Exploring the Potential to Capture Variation in Grain-straw Yield and Straw Quality Traits of Tef [*Eragrostis tef* (Zucc.) Trotter] Varieties

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Abstract

Tef [*Eragrostis tef* (Zucc.) Trotter] is an indigenous Ethiopian cereal which helps provide healthy and nutritious diets for people and a palatable straw for livestock feed. This study was conducted to determine the variation in grain-straw yield and straw quality traits of 35 tef varieties and a local check grown in two locations for two years. Straw crude protein (CP), *in vitro* organic matter digestibility (IVOMD), metabolizable energy (ME) and the yields of grain (GY) and straw (STY) were significantly ($P < 0.01$) affected by variety, environment and their interactions. GY, CP, ME and IVOMD were significantly higher in the Debre Zeit site compared to Holetta and, except for GY, in 2016 compared to 2015. About 150% and 25% higher mean CP content was recorded in Debre Zeit than in Holetta, and in 2016 than 2015, respectively. Positive and significant ($P<0.01$) associations were observed between GY and STY, among CP, ME and IVOMD, and among NDF, ADF and ADL. Among all studied varieties, *Melko* produced the highest grain-straw yield and best fodder quality traits. Based on the yields and qualities of both grain and straw, the production of *Gimbichu*, *Quncho* and *Gola* varieties conferred more than 40% economic advantage over the local check in the local markets. Our study generally identified varieties with high grain-straw yield and/ or straw quality traits which provided economic advantages for tef production and an opportunity for future utilization in tef improvement programs.

Keywords: Eragrostis tef; grain-straw yield; tef; variation; variety

Abbreviations: ADF, acid detergent fiber; ADL, acid detergent lignin; CP, crude protein; GY, grain yield; IVOMD, *in vitro* organic matter digestibility; NDF, neutral detergent fiber; NIRS, Near Infrared Reflectance Spectroscopy; ME, metabolizable energy; STY, straw yield

1. 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 approximatley 5.7 million tons of grain annually [1]. The grain of tef is gluten free [2] and considered a nutritious human food [3, 4] while its straw is a good source of livestock feed [5, 6]. Though tef adapts to a wide range of environments including soil, altitude, rainfall and temperature conditions, its grain-straw yield and quality is a function of the genotype, the environment and of their interactions [4, 7]. 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 [8]. 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 [8].

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 [9, 10]. 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 [9, 11, 12]. 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]. Efficient use of available crop residues is an option suggested to fill the gaps in feed availability, though it is highly dependent on the farming system, type of crop and intensity of cultivation [9]. The appropriate identification and utilization of dual purpose crop cultivars is an additional option to help address these shortages in quality feed. Dual purpose crops are also useful to reduce land and water use competition in addition to increasing feed quality. 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 [13-15]. In Ethiopia, it is also important to identify dual purpose tef cultivars since tef covers the largest area under cereal production and its straw provides nearly half of the total annual cereal straws in the central highlands [6] and a quarter of the total straw in the country [16]. The national tef improvement program, which has been able to double average grain productivity [1], to date has not paid significant attention to the improvement of fodder quality traits. Anecdotal evidence indicates that farmers in major tef growing areas 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 [14, 17-19]. 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-straw yield and straw fodder quality traits of improved tef varies, 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.

2. Materials and Methods

2.1. 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 6 ^{0}C and 20 ^{0}C, respectively and the major soil type is a Nitosol. Debre Zeit is located at 1900 masl and receives 851mm annual rainfall in a similar pattern to Holetta. Its temperature ranges between 6 ^{0}C and 20 ^{0}C and the major soil type is a Pellic Vertisol.

2.2. Plant materials and design

Thirty-five improved tef varieties, released between 1970 and 2014 in Ethiopia [20], 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 with 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. 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. Maximum care was taken to properly consider the various plant components (leaf, stem and chaff) of the straw samples from each plot.

2. 3. Assessment of tef straw fodder quality attributes

Four hundred and thirty-two tef straw samples, pre-dried overnight in an oven at 60 ^{0}C, 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 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 AOAC [21], NDF, ADF and ADL following [22], ME following [23] and IVOMD according to [24]. Total N was determined following the Kjeldahl procedure [25] 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, with R^2 values ranging between 0.893 (ADL) and 0.992 (ME), and low SEC values ranging between 0.813 (ADF) and 0.034 (ME) (Table 2), supporting the robustness of the equations and potential use of NIRS to predict tef straw quality [26].

2.4. Statistical analysis

The analysis of variance was conducted using the general linear model procedure of SAS software [27] and the test for mean separations were declared at $P \leq 0.05$ using the least significant difference procedure. Estimation of Pearson correlation among the studied food-feed traits was performed using MINITAB software [28], and analysis of clusters and the principal component bi-plots, showing the distribution of studied traits and varieties, were performed using R software [29-32].

2.5. Analysis of economic advantage

The economic advantage of producing different tef varieties was compared against the local check. For this purpose, average market prices of 23.0, 21.0, 20.0, 18.0 and 2.5 Ethiopian birr per Kg was used for very white, creamy white, mixed and brown tef grain and tef straw, respectively, based on data collected from Ada District of East Shewa zone (unpublished socio-economic data from Dr. Abate Bekele, socio-economist at Debre Zeit Agricultural Research Center). The various analyses were performed as follows:

$$Total\ grain\ income\ of\ variety\ “Z” = Variety\ “Z”\ total\ grain\ yield\ (kg/ha)\ X\ its\ grain\ price\ category$$

$$Total\ straw\ income\ of\ variety\ “Z” = Variety\ “Z”\ total\ straw\ yield\ (kg/ha)\ X\ 2.5\ Birr$$

$$Total\ income\ of\ variety\ “Z” = Total\ grain\ income + Total\ straw\ income\ of\ variety\ “Z”$$

$$Economic\ income\ of\ variety\ “Z”\ (\%) = \frac{Total\ income\ of\ variety\ “Z” - Total\ income\ of\ local\ variety}{Total\ income\ of\ local\ variety}$$

Where: “Z” is the name of variety employed in this study

3. Results

3.1. Analysis of variance

Combined analysis of variance for grain-straw yield and straw quality traits revealed that the mean square values for all studied traits were significantly ($P < 0.01$) affected by the variety (G) and the location (L) (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 ($P < 0.01$). Among all the studied traits, differences in ADL were not significant under any of the interactions.

