Advances in Crop Science and Technology
ISSN: 2329-8863

Jifar et al., Adv Crop Sci Tech 2022, 10:2

Research Article | Open Access

Exploring the Variation in Grain and Straw Yield and Straw Quality Traits of Improved Varieties of Tef [*Eragrostis tef (Zucc.) Trotter*]

Habte Jifar[1], Kebebew Assefa[1], Zerihun Tadele[2], Kassahun Tesfaye[3,4], Kifle Dagne[5], Alemayehu Teressa Negawo[6], Michael Blümmel[6] and Chris S. Jones[7]*

[1]*Ethiopian Institute of Agricultural Research, Debre Zeit, Ethiopia*
[2]*Institute of Plant Sciences, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland*
[3]*Addis Ababa University, Institute of Biotechnology, Addis Ababa, Ethiopia*
[4]*Ethiopian Biotechnology Institute, Addis Ababa, Ethiopia*
[5]*Department of Microbial, Cellular and Molecular Biology, Addis Ababa University, Addis Ababa, Ethiopia*
[6]*International Livestock Research Institute, P.O. Box 5986 Addis Ababa*
[7]*International Livestock Research Institute, P.O. Box 30709, Nairobi 00100, Kenya*

Abstract

Tef [*Eragrostis tef (Zucc.) Trotter*] is an indigenous Ethiopian cereal providing healthy and nutritious diets for people and a palatable straw for livestock. Thirty-five released varieties and a local check were grown at two locations over two years in Ethiopia to investigate the variation in grain and straw yield and straw quality traits of tef. The investigated traits were grain yield (GY), straw yield (STY), crude protein (CP), in vitro organic matter digestibility (IVOMD), metabolizable energy (ME), acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL). GY, CP, IVOMD and ME were significantly ($P < 0.01$) affected by the variety of tef, the cultivation environment and their interactions. The performances of the GY, CP, IVOMD and ME traits were higher ($P < 0.01$) at mid-altitude, in Debre Zeit, compared to the high-altitude site, Holetta, and in 2016 than 2015. Similarly, the associations observed between GY and STY, among CP, ME and IVOMD, and among NDF, ADF and ADL were significant ($P<0.01$) and positive. Conversely, the association between yield and quality traits was significant and negative. The present study also identified four groups of varieties based on their grain and straw yield and straw quality traits, with some varieties performing above the mean for both yield and quality traits. Hence, varieties like Melko which possess better grain and straw yield and quality traits could be promoted for immediate utilization as a dual-purpose variety or as a parental line in changing the existing tef breeding strategy that focuses on grain yield improvement alone.

Keywords: *Eragrostis tef*; Grain yield; Straw yield; Straw quality; Tef variety; Variation

Introduction

Tef [*Eragrostis tef (Zucc.) Trotter*] is an indigenous cereal crop widely grown in Ethiopia, where it is cultivated on 3.1 million hectares of land by 7.1 million households and produces approximately 5.7 million tons of grain annually [1]. The grain of tef is gluten free and considered to be a nutritious human food [2-4] while its straw is used as a good source of livestock feed [5, 6]. Consequently tef is growing in popularity, both for its grain and as a forage crop, in more countries around the world [7-9]. Though tef adapts to grow across a wide range of soil, altitude, rainfall and temperature conditions, its grain and straw yield and quality are a function of the genotype, the environment and of their interactions [4, 10]. This is not unusual and environmental factors significantly affect the quality of forage crops, particularly those grown in environments with varying degrees of different stresses [11]. Temperature, in particular, affects the digestibility of grasses, mainly through its effect on leaf-to-stem ratios and on increases in the indigestible cell-wall fraction and the concurrent reduction in nonstructural carbohydrates. On the other hand, the effect of drought on forage quality is usually only slightly negative, and can even be positive, particularly if the stress on leaf mass is not severe, and the effect of soil nutrients on forage quality of many grasses is also relatively small [11].

Natural pastures, crop residues, agro-industrial by-products, and improved forage and pasture crops are the major sources of animal feed in Ethiopia, with the first two contributing the largest share [12, 13]. However, grazing lands are shrinking due to conversion into arable lands to support the ever increasing human population and the associated demand for food. Consequently the lack of feed, both in terms of quality and quantity, is becoming the major constraint to livestock productivity in Ethiopia, especially during the dry season [14, 15]. This in turn affects the ability of farmers to produce food and cash crops by reducing the availability of draft power, cash and manure [6]. More efficient use of crop residues is an option suggested to fill the gaps in feed availability. However, this opportunity is highly dependent on the farming system, type of crop and intensity of cultivation [12]. The appropriate identification and utilization of dual purpose crop cultivars is an additional option to help address these shortages in quality feed as well as to reduce competition for land and water. Various works demonstrating the potential of dual purpose cereal crops, such as maize, sorghum, wheat and rice in different parts of the world, including Ethiopia, have previously been presented [16-18]. The identification of dual purpose tef cultivars is also important since the crop covers the largest area under cereal production and provides nearly half of the total annual cereal straws in the central highlands [6] and a quarter of the total straw in Ethiopia [19]. The national tef improvement program, which has been able to double grain productivity, to date, has not paid significant attention to the improvement of fodder quality traits [1]. Anecdotal evidence indicates that farmers in major tef growing areas

***Corresponding author:** Chris S. Jones, International Livestock Research Institute, P.O. Box 30709, Nairobi 00100, Kenya, Tel: +254-710 915 068; E-mail: C.S.Jones@cgiar.org

Received: Nov-24-2021, Manuscript No: acst-21-48285, **Editor assigned:** Nov-26-2021, PreQC No: acst-21-48285(PQ), **Reviewed:** Feb-03-2022, QC No: acst-21-48285, **Revised:** Feb-10-2022, Manuscript No: acst-21-48285 (R), **Published:** Feb-16-2021, DOI: 10.4172/2329-8863.1000494

Citation: Jifar H, Assefa K, Tadele Z, Tesfaye K, Dagne K, et al. (2022) Exploring the Variation in Grain and Straw Yield and Straw Quality Traits of Improved Varieties of Tef [*Eragrostis tef (Zucc.) Trotter*]. Adv Crop Sci Tech 10: 494.

are concerned that high yielding improved grain varieties have fibrous straw which is less liked by livestock. However, studies conducted so far on tef straw yield and fodder quality traits to confirm such speculation have been limited. The importance of tef as a food and a feed crop, together with the farmers demand to have varieties with higher yield and straw quality traits, calls for the identification, development and release of dual purpose tef varieties in the future.

A substantial amount of research performed over the last few decades has revealed the presence of significant variation in feed traits, both within and between cultivars, of several cereal crops, and demonstrated that this variation can be exploited without compromising the grain traits [17, 20-22]. Considering the importance of feeding the straw in support of livestock production, little effort has been put into exploiting the opportunity to improve both the grain and crop residue traits of tef concurrently. Therefore, this study was designed to assess the grain and straw yield and straw fodder quality traits of 36 tef varieties, consisting of 35 released varieties and a local check, both within the selected varieties and across growing environments, and to provide recommendations for tef breeding programs on selecting for both food and feed values in the future.

Materials and Methods

Description of the study area

The field study was conducted at Holetta and Debre Zeit Agricultural Research Centers in central Ethiopia during the main cropping seasons of 2015 (Year 1) and 2016 (Year 2). The distribution of major weather variables in Holetta and Debre Zeit in 2015 and 2016 are summarized in Figure 1. Holetta is located at 2400 meters above sea level (masl) and receives 1100 mm annual rainfall in a bimodal pattern with the main rains falling between July and September. Its minimum and maximum temperatures are 6⁰C and 20⁰C, respectively and the major soil type is a Nitosol. Debre Zeit is located at 1850 masl and receives 851mm annual rainfall in a similar pattern to Holetta. Its temperature ranges between 6⁰C and 20⁰C and the major soil type is a Pellic Vertisol.

