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SEMI-DWARF TEF LINES FOR HIGH SEED YIELD AND LODGING TOLERANCE IN CENTRAL ETHIOPIA

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ABSTRACT

Tef [*Eragrostis tef* (Zucc.) Trotter] is the major cereal crop in the Horn of Africa, especially in Ethiopia where it is a staple food for over 60% of its 90 million population. The crop performs better than other cereal crops under extreme environmental conditions. The grain of tef is not only nutritious but also gluten-free, the cause for celiac disease, which affects humans world wide. The objective of this study was to evaluate the morpho-agronomic performance of newly developed semi-dwarf tef genotypes for grain yield and yield related agronomic traits under diverse environmental conditions. Twenty-four tef lines were evaluated, along with one local and three standard checks, at three locations in the Central Ethiopia. The mean squares due to genotypes, locations and genotype by location interactions were highly significant ($P<0.01$) for all the studied traits. Three genotypes, namely RIL- 91, RIL-244 and RIL-11, gave the highest seed yield, ranging between 4.4 to 4.7 t ha^{-1}, compared to the popular and widely cultivated tef variety called *Quncho* which gave 4.2 t ha^{-1}. Genotypic and phenotypic coefficients of variations ranged from 0.002 to 173.9% and from 0.004 to 255.9%, respectively. The highest genetic advance (20.2 cm) and heritability estimates (86.7%) were obtained for plant height indicating that selection for this trait can be made easily. Grain yield showed significant and positive genotypic association with plant height, whole culm and second culm internode length, second culm internode diameter, number of spikelet per panicle and shoot biomass yield. Cluster analysis grouped the genotypes into six distinct classes. The first five principal components with eigenvalues greater than one accounted for 85% of the total variation. Generally, this study identified tef genotypes with better grain yield and reasonable lodging tolerance for further evaluation and eventual release to the farming communities.

Key Words: *Eragrostis tef,* genetic advance, genotypic coefficients of variations, heritability, phenotypic coefficients of variation, tef

RÉSUMÉ

Tef [*Eragrostis tef* (Zucc.) Trotter] est une culture majeure de céréale dans la corne de l'Afrique, particulièrement en Ethiopie où elle est un aliment de base pour plus de 60% de son 90 million de population. La culture performe mieux que d'autres cultures céréalières dans des conditions environnementales extrêmes. Les grains du tef ne sont pas seulement nutritifs mais aussi ne contiennent pas de gluten, la cause des maladies des céréales, qui affectent les hommes dans le monde. L'objectif de cette étude était d'évaluer la performance morpho-agronomique des génotypes semi-nain de tef nouvellement développés pour le rendement en grain et les composantes du rendement sous diverses conditions environnementales. Vingt-quatre lignées de tef étaient évaluées, ensemble avec un local et trois contrôles standards, dans trois locations dans la région centrale de l'Ethiopie. Les carrées moyens dus aux génotypes, locations et aux interactions entre le génotype et l'environnement étaient hautement significatifs ($P<0.01$) pour tous les traits étudiés. Trois génotypes, nommés RIL-91, RIL-244 and RIL-11, ont donné les rendements les plus élevés en grain variant de 4,4 à 4,7 t ha^{-1}, comparés à la variété de tef populaire et largement cultivée appelée *Ounho* qui a donné 4,2 t ha^{-1}. Les coefficients de variation génotypique et phénotypique ont varié de 0,002 à 173,9% et de 0,004 à 255,9%, respectivement. La plus grande avancée génotypique (20,2 cm) et les estimations d'héritabilité (86,7%) étaient obtenues pour la taille de la plante montrant que la sélection pour ce trait peut être faite plus tôt. Le rendement en grain a montré une association significative et positive avec la taille de la plante, la longueur de l'entre-nœud au niveau de la canne intégrale et la seconde canne, le diamètre de la seconde canne de l'entre-nœud, le nombre d'épillet par panicule et le rendement en biomasse de la tige. L'analyse en class a groupé les génotypes en six classes distinctes. Les cinq premières composantes principales avec des valeurs propres supérieures à un ont pris en compte 85% de la variation totale. En générale, cette étude a identifié des génotypes de tef avec des meilleurs rendements en grains et de tolérance raisonnable à la verse pour davantage évaluation et éventuelle libération aux communautés paysannes.

Mots Clés : Coefficient de variation génotypique, coefficient de variation phénotypique, *Eragrostis tef,* héritabilité, progrès génétique, tef

INTRODUCTION

Tef, *Eragrostis tef* (Zucc.) Trotter, is a major cereal crop in the Horn of Africa, especially in Ethiopia where it is annually cultivated by about 6.5 million smallholder farmers on over three million hectares of land; which is equivalent to 30% of the area allocated to cereal crops (CSA, 2015). Tef plant perform better than other cereals under extreme climatic conditions, which include both excess and scare moisture. Utilisation of tef grain as food crop has been limited to Ethiopia for quite many centuries. However, it is recently becoming a potential diet of attraction worldwide due to its gluten-free nature (Spaenij-Dekking *et al.,* 2005) and many other health-related benefits.

Tef is an allotetraploid, with $2n=4x = 40$ chromosomes (Tavassoli, 1986), having its centres of both origin and diversity in Ethiopia (Vavilov, 1951). It is the only cereal cultivated for human consumption in the genus *Eragrostis* (Tefera and Ketema, 2001; Tefera *et al*., 2003). Tef is adapted to a wide range of environmental conditions and fits in different cropping systems. It also exhibits, high level of phenotypic plasticity in phenology, morphology and agronomic performance (Assefa *et al*., 2001). Despite its high importance to the livelihoods of millions of people, the productivity of tef is very low compared to major cereals. The national average yield in Ethiopia for tef is 1.6 t ha^{-1}; while those of maize and wheat are 3.4 and 2.5 t ha^{-1}, respectively (CSA, 2015). Lodging, wider uses of low yielding cultivars, drought and different other stresses are the major factors contributing to the low productivity of tef (Assefa *et al.,* 2011). Lodging affects both the grain yield and quality of tef, and is found to reduce grain yield by approximately 15 to 45% (Ketema, 1993; Zhu *et al*., 2012), depending on the weather condition and inherent nature of the variety. Hence, lodging is a crucial problem to address as long as tef production and research is concerned.

Efforts made so far have enabled the development and release of over 35 improved varieties to the farming communities in Ethiopia (MoA, 2014). Some of these varieties provide over 4.5 t ha^{-1} grain yield under optimum management practices and non-lodging conditions (Tefera and Ketema, 2001). However, development of high yielding and lodging tolerant tef varieties, adapting to the changing climate remains to be the primary focus of tef research.

Currently, tef researchers are doing their best to tackle lodging, by employing both conventional and modern molecular tools such as TILLING (Targeted Induced Local Lesion in Genome) (Tadele *et al*., 2010; Esfeld *et al*., 2013). To this end, tef mutant lines showing promising results regarding lodging tolerance (for instance, *Kegne* and *Kinde* mutant tef lines) have been developed in collaboration between the University of Bern and the Ethiopian Institute of Agricultural Research (EIAR). *Kegne* is linked to the mutation in the *Alpha-tubulin-1*gene and is characterised by a right-hand twisting phenotype and resistance to microtubule-related drugs like oryzalin (Jost *et al.,* 2015). On the other hand, *Kinde* has been identified as a promising line, having semi-dwarf stature, increased numbers of tillers, tolerance to lodging, larger leaf size and deep green phenotype.