3.2. Effect of environment on yield and quality traits in tef

The grain-straw yield and straw quality traits of the 35 tef varieties and a local check varied significantly between the two locations in both years (Table 4). The CP content ranged from 52.8 to 107.2 g kg^{-1} DM with a mean of 81.3 g kg^{-1} DM in Debre Zeit, while, it ranged from 13.8 to 49.7 g kg^{-1} DM with a mean of 32.6 g kg^{-1} DM in Holetta. Similarly, IVOMD ranged from 44.4 to

52.8 % with a mean of 48.3 % in Debre Zeit whereas in Holetta it ranged from 40.7 to 45.1 % with a mean of 42.9 %. Furthermore, GY ranged from 2160 to 5780 kg ha^{-1} with a mean of 4140 kg ha^{-1} in Debre Zeit while it ranged from 2810 to 4800 kg ha^{-1} with a mean of 3622 kg ha^{-1} in Holetta. The STY ranged from 4970 to 13920 kg ha^{-1} with a mean of 10070 kg ha^{-1} in Debre Zeit whereas in Holetta it ranged from 6900 to 24410 kg ha^{-1} with a mean of 13805 kg ha^{-1}. Regarding the two locations, higher values for CP, ME, IVOMD and GY were recorded in Debre Zeit while the straw yield and all fiber contents were higher in Holetta.

With respect to years, the CP content ranged from 13.8 to 102.1 g kg^{-1} DM with a mean of 50.6 g kg^{-1} DM in 2015 while, it ranged from 23.2 to 107.2 g kg^{-1} DM with a mean of 63.2 g kg^{-1} DM in 2016. Similarly, IVOMD ranged from 40.7 to 52.8 % with a mean of 45.3 % in 2015 whereas in 2016 it ranged from 41.6 to 51.1 % with a mean of 45.8 %. Furthermore, GY ranged from 2580 to 5780 kg ha^{-1} with a mean of 3886 kg ha^{-1} in 2015 while it ranged from 2160 to 5200 kg ha^{-1} with a mean of 3877 kg ha^{-1} in 2016. The STY ranged from 4970 to 24410 kg ha^{-1} with a mean of 13828 kg ha^{-1} in 2015 whereas in 2016 it ranged from 6530 to 13920 kg ha^{-1} with a mean of 10042 kg ha^{-1}. From the two study years, higher values for CP, ME and IVOMD were obtained in 2016 compared to 2015 whereas the grain and straw yield and all fiber contents were significantly higher in 2015.

Based on the combined means over years and 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 % with a mean of 45.6 %. Furthermore, GY ranged from 3230 to 4630 kg ha^{-1} with a mean of 3882 kg ha^{-1} while straw yield ranged from 9730 to 14830 kg ha^{-1} (Table 4).

3.3. Variation of grain-straw yield and the quality of straw between tef varieties

In this study, both the grain-straw yield and straw quality traits varied significantly among the studied varieties across the locations, years and years by locations. One way of assessing the variations among genotypes is to use a scatterplot based on pairs of yield and quality traits such as GY vs CP; GY vs IVOMD; STY vs CP; and STY vs IVOMD. This scatterplot analysis identified four groups of genotypes including those performing: above average for both traits (group-I); above average for the trait on the y-axis and below average for the trait on the x-axis (group-II); below average for both traits (group-III); and below average for the trait on the y-axis and above average for the trait on the x-axis (group-IV). The details are presented below for Debre Zeit (Fig. 2a-d), Holetta (Fig. 3a-d) and for the combined data over years by locations (Fig. 4a-d).

Based on the two years combined mean in Debre Zeit, the varieties *Menagesha*, *Melko*, *Gerado*, *Yilmana* and *Dukem* (red font (group -I)) performed above average while *Mechare*, *Magna*, local check and *Etsub* varieties (aqua font (group-III)) performed below average for CP and GY (Fig. 2a). For IVOMD and GY, *Gerado, Yilmana, Koye* and *Mengesha* varieties performed above average while *Magna*, *Asgori*, *Simada*, *Mechare* and *Etsub* varieties performed below average (Fig. 2b). For CP and STY, *Guduru, Yilmana, Worekiyu, Wolenkomi, Melko, Dukem and Asgori* varieties performed above average while *Boset*, *Mechare*, *Etsub*, *Koye*, *Dima* and *Gibe* performed below average (Fig. 2c). Finally, for IVOMD and STY, *Wolenkomi*, *Guduru*, *Yilmana*, local check and *Workiyu* varieties performed above average while *Boset*, *Mechare*, *Etsub*, *Dima*, *Simada* and *Gibe* performed below average (Fig. 2d).

Based on two years combined means in Holetta, the varieties *Gimbichu*, *Melko*, *Gerado*, *Gibe*, *Genet*, *Ajora* and *Koye* performed above average while *Boset*, *Magna*, *Laketch*, *Simada*, local check, *Amarach, Ambo-Toke, Ziquala*, *Wolenkomi*, *Asgori* and *Holetta Key* performed below average for CP and GY (Fig. 3a). For IVOMD and GY, *Melko*, *Gola*, *Gimbichu, Yilmana, Quncho*, *Gibe*, *Ajora*, *Koye* and *Key Tena* varieties performed above average while *Boset*, *Amarach*, local check, *Asgori*, *Ambo-Toke*, *Mechare*, *Tsedey*, *Magna*, *Wolenkomi* and *Guduru* performed below average (Fig. 3b). For CP and STY, *Melko*, *Gimbichu*, *Ajora*, *Koye*, *Kena*, *Zobel* and *Worekiyu* varieties performed above average while *Boset*, *Amarach*, local check, *Ambo-Toke*, *Magna*, *Simada*, *Key Tena*, *Yilmana*, *Ziquala* and *Gemechis* performed below average (Fig. 3c). Finally, for IVOMD and STY, *Melko*, *Gola*, *Gimbichu*, *Quncho*, *Ajora*, *Koye*, *Zobel*, *Kena*, *Worekiyu*, *Laketch* and *Holetta Key* varieties performed above average while *Boset*, *Amarach*, local check, *Ambo-Toke*, *Mechare*, *Tsedey*, *Magna*, *Gemechis*, *Gerado* and *Guduru* performed below average (Fig. 3d).