Treatments and trial design

Thirty-five improved tef varieties, released between 1970 and 2014 in Ethiopia [23], and a local check [Table 1] were evaluated in a randomized complete block design with three replications. A plot area of 1m x 1m was used at a spacing of 0.2 m, 1 m and 1.5 m between rows, plots and replications, respectively. A fertilizer rate of 60 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} N was applied at the Debre Zeit experimental site while 60 kg ha^{-1} P_2O_5 and 40 kg ha^{-1} N was applied in Holetta. The entire P_2O_5 and half of the recommended N was applied in the form of diammonium phosphate (DAP) at planting while the remaining N was applied in the form of urea at tillering, about 30 - 40 days after planting, depending on the climatic conditions of the experimental sites. In this study, 50% more N was applied to the black vertisol soil, in Debre Zeit, which is more exposed to fertilizer leakage than the red nitosol soils in Holetta, based on the national fertilizer recommendation rates. All agronomic and cultural practices were applied as per the recommendation for each location. Harvesting of the tef crop was performed close to ground level at the full grain maturity stage and straw samples, for laboratory analysis, were taken after threshing and partitioning of shoot biomass into grain and straw. All necessary care was taken not to miss the various straw components (leaf, stem and chaff) of the samples from each plot.

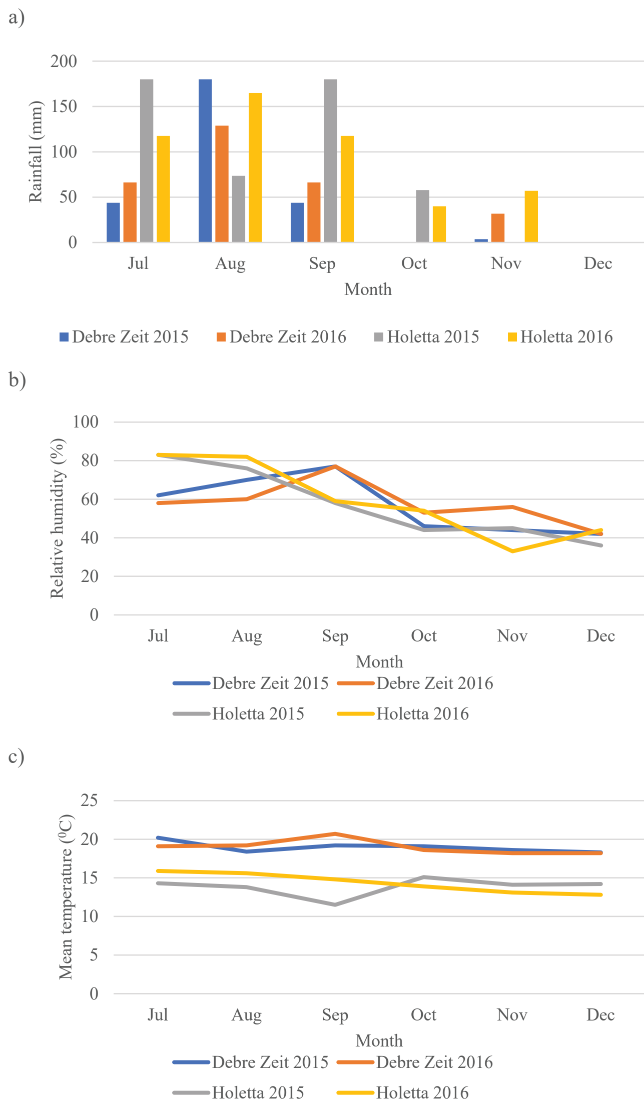

Figure 1: Patterns of: a) rainfall (mm); b) relative humidity (%) and; c) mean temperature (°C) during the tef growing seasons in 2015 and 2016 in the two research centers.

Assessment of tef straw fodder quality attributes

Four hundred and thirty-two tef straw samples, pre-dried overnight in an oven at 60⁰C, were analyzed using Near Infrared Spectroscopy (NIRS) at the ILRI Nutrition Laboratory in Addis Ababa, Ethiopia. A FOSS Forage Analyzer 5000 with software package WinISI II (version 1.5, Intra Soft International, LLC) and specifically developed calibration equations, was employed at a scanning wavelength of 1100 nm to 2500 nm. The determined feed constituents were dry matter (DM), ash, Nitrogen (N), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), metabolizable energy (ME) and *in vitro* organic matter digestibility (IVOMD).

For wet chemistry analysis, 104 representative samples were selected based on their NIRS spectra to develop and validate the tef straw calibration equations at the ILRI Nutrition facilities in Addis Ababa, Ethiopia and Hyderabad, India. From these, 52 samples were used to develop the calibration and a further 52 samples were used to validate this calibration. Following validation, the calibration was finalized

Table 1: List of tef varieties used in the current study.

No.	Varieties		No.	Varieties	
	Pedigree	Common name		Pedigree	Common name
1	DZ-01-354	Enatit	19	DZ-01-1821	Zobel
2	DZ-01-99	Asgori	20	DZ-01-2423	Dima
3	DZ-01-196	Magna	21	DZ-01-1868	Yilmana
4	DZ-01-787	Wolenkomi	22	DZ-01-2675	Dega Tef
5	DZ-Cr-44	Menagesha	23	DZ-01-899	Gimbichu
6	DZ-Cr-82	Melko	24	Ho -Cr-136	Amarach
7	DZ-Cr-37	Tseday	25	DZ-Cr-387	Quncho
8	DZ-Cr-255	Gibe	26	DZ-01-1880	Guduru
9	DZ-Cr-358	Ziquala	27	DZ-Cr-387 (RIL-127)	Gemechis
10	DZ-01-974	Dukem	28	Acc. 205953	Mechare
11	DZ-01-2053	Holeta Key	29	23-Tafi Adi-72	Kena
12	DZ-01-1278	Ambo-Toke	30	DZ-01-3186	Etsub
13	DZ-01-1281	Gerado	31	RIL 273	Laketch
14	DZ-01-1285	Koye	32	DZ- CR-385 (RIL-295)	Simada
15	DZ-01-1681	Key Tena	33	DZ-Cr-409 (RIL 50d)	Boset
16	DZ-01-2054	Gola	34	133B (Quncho x K. Muri)	Kora
17	PGRC/E 205396	Ajora	35	214746A	Worekiyu
18	DZ-01-146	Genet	36	Farmers' variety	Local check

Table 2: Tef straw global calibration models.

	52 Calibration			52 Validation			104 Calibration		
Constituent	n	R^2_{cal}	SEC	n	R^2_{val}	SEC	N	R^2_{Global}	SEC
N	49	0.996	0.035	52	0.951	0.122	100	0.985	0.066
NDF	47	0.964	0.8	52	0.92	1.628	99	0.976	0.763
ADF	44	0.944	0.645	52	0.918	0.902	103	0.922	0.813
ADL	49	0.938	0.176	52	0.789	0.305	102	0.893	0.229
IVOMD	50	0.995	0.255	52	0.971	0.58	104	0.99	0.341
ME	50	0.991	0.036	52	0.969	0.067	102	0.992	0.034

N = Nitrogen; NDF = Neutral detergent fiber; ADF = Acid detergent fiber; ADL = Acid detergent lignin; IVOMD= In vitro organic matter digestibility; ME = Metabolizable energy; SEC = standard error of calibration.

using all 104 samples. Determination of DM, ADF, NDF and N were performed in duplicate and expressed on a dry weight basis using 2 g, 1 g, 0.5 g and 0.3 g of ground samples, respectively. DM, ash and N were analyzed according to the Association of Official Agricultural Chemists (AOAC) [24], NDF, ADF and ADL following [25], ME following [26] and IVOMD according to [27]. Total N was determined following the Kjeldahl procedure [28] and the crude protein (CP) concentration was calculated as $N^*6.25$. Prediction of all samples scanned by NIRS was performed after developing and validating the new tef straw equations. The developed equations showed very strong and consistent correlation between NIRS and chemical analysis. Thus, the coefficient of determination (R^2) values, ranging between 0.893 (ADL) and 0.992 (ME), and low standard error of calibration (SEC) values, ranging between 0.813 (ADF) and 0.034 (ME), [Table 2] support the robustness of the equations and potential use of NIRS to predict tef straw quality [29].

Statistical analysis

The analysis of variance was conducted using the general linear model procedure of SAS software [30] and the test for mean separations were declared at $P < 0.05$ using the least significant difference procedure. Estimation of the Pearson correlation coefficient among the studied food-feed traits was performed using MINITAB software [31] and analysis of clusters and the principal component bi-plots, showing the distribution of studied traits and varieties were performed using R software [32-34].