In spite of the many desirable traits of *Kinde*, its grain yield is not as high as improved cultivars such as *Quncho*. Therefore, introgression of *Kinde* to the locally adapted commercial tef varieties and cultivars has been made at Debre Zeit Agricultural Research Centre (DZARC) in Ethiopia. Field tests of the progenies of such crosses have also been conducted at DZARC, to identify lines with desired traits for the current and future tef breeding programme. This study was, therefore, conducted to evaluate at representative locations the performance of selected progenies from two independent crosses to *Kinde* in order to identify promising lines with desirable traits for further improvement of tef.

MATERIALS AND METHODS

Experimental sites. The field experiment was conducted in 2015 at Holetta, Debre Zeit and AlemTena locations in the Central Highland of Ethiopia, during the main cropping season of 2015. Holetta is located at 9° 44’ N, 38° 30’ E, with an altitude of 2400 m above sea level (m asl). It receives an average annual rainfall of 1100 mm, with annual minimum and maximum temperature of 6 and 22 °C, respectively. Debre Zeit is located at 8 44’ N, 38 58’ E, and an altitude of 1900 m asl. It receives an annual average rainfall of 851 mm, with annual minimum and maximum temperature of 8.9 to 28.3°C, respectively. Alem Tena is situated at 8°20’ N, 39°E and an altitude of 1580 m asl. This particular location is situated in the Central Rift Valley, known to have poor distribution of rainfall, relatively high temperatures and a light sandy soil with low moisture retaining capacity. The study was conducted on the Nitosols at Holetta, and on a black clay soil (Pellic Vertisol) with high moisture holding capacity at Debre Zeit and on a light sandy soil at Alem Tena.

Plant materials. A total of 28 tef genotypes, including 24 promising recombinant inbred lines (RILs), three standard checks and a local check (Table 1) were evaluated in the field experiment. The RILs were selected from the crosses of *Quncho* by *Kinde* and from *Kinde* by *Kaye Murri*. The three standard checks were *Kinde*, a semi-dwarf mutant line identified at the University of Bern from mutagenised tef population; *Quncho,* a popular tef variety released for high potential areas in Ethiopia; and *Tsedey,* an improved variety released for moisture-limited environments. The local check was a farmer variety from each location.

Experimental design and management. A Randomised Complete Block Design (RCBD), with three replications was used per site, with a plot size of 1 m x 1 m at spacing of 0.2 m, 1m and 1.5m between rows, plots and replication, respectively. Sowing was done at the recommended period for each location (July 14 at Holetta, July -24 at Alem Tena and August 1 at Debre Zeit). Seeds were drilled along the five rows of each plot at the rate of 10 kg ha^{-1}. Fertiliser was applied according to recommendation for each location (60 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} N at Debre Zeit and 60 kg ha^{-1} P_2O_5 and 40 kg ha^{-1} N at Holetta and Alem

TABLE 1. Lists of tef genotypes used in a study on semi-dwarf tef lines at Holetta, Debre Zeit and Alem Tena in Ethiopia

No.	Genotypes	Source	Remarks
1	RIL-13	*kinde* X *Key Murri* (PVT-2014)	Early set
2	RIL-81	*kinde* X *Key Murri* (PVT-2014)	Early set
3	RIL-302	*kinde* X *Key Murri* (PVT-2014)	Early set
4	RIL-232	*kinde* X *Key Murri* (PVT-2014)	Late set
5	RIL-227	*kinde* X *Key Murri* (PVT-2014)	Late set
6	RIL-181	*kinde* X *Key Murri* (PVT-2014)	Late set
7	RIL-110	*kinde* X *Key Murri* (PVT-2014)	Late set
8	RIL-121	*kinde* X *Key Murri* (AON-2014)	Late set
9	RIL-69	*kinde* X *Key Murri* (AON-2014)	Late set
10	RIL-134	*kinde* X K.Murri (AON-2014)	Early set
11	RIL-11	*kinde* X K.Murri (AON-2014)	Early set
12	RIL-133	*kinde* X *Key Murri* (AON-2014)	Early set
13	RIL-271	*kinde* X K.Murri (AON-2014)	Early set
14	RIL-244	*kinde* X *Key Murri* (AON-2014)	Early set
15	RIL-171	*kinde* X *Key Murri* (AON-2014)	Late set
16	RIL-91	*Quncho* X *kinde* (AON-2014)	Late set
17	RIL-115	*Quncho* X *kinde* (AON-2014)	Late set
18	RIL-180	*Quncho* X *kinde* (AON-2014)	Late set
19	RIL-103	*Quncho* X *kinde* (AON-2014)	Late set
20	RIL-96	*Quncho* X *kinde* (AON-2014)	Late set
21	RIL-132	*Quncho* X *kinde* (AON-2014)	Late set
22	RIL-159	*Quncho* X *kinde* (AON-2014)	Late set
23	RIL-85	*Quncho* X *kinde* (AON-2014)	Early set
24	RIL-137	*Quncho* X *kinde* (AON-2014)	Early set
25	*Quncho*	Parent (Standard check)	Released for high potential areas
26	*kinde*	Parent (Standard check)	Mutant parental line
27	*Tsedey*	Original line	Released for moisture-limited areas
28	Local	Farmers' variety (local check)	

AON = Advanced Observation Nursery; PVT = Preliminary variety trial; RIL = recombinant inbred line

Tena). All amount of P_2O_5 was applied at planting in the form of di-ammonium phosphate (DAP: 46% P_2O_5 and 18% N). However, N was applied partly at planting (from DAP) and the remainder in the form of urea (46% N) at tillering stage (about 30 -40 days after planting). All other agronomic practices were employed as per the recommendations of the respective test locations.

Data collection. Data on days to panicle emergence, grain filling period, days to maturity, shoot biomass, seed yield, thousand kernel weight, lodging and harvest index, were recorded on plot base. Days to panicle emergence was recorded as the number of days taken from seedling emergence to the appearance of panicles in 50% of the plants. Similarly, days to maturity was recorded as the number of days taken from seedling emergence to physiological maturity, when 75% of the straw colour changes to yellowish. On the other hand, grain filling period was computed as the difference between days to maturity and days to panicle mergence.

Shoot biomass was measured as the dry weight of the above ground biomass per plot before threshing; while seed yield refers to the weight of tef grains after threshing. Furthermore, 1000-kernel weight was measured as the weight of 1000 grains of tef. Lodging index was assessed following the method suggested by Caldicott and Nuttall (1979), while harvest index was calculated as a ratio of the grain yield to the above ground shoot biomass. Other data such as plant height, panicle length, peduncle length, whole culm and second basal culm internode length and second basal culm internode diameter were recorded for five randomly selected plants from the central rows.

Data analysis. All data were subjected to analysis of variance (ANOVA) for RCBD, as described by Gomez and Gomez (1984), using SAS version 9 (SAS, 2002). Combined analysis of variance was made, after testing for the homogeneity of variances for each trait using the F_{max} procedure, by dividing the largest variance to the smallest one. Genotypic and phenotypic coefficients of variations were estimated following the method suggested by Burton and Devane (1953).