Based on the combined means over years by locations, the varieties *Melko*, *Gerado*, *Dukem*, *Yilmana* and *Menagesha* performed above average while *Wolenkomi*, *Asgori*, *Etsub*, local check, *Tsedey*, *Magna* and *Simada* performed below average for CP and GY (Fig. 4a). For IVOMD and GY, *Melko*, *Koye*, *Key Tena*, *Yilmana*, *Holetta Key and Gerado* performed above average while *Asgori*, *Etsub*, *Tsedey*, *Magna*, *Mechare* and *Simada* performed below average (Fig. 4b). For CP and STY, *Dukem*, *Melko*, *Worekiyu*, *Menagesha*, *Laketch*, *Zobel* and *Guduru* varieties performed above average while *Etsub*, local check, *Koye*, *Tsedey*, *Gibe*, *Boset*, *Magna* and *Simada* performed below average (Fig. 4c). Finally, for IVOMD and STY, *Guduru*, *Zobel*, *Laketch*, *Wellenkomi*, *Melko*, *Key Tena*, *Holetta Key*, and *Worekiyu* varieties performed above average while *Wolenkomi*, *Asgori*, *Etsub*, local check, *Tsedey*, *Magna* and *Simada* performed below average (Fig. 4d). All the remaining varieties in each figure performed above average for one trait while performing below average for the counter trait.

3.4. Relationships between grain-straw yield and straw fodder quality traits in tef

A Pearson correlation coefficient among grain-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 ($P < 0.01$).

3.5. Principal component analysis

The first two principal components based on Debre Zeit data, which accounted for 85.7% (PC_1 = 73.12% and PC_2 = 12.60 %) of the total variation, grouped the 36 varieties into four groups (Fig. 5a). 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 three released varieties and the local check with the lowest grain-straw yield and CP, IVOMD and ME contents.

In the case of Holetta, the first two principal components, which accounted for 74.5% (PC_1 = 55.6% and PC_2 = 18.9 %) of the total variation, grouped the 36 tef varieties into four groups (Fig. 5b). Group-I consisted of eight varieties which had high grain and straw yields while Group-II consisted of 12 released varieties and the local check which had moderately low values of all the eight 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.

Based on the combined data from both sites, the first two principal components, which accounted for 84.2% (PC_1 = 69.9% and PC_2 = 14.5 %) of the total variation, produced four varietal groups (Fig. 6). Group-I consisted of eight varieties with high fiber contents (NDF, ADF and ADL). These include the varieties *Tsedey*, *Boset*, *Gibe*, *Dima*, *Gemechis*, *Ajora*, *Quncho* and *Gola*. Group-II consisted of 12 released varieties with higher CP, IVOMD and ME while group-III consisted of four released varieties and the local check which had moderately low values of all the eight studied traits. These include *Etsub*, *Mechare*, *Magna*, *Menagesha* and the local check. Group-IV consisted of nine released varieties (*Dega Tef*, *Gimbichu*, *Kora*, *Dukem*, *Melko*, *Key Tena*, *Holetta Key*, *Koye* and *Yilmana*) which have higher values of grain and straw yield.

3.6. Hierarchical cluster analysis

A hierarchical cluster analysis based on the combined means of grain-straw yield, and straw fodder quality traits, grouped the 36 tef varieties and the eight traits into four and three major clusters, respectively (Fig. 7). The three groups of traits were: CP, IVOMD and ME in cluster-I; NDF, ADF, ADL in cluster-II; and GY and STY in cluster-III. For the grouping of varieties, cluster-I consisted of eight varieties with the highest fiber contents (NDF, ADF and ADL). Cluster-II consisted of 12 varieties with the highest values of CP, IVOMD and ME. Cluster-III consisted of seven varieties with moderately low yields of all of the studied traits, with the exception of ADL. Cluster-IV consisted of nine varieties with the highest GY and STY.

3.7. Economic benefit of tef varieties from different categories

The economic advantage of producing selected varieties from the four categories is summarized in Table 6. Based on this analysis, farmers obtained the highest economic return from the grain sales of *Quncho* (98,900 Birr ha^{-1}) followed by *Gimbichu* (97,587 Birr ha^{-1}), *Gola* (95,718 Birr ha^{-1}) and *Melko* (96,768 Birr ha^{-1}). On the other hand, the highest economic return from tef straw sales was obtained from *Dukem* (37,575 Birr ha^{-1}) followed by *Gimbichu* (36,350 Birr ha^{-1}), *Gola* (36,000 Birr ha^{-1}), *Quncho* (34,525 Birr ha^{-1}) and *Melko* (33,900 Birr ha^{-1}). When combining sales of both grain and straw, the highest economic return was obtained from *Gimbichu* (133,937 Birr ha^{-1}) followed by *Quncho* (132,965 Birr ha^{-1}), *Gola* (131,718 Birr ha^{-1}) and *Melk*o (130,668 Birr ha^{-1}). In this case, the economic advantage of improved varieties over the local check was 43.2% for *Gimbichu*, 42.2% for *Quncho,* 40.9% for *Gola* and 39.7% for *Melko.*

4. Discussion

4.1. Effect of location on yield and quality

In this study, the existence of exploitable genetic variation in tef for grain-straw yield and straw fodder quality traits was observed over years and across locations. This is in line with reports for other cereal crop residues such as maize, sorghum, rice and wheat, both in Ethiopia and other parts of the world [14, 17-19]. Except for the three fiber related traits, which are negatively correlated with other fodder quality traits, and straw yield, the performances of traits were significantly higher in Debre Zeit compared to Holetta. For example, the crude protein, grain yield and IVOMD in Debre Zeit were 150%, 12.5 % and 11.2 % higher than in Holetta, respectively. This could be due to differences in soil and climate variables between the two locations (Table 1). For example, the low crude protein content of tef straw in Holetta might be due to its high rainfall, supporting the positive effect of drought on forage quality reported by others [8], and the relatively higher acidic nature of the Holetta soil as opposed to the conditions in Debre Zeit where the black Vertisols are only partially affected by soil acidity. Altitude may also be a contributing factor and, in line with this, a previous study reported that samples from mid-altitude areas had three-fold the proline levels compared to samples from high-altitude areas and also a decrease in lysine content of tef straw with an increase in altitude [33]. This could be a possible explanation for Debre Zeit, which is located in a mid-altitude environment, to have higher crude protein content compared to Holetta, which is a true highland location. The variation in straw quality traits across locations in the present study is also in line with those previously reported in Holetta and Ginchi [16] and in Debre Zeit and Akaki [34]. The observed varietal trait differences in our study are also in agreement with other previous reports [5, 17].

4.2.Effect of years on yield and quality

Significant variation was also observed between years in this study, with CP content and IVOMD higher in 2016 than 2015. Mean values were 24.9 % and 5.7 % higher for CP and IVOMD respectively, while the reverse was observed for straw yield and all fiber traits over the two cropping seasons. GY and ME, however, did not show significant variation between the two cropping seasons. The higher values of CP and IVOMD in the year 2016 compared to 2015 might be due to a higher amount and distribution of rainfall in 2016 (Fig. 1). The increased performance of the crop due to suitable environmental conditions such as rainfall could result in a positive impact on the uptake of useful assimilates for better straw quality. The higher CP content observed for the year 2016 than 2015, on the other hand, might also be due to the fact that fresh samples have higher CP content than those stored for a longer duration. A separate study conducted on the effect of storage duration of tef and wheat straw quality showed a decrease in CP content following prolonged storage [35].