Results and Discussion

Analysis of variance

Combined analysis of variance for grain and straw yield and straw quality traits revealed significant ($P < 0.01$) effects of variety (G) and location (L) on all the studied traits of tef [Table 3]. The effect of: year (Y), except for grain yield and ME; interaction of L x Y, except for NDF and ADL; and that of G x L, G x Y and G x L x Y, except for ADL, were all highly significant ($P < 0.01$). Surprisingly, ADL was not significantly affected under all types of interactions.

Effect of location on yield and quality traits of 36 tef varieties

The studied grain and straw yield and straw quality traits of the 36 tef varieties at Holetta and Debre Zeit in both years are presented in Table 4. The CP content ranged from 52.8 to 107.2 and 13.8 to 49.7 g kg^{-1} DM in Debre Zeit and Holetta, respectively. Similarly, IVOMD ranged from 44.4 to 52.8% in Debre Zeit, while in Holetta it ranged from 40.7 to 45.1%. Furthermore, the GY ranged from 2160 to 5780 kg ha^{-1} and from 2810 to 4800 kg ha^{-1} in Debre Zeit and Holetta, respectively. The STY ranged from 4970 to 13920 kg ha^{-1} in Debre Zeit, while in Holetta it ranged from 6900 to 24410 kg ha^{-1}. In general, the existence of exploitable genetic variation in grain and straw yield and straw quality traits were observed over years and across locations in Table 4. This is in line with reports on other cereal crop residues such as maize, sorghum, rice and wheat in Ethiopia and other parts of the world [17,

Table 3: Mean square values for the combined ANOVA across two locations by two years.

Source	DF	CP	NDF	ADF	ADL	ME	IVOMD	GY	STY
Entry (G)	35	1.08***	3.91***	3.54***	0.25***	0.03**	2.11**	1.86**	23.54***
Loc (L)	1	2556.9***	5295.1***	7134.6***	141.8***	37.9**	3178.7**	28.98**	1510.7**
L*G	35	1.06***	3.71***	3.23***	0.22ns	0.04**	2.45**	0.28**	7.19***
Year (Y)	1	171.7***	338.85***	107.57***	16.6***	0.06ns	25.00**	0.01ns	1548.1**
Y*G	35	0.97***	5.19***	3.02***	0.22ns	0.03**	1.87**	2.23**	23.87***
Y*L	1	19.19***	2.25ns	81.35***	0.00ns	0.45**	13.3**	8.63**	1607.4**
Y*L*G	35	0.88***	3.36***	3.66***	0.20ns	0.03**	2.04**	0.26**	3.94***
Error	286	0.28	1.77	1.23	0.15	0.02	0.80	0.02	0.44
Mean	56.9	801.8	401.7	76.9	6.60	455.8	3880	11920	
CV (%)	9.27	1.66	2.39	5.03	1.98	1.96	3.56	5.55	
R2	0.97	0.92	0.95	0.82	0.90	0.94	0.97	0.98	

DF = Degrees of freedom; CP = Crude protein; NDF = Neutral detergent fiber; ADF = Acid detergent fiber; ADL = Acid detergent lignin; ME = Metabolizable energy; IVOMD= In vitro organic matter digestibility; GY = grain yield; STY = Straw yield. ** Significant at P < 0.01, *** significant at P < 0.001, ns: not significant.

Table 4: Descriptive statistics showing the variation in grain and straw yield and straw quality traits of tef evaluated in Debre Zeit and Holetta in the 2015 and 2016 cropping seasons.

Traits	Comparison of means				Ranges of values for various traits for each location, year and combined data										Over all
	Between locations		Between years		Debre Zeit		Holetta		2015		2016		Combined		combined
	Debre Zeit	Holetta	2015	2016	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	means
CP	81.3a	32.6b	50.6b	63.2a	52.8	107.2	13.8	49.7	13.8	102.1	23.2	107.2	50.4	62.6	56.9
NDF	766.7b	836.8a	810.6a	792.9b	711	827.1	788.9	874.4	711	874.4	716.9	859.7	790.8	811.8	801.8
ADF	430.1b	511.4a	475.7a	465.7b	383.2	474.9	479.7	544.1	383.2	544.1	400.3	529.5	460.5	479.4	470.8
ADL	71.2b	82.7a	78.9a	75.0b	57.7	85.8	69.2	93.9	57.7	93.9	59.9	89.7	6.4	9.4	76.9
ME	6.89a	6.30b	6.58a	6.61a	6.39	7.66	6.02	6.61	6.02	7.66	6.13	7.22	6.21	7.14	6.6
IVOMD	48.3a	42.9b	43.3b	45.8a	44.4	52.8	40.7	45.1	40.7	52.8	41.6	51.1	44.9	46.3	45.6
GY	4140.0a	3622.4b	3886.2a	3876.6a	2160	5780	2810	4800	2580	5780	2160	5200	3230	4630	3881.4
STY	10070b	13805a	13828a	10042b	4970	13920	6900	24410	4970	24410	6530	13920	9760	14830	11938

ADF = acid detergent fiber (g kg^{-1} DM); ADL = acid detergent lignin (g kg^{-1} DM); CP = crude protein (g kg^{-1} DM); GY = grain yield (Kg ha^{-1}); IVOMD = *in vitro* organic matter digestibility (%); ME = metabolizable energy (MJ); NDF = neutral detergent fiber (g kg^{-1} DM); STY = straw yield (Kg ha^{-1}). Values with different letters indicate statistically significant differences (P <0.05).

20-22]. The performances of all traits were significantly higher in Debre Zeit compared to Holetta except for all fiber related traits, which are negatively correlated with other straw quality traits and straw yield. For example, the crude protein, grain yield and IVOMD were 150%, 12.5% and 11.2%, respectively, higher in Debre Zeit compared to Holetta. This could be due to differences in management practices and, in soil and climate variables between the two locations [Figure 1]. For example, the low crude protein content of tef straw observed at Holetta might be due to its high rainfall, supporting the positive effect of drought on forage quality reported by [11]. It could also be due to the relatively acidic nature of the soil at Holetta (pH = 6.32) [35] unlike Debre Zeit where the black Vertisols are found to be neutral (pH = 7.03) [36]. Furthermore, altitude could also be a contributing factor. In line with this, samples from mid-altitude areas have been reported to have three-fold the proline levels compared to those from the high-altitude areas and also a decrease in lysine content of tef straw with an increase in altitude [37]. This could be a possible explanation for Debre Zeit, which is located at 1850 m above sea level in the mid-altitude environment, to have higher crude protein content compared to Holetta, which is a true highland site, located at 2400 m above sea level. The variation in straw quality traits across locations in the present study is also in line with previous reports for Holetta and Ginchi [19] and for Debre Zeit and Akaki [38]. The observed varietal trait differences in our study are also in agreement with the report by [5]. The previous studies reported the variation in either grain or straw yield or straw quality traits alone based on the assessment of only a few varieties. Our research builds on these initial studies by undertaking a comprehensive assessement of the variation in grain and straw yield as well as straw quality traits of 35 released varieties and a local check evaluated at two locations for two years.

Effect of years on yield and quality

With respect to years, the CP content ranged from 13.8 to 102.1 and 23.2 to 107.2 g kg^{-1} DM in 2015 and in 2016, respectively. Similarly, IVOMD ranged from 40.7 to 52.8 and 41.6 to 51.1% in 2015 and 2016, in that order. Thus, a 24.9% and 5.7% higher CP content and IVOMD, respectively, were observed in 2016 than 2015, while the reverse was observed for straw yield and all fiber traits in both years. On the other hand, GY ranged from 2580 to 5780 and 2160 to 5200 kg ha^{-1} in 2015 and in 2016, respectively, while the STY ranged from 4970 to 24410 and 6530 to 13920 kg ha^{-1} in 2015 and 2016, in that order. In general, the highest values of CP, ME and IVOMD were obtained in 2016 compared to 2015 while the performances of grain and straw yields and all fiber contents were higher in 2015 than 2016. Such better CP content and IVOMD in 2016 compared to 2015 might be due to a better amount and distribution of rainfall in 2016 [Figure 1] by increasing the uptake of useful assimilates. The higher CP content observed in 2016 compared to 2015 samples might also be due to variation in storage duration. Because, fresh samples are said to have higher CP content than those stored for longer duration. In line with this, a study conducted on the effect of storage duration of tef and wheat straw quality reported a decrease in CP content with prolonged storage [39].