Broad sense heritability was estimated as per Allard (1960); whereas genetic advance (GA) and genetic advance as percent of the mean (GAM), assuming selection of the superior 5% of the genotypes, was estimated as suggested by Singh and Chaudhary (1996). Besides, phenotypic and genotypic correlation coefficients were computed from the components of variance and covariance based on the method described by Singh and Chaudhary (1996), using the CANDISC procedure of SAS system (SAS, 2002).

Genetic diversity assessment was made through cluster analysis and principal component analyses, using SAS Statistical Software Version 9 (SAS, 2002) and Minitab Statistical software, release 15 for windows (Minitab, 2007). Determination of the number of clusters was made based on the Pseudo-F and Pseudo-T^2 options. Significance of the squared distances was tested as described in the work of Million (2012) for each cluster, against the tabulated X^2 values at p degrees of freedom (where, p is number of traits considered for clustering) at 5% probability level. A complete linkage Euclidian distance method was used to construct dendrogramme.

RESULTS

The combined analysis of variance over three locations, showed that the mean squares due to genotypes, locations and genotype by location interactions were highly significant ($P<0.01$) for all the 16 agronomical and morphological traits evaluated (Table 2).

The combined means across three locations was also computed for the 16 traits of 28 tef genotypes and compared (Tables 3 and 4). Based on this result, RIL-91, RIL-244 and RIL-11 had grain yields of 4.7, 4.4 and 4.4 t ha^{-1}, respectively; which was 4.8-11.9% higher than *Quncho* (4.2 t ha^{-1}). Comparison of the mean performances of each trait at the three environments, also clearly showed that some locations were good enough for the accomplishment of some traits; while others were moderate or even the least for the performance of same traits (Tables 3 and 4). Thus, the highest value for phenologic traits such as peduncle length and lodging index were recorded at Holetta; whereas all traits other than days to heading, length of panicle and second basal culm, and lodging index exhibited the least at Alem Tena.

Ranges of traits. The mean, minimum and maximum values for the 16 traits of the tef genotypes were computed based on combined analyses over three locations, and showed the existence of significant amount of variability among the test genotypes for all the studied traits (Table 5). RIL-302 exhibited the shortest plant height and length of the whole culm, panicle and second basal culm. However, the mutant parental line (*Kinde*) and the original line used for mutagenesis (*Tsedey,* also known as DZ-Cr-37), had the shortest days to phenologic traits compared to the other genotypes. On the other hand, RIL-91 gave the longest panicle, and the highest number of spikelets per panicle, shoot biomass and grain yield. Similarly, RIL-244 gave the second largest grain yield and the highest harvest index value with moderately short days of phonologic traits. Furthermore, RIL-132 is

TABLE 2. Mean squares from the combined analysis of variance for 16 agronomical and morphological related traits of 28 tef genotypes evaluated at three locations in Central Ethiopia

Traits	Replications within locations (DF=6)	Genotypes (G) (DF=27)	Locations (L) (DF=2)	G x L interaction (DF=54)	Error (DF=162)	CV (%)
Days to heading (days)	3.50**	59.77***	10839.83***	17.22***	1.22	2.30
Grain filling period (days)	4.56ns	69.77***	24974.26***	59.18***	2.30	2.90
Days to maturity (days)	4.35ns	115.28***	64974.47***	62.21***	2.72	1.64
Plant height (cm)	0.28ns	1018.13***	2071.83***	53.54***	0.702	0.93
Culm length (cm)	0.28ns	399.74***	1369.17***	91.34***	0.999	1.80
Panicle length (cm)	0.80ns	232.60***	208.43***	68.85***	0.743	2.52
Peduncle length (cm)	0.71ns	34.87***	442.77***	8.75***	0.931	5.15
Second basal culm internode length (cm)	0.77ns	30.61***	20.65***	2.97***	0.458	5.94
Second basal culm internode diameter (mm)	0.16*	0.24***	11.42***	0.185***	0.075	13.30
No. of spikelets/ panicle	0.0018ns	0.063***	1.74***	0.018***	0.001	1.38
No. fertile tillers/plant	0.36**	1.12***	128.37***	1.03***	0.12	10.50
Shoot biomass (t ha^{-1})	0.0015ns	0.061***	2.10***	0.016***	0.0007	2.45
Grain yield (t ha^{-1})	0.0001ns	0.044***	2.74***	0.011***	0.0005	3.70
Harvest index (%)	1.67ns	53.81***	2724.92***	26.34***	1.40	4.31
Lodging index (%)	2.93ns	447.13***	5130.57***	68.85***	4.66	3.36
Thousand kernel weight (g)	0.16ns	19.77***	130.04***	13.30***	0.235	1.80

DF = Degrees of freedom; *, ** and *** = significant at P< 0. 05, P< 0. 01 and P< 0. 001, respectively; ns = Non-significant at P<0.05

TABLE 3. Mean of eight agronomical traits of 28 tef genotypes evaluated at Holetta, Debre Zeit and Alem Tena in Ethiopia

No.	Genotypes	Days to heading	Grain filling period (days)	Days to maturity	Shoot biomass yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index (%)	1000-kernel weight (mg)	Lodging index
1	RIL-13	45.44	53.44	98.89	11.40	3.13	27.29	22.77	60.55
2	RIL-81	52.1	50.22	102.33	10.20	2.58	24.03	23.88	74.36
3	RIL-302	49.22	50.89	100.19	8.34	2.29	25.13	22.73	60.12
4	RIL-232	47.44	58.56	106.00	11.02	3.44	29.93	22.79	72.47
5	RIL-227	47.00	53.00	99.96	11.18	3.45	29.83	22.24	63.56
6	RIL-181	46.89	51.81	97.59	12.92	3.78	27.77	22.70	53.82
7	RIL-110	48.44	54.89	103.56	12.80	3.78	29.16	22.64	68.36
8	RIL-121	44.67	51.26	95.93	11.56	3.62	29.88	22.58	65.22
9	RIL-69	48.89	52.37	101.26	12.64	3.26	24.90	22.94	66.68
10	RIL-134	48.44	48.89	97.33	7.54	2.07	25.79	28.80	71.10
11	RIL-11	44.89	53.30	98.19	12.72	4.35	32.55	27.00	66.10
12	RIL-133	47.26	51.89	99.19	13.29	3.92	28.60	22.35	67.19
13	RIL-271	48.00	54.26	102.26	13.44	3.73	27.06	22.08	63.51
14	RIL-244	44.11	51.70	95.81	13.59	4.47	32.19	22.37	64.98
15	RIL-171	48.22	53.48	101.70	12.87	3.60	27.01	22.25	70.46
16	RIL-91	50.44	56.44	105.78	17.13	4.72	27.29	22.91	59.64
17	RIL-115	47.04	50.11	97.22	10.78	3.28	29.93	22.93	68.51
18	RIL-180	47.04	50.44	97.70	13.26	3.38	25.03	22.65	52.56
19	RIL-103	52.56	54.56	107.11	15.15	3.97	24.55	22.20	58.58
20	RIL-96	49.89	51.11	100.67	11.87	3.16	24.74	22.34	65.53
21	RIL-132	48.63	49.56	98.22	13.82	3.99	28.29	24.28	56.25
22	RIL-159	47.67	50.33	98.00	12.71	3.90	29.39	22.90	77.03
23	RIL-85	48.56	55.56	104.19	13.14	3.55	24.81	25.62	60.60
24	RIL-137	53.00	48.33	101.00	14.34	3.65	23.68	22.17	65.75
25	*Quncho*	53.11	52.44	105.56	15.33b	4.17	25.61	22.31	75.28
26	*Kinde*	48.33	47.22	95.56	7.39o	1.98	26.79	22.94	47.14

TABLE 3. Contd.