4.3. Effect of years by location on yield and quality

The combined means over years by locations for CP content (56.9 g kg^{-1} DM) in our study is higher than the previous reports of 39 g kg^{-1} DM [12] and 46.0 g kg^{-1} DM [36] while it is comparable with CP values ranging from 45.4 to 61.3 g kg^{-1} DM [37] and 60 g kg^{-1} DM using 21 tef varieties [38]. The observed mean CP content in this study was much lower than the 90 -140 g kg^{-1} DM earlier reported for tef [39], although this could be due to variation in the stages of crop harvest since in our case the straw samples were collected after the grain harvest while in this other study the samples were harvested at the green stage as the crop was only grown for forage purposes. In this study, a wider variation was observed among tef varieties for grain and straw yield compared to straw fodder quality traits, probably due to the previous tef breeding strategy which has paid little attention to improve straw quality traits compared to grain yield.

4.4.Relationships between traits and their implications

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 [11, 40]. The fact that the yields of grain and straw showed a significant negative association with CP, IVOMD and ME in this study is in line with a previous report for grain yield and crude protein content [10]. The negative correlation between the 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 for either yield or feed quality traits. However, tef breeders are currently inclined to select for improvements in both traits simultaneously as getting enough cultivable land for both programs is becoming very difficult. On the other hand, the moderately negative association between the grain-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-straw yield (Table 7). In this case, varieties such as *Melko* play a vital role as they provide relatively high yields of grain and straw, along with good straw quality traits. Previous studies also reported the possibility for simultaneous improvement of grain-stover yield traits 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].

4.5.Groupings based on PCA-biplots and Cluster Analysis

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 varieties improved for both food and feed traits. Cluster and PCA bi-plot analyses identified three groups of traits, namely the: yield related traits (GY and STY); fiber related traits (NDF, ADF and ADL) and; feed quality traits (CP, IVOMD, ME). The analyses also identified four groups of varieties: those with high grain-straw yield; high straw quality; high fiber and yield; and moderately low values of all the eight studied traits. For example, *Gola* and *Quncho* which were grouped in cluster-I based on their high cell wall constituents also had the highest grain-straw yield in this study. The fact that our popular high yielding improved variety *Quncho* was clustered with those having the highest cell wall constituents in this study confirmed the farmers suspicion that the straw of this variety 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. Among the varieties in cluster-IV which were identified to have high grain-straw yield, *Gimbichu* possessed the highest GY and STY while *Dukem* and *Melko* had the highest STY and GY, respectively.

Among all of the 36 varieties in the current study, varieties consistently performing above or below the mean for all the four pairs of yield and quality traits were clearly identified by the scatterplot analyses. The variety *Yilmana* consistently performed above the mean while the varieties *Mechare* and *Etsub* performed below the mean in Debre Zeit. In Holetta the varieties *Melko*, *Ajora* and *Koye* consistently performed above the mean while *Amarach*, *Ambo-Toke*, *Magna* and the local check performed below the mean. Furthermore, based on combined data the variety *Melko* consistently performed above the mean while *Etsub*, *Simada*, *Magna* and *Tsedey* performed below the mean. Surprisingly, some varieties which performed better under one situation were found to perform poorly in another. For example, *Guduru* was amongst the varieties with high CP, IVOMD and ME values in Debre Zeit while it was amongst those with high fiber content in Holetta. The variety *Etsub*, on the other hand, performed poorly in Debre Zeit while it was amongst varieties with high CP, IVOMD and ME values in Holetta. The variety *Melko* combined higher grain-straw yield along with reasonable values of CP, IVOMD, GY and STY under all circumstances. Hence, it could be useful in developing a dual-purpose variety.

5. Conclusions

In the present study, the variation and relationships in food and feed traits due to the effect of growing environment and varieties was assessed in 36 tef varieties, including a local check. The straw feed quality traits were analyzed using the NIRS technique which was confirmed to be robust by relating the results to wet chemistry analyses. Our findings revealed the existence of a wide range of variations in grain-straw yield and straw fodder quality traits across environments and the studied varieties. Thus, the Debre Zeit location showed very good performances of grain and straw yield and straw quality traits. Based on the various analyses, four groups of varieties namely those with: 1) high grain-straw yield; 2) high straw quality; 3) high fiber content and moderately high yield; and 4) low yield and straw quality traits were identified. Among the studied varieties, *Melko* combined higher grain-straw yield and fodder quality traits while *Etsub* and *Simada* varieties performed poorly under all circumstances. Hence, *Melko* which possessed high yield and quality traits can be promoted for immediate utilization as a dual-purpose variety or as a parental line in future tef breeding to change the current situation that focuses on grain yield improvement alone.

Acknowledgments

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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

Constituent	52 Calibration			52 Validation			104 Calibration		
	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	0.800	52	0.920	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	0.580	104	0.990	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 = the secant.

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
R^2		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-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 combined means
	Between locations		Between years		Debre Zeit		Holetta		2015		2016		Combined		
	Debre Zeit	Holetta	2015	2016	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
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	50.40	62.60	56.9
NDF	766.7b	836.8a	810.6a	792.9b	711.0	827.1	788.9	874.4	711.0	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	6.35	9.39	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	6.60
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	4140a	3622.4b	3886.2a	3876.6a	2160	5780	2810	4800	2580.0	5780.0	2160	5200	3230	4630	3881.4
STY	10070b	13805a	13828a	10042b	4970	13920	6900	24410	4970.0	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 ($P < 0.05$).

Table 5. Pearson correlation coefficient among grain-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 $P < 0.001$.