Effect of years by location interaction on yield and quality of tef

Based on data from the combined means over years by locations, the CP content ranged from 50.4 to 62.6 g kg^{-1} DM with a mean of 56.9 g kg^{-1} DM while IVOMD ranged from 44.9 to 46.3%. On the other hand, the GY ranged from 3230 to 4630 kg ha^{-1} while straw yield ranged from 9730 to 14830 kg ha^{-1} [Table 4]. The observed mean CP values in the present study are higher than previous reports of 39 g kg^{-1} DM [15] and 46.0 g kg^{-1} DM [40] while they are comparable with CP values ranging from 45.4 to 61.3 g kg^{-1} DM [41] and a CP value of 60 g kg^{-1} DM reported for 21 tef varieties [42]. On the other hand, our CP content values are much lower than the 90 -140 g kg^{-1} DM reported for tef by [43]. Such variation in values of CP contents among the various reports could be a result of differences in the stages of crop harvesting. Because, in our case the straw samples were collected after the grain harvest while the samples in the Miller [43] study were collected at a green stage from a crop entirely grown for forage purposes. In the present study, generally, a wider range of variation was observed among tef varieties for grain and straw yields compared to straw quality traits probably due to the existing breeding strategy that has been entirely focusing on improvement of the grain yield.

Relationships between traits and their implications in tef improvement

A Pearson correlation coefficient among grain and straw yield and straw quality traits of tef was estimated based on combined means across two locations by two years [Table 5]. Positive and significant ($P < 0.01$) associations were observed between GY and STY, and among CP, ME and IVOMD while the latter three traits were negatively and significantly ($P < 0.01$) correlated with the remaining studied traits. On the other hand, the association among the three cell wall constituents (NDF, ADF and ADL) and their correlations with GY and STY were positive and significant ($P < 0.01$).

The positive association observed between GY and STY and among CP, IVOMD and ME indicates the possibility of improving those traits simultaneously in a breeding program. This finding is in alignment with previous reports for other crops [14, 44]. The fact that the yields of grain and straw showed significant negative association with CP, IVOMD and ME in this study is also in line with those reported for grain yield and crude protein content [13]. The negative correlation observed between straw feed quality and food-feed yield traits indicates the difficulty associated with improving both traits simultaneously. This phenomenon suggests that the breeder may need to develop varieties primarily used for either yield or feed quality traits. However, the interests of tef breeders are now to make simultaneous improvements in both trait categories since it is becoming very difficult to get enough cultivable land for independent programs. On the other hand, the moderately negative association between the grain and straw yield and straw fodder quality traits in our study highlights the possibility to select for improved feed quality traits without significantly impacting the grain and straw yield [Table 5]. In this study, varieties like Melko which provided relatively higher yields of grain and straw, along with good straw quality traits could have a potential role to play with this regard. In line with this, the possibility for simultaneous improvement of grain and stover yield traits has also been reported to alleviate the critical problem of developing dual purpose grain-fodder varieties of maize in the maize-livestock mixed farming system of Eastern Africa [5].

Grouping of the studied traits and varieties of tef

Based on scatter plot, principal component biplot and cluster analyses, the eight studied traits and 36 varieties were categorized into groups as follows. The use of a scatterplot analysis based on pairs of important yield and quality traits such as GY and CP; GY and IVOMD; STY and CP; and STY and IVOMD was one way of assessing the variations in performance among the 36 studied varieties. With this analysis, four groups of varieties were identified and these include those performing: 1) above average for both traits; 2) above average for trait on the y-axis and below average for trait on the x-axis; 3) below average for both traits; and 4) below average for trait on the y-axis and above average for trait on the x-axis. Thus, some varieties were found to consistently perform above or below the mean for GY and CP, GY and IVOMD, STY and CP, and STY and IVOMD. The details are presented in Fig. 2a-d, 3a-d and 4a-d for Debre Zeit, Holetta and the combined data over years by locations, respectively.

At Debre Zeit, for example, five varieties marked with red font (group-I) performed above average while the local check and three other varieties marked with aqua font (group-III) performed below average for CP and GY [Figure 2a]. For IVOMD and GY, on the other hand, four and five varieties were found to perform above and below average, respectively [Figure 2b]. Furthermore, seven and six varieties respectively were found to perform above and below average for CP and STY [Figure 2c]. Similarly, the local check and four other varieties were found to perform above average unlike the seven varieties which performed below average for IVOMD and STY [Figure 2d]. The Yilmana variety, however, consistently performed above the mean while Mechare and Etsub performed below the mean in Debre Zeit for all studied pairs of traits [Figure 2a-d].

Based on Holetta data, seven varieties performed above average unlike the local check and 10 released varieties which performed below average for CP and GY [Figure 3a]. Nine varieties also performed above average while the local check and nine released varieties performed below average for IVOMD and GY [Figure 3b]. Furthermore, for CP and STY, seven released varieties performed above average while

Table 5: Pearson correlation coefficient among grain and straw yield and straw quality traits of tef.

	CP	NDF	ADF	ADL	ME	IVOMD	GY
CP (g kg^{-1} DM)	1						
NDF (g kg^{-1} DM)	-0.79***	1					
ADF (g kg^{-1} DM)	-0.90***	0.84***	1				
ADL (g kg^{-1} DM)	-0.54***	0.75***	0.75***	1			
ME (MJ)	0.73***	-0.82***	-0.83***	-0.84***	1		
IVOMD (g kg^{-1} DM)	0.82***	-0.88***	-0.89***	-0.81***	0.98***	1	
GY (kg ha^{-1})	-0.45**	0.40*	0.47***	0.47***	-0.48**	-0.51**	1
STY (kg/ha)	-0.40*	0.41*	0.42*	0.40*	-0.45**	-0.48**	0.71***

ADF = acid detergent fiber; ADL= acid detergent lignin; CP = crude protein; GY = grain yield; IVOMD = *in vitro* organic matter digestibility; ME = metabolizable energy; NDF = neutral detergent fiber; STY = straw yield. * Significant at $P < 0.05$, ** Significant at $P < 0.01$, *** significant at $P < 0.001$.

the local check and seven released varieties performed below average [Figure 2c]. For IVOMD and STY, on the other hand, 11 released varieties performed above average while the local check and nine released varieties performed below average [Figure 3d]. In general at Holetta, Melko, Ajora and Koye varieties consistently performed above the mean while Amarach, Ambo-Toke, Magna and the local check performed below the mean [Figure 3a-d].

Based on combined mean data over years by locations, five released varieties performed above average while the local check and five varieties performed below average for CP and GY [Figure 4a]. For IVOMD and GY, six released varieties performed above average while another six released varieties performed below average [Figure 4b]. For CP and STY, seven released varieties performed above average while the local check and seven other released varieties performed below