No.	Genotypes	Days to heading	Grain filling period (days)	Days to maturity	Shoot biomass yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index (%)	1000-kernel weight (mg)	Lodging index
27	*Tsedey*	42.89	51.22	93.78	12.74	3.97	30.06	27.80	66.31
28	Local check	46.00	58.56	104.56	12.57	3.61	27.95	30.82	58.08
	LSD (0.05)	1.057	1.418	1.539	0.616	0.198	1.10	0.450	1.988
	Mean of locations								
	Alem Tena	42.6	36.6	79.1	7.7	1.7	21.5	58.8	26.
	Debre Zeit	40.5	49.7	90.2	15.3	5.1	32.9	60.8	28.3
	Holetta	61.1	70.8	131.8	14.0	3.0	28.0	73.2	26.6
	LSD (0.05)	0.346	0.464	0.504	0.202	0.065	0.360	0.147	0.651

also among the high yielding genotypes and had the largest diameter of the second basal culm internode.

Estimates of genetic variability. Estimates of variability parameters are presented in Table 6. The highest genotypic coefficients of variation (GCV) were estimated for thousand kernel weight (173%), plant height (123%) and culm length (67.9%); whereas the least were noted for number of spikelets per panicle (0.004%), shoot biomass (0.092%) and grain yield (0.227%) in that order. Likewise, the highest phenotypic coefficients of variation (PCV) values of 143.6, 134.4 and 128.4% were estimated for plant height, panicle length and culm length, respectively. However, the least PCV estimates of 0.002, 0.05 and 0.126% were obtained for number of spikelets per panicle, shoot biomass and grain yield, respectively. The number of spikelets per panicle, shoot biomass and grain yield had the lowest values for both GCV and PCV.

Estimation of the broad sense heritability (H) and genetic advance (GA) showed the highest genetic advance coupled with high heritability value for plant height (20.2 cm, 86.7%) and thousand seed weight (11.6 mg, 68.1%). On the other hand, a high heritability value, accompanied with low genetic advance was estimated for second culm length (78.6%, 3.3 cm).

Association of traits. The correlations among the different grain yield and lodging related traits of the test tef genotypes are presented in Tables 7 and 8. There was positive and highly significant ($P<0.01$) phenotypic association between grain yield and of all traits, other than days to heading. Besides, a significant and positive genotypic association was detected between grain yield and all traits, except days to heading and maturity, peduncle length, number of fertile tillers per plant, lodging index and thousand kernel weight. Similarly, shoot biomass had positive and highly significant ($P<0.01$) phenotypic association with all traits, other than thousand

TABLE 4. Mean of eight morphological traits of 28 tef genotypes evaluated at Holetta, Debre Zeit and Alem Tena in Ethiopia

No.	Genotype	Plant height (cm)	Culm length (cm)	Panicle length (cm)	Peduncle length (cm)	Second basal culm internode length (cm)	Second basal culm internode dia. (mm)	Number of fertile tillers/ plant	Number of spikelets/ panicle
1	RIL-13	85.88	53.51	32.43	16.25	11.21	2.03	3.05	315.10
2	RIL-81	82.68	52.01	30.87	15.69	10.08	2.00	3.27	320.85
3	RIL-302	61.20	34.60	26.84	17.61	6.89	2.00	3.17	241.68
4	RIL-232	88.41	59.97	28.03	21.89	12.01	1.73	2.83	240.30
5	RIL-227	88.94	56.37	32.04	19.78	9.82	2.13	3.63	277.44
6	RIL-181	93.58	56.95	36.63	18.01	11.69	2.04	3.82	315.53
7	RIL-110	89.36	54.38	34.98	17.54	11.38	2.28	3.99	380.22
8	RIL-121	84.02	52.08	31.95	86.25	10.26	2.16	4.13	285.23
9	RIL-69	92.32	54.74	37.88	19.16	10.47	2.15	3.40	437.01
10	RIL-134	73.27	46.31	26.88	18.72	8.03	1.72	3.33	293.37
11	RIL-11	86.83	56.99	29.84	20.36	11.50	2.03	3.34	282.09
12	RIL-133	88.11	58.31	29.80	19.74	11.22	2.00	3.03	290.27
13	RIL-271	94.91	58.05	36.86	23.36	12.3	2.13	3.00	349.89
14	RIL-244	86.00	55.53	30.47	20.78	11.34	2.04	3.80	307.77
15	RIL-171	90.64	59.35	31.28	17.58	12.76	2.14	3.55	419.34
16	RIL-91	108.43	63.54	44.88	17.75	14.59	2.13	3.25	447.10
17	RIL-115	87.19	52.29	34.90	18.87	11.95	1.71	3.02	288.22
18	RIL-180	90.31	57.18	33.13	21.53	12.03	2.14	3.63	328.77
19	RIL-103	101.80	61.94	39.86	196.25	13.22	2.21	3.15	461.37
20	RIL-96	93.90	55.03	38.87	18.32	11.78	1.86	3.41	397.10
21	RIL-132	99.54	63.62	35.92	22.28	12.93	2.33	2.71	353.69
22	RIL-159	101.44	57.48	43.96	18.04	12.04	2.18	3.34	382.91
23	RIL-85	94.22	59.11	35.11	20.17	11.95	1.97	3.17	341.80
24	RIL-137	99.77	62.56	37.21	18.20	13.18	2.14	3.03	379.33
25	*Quncho*	108.78	64.25	44.53	18.74	14.87	2.29	2.64	420.44
26	*Kinde*	66.72	39.53	27.19	15.32	7.18	1.92	3.08	273.09

TABLE 4. Contd.

No.	Genotype	Plant height (cm)	Culm length (cm)	Panicle length (cm)	Peduncle length (cm)	Second basal culm internode length (cm)	Second basal culm internode dia. (mm)	Number of fertile tillers/ plant	Number of spikelets/ panicle
27	*Tsedey*	84.44	52.78	31.66	276.25	11.07	2.08	3.63	310.62
28	Local check	88.51	53.87	34.64	286.25	11.23	2.19	3.43	213.62
LSD (0.05)		0.774	0.922	0.805	0.899	0.635	0.259	0.349	14.528
Mean of locations									
Alem Tena		85.0	51.0	34.0	16.2	11.6	1.8	2.4	245.5
Debre Zeit		94.7	58.9	35.9	19.6	11.8	2.5	4.7	472.7
Holetta		89.3	56.4	32.8	20.5	10.8	2.0	2.8	284.1
LSD (0.05)		0.253	0.302	0.264	0.294	0.208	0.085	0.114	4.756

kernel weight. Likewise, a significant and positive genotypic association was also detected between shoot biomass and all traits, except days to heading, number of fertile tillers, harvest index, lodging index and thousand kernel weight. Surprisingly, lodging which is a major constraint to tef production had no significant ($P<0.05$) genotypic association with all the studied traits. However, it had a positive and significant ($P<0.01$) phenotypic association with days to heading and maturity, culm and peduncle length as well as shoot biomass and grain yield.