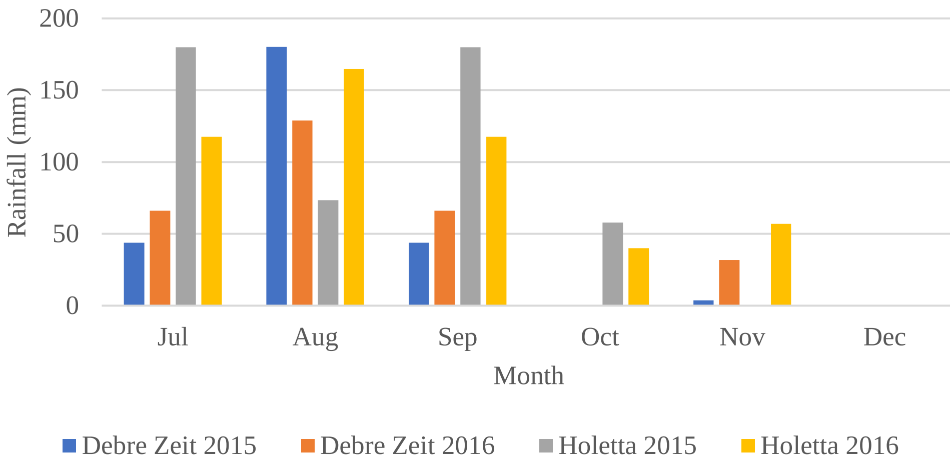
Table 6. Economic benefit analysis of producing tef varieties with various traits

Group		Quality (%)	Yield (kg ha^{-1})		Price (Eth. Birr) †			Economic
	Varieties	IVOMD	GY	STY	Grain	Straw	Total	advantage (%)
I	Dukem	45.60	4100	15000	86226	37575	123801	32.40
	Melko	45.90	4600	13600	96768	33900	130668	39.74
	Gola	45.20	4600	14400	95718	36000	131718	40.86
	Gimbichu	45.40	4700	14500	97587	36350	133937	43.24
	Quncho	45.10	4300	13800	98440	34525	132965	42.20
II	Kenna	46.40	3200	11600	67794.	29025	96819	3.54
	Genet	46.10	3700	10600	78183	26575	104758	12.03
	Ambo-Toke	46.30	3700	9700	77112	24222	101334	8.37
III	Ajora	45.00	4300	1300	89586	32575	122161	30.64
	Gemechis	45.10	4300	1220	98072	30500	128572	37.50
	Gibe	45.00	4100	1150	85008	28850	113858	21.76
	Tsedey	45.00	3800	1170	78876	29350	108226	15.74
IV	Local	45.50	3400	9700	67680	25827	93507	0.00
	Simada	45.30	3700	10000	77133	25015	102148	9.24
	Etsub	45.30	3300	9700	68739	24262	93001	0.54

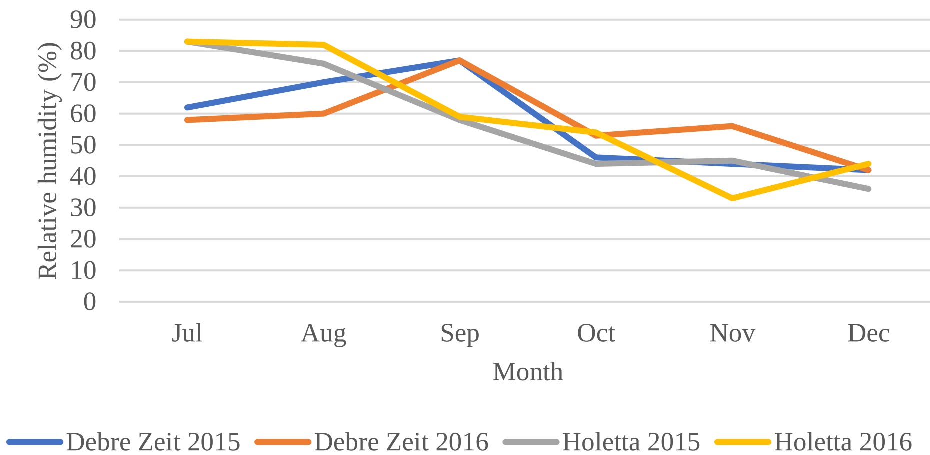
† The average market price for very white, creamy white, mixed and brown tef grain and tef straw for all varieties in east Shewa is 23.0, 21.0, 20.0, 18.0 and 2. 5 Birr kg^{-1}, respectively. GY = grain yield (kg ha^{-1}), STY = Straw yield (kg ha^{-1}).

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

a)



b)



c)

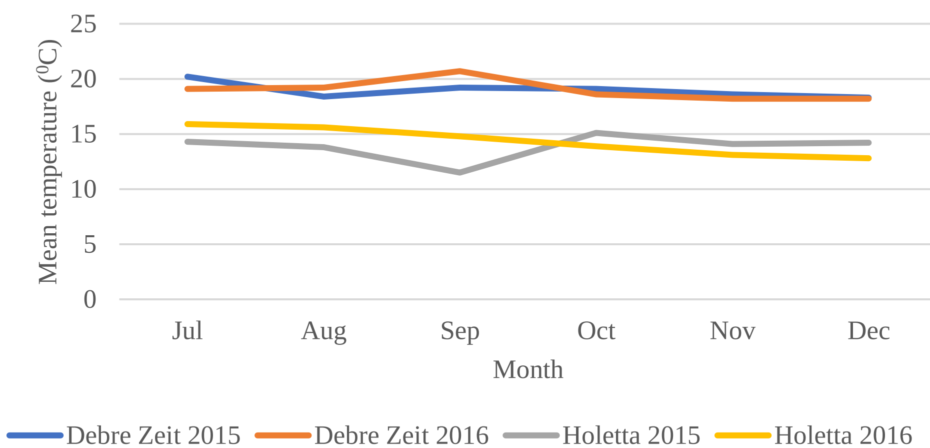


Figure 2. Scatter plots showing the performance of 35 released tef varieties and a local check in Debre Zeit for (a) GY vs CP; (b) GY vs IVOMD; (c) STY vs CP; and (d) STY vs IVOMD. Red and aqua font colours indicate best and worst performing varieties, respectively.

