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Characterization and Evaluation of the Mechanical and Physical Properties of *Tef* Stem (*Eragrostis tef* (Zucc.) Trotter)

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ABSTRACT

Tef (*Eragrostis tef* (Zucc.) Trotter) is a typical crop growing in most areas of Ethiopia, with the first area coverage. In this study mechanical properties of *tef* stem the major four varieties, viz., Local, Dz-Cr-438- (Kora), Dz-Cr-387/RIL-355 (Quncho) and Dz-01-1880 (Guduru) were determined. The factors considered were moisture content, diameter and thickness of the *Tef* stem and analyzed their mechanical properties using Texture Analyzer and Universal Testing Machine. The results indicated that the minimum and maximum value of modulus of elasticity was 0.13 and 2.6 Gpa at moisture level 8.82% and 16.6%; 1.03 and 3.6 Gpa at moisture level 10.32% and 13.79%; 0.85 and 3.22 Gpa at moisture level 7.65% and 12.72%; 1.27 and 3.88 Gpa at moisture level 5.5% and 19.70% at upper and bottom position for Local, Kora, Quncho and Guduru varieties, respectively. The shear stress at different moisture contents was 8.58 and 32.12 Mpa; 6.30 and 28.40 Mpa; 10 and 26.30 Mpa; 2 and 29.60 Mpa at upper and bottom position for Local, Kora, Quncho and Guduru varieties, respectively. The ability to track significant differences between the varieties and their individual mechanical and physical properties provides a path forward for tailoring harvesting, threshing and separation operations. To tackle the problem of lodging it is better to look on the morphological structure of each varieties of *Tef* stem that has better modulus of elasticity, flexural rigidity and diameter of the stem. Since the *Tef* stem has better mechanical properties than some cereals, it is recommended to identify the fiber properties and use as material for composite.

Keywords: Modulus of elasticity, Flexural rigidity, Shear stress, *Tef* stem, Variety

INTRODUCTION

Ethiopian economy is much dependent on agricultural production, where crop production contributes largely to the local and export markets. Different types of cereals are grown in almost all regions of Ethiopia. The area coverage out of the total grain crop area is 78.17% (9,601,035.26 hectares) was under cereals. *Tef*, maize, sorghum and wheat took up 22.23% (about 2,730,272.95 hectares), 16.39% (about 2,013,044.93 hectares), 13.93% (1,711,485.04 hectares) and 13.25% (1,627,647.16 hectares) of the grain crop area, respectively. Also in production cereals contributed 84.96% (about 196,511,515.46 quintals) of the grain production. Maize, *tef*, wheat and sorghum made up 26.63% (61,583,175.95 quintals), 16.28% (37,652,411.66 quintals), 14.85% (34,347,061.22 quintals) and 15.58% (36,