Cluster and divergence analysis. The 28 tef genotypes in the current study were grouped into six distinct clusters, based on 16 traits, using the average linkage method (Fig. 1). The number of genotypes per each cluster ranged from two genotypes for cluster 4 up to 9 genotypes for cluster 1. Cluster 2 and 3 had seven and four genotypes, respectively; whereas cluster 5 and 6 had three genotypes each. The different genotypes grouped within a given cluster were assumed to be more closely related in terms of the studied traits than those genotypes grouped into different clusters.

A commercial variety released for the low moisture stress areas (*Tsedey*) was grouped into cluster 1, along with eight recombinant inbred lines. On the other hand, a commercial variety released for the high potential areas (*Quncho*) was grouped into cluster 5 along with two recombinant inbred lines (RIL-91 and RIL-103). Genotypes in cluster 1 had relatively shorter phonologic traits; and an average performance for the remaining traits; whereas those in cluster 5 had high value for almost more than 50% of the traits under investigation. Compared to genotypes in other clusters, those in cluster 5 had higher values for days to heading and maturity, plant height, culm and panicle length, spikelet number per panicle as well as shoot biomass and grain yield. On the other hand, cluster 6 consisted of the semi-dwarf parental line (*kinde*), along with RIL-302 and RIL-134, which had the least values

TABLE 5. Ranges and mean values of 16 traits of tef genotypes evaluated at Holetta, Debre Zeit and Alem Tena in Ethiopia

Traits	Minimum		Maximum		Mean
	Value	Genotype	Value	Genotype	
Days to heading	42.89	*Tsedey*	53.11	*Quncho*	48.08
Grain Filling period (days)	47.22	*kinde*	58.56	RIL-232	52.35
Days to maturity	93.78	*Tsedey*	107.11	RIL-103	100.34
Plant height (cm)	61.20	RIL-302	108.78	*Quncho*	89.69
Culm length (cm)	34.60	RIL-302	64.25	*Quncho*	55.44
Panicle length (cm)	26.84	RIL-302	44.89	RIL-91	34.24
Peduncle length (cm)	15.32	*kinde*	23.36	RIL-271	18.74
Second basal culm internode length (cm)	6.89	RIL-302	14.87	*Quncho*	11.39
Second basal culm internode diameter (mm)	1.71	RIL-115	2.33	RIL-132	2.06
Number of fertile tillers/plant	2.64	*Quncho*	4.13	RIL-121	3.32
Number of spikelets/panicle	213.62	Local	461.37	RIL-91	334.08
Shoot biomass (t ha^{-1})	7.39	*kinde*	17.13	RIL-91	12.35
Grain yield (t ha^{-1})	1.98	*kinde*	4.73	RIL-91	3.53
Harvest index (%)	23.68	RIL-137	32.55	RIL-244	27.47
Thousand kernel weight (mg)	23.88	RIL-81	30.82	Local	26.90
Lodging index (%)	47.14	*kinde*	77.03	RIL-159	64.28

TABLE 6. Estimates and genotypic coefficient of variation and heritability as percent of mean for 16 traits of tef genotypes

Traits	Phenotypic coefficient of variation (PCV) (%)	Genotypic coefficient of variation (GCV) (%)	Broad sense heritability (%)	Genetic advance (GA)	GA as percent of the means
Days to heading	23.67	12.30	51.95	3.61	7.51
Grain filling period (days)	47.00	10.30	21.91	2.24	4.28
Days to maturity	30.33	10.27	33.85	3.85	3.83
Plant height (cm)	143.58	123.86	86.26	20.17	22.48
Culm length (cm)	128.40	73.88	57.54	10.00	18.04
Panicle length (cm)	134.42	67.87	50.49	7.06	20.61
Peduncle length (cm)	33.04	18.58	56.23	2.88	15.38
Second basal culm internode length (cm)	36.40	28.60	78.57	3.30	28.93
Second basal culm internode dia. (mm)	2.88	0.692	24.06	0.12	5.86
No. of fertile tillers/plant	14.46	2.276	15.74	0.22	6.77
No. of spikelet/panicle	0.004	0.002	52.00	0.12	0.04
Shoot biomass yield (kg ha^{-1})	0.092	0.050	54.22	0.12	0.96
Grain yield (kg ha^{-1})	0.227	0.126	55.56	0.10	2.90
Harvest index (%)	48.67	17.84	36.65	2.76	10.05
Thousand kernel weight (mg)	255.39	173.93	68.10	11.63	43.23
Lodging index	9.44	2.62	27.80	1.41	2.19

TABLE 7. Genotypic (upper diagonal) and phenotypic (lower diagonal) correlations among 8 traits of 28 semi dwarf tef genotypes at Holetta, Debre Zeit and Alem Tena in Ethiopia

Variable	DH	DM	PH	CL	PL	PdL	SCL	SCD
Days to heading (DH)	1	0.64***	0.36ns	0.23ns	0.45*	-0.14ns	0.28ns	0.16ns
Days to maturity (DM)	0.92***	1	0.48**	0.44**	0.43*	0.066ns	0.47*	0.21ns
Plant height (cm) (PH)	0.03ns	0.11ns	1	0.93***	0.87***	0.28ns	0.94***	0.50***
Culm length (cm) (CL)	0.11ns	0.20**	0.84***	1	0.63***	0.43*	0.93***	0.42*
Panicle length (cm) (PL)	-0.09ns	-0.08ns	0.69***	0.20**	1	0.01ns	0.74***	0.50**
Peduncle length (cm) (Pdl)	0.32***	0.46***	0.30***	0.42***	-0.02ns	1	0.31ns	0.003ns
Second basal culm internode length (cm) (SCL)	-0.11ns	-0.10ns	0.76***	0.66***	0.51***	0.15*	1	0.42*
Second basal culm internode dia. (mm) (SCD)	-0.17**	0.01ns	0.39***	0.36***	0.22***	0.23***	0.20**	1
No. of spikelet/panicle (SPK)	-0.26***	-0.09ns	0.60***	0.46***	0.48***	0.23**	0.38***	0.59***
No. of fertile tillers/plant (FT)	-0.39***	-0.15*	0.22***	0.20***	0.13*	0.21***	-0.01ns	0.57***
Shoot biomass yield (kg ha^{-1}) (SBM)	0.23***	0.44***	0.67***	0.66***	0.33***	0.54***	0.46***	0.56***
Grain yield (GY) (kg ha^{-1})	0.06ns	0.32***	0.59***	0.61***	0.26***	0.55***	0.36***	0.62***
Harvest index (%)	-0.11ns	0.18**	0.26***	0.35***	0.01ns	0.46***	0.02ns	0.52***
Lodging index (LG)	0.58***	0.62***	0.12ns	0.19**	-0.04ns	0.27***	-0.02ns	-0.08ns
Thousand kernel weight (mg) (TKW)	-0.35***	-0.23***	0.04ns	0.03ns	0.03ns	-0.05ns	-0.01ns	0.23***

*, ** and *** = significant at ≤ 0. 05, at ≤ 0. 01 and at ≤ 0. 001, respectively

TABLE 8. Genotypic (upper diagonal) and phenotypic (lower diagonal) correlations among 7 traits of 28 semi dwarf tef genotypes