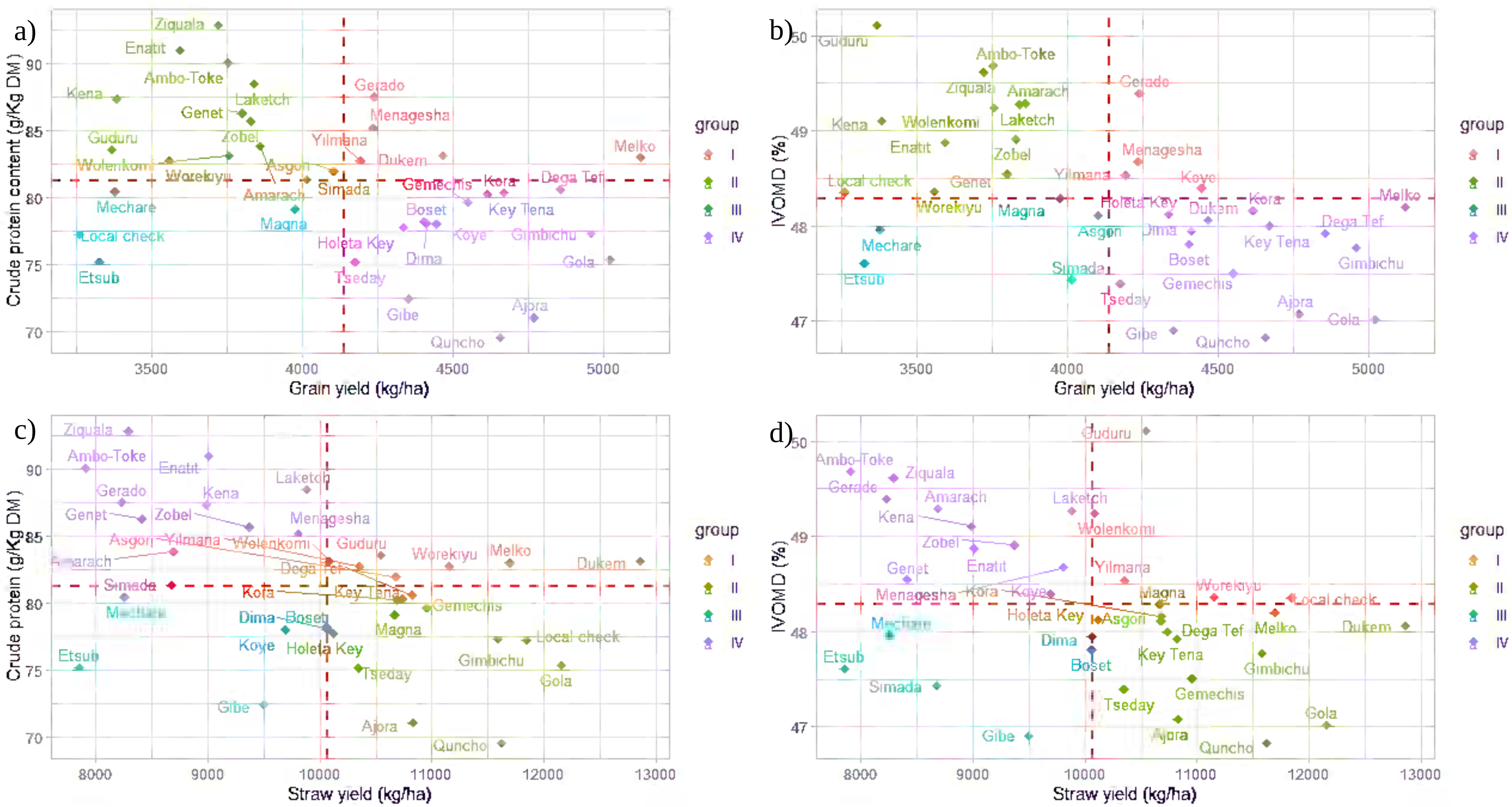


Figure 3. Scatter plots showing the performance of 35 released tef varieties and a local check in Holetta for (a) GY vs CP; (b) GY vs IVOMD; (c) STY vs CP; and (d) STY vs IVOMD. Red and aqua font colours indicate best and worst performing varieties, respectively.

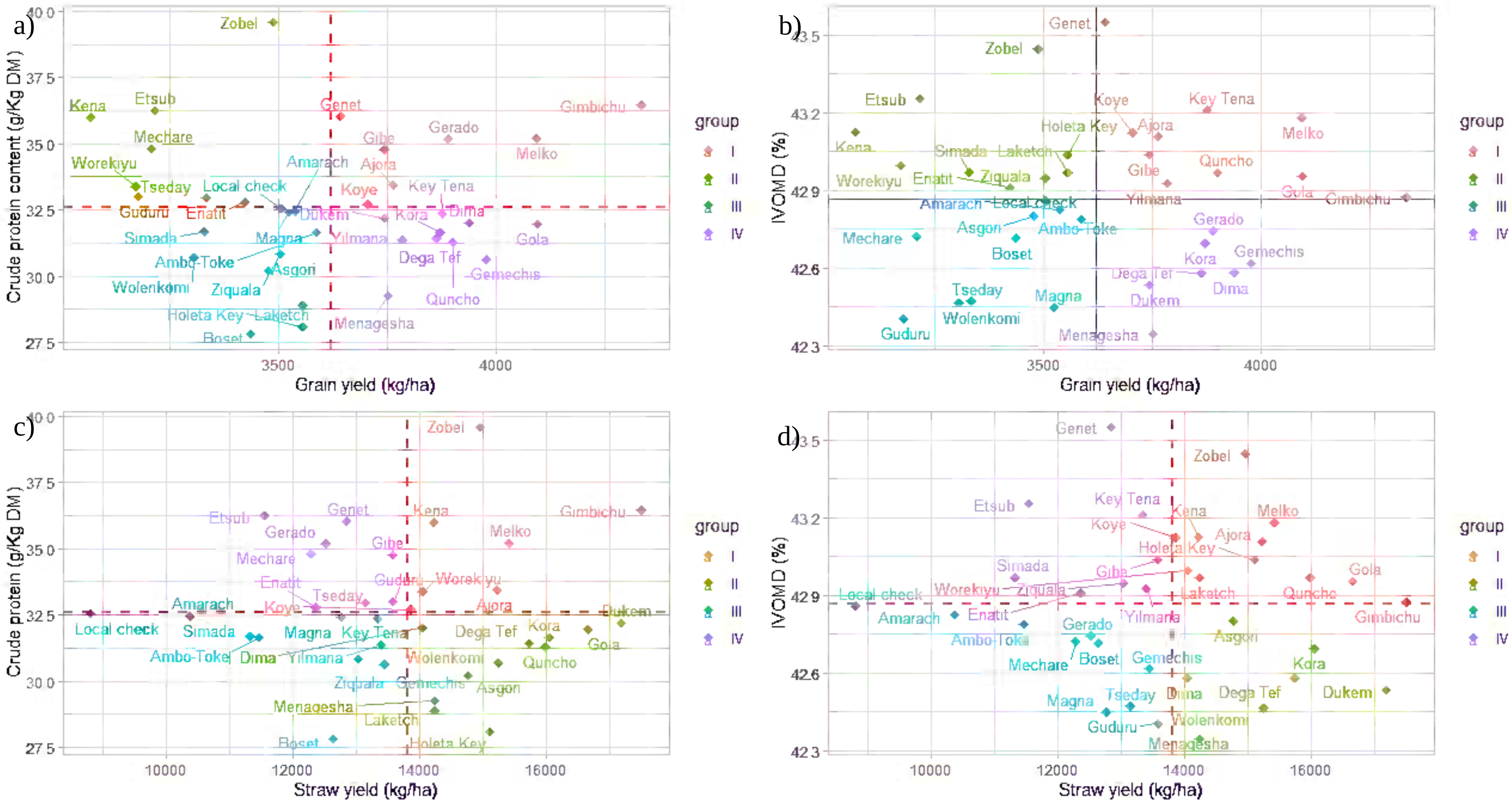


Figure 4. Scatter plots showing the performance of 35 released varieties and a local check over years and locations for (a) GY vs CP; (b) GY vs IVOMD; (c) STY vs CP; and (d) STY vs IVOMD. Red and aqua font colours indicate best and worst performing varieties, respectively.

