates that the use of AMMI model fit the data well and justifies the use of AMMI1 and AMMI2. Since the IPCA1 score contributes more to the GE sum of square, it has to be weighted by the proportional difference between IPCA1 and IPCA2 scores to compensate for the relative contribution of IPCA1 and IPCA2 total GE interaction sum squares.

In the AMMI 1 biplot model, the IPCA 1 scores of genotypes and environments have been plotted against their respective means (Fig. 1). The plot is helpful to visualizing the average productivity of the genotypes, environments, and their interaction for all possible variety by environment combinations. AMMI analysis provides a graphical representation to summarize information on the main effects and the first principal component scores of the interactions (IPCA1) of both genotypes and environments simultaneously (Crossa *et al*., 1990, Gauch and Zobel, 1996; Purchase, 1997; Alberts, 2004).

Table.1 Description of the test environments

Locations	Altitude (m.a.s.l)	Coordinates	Soil type	Temp (^{0}C)	Rainfall (mm)
Gechi	2087	$8^0$27′N 36°21′E	Nitosols	20.7	1800
Gooma	1,560	$7^0$51′N 36°35′E	Nitosols	19.7	1764
Kersa	>1780	NA	Nitosols	20.3	2000
Mana	1770	$7^0$45′N 36°45′E	Nitosols	18.9	1624
Melko	1753	$7^0$47’N 360 47’’E	Nitosols	22	1639
Omonada	1975	7^0 41’N 37°12’’E	Nitosols	20	1600

Table.2 Description of experimental materials used in the study

Variety name	Year of release	Days to maturity	Released center	Rainfall (mm)	Altitude (m.a.s.l)	Grain yield (t/ha)	
						On station	On farm
Dagim	2016	112-115	DZARC	-	-	2.6–3.2	-
Kora	2014	110-117	DZARC	-	-	2.5–2.8	2.0–2.2
Felagot	2017	108 -112	DZARC	-	-	2.2–2.9	-
Abola	2016	110-118	Adet	-	-	2.1–2.8	1.5–1.7
Gibe	1993	114–126	DZARC		1850	2.0-3.0	1.6-2.2
Heber-1	2017	112–124	Adet	-	-	2.2–2.7	-
Tesfa	2017	112–120	DZARC	-	-	2.3–3.0	-

Table.3 ANOVA for grain yield (kg/ha) of eight Tef genotypes tested at six environments

Source of variation	Df	Mean square	Pr>f	Proportion of TSS
Genotype (G)	7	13.835**	<.0001	7.50%
Location	5	178.811**	<.0001	69.22%
Rep within location	2	0.04778	0.8934	
Genotype X Environment (GxE)	35	7.452**	<.0001	20.19%
Pooled error	94	0.4232		3.08%
Mean=7.5 R-square=0.96		CV=8.9		

*CV= coefficient of variation df=degree of freedom, TSS= total sum square

Table.4 Combined Analysis of variance and mean performance of different traits of tef varieties tested at different locations

Varieties	Traits								
	HD	MD	PH	PL	CL	LI (%)	SHB	GY	HI
Dagim	56.4	107.3	106.1	41.4	64.6	54.9	35.8	8257	23.2
Negus	54.3	106.6	96.9	38.2	58.7	58.9	37.4	7783	22.6
Tesfa	55.6	106.9	97.8	36.5	61.3	56.2	35.8	6467	18.2
Felagot	54.8	101.8	85.3	31.7	53.6	62.2	35.2	7933	23.4
Abola	55.6	107.4	101.7	39.3	62.7	57.2	40.6	7592	19.7
Heber-1	55.3	109.2	106.2	42.6	63.5	54.6	40.1	7674	20.1
Gibe	55	110.2	95.4	39.3	56.1	61.7	32.3	5812	19.1
Kora	55.4	108.6	110.7	43.7	67	58.8	35.7	8264	24.0
Mean	**55.3**	**107.3**	**100.2**	**39.1**	**60.9**	**58.1**	**36.6**	**7473**	**21.2**
F test	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0002**	**<.0001**	**<.0001**
LSD value	**0.67**	**0.89**	**3.1**	**1.8**	**2.3**	**2.51**	**3.52**	**0.445**	**0.0218**
CV (%)	**1.82**	**1.25**	**4.6**	**7.3**	**5.7**	**6.5**	**14.5**	**8.98**	**15.5**
R-square	**0.94**	**0.953**	**0.94**	**0.83**	**0.92**	**0.89**	**0.89**	**0.97**	**0.86**

HD=Days to heading, MD= days to maturity, PH=plant height (cm), PL=Panicle length, CL=culm length, LI=lodging index, SHB=shoot biomass, GY=grain yield (Kg), HI=harvest index

Table.5 AMMI analysis of variance for grain yield of eight Tef genotypes tested at six locations.