Variable	SPK	FT	SBM	GY	HI	LG	TKW
Days to heading (DH)	0.57**	-0.51**	0.20ns	-0.14ns	-0.76***	0.15ns	-0.38*
Days to maturity(DM)	0.39*	-0.38ns	0.43*	0.21ns	-0.40*	0.17ns	-0.08ns
Plant height (cm) (PH)	0.70***	-0.21ns	0.89***	0.76***	-0.08ns	0.19ns	-0.14ns
Culm length (cm) (CL)	0.55**	-0.21ns	0.86***	0.78***	0.05ns	0.21ns	-0.18ns
Panicle length (cm) (PL)	0.74***	-0.17ns	0.74***	0.55**	-0.23ns	0.13ns	-0.066ns
Peduncle length (cm) (Pdl)	-0.05ns	-0.23ns	0.28ns	0.35ns	0.23ns	0.02ns	-0.21ns
Second basal culm internode length (cm) (SCL)	0.61***	-0.22ns	0.90***	0.80***	-0.001ns	0.19ns	-0.02ns
Second basal culm internode dia. (mm) (SCD)	0.46*	0.13ns	0.62***	0.52**	-0.05ns	-0.11ns	-0.04ns
No. of spikelet/panicle (SPK)	1	-0.09ns	0.63***	0.38*	-0.42*	0.16ns	-0.25ns
No. of fertile tillers/plant (FT)	0.67***	1	-0.05ns	0.10ns	0.31ns	-0.01ns	0.39ns
Shoot biomass yield (kg ha^{-1}) (SBM)	0.63***	0.44***	1	0.90***	0.02ns	0.03ns	-0.03ns
Grain yield (GY) (kg ha^{-1})	0.67***	0.60***	0.93***	1	0.45*1	0.12ns	0.08ns
Harvest index (%)	0.50***	0.66***	0.54***	0.78***	1	0.14ns	0.27ns
Lodging index (LG)	-0.07ns	-0.13*	0.21**	0.17**	0.12ns	1	0.11ns
Thousand kernel weight (mg) (TKW)	0.19**	0.43***	0.09ns	0.19**	0.27***	-0.09ns	1

*, ** and *** = significant at ≤ 0. 05, at ≤ 0. 01 and at ≤ 0. 001, respectively

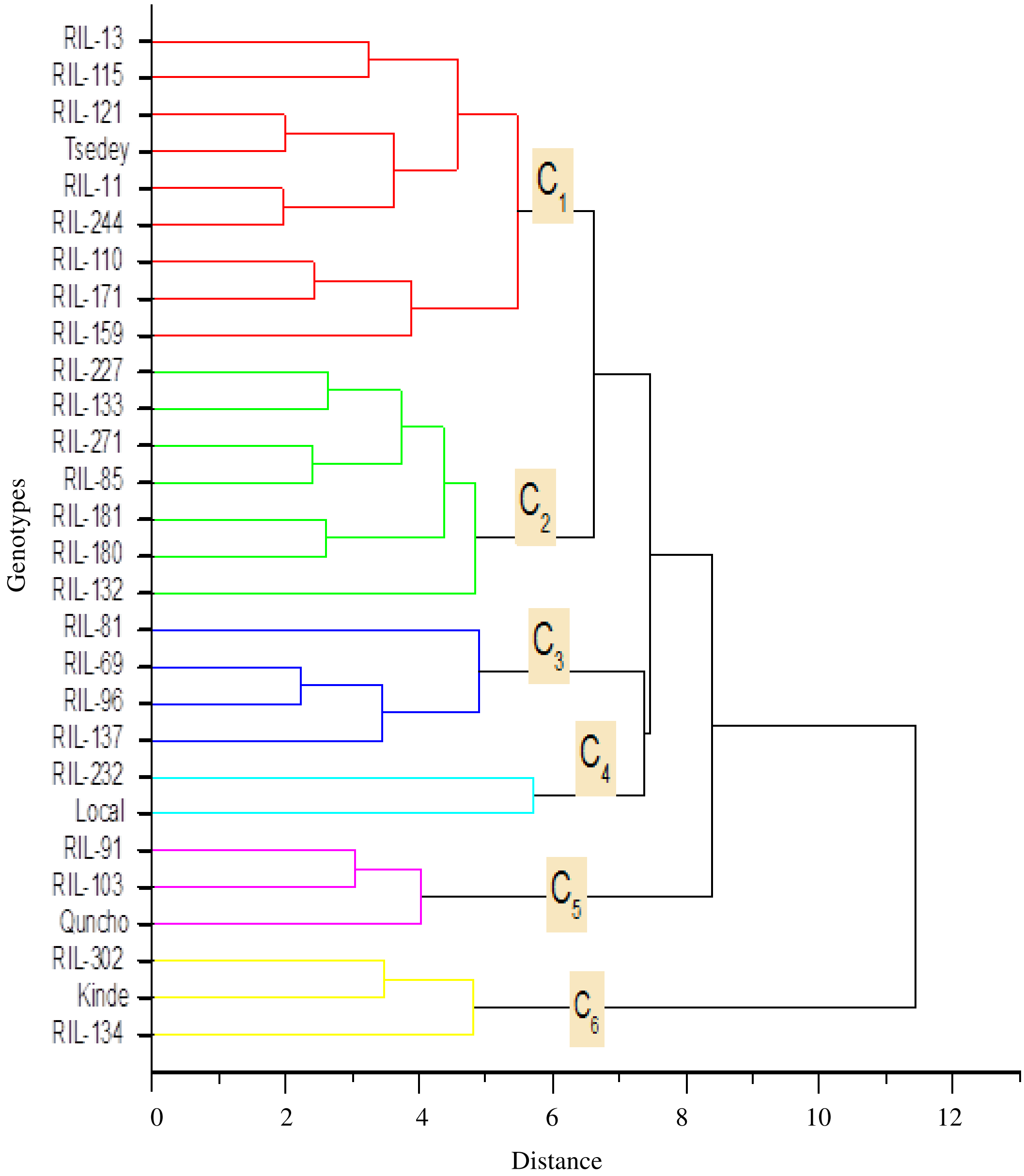

Figure 1. Dendrogram showing the clustering patterns of 28 tef genotypes evaluated for 16 grain yield and lodging related traits of tef at Holetta, Debre Zeit and Alem Tena in Ethiopia.

for nine of the 16 studied traits (Table 9). Among others, they had the shortest days to maturity and for all growth related traits, as well as smaller values of shoot biomass, grain yield and lodging index. Genotypes in certain clusters showed preferential advantages in specific agronomic traits, which can be used for further development into improved varieties. For instance, genotypes in cluster 6 possess lodging-tolerance related traits; while those in cluster 5 are associated to high grain yield.

The distance analysis was estimated for all the 15 possible pairs of clusters in the current study and is presented in Table 10. A maximum distance was observed between cluster 4 and 6 (D^2 = 602.7); followed by cluster 1 and 6 (D^2 = 501.6) and cluster 5 and 6 (462.6). On the other hand, the minimum distance was obtained between cluster 2 and 3 (D^2 = 45.3); followed by that between cluster 2 and 5 (D^2 = 49.4).