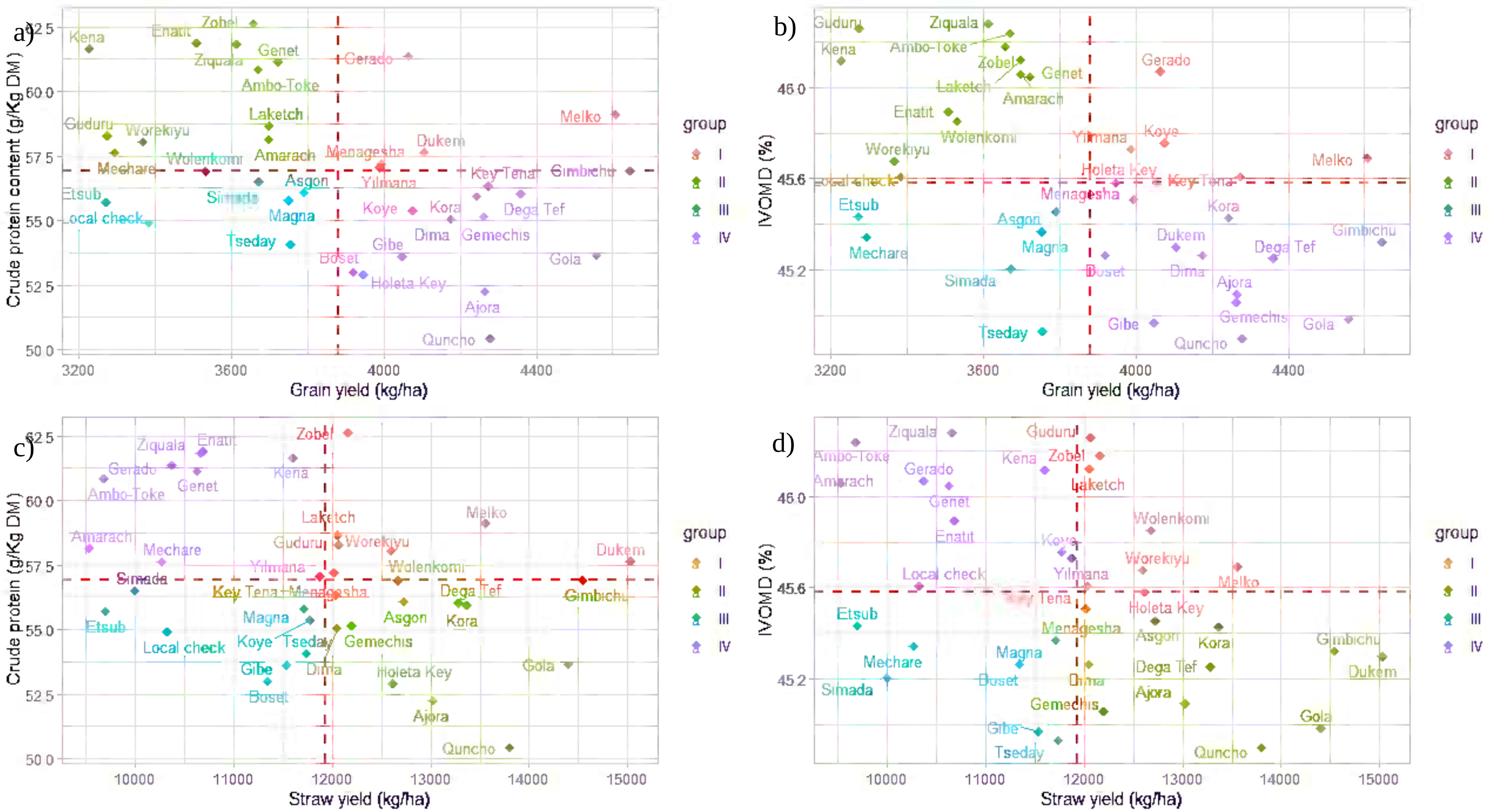


Figure 5. PCA bi-plots showing the relationship between the studied varieties and their traits in (a) Debre Zeit and (b) Holetta. CP = Crude protein; IVOMD = in vitro organic matter digestibility; ME = Metabolizable energy; ADL = Acid detergent lignin; NDF = Neutral detergent fiber; ADF = Acid detergent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