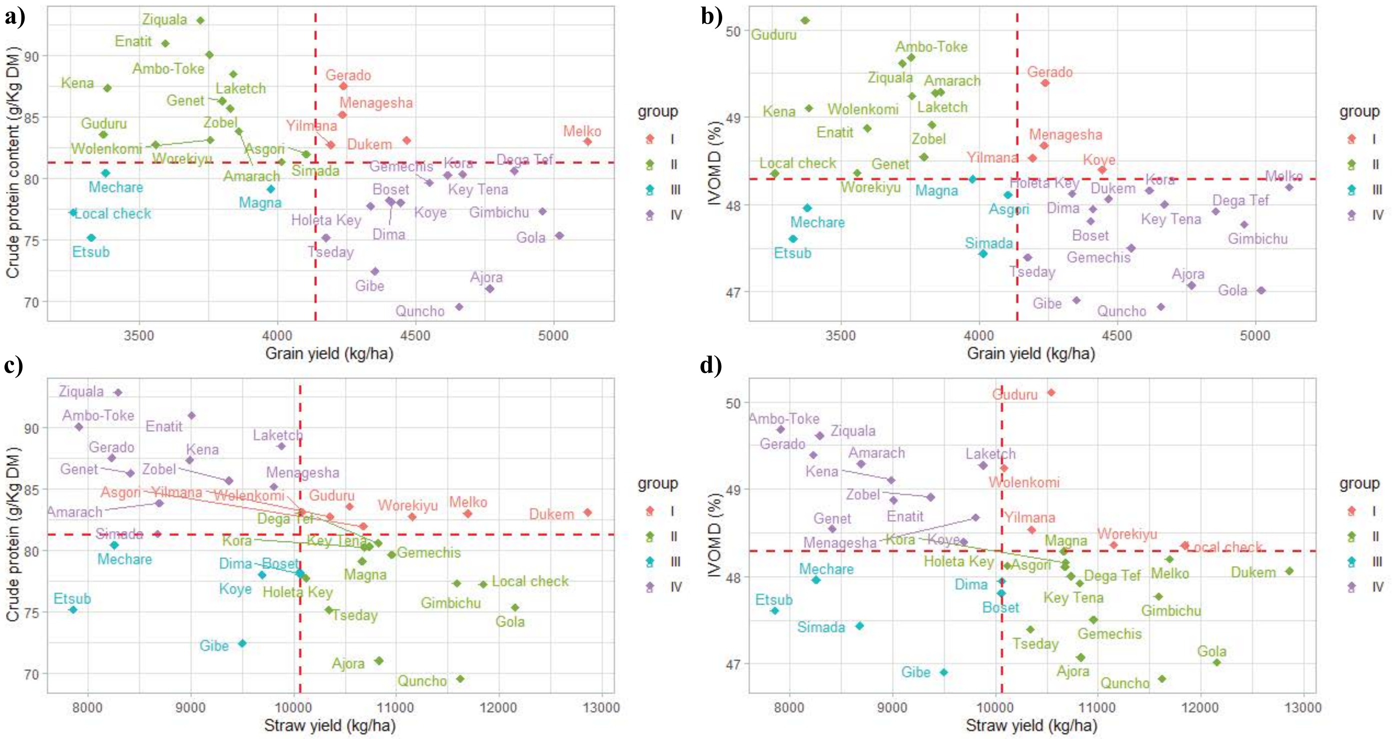

Figure 2: Scatter plots showing the performance of 36 tef varieties in Debre Zeit for (a) Grain yield vs Crude protein; (b) Grain yield vs In vitro organic matter digestibility; (c) Straw yield vs Crude protein; and (d) Straw yield vs In vitro organic matter digestibility. Red and aqua font colours indicate best and worst performing varieties, respectively.

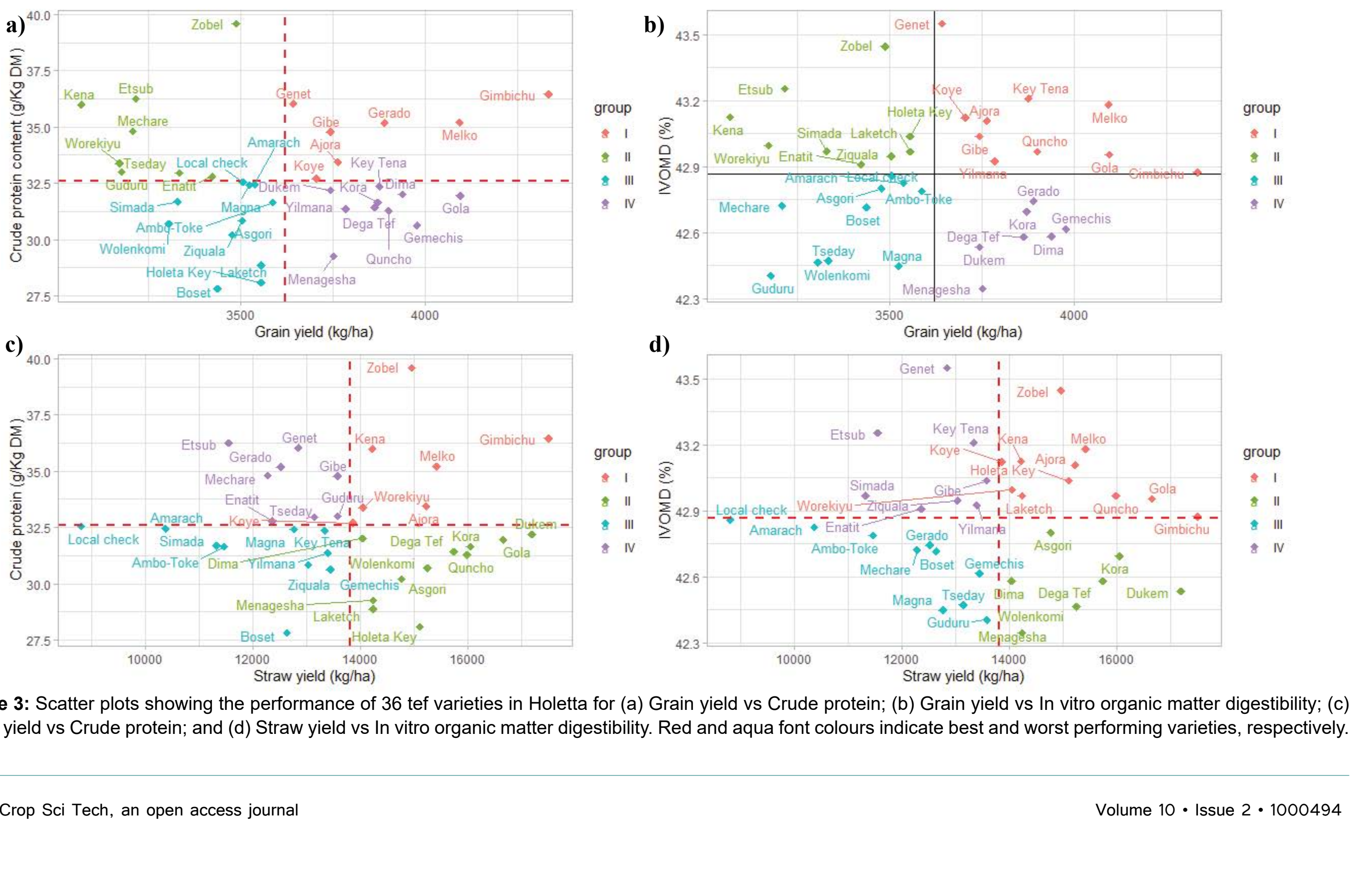

Figure 3: Scatter plots showing the performance of 36 tef varieties in Holetta for (a) Grain yield vs Crude protein; (b) Grain yield vs In vitro organic matter digestibility; (c) Straw yield vs Crude protein; and (d) Straw yield vs In vitro organic matter digestibility. Red and aqua font colours indicate best and worst performing varieties, respectively.

average [Figure 4c]. Furthermore, for IVOMD and STY, eight released varieties performed above average while the local check and another six varieties performed below average [Figure 4d]. Surprisingly, some varieties performing better at one location were found to perform poorly in another location. For example, the Guduru variety was amongst the varieties with high CP, IVOMD and ME values at Debre Zeit while it had the lowest values of these traits at Holetta. The Etsub variety, on the other hand, performed poorly at Debre Zeit while it had the highest CP, IVOMD and ME values at Holetta. Generally under all circumstances, Etsub, Simada, Magna and Tsedey performed below the mean, while the Melko variety consistently performed above the mean. Melko, which combined higher grain and straw yield as well as reasonable values of CP, IVOMD, GY and STY under all circumstances, will be useful in developing a dual-purpose tef variety [Figure 4a-d].

Principal component and cluster analyses were also used to group the eight studied traits and 36 tef varieties into various distinct categories. Thus, the first two PCs which accounted for 85.7%, 74.5% and 84.2% of the total variation based on Debre Zeit data [Figure 5a], Holetta data [Figure 5b] and combined data [Figure 6], respectively, revealed the formation of three groups of traits and four groups of varieties. Hierarchical cluster analysis, based on combined mean data over location by years, also revealed the formation of three groups of traits and four groups of tef varieties [Figure 7]. Based on both cluster and PCA bi-plot analyses, similar grouping patterns were observed among the studied tef varieties and traits, to design breeding strategies targeting suitable improved varieties for both food and feed traits. Both analyses identified three groups of traits whereby GY and STY; CP, IVOMD and ME; and NDF, ADF and ADL were grouped into clusters I, II and III, respectively. Both analyses also grouped the 36 studied tef varieties in to four categories: 1) those with high grain and straw yield; 2) those with high straw quality; 3) those with moderately high yield and straw quality; and 4) those with the lowest values of all studied traits.