Principal component analysis. The patterns of variations among 28 tef genotypes were assessed simultaneously based on the 16 studied traits. The result showed that the first five principal components, with eigen value greater than one, accounted for 85% of the total variations among the studied genotypes (Table 11). Out of this, the first principal component alone had explained 41.3% of the gross variability among the genotypes evaluated mainly due to variations in plant height, second culm and whole culm length. On the other hand, about 17.8% of the total genetic variation in the present study was accounted for the second principal component due mainly to variations in days to heading and maturity, grain yield and number of spikelet per panicle. Furthermore, the third, fourth and fifth principal component contributed for 10, 8.9 and 7% of the total variations, respectively. The main traits that contributed for such variations in principal component three were number of spikelets per panicle, peduncle length, second culm diameter, and days to grain filling and maturity; whereas those contributed for principal component four were days to grain filling and maturity, peduncle length and lodging index. On the other hand, thousand kernel weight followed by days to grain filling

TABLE 9. Mean values for agronomical and morphological related traits of the seven clusters of tef genotype at Holetta, Debre Zeit and Alem Tena in Ethiopia

Traits	Clusters						
	I	II	III	IV	V	VI	VII
Days to heading	45.93	47.63	50.97	46.72	52.04	48.66	45.93
Grain filling period (days)	52.19	52.36	50.51	58.56	54.48	49	52.19
Days to maturity	98.12	99.87	101.32	105.28	106.15	97.69	98.12
Plant height(cm)	88.42	92.8	92.17	88.46	106.34	67.06	88.42
Culm length(cm)	54.93	58.51	56.09	56.92	63.24	40.15	54.93
Panicle length(cm)	33.5	34.21	36.21	31.34	43.09	26.97	33.5
Peduncle length(cm)	18.2	20.7	17.84	19.56	17.98	17.22	18.2
Second basal culm internode length(cm)	11.5	11.71	11.38	11.62	14.23	7.37	11.5
second basal culm internode diameter (mm)	2.07	2.11	2.04	1.96	2.21	1.88	2.07
number of spikelet per panicle	330.17	322.48	383.57	226.96	442.97	269.38	330.17
Number of fertile tiller/plant	3.54	3.28	3.28	3.13	3.01	3.19	3.54
Shoot biomass weight (t/ha)	12.35	13.01	12.26	11.8	15.87	7.76	12.35
Grain yield per hectare (t/ha)	3.79	3.69	3.16	3.53	4.29	2.11	3.79
Harvest index (%)	29.72	27.34	24.34	28.94	25.81	25.9	29.72
Lodging index (%)	67.5	59.64	68.08	65.28	64.5	59.45	67.5
Thousand kernel weight (mg)	27.68	25.85	25.58	28.81	26.97	27.46	27.68

TABLE 10. Pair-wise generalised square distance (D^2) among seven clusters constructed from 28 tef genotypes

Clusters	1	2	3	4	5	6
1	0					
2	68.10**	0				
3	129.69**	45.31**	0			
4	83.88**	88.46**	219.10**	0		
5	58.28**	49.41**	77.18**	111.37**	0	
6	501.61**	365.11**	223.22**	602.71**	462.55**	0

*, ** = significant at P≤ 0. 05 and P≤ 0. 01, respectively

TABLE 11. Eigenvectors and Eigen values of the first five principal components for 16 traits of 28 tef genotypes

Traits	Eigenvectors				
	PC1	PC2	PC3	PC4	PC5
Days to heading	0.166	0.503	-0.028	0.070	0.050
Days to grain filling	0.161	-0.196	-0.363	0.475	-0.329
Days to maturity	0.235	0.212	-0.320	0.417	-0.213
Plant height (cm)	0.377	-0.023	0.027	-0.067	0.082
Culm length (cm)	0.354	-0.100	-0.109	-0.141	0.056
Panicle length(cm)	0.325	0.089	0.209	0.047	0.099
Peduncle length (cm)	0.109	-0.174	-0.439	-0.438	-0.120
Second culm length (cm)	0.366	-0.078	-0.054	-0.032	0.083
Second culm diameter (mm)	0.223	-0.058	0.397	-0.006	-0.262
Number of fertile tiller	0.286	0.210	0.282	-0.015	0.150
Number of spikelet per panicle	-0.085	-0.290	0.458	0.198	-0.030
Shoot biomass weight (t ha^{-1})	0.363	-0.130	0.101	-0.034	-0.101
Grain yield per hectare (t ha^{-1})	0.301	-0.340	0.047	-0.069	0.005
Harvest index (%)	-0.049	-0.521	-0.089	-0.097	0.163
Thousand seed weight (mg)	0.071	-0.012	-0.199	0.191	0.812
Lodging index (%)	-0.056	-0.271	0.079	0.534	0.122
Eigen values	6.60	2.86	1.60	1.43	1.12
Percent variation explained	41.3	17.80	10.0	8.90	7.0
Cumulative % of total variance explained	41.30	59.10	69.10	78.0	85.0

and second culm diameter were the major traits contributed for the variations exhibited for principal component five.

DISCUSSION

Ranges of traits. The substantial variability among the tef genotypes for several agronomic and morphological traits (Tables 2, 3 and 4) could be due to gene recombination or reshuffling resulting from mutagenesis and subsequent crossings. The significant mean square due to locations indicates that the locations were contrasting and adequate for the evaluation of the genotypes. Furthermore, the highly significant genotype by environment interaction effects revealed differential performances of the test genotypes across the locations. Hence, further evaluation of the genotypes under the environment where they perform well will enable their recommendation for specific release. Previous works using various sets of tef genotypes, including germplasm accessions (Assefa *et al.*, 1999), released varieties (Jifar *et al.,* 2015a), and elite brown seed genotypes (Jifar *et al.,* 2015b) indicated the existence of significant variability for diverse traits due to genotype, location, and genotype by location interaction effects on different traits. Besides, highly significant genotype by location interactions was also reported for days to heading, whole culm and second culm length, second culm internode diameter, peduncle length and harvest index (Assefa *et al*., 2000). The significant genotype by environment interaction for days to heading in the present study could probably reveal the presence of high level of phenotypic plasticity in tef genotypes.

RIL-91 gave significantly higher plant height, culm and panicle length, and the highest number of spikelets per panicle, shoot biomass and grain yield compared to all the tef genotypes tested. Also, it exhibited moderately thicker second basal culm internode diameter and low lodging index (Tables 3 and 4). A genotype like RIL-91 possessing these desirable traits is suggested for fast track release and to be used as a parental line for future tef breeding programmes. Thus, the high number of spikelets per panicle, as well as high shoot biomass and grain yields of this particular genotype will play a key role in developing varieties with superior yield. Similarly, the thick culm internode and low lodging index of the same genotype will be a cornerstone towards developing tef cultivars with substantial tolerance to lodging. The development of new varieties for these vital traits can be made through methods which involve stringent selection procedures and/ or crossing to popular improved varieties.

RIL-244 and RIL-11 also had the second and third highest grain yield (Table 3), and intermediate number of days to heading and maturity. The performance of the yield-related traits of these three genotypes were even better than *Quncho*, popular tef variety in high potential areas and by far better than *Tsedey*, a widely cultivated variety in moisture-limited areas in Ethiopia (Assefa *et al*. 2011). This study, therefore, suggests the possibility of promoting RIL-91 for moisture-unlimited and high potential areas, while RIL-244 and RIL-11 for both high potential and average environments in Ethiopia. On the other hand, RIL-302 with its shortest plant height, culm length, and second basal culm can be the right candidate towards developing tef varieties with lodging resistance. Besides, RIL-132 which is also among the high yielding genotypes and had the largest diameter of the second basal culm internode, would play a key role to further improve grain yield and to tackle the problem of lodging.