Source	DF	Sum Square	Mean Square	Proportion of TSS %	PC SS %
Total	143	1290.8	9.03		
Treatments	47	1250.9	26.61**		
Genotypes	7	96.8	13.82**	7.5	
Environments	5	893.2	178.65**	69.22	
Block	12	1.9	0.15		
Interactions	35	260.9	7.45**	20.19	
IPCA 1	11	162.5	14.77**		62.26
IPCA 2	9	72.4	8.04**		27.74
IPCA 3	7	19.1	2.73**		7.32
IPCA 4	5	5.8	1.16*		2.22
IPCA 5	3	1.2	0.39ns		0.46
Error	84	38.1	0.45		

Fig.1 AMMI1 biplot for additive effects vs. IPCA1 in eight varieties of Tef grain yield from six environments. Where G1=Dagim, G2=Negus, G3= Tesfa, G4=Felagot, G5=Abola, G6=Heber-1, G7-Gibe and G8=Kora. E1=Kersa, E2=Melko, E3=Somodo, E4=Gooma, E5=Omonada and E6=Gechi.

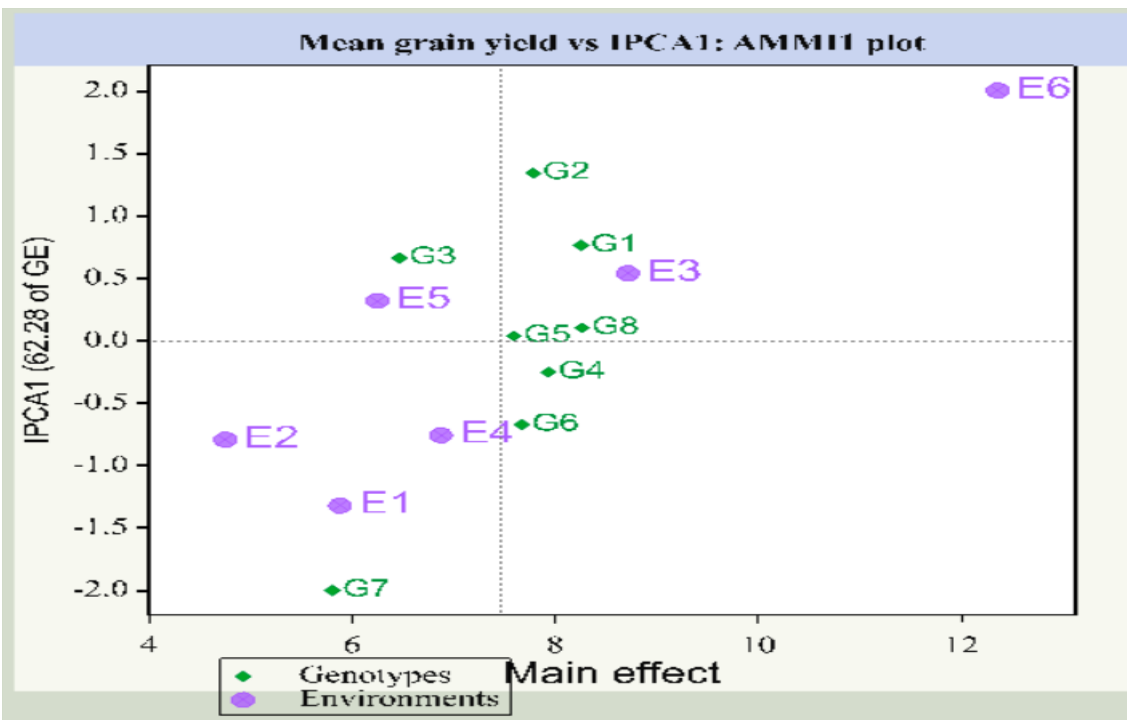
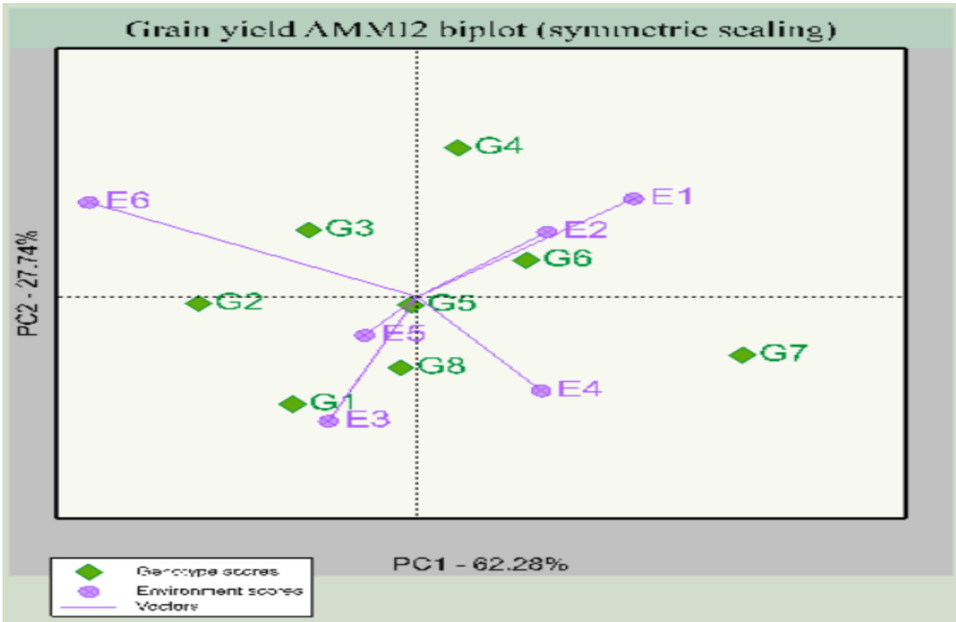