At Debre Zeit, group-I consisted of nine released varieties with high yield and high fiber content while group-II consisted of 11 released varieties with high CP, IVOMD and ME. Group-III consisted of six varieties with high yield and moderately low fiber contents while group-IV consisted of the local check and three released varieties having the lowest values of all studied traits. At Holetta, on the other hand, group-I consisted of eight varieties with high grain and straw yields while group-II consisted of the local check and 12 released varieties which had moderately low values of all studied traits. Group-III consisted of nine released varieties with high fiber contents while group-IV consisted of four varieties with high CP, IVOMD and ME. Furthermore, based on combined data, group-I consisted of eight varieties which had the highest fiber contents while group-II consisted of 12 released varieties with higher CP, IVOMD and ME. Group-III consisted of a local check and four released varieties which had lower values of all studied traits while group-IV consisted of nine released varieties with higher values of grain and straw yield.

In the cluster analysis, some varieties like Gola and Quncho which were in cluster-I produced both the highest grain and straw yield, along with high cell wall constituents [Figure 7]. The fact that our popular high yielding improved variety Quncho was included in this cluster might confirm the suspicion of farmers that suggest that its straw is fibrous and less palatable. Guduru and Zobel varieties in cluster-II had the highest value of ME and CP, respectively, while Kenna had the highest CP, IVOMD and ME along with the lowest value of ADL. The varieties in cluster-III were generally identified as the poorest performers of all the studied varieties [Figure 7]. Among the varieties in cluster-IV which were identified to have high grain and straw yield,

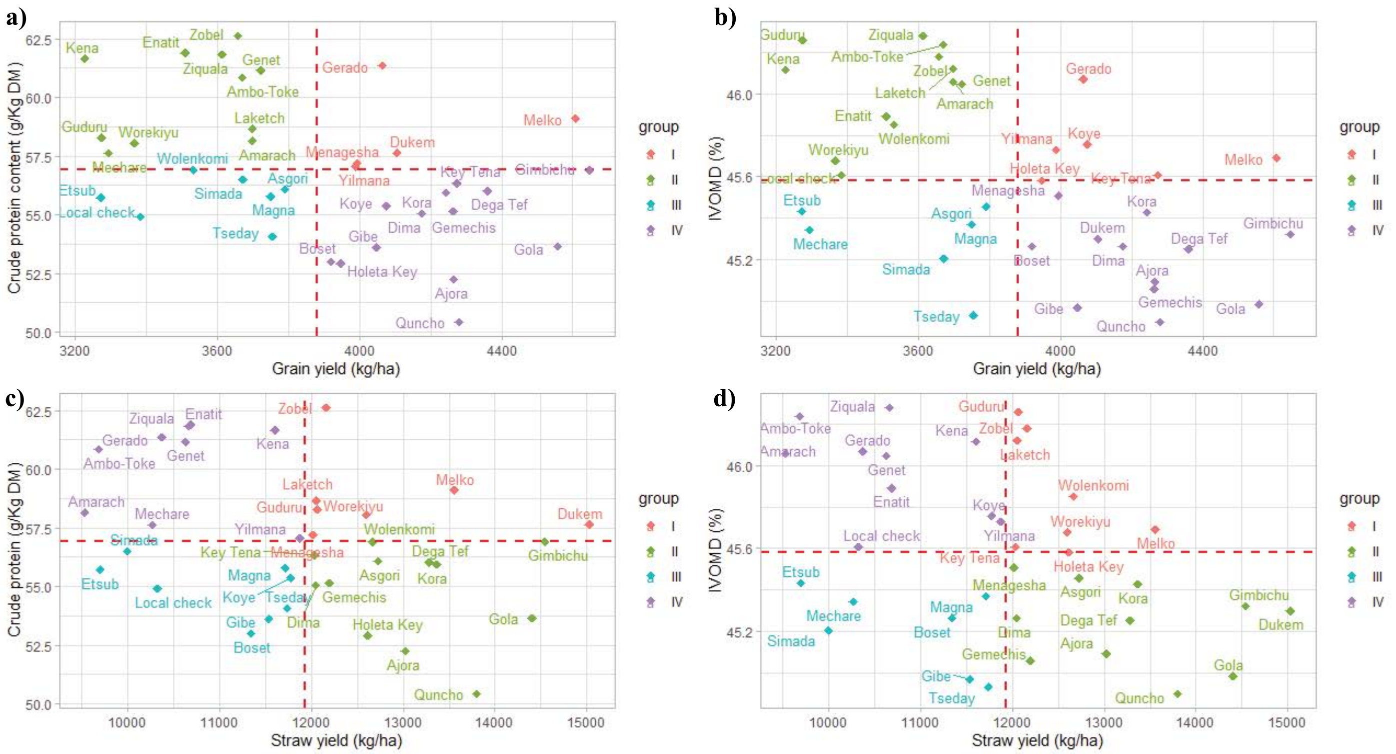

Figure 4: Scatter plots showing the performance of 36 tef varieties over years and locations for (a) Grain yield vs Crude protein; (b) Grain yield vs In vitro organic matter digestibility; (c) Straw yield vs Crude protein; and (d) Straw yield vs In vitro organic matter digestibility. Red and aqua font colours indicate best and worst performing varieties, respectively.

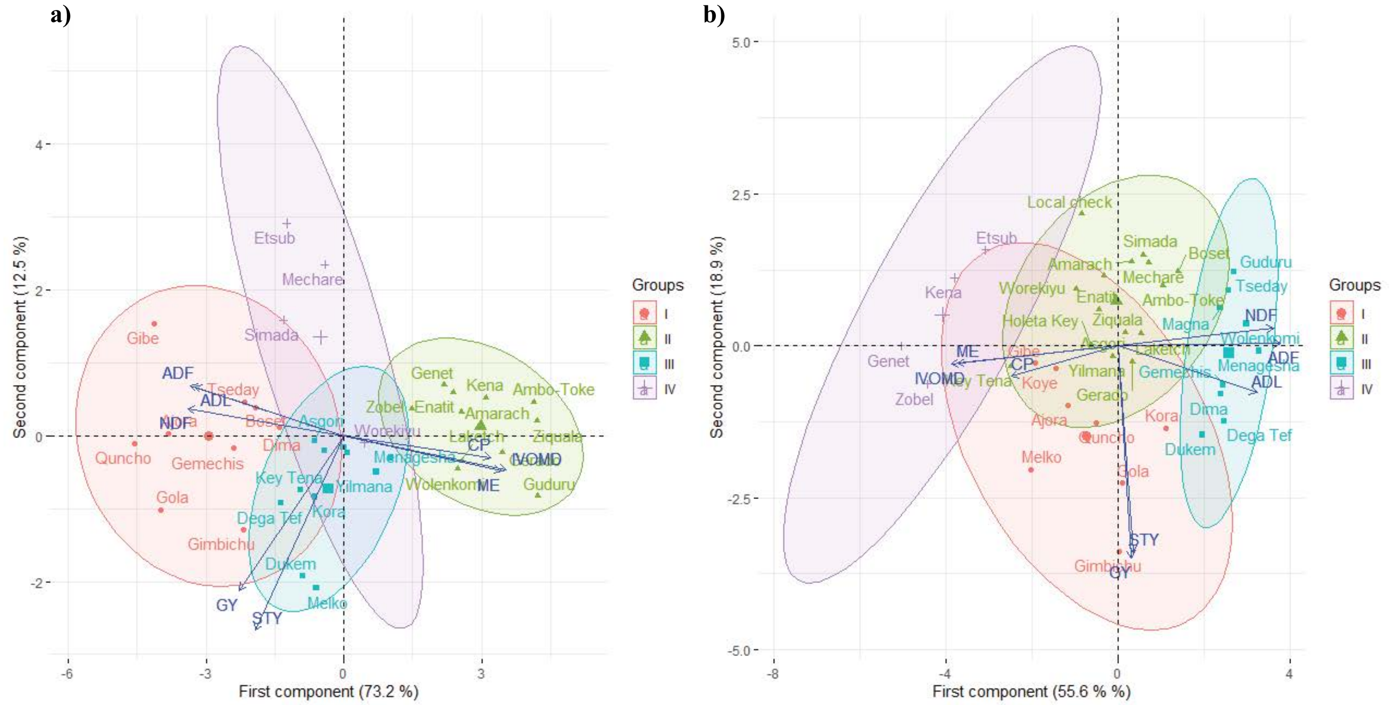

Figure 5: PCA bi-plots showing the relationship between the studied varieties and their traits in (a) Debre Zeit and (b) Holetta. CP = Crude protein; IVOMD = in vitro organic matter digestibility; ME = Metabolizable energy; ADL = Acid detergent lignin; NDF = Neutral detergent fiber; ADF = Acid detergent fiber; GY = grain yield; STY = Straw yield.