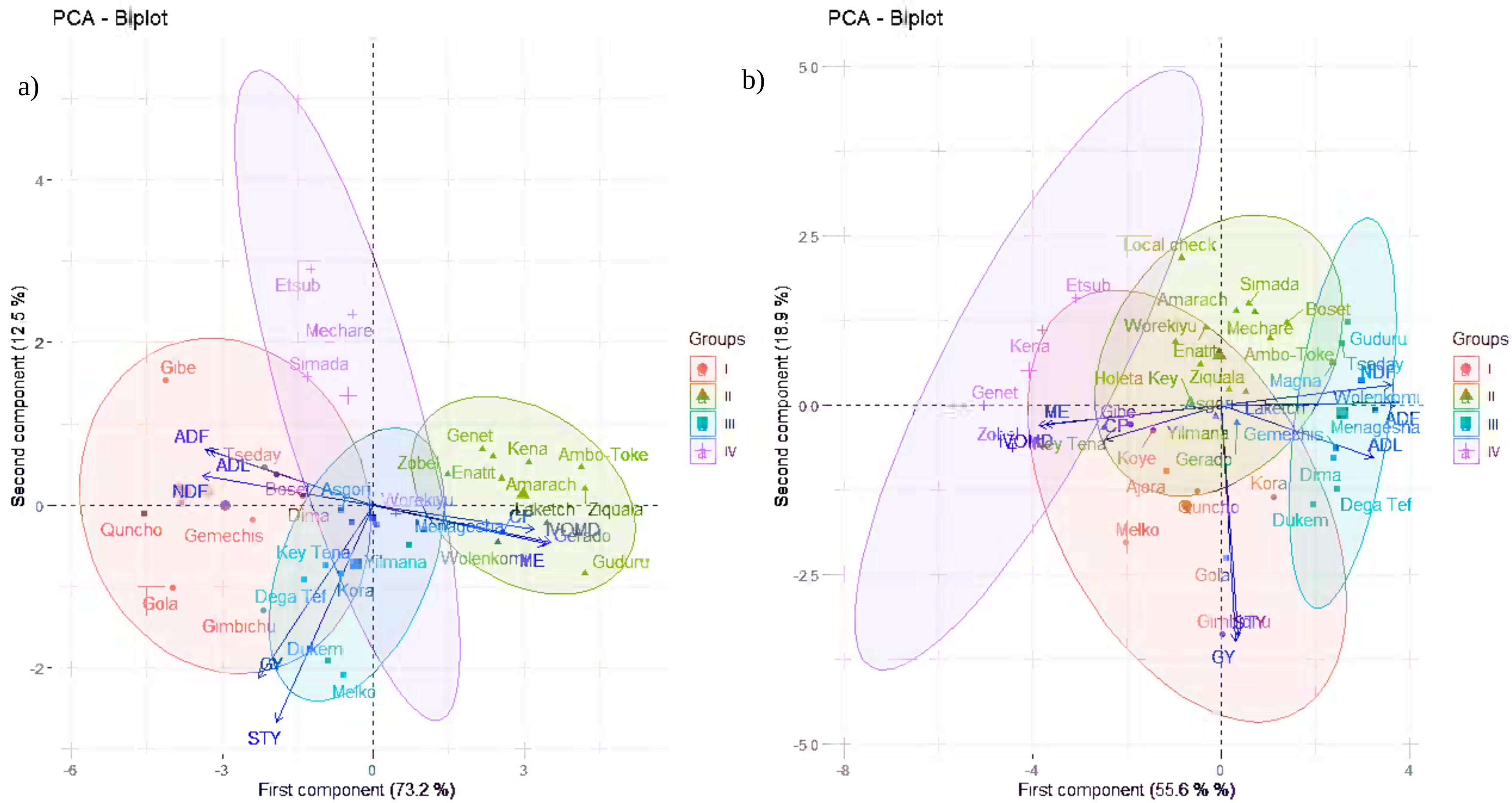


Figure 6. PCA bi-plot showing the relationship between the studied varieties and their traits based on the combined data. CP = Crude protein; IVOMD = in vitro organic matter digestibility; ME = Metabolizable energy; ADL = Acid detergent lignin; NDF = Neutral detergent fiber; ADF = Acid detergent fiber;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

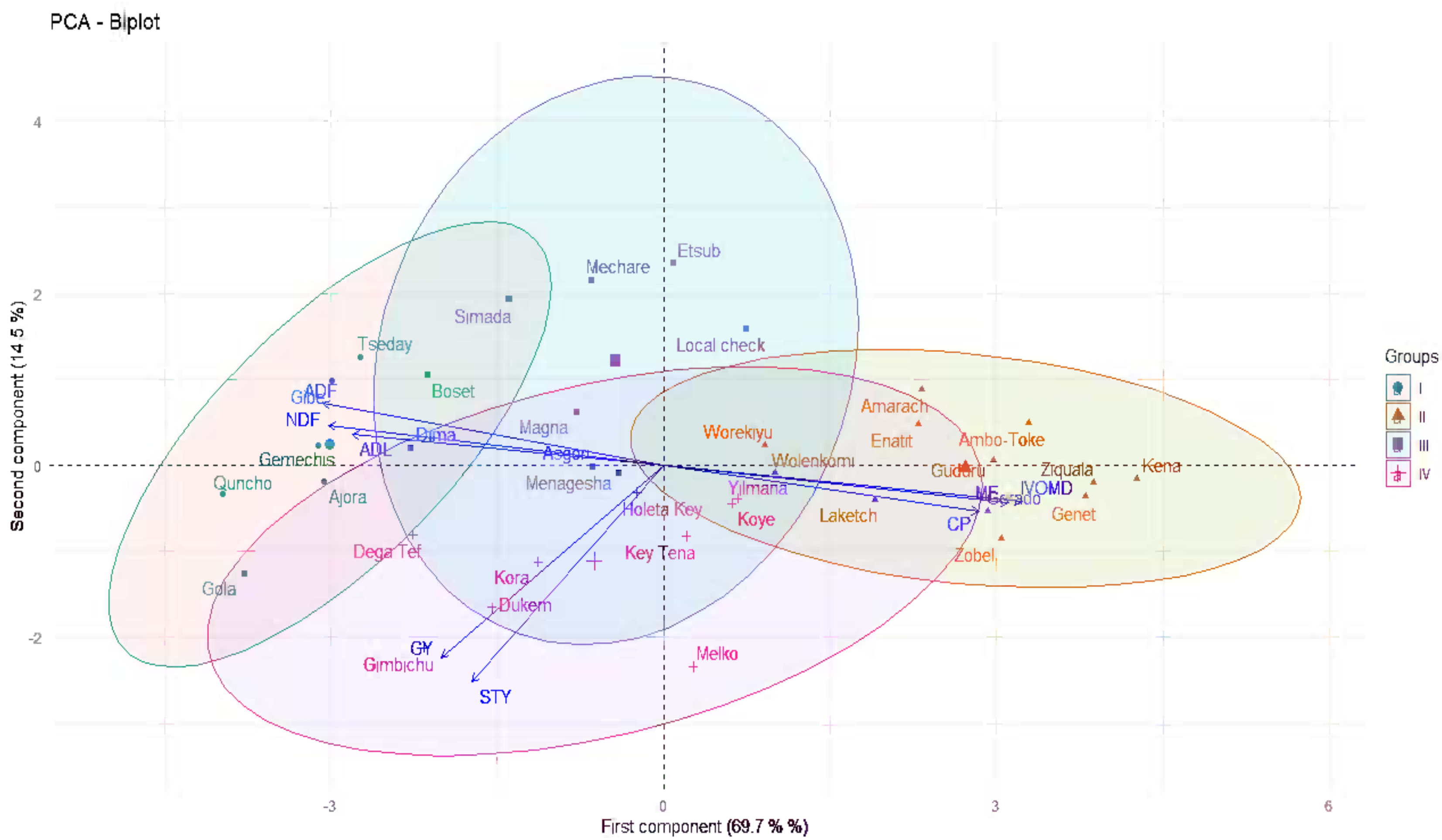


Figure 7. Hierarchical cluster analysis showing the four clusters of 36 studied tef varieties and their relative values for eight food-feed traits. CP = Crude protein; IVOMD = in vitro organic matter digestibility; ME = Metabolizable energy; ADL = Acid detergent lignin; NDF = Neutral detergent fiber;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