Fig.2 AMMI2 biplot showing the two main axes of interaction (IPCA2 vs. IPCA1) in eight varieties of Tef grain yield from six environments. Where G1=Dagim, G2=Negus, G3= Tesfa, G4=Felagot, G5=Abola, G6=Heber-1, G7- Gibe and G8=Kora. E1=Kersa, E2=Melko, E3=Somodo, E4=Gooma, E5=Omonada and E6=Gechi.



The greater the IPCA scores, negative or positive, (as it is a relative value), the genotype are specifically adapted to certain environments (large interaction). The more the IPCA scores approximate to zero, the more stable or adapted the genotype is over all the environments sampled (Crossa *et al*., 1990, Gauch and Zobel, 1996). Hence, varieties G-5 (abola), G-8 (kora), and G-4 (felagot) exhibit small interactions (smaller scores) and appear close to the center of the axes and therefore, is relatively stable indicating that these varieties were less influenced by the environments (Fig. 1).

However, among these widely adopted or stable varieties, high mean performance exceeding grand mean were exhibited by G-8 (kora), G-4 (felagot), and G-5 (abola) varieties. Conversely, varieties such as G-7 (gibe), G-2 (negus), G-1 (dagim), G-6 (heber-1) and G-3 (tesfa) are relatively far apart from the origin (greater IPCA1 scores) and thus show strong interaction effects and unstable or specifically adopted (Fig. 1). varieties G-1 (dagim), G-2 (negus) and G-6 (heber-1) were exhibited highest average yield above grand mean and they were unstable or specifically adopted to their respective favorable environments. Environments with IPCA score located near to the origin in the biplot were less interacting with the genotypes, while environments with IPCA score located away from the origin in the biplot were more interacting with the genotypes and make the selection difficult. Accordingly, among six environments E-6 (Gechi), E-1 (Kersa), E-2 (Melko) and E-4 (Gooma) located far apart from the origin in the biplot was the most interactive environments meaning that contribute higher amount of variation to the total GEI. Conversely, the environments E-5 (Omonada) and E-3 (Somodo) located relatively near to the origin and they were less interacting environments, they contribute less amount of variation to the total GEI (Fig. 1).

The AMMI 2 biplot is generated using the genotype environment scores of the first two AMMI components. Though, the first four principal component axes of the interaction were significant for the model, the prediction assessment indicated that AMMI 2 with only two interaction principal component axes was the best predictive model (Vargas and Crossa, 2000; Zobel *et al*., 1988). In AMMI2 biplot, genotypes and environments that are located far away from the center are more responsive or unstable, while genotypes that are positioned closer to the biplot center have higher stability performance (Purchase, 1997). Accordingly, genotypes G-5 (abola) and G-8 (kora) were plotted relatively close to each other at the center or origin indicating their similar yielding potential to all environments (stable performance) (Fig. 2). These stable varieties were exhibited better yield than grand mean. Therefore, only varieties G-5 (abola) and G-8 (kora) were considered as a high yielding and widely adopted genotypes indicating their minimum contribution to the total G x E interaction variance. On the other hand varieties like G-7 (Gibe), G-4 (Felagot) and G-2 (Negus) far away from center of biplot; G-2 (Negus), G-3 (Tesfa) and G-6 (Heber-1) were relatively distant from the origin and have considerable contribution to the G x E interaction variance considered as specifically adopted to their respective favorable environments or unstable (Fig. 2).

The AMMI model analysis of variance for Tef grain yield revealed significant variation ($p<0.001$) for both main and interaction effects indicating the existence of a wide range of variations between genotypes, environments and their interactions. This may make a varietal selection both a challenge and an opportunity for plant breeders. Furthermore, the AMMI model partitioned four significant IPCAs components which accounted a total 99 % of interaction sum of squares. The first two IPCA scores were significant at ($P<0.01\%$) and cumulatively accounted for 90 % of the total GxE interaction. A graphical interpretation of AMMI 1 and AMM2 detected varieties G-5 (abola) and G-8 (Kora) as the most stable genotypes across tested environments. The varieties G-5 (7592 kg/ha) and G-8 (8264 kg/ha) varieties had the average yield which was greater than the grand mean (7473 kg/ha). With respect to environment E-5 (Omonada) and E-3 (Somodo) located relatively near to the origin and they were less interacting environments, considered as favorable environments.

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