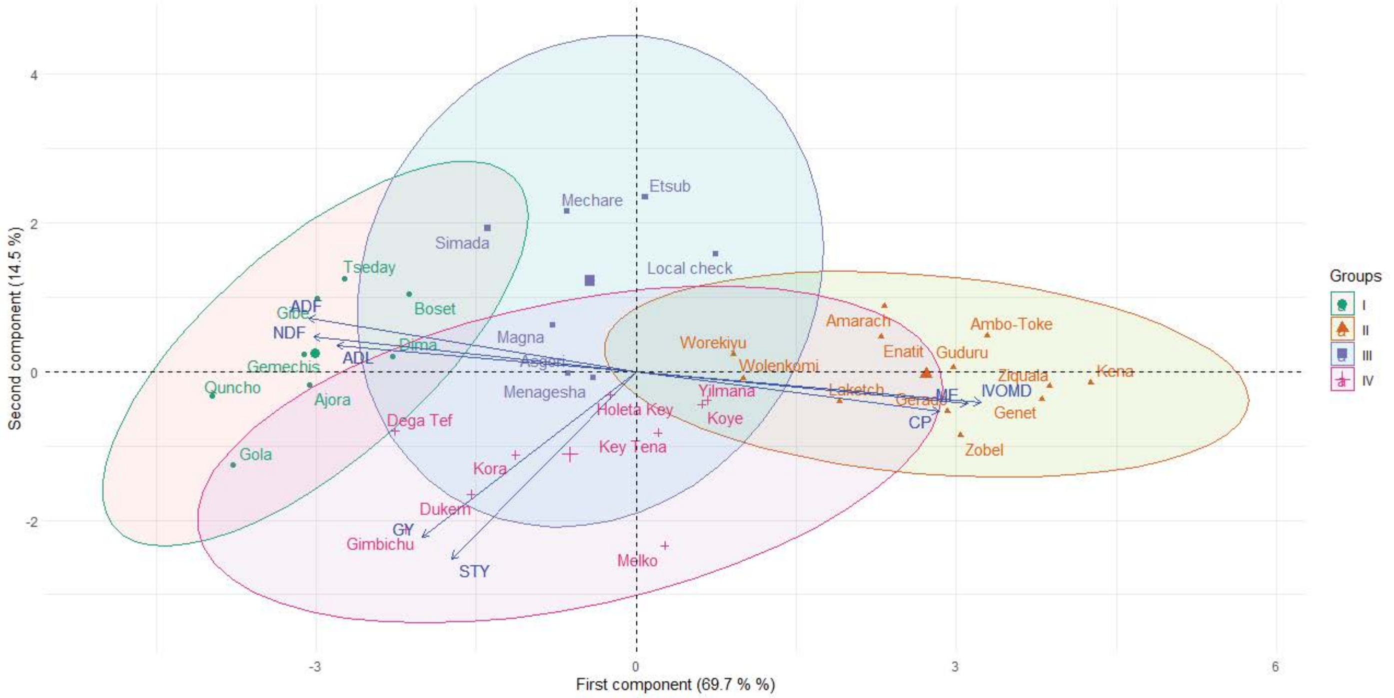

Figure 6: PCA bi-plot showing the relationship between the studied varieties and their traits based on the combined data. CP = Crude protein; IVOMD = in vitro organic matter digestibility; ME = Metabolizable energy; ADL = Acid detergent lignin; NDF = Neutral detergent fiber; ADF = Acid detergent fiber; GY = grain yield; STY = Straw yield.

Gimbichu, Dukem and Melko possessed the highest GY and STY and moderately high ADL; highest STY and moderately high NDF; and GY and moderately high STY and CP, respectively.

Conclusions

The National Tef Breeding Program in Ethiopia has mainly been focusing on grain yield improvement alone in developing new varieties.

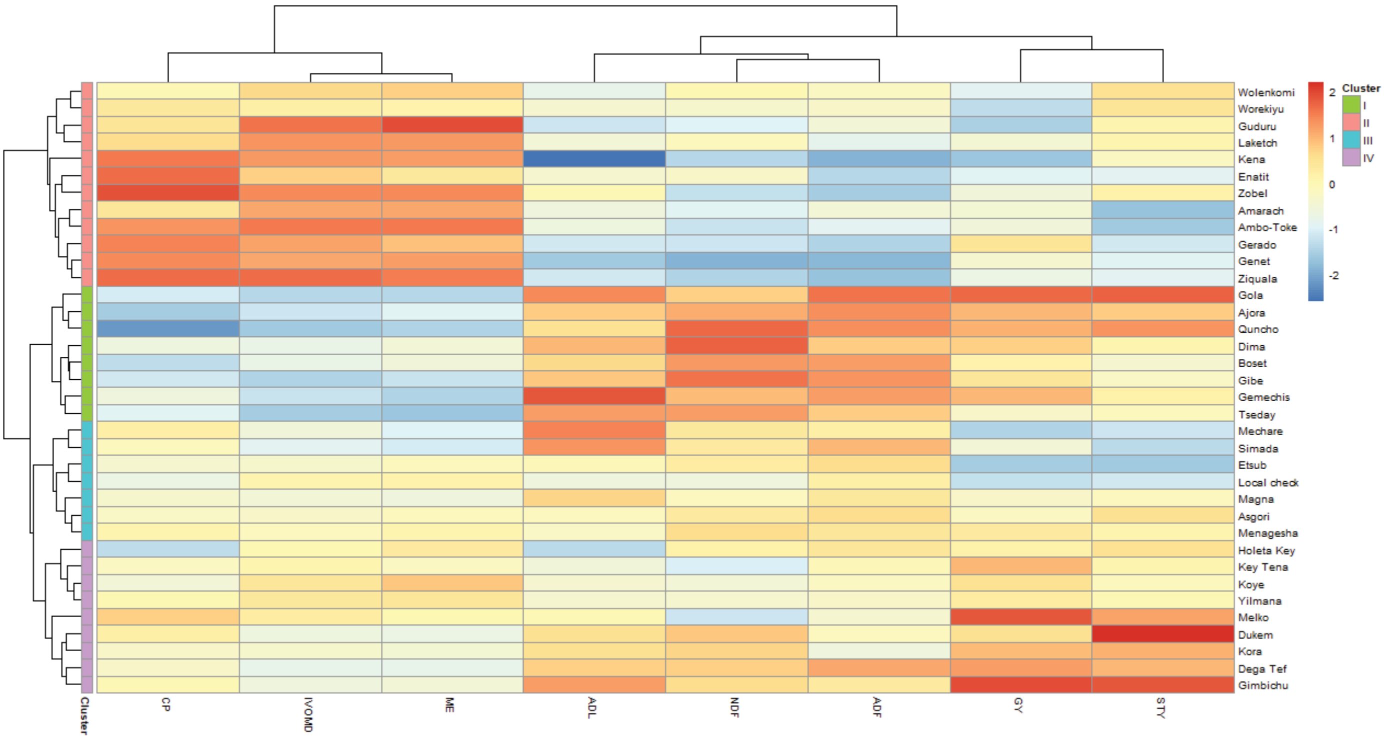

Figure 7: Hierarchical cluster analysis showing the four clusters of 36 studied tef varieties and their relative values for eight food-feed traits. CP = Crude protein; IVOMD = in vitro organic matter digestibility; ME = Metabolizable energy; ADL = Acid detergent lignin; NDF = Neutral detergent fiber; ADF = Acid detergent fiber; GY = grain yield; STY = Straw yield.

In this study, 35 tef varieties approved for release in Ethiopia until 2015 and a local check were investigated for key grain- and straw-related traits including straw crude protein, *in vitro* organic matter digestibility and metabolizable energy. The straw feed quality traits were assessed by the NIRS technique which was confirmed to be robust. Our findings revealed the existence of a wide range of variations in grain and straw yield and straw quality traits across growing environments, tef varieties and their interactions. Thus, a better tef grain and straw yield as well as straw quality traits were observed at Debre Zeit compared to Holetta. PCA bi-plot and cluster analyses have enabled us to identify varieties with: 1) high grain and straw yield; 2) high straw quality; 3) high fiber content and moderately high yield; and 4) low yields of all studied traits. Among all studied varieties, Melko combined higher grain and straw yield and fodder quality traits while Etsub and Simada varieties performed poorly under all circumstances. The current findings show that future tef breeding programs need to also consider straw quality traits in the development of new varieties. Hence varieties like Melko, which combined most of the important traits, could be promoted for immediate utilization as a dual-purpose variety or as a parental line in changing the existing tef breeding strategy that focuses on grain yield improvement alone.