Regarding the test locations, Holetta had the longest phonologic traits compared to the other two locations (Tables 3 and 4). This is partly due to the long growing season at Holetta which is associated with cooler and higher rainfall environment than the other two locations (Materials and Methods). At Debre Zeit, the majority of the studied traits (70%) showed the highest performance. This might be due to the favourable condition for tef growth on the black soil of Debre Zeit which has high water holding capacity. On the other hand, at Alem Tena, drought-prone location characterised by frequent crop failures due to moisture scarcity, only culm length had the highest values. Hence, the sub-optimal condition at Alem Tena negatively affect the majority of agronomical and morphological traits of tef. Despite obvious negative effects on major traits of tef at Alem Tena, this particular site will continue to serve as the best site to breed for varieties with drought tolerance.

Estimates of genetic variability. The high GCV values estimated for some of the traits in this study (Table 6) indicates the presence of considerable diversity for those traits among the tef genotypes examined. The range of variations estimated for both PCV (0.004 to 255.4%) and GCV (0.002 to173.9%) in the current work were greater than previous reports of 6.1 to 40.2% for PCV and 3.0 to 22.1% for GCV by Assefa et al. (1999) or 2 to 58% for PCV and less than 1 to 35% for GCV by Assefa et al. (2000). Besides, the value of the present finding is much higher than the estimated range of 4.3 to 21.7 for PCV and 4.0 to 20.3% for GCV by Jifar *et al.* (2015a).

High genetic advance, coupled with high heritability values (Table 6) revealed that the heritability of those traits was mainly due to additive gene effects and, hence, selection may be effective to improve those traits. However, high heritability, accompanied with low genetic advance, indicates such high heritability of a given trait is mainly due to favourable influence of the environment rather than the genotype. The broad sense heritability estimates obtained in this study are commensurate with other earlier studies (Assefa *et al.* 1999; Assefa *et al.*, 2000). However, our results were also either slightly higher (Tilahun *et al.*, 2012), or lower (Jifar *et al.* 2015a; Jifar *et al.*, 2015b) than earlier studies. These discrepancies could be due to the differences in the test genotypes and environments used.

Association of traits. The existence of positive associations (Table 6) among traits indicates that improving one of them would bring an improvement in the other trait. This indicates that selection for such related traits can be made based on only those traits that can be assesses relatively easily. The positive and significant association detected among grain yield and that of shoot biomass and harvest index in this study is in line with the findings of several researchers (Chanyalew *et al.*, 2006; Chanyalew *et al.*, 2009; Jifar and Assefa, 2013; Jifar *et al.*, 2015a; Jifar *et al.*, 2015b). This indicates the relatively consistent association of the tef traits in various studies. Similarly, the positive and significant phenotypic association of lodging index with days to heading and maturity is in line with Jifar *et al.* (2015b) but contrary to Jifar *et al.* (2015a) with respect to the direction of association. These contrasting relationships between lodging index and days to heading was due to the differences in the type of tef varieties used in the two experiments. Varieties with long heading time are more vulnerable to lodging due to longer period of exposure to wind and rain while those with shorter heading time score lower degree of lodging. Besides, Chanyalew *et al.* (2009) also reported a positive and significant phenotypic association between lodging index and grain yield. This indicates that the problem of lodging is more severe in high yielding than in low yielding genotypes since the heavy weight of the panicles in high yielders contributes to the lodging inducing torque or force.

Cluster and divergence analysis. Among the seven distinct clusters, genotypes in cluster 5 were characterised to have high grain yield accompanied with longest days to heading and maturity that enable to address varietal development and release in high potential environments. High yielding genotypes are usually late maturing types and are suitable for areas with optimum rainfall and long growing period.

Genotypes in cluster 5 had the highest number of spikelet per panicle, shoot biomass and grain yield; whereas those in cluster 4 had the highest 1000-kernel weight. In addition to those in cluster 5 and 4, genotypes in cluster 1 had the shortest days to heading and to maturity, the highest number of fertile tillers and the harvest index value. Such desirable traits observed in these clusters are important for further improvement of yield related traits of tef.

Existence of maximum amount of genetic recombination and genetic segregation is generally suggested for crosses being made between clusters with maximum distances. Thus, crosses of tef genotypes from cluster 4 and 6 will enable us to get maximum recombination, based on the present investigation. The total number of clusters investigated in this study is similar to the works of Jifar *et al.* (2015a) who used 36 brown seeded tef genotypes based on ten yield related traits. Another closer result was reported by Plaza-Wüthrich *et al*. (2013) who obtained six distinct clusters based on ten traits using 18 tef genotypes (15 landraces and three improved varieties). Though the number of genotypes studied varied for diverse studies, this cluster analysis generally revealed the existence of significant genetic variation that can be utilised for further tef improvement.

Principal component analysis. Based on principal components analysis (Table 11), the total variation that was explained in the present study (85%) was higher than that of Plaza-Wüthrich *et al.* (2013), who reported 79.6% for the first four principal components with eigenvalue greater than one. Similarly, it was higher than that of Assefa *et al.* (1999) and Jifar *et al*. (2015a), who reported a value of 73.7 and 78.3% for the first four and first three principal components with eigenvalue greater than one, respectively. However, the variability explained by the first principal component (41.3%) in the present study is almost similar with Jifar *et al*. (2015a); Plaza-Wüthrich *et al*. (2013); Assefa *et al*. (1999) who reported 44. 7, 39.7 and 34.4% respectively using different sets of tef germplasm. Generally, this indicates that most of the variation in phenology and morpho-agronomic traits of tef can be explained on the basis of the first two to three or four principal components.

On the other hand, variations in plant height, second culm and whole culm length were the main contributors for the gross variation explained by principal component one (41.3%) while variations in days to heading and maturity, grain yield and number of spikelet per panicle had mainly contributed to second principal component (17.8%). The remaining traits were also mainly contributing to principal component 3, 4 and 5, respectively. The result, therefore, revealed that tef is a very versatile and complex species whereby almost all the studied traits appeared to have high contributions towards the gross phenotypic variability present among the genotypes.

CONCLUSION

Results of evaluation of some promising lines of tef for lodging and yield improvement reveal that grain yield is significantly and positively associated with all traits, except days to heading and to maturity; peduncle length, number of fertile tillers, lodging and 1000-kernel weight. This suggests the possibility of improving grain yield by considering any one of the associated traits.

Cluster analysis groups the 28 tef genotypes into six distinct clusters, of which 32.1% was grouped in cluster 1, followed by cluster 2 (25%). The first five principal components with eigenvalues greater than one accounts for 85% of the total variations among the genotypes investigated.

In general, the existence of considerable variations for all traits of the test genotypes have been detected. Thus, genotypes like RIL 91 (a cross between *Quncho* and *kinde*) has significantly longer panicle, higher number of spikelet per plant, as well as the highest shoot biomass and grain yield. Besides, RIL-244 and RIL-11, both from the crosses of *kinde* by *Kaye Murri,* are ranked the second and third high yielding genotypes, with relatively shorter days to heading and to maturity. Genotypes identified with better grain yield related traits and reasonable lodging tolerance require further evaluation and eventual release to the farming communities in tef growing environments in Ethiopia.

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