Acknowledgments

We would like to acknowledge Syngenta Foundation for Sustainable Agriculture, Ethiopian Institute of Agricultural Research and the CGIAR Research Program on Livestock for co-funding this work. We are also indebted to tef breeding staff at Holetta and Debre Zeit Agricultural Research Centers for field management and the Feeds and Nutrition staff of International Livestock Research Institute for facilitating the laboratory work.

References

1. Spaenij-Dekking L, Kooy-Winkelaar Y, Koning F (2005) The Ethiopian Cereal Tef in Celiac Disease. N Engl J Med 353: 1748-1749.
2. Ketema S (1993) Tef (*Eragrostis tef*): Breeding, Genetic Resources, Agronomy, Utilization and Role in Ethiopian Agriculture. Addis Ababa: Agri Rese.
3. Assefa K, Yu JK, Zeid M, Belay G, Tefera H, et al. (2011) Breeding tef [*Eragrostis tef (Zucc.) trotter*]: Conventional and molecular approaches. Plant Breed 130: 1-9.
4. Bediye S, Fekadu D (2001) Potential of tef straw as livestock feed. Proceedings of the International Workshop Tef Genetics and Improvement. Agri Res: 245-254.
5. Yami A (2013) Tef Straw: A Valuable Feed Resource to Improve Animal Production and Productivity. Livestock Feed: 244-379.
6. Habte E, Muktar MS, Negawo AT, Lee S, Lee K, et al. (2019) An Overview of Tef (*Eragrostis tef Zuccagni) Trotter*) as a Potential Summer Forage Crop in Temperate Systems. J Korean Soci Gras for Sci 39: 185-188.
7. Girija A, Jifar H, Jones CS, Yadav R, Doonan J, et al. (2021) Tef, a tiny grain with enormous potential. Trends Plant Sci.
8. Sugg JD, Sarturi JO, West CP, Ballou MA, Henry DD (2021) Tef grass for continuous stocking in the Southern High Plains by growing beef steers receiving protein supplements. Transl Anim Sci 5:1-11.
9. Ketema S (1997) Tef-Eragrostis Tef (Zucc.) Promoting the conservation and use of underutilized and neglected crops. 12. Addis Ababa: Bioversity International.
10. Lascano CE, Schmidt A, Barahona Rosales R (2001) Forage quality and the environment.
11. Mengistu A, Kebede G, Feyissa F, Assefa G (2017) Review on major feed resources in Ethiopia: Conditions, challenges and opportunities. Research J Agric Sci Res 5: 176-85.
12. Geleti D, Hailemariam M, Mengistu A, Tolera A (2013b) Nutritive Value of Selected Browse and Herbaceous Forage Legumes Adapted to Medium

Altitude Sub Humid Areas of Western Oromia, Ethiopia. Global Veterinaria 11: 809-816.

13. Tolera A, Berg T, Sundstol F (1999) The effect of variety on maize grain and crop residue yield and nutritive value of the stover. Animal Feed Sci Tech 79: 165-177.
14. Geleti D, Hailemariam M, Mengistu A, Tolera A (2013) Herbage yield and quality of selected accessions of Centrosema species grown under sub-humid climatic conditions of Western Oromia, Ethiopia. Global Veterinaria 11: 735-741.
15. Bezabih M, Adie A, Ravi D, Prasad KV, Jones C, et al. (2018) Variations in food-fodder traits of bread wheat cultivars released for the Ethiopian highlands. Field Crops Research 229: 1-7.
16. Blümmel M, Grings EE, Erenstein O (2013) Potential for dual-purpose maize varieties to meet changing maize demands: Synthesis. Field Crops Res 53: 107-112.
17. Somegowd VK, Vemula A, Naravula J, Prasad G, Rayaprolu L, et al. (2021) Evaluation of fodder yield and fodder quality in sorghum and its interaction with grain yield under different water availability regimes. Current Plant Biology 25: 100191.
18. Bediye S, Sileshi Z, Mengistie T (1996) Tef [*Eragrostis tef (Zucc.) Trotter*] straw quality as influenced by variety and locations. Ethiopian Society of Animal Production.
19. Lenné JM, Fernandez-Rivera S, Blümmel M (2003) Approaches to improve the utilization of food–feed crops—synthesis. Field Crops Research 84: 213-222.
20. Pattanaik AK, Sharma K, Anandan S, Blümmel M (2010) Food-feed crops research: a synthesis. Ani Nutri Feed Techno10: 1-10.
21. Blümmel M, Duncan AJ, Lenné JM (2020) Recent Advances in Dual Purpose Rice and Wheat Research: a synthesis. Field Crops Res 253: 107823.
22. Addis A (2014) Plant Variety Release, Protection and Seed Quality Control Directorate. Field crops Res 223: 1-5
23. AOAC (1990) Official Methods of Analysis: Changes in Official Methods of Analysis Made at the Annual Meeting. J Assoc Off Anal Chem 22: 5-6
24. Van Soest PJ, Robertson JB (1985) Analysis of forages and fibrous foods. Cornell University.
25. NRC (2001) Nutrient requirements of dairy cattle. NRC: 381.
26. Menke KH, Steingass H (1988) Estimation of the energetic feed value obtained from chemical analysis and in vitro gas production using rumen fluid. Anim Res Dev 28: 7-55.
27. Padmore JM (1990) Protein (crude) in animal feed. Official Methods of Analysis: 70-74.
28. Jifar H (2018) Analyses of Phenotypic and Molecular Diversity, Genotype by Environment Interaction and Food-feed Traits in Tef [*Eragrostistef (Zucc.) Trotter*]. Doctoral dissertation.
29. SAS (2002) System Analysis Software. Version 9.0. SAS Institute Inc. Cary, North Carolina.
30. Minitab (2007) Minitab Statistical Software, Release 15 for Windows. Pennsylvania State College, Pennsylvania, USA.
31. Raivo K (2019) Pheatmap: pretty heatmaps. R package version 1(8).
32. Kassambara A, Mundt F (2020) factoextra: extract and visualize the results of multivariate data analyses. R package version 1(5), 337-354.
33. Wickham H (2016) ggplot2: Elegant Graphics for Data Analysis. New York: Springer-Verlag.
34. Jifar H, Assefa K, Tadele Z (2015) Grain yield variation and association of major traits in brown-seeded genotypes of tef [Eragrostis tef (Zucc.) Trotter]. Agric Food Secur 4 (7): 1-9.
35. Assefa K, Tefera H, Merker A, Kefyalew T, Hundera F (2001) Quantitative trait diversity in tef [Eragrostis tef (Zucc.) Trotter] germplasm from Central and Northern Ethiopia. Genet. Resour Crop Evol 48: 53-61.
36. Kassier SB (2002) Comparative responses of fodder and grain teff [Eragrostis tef (zucc.) Trotter] cultivars to spatial, Temporal and nutritional management. RSA.
37. DZARC (1989) Debre Zeit Agricultural Research Center Annual Research Report for 1988/89,. Debre Zeit, Ethioia: Debre Zeit Research Center.
38. Feyissa F, Kebede G, Assefa G (2015) Dynamics in nutritional qualities of tef and wheat straws as affected by storage method and storage duration in the central highlands of Ethiopia. Afr J Agric Res 10(38): 3718-3725.
39. Fekadu D, Walelegn M, Terfe G (2017) Indexing Ethiopian Feed Stuffs Using Relative Feed Value: Dry Forages and Roughages, Energy Supplements, and Protein Supplements. J Biol Agric and Healthcare 7:57-60.
40. Fekadu D, Bediye S, Silesh Z (2010) Characterizing and predicting chemical composition and in vitro digestibility of crop residue using near infrared reflectance spectroscopy (NIRS). Livest Res Rural Dev 22:5- 2.
41. Bediye S, Sileshi Z (1989) The composition of Ethiopian feedstuffs. Livest Res Rural Dev
42. Miller D (2009) Tef Grass: A new alternative. Livest Res Rural Dev 44: 345-346.
43. Ketema S (1993) Tef (*Eragrostis tef*): Breeding, Genetic Resources, Agronomy, Utilization and Role in Ethiopian Agriculture. Addis Ababa: Agri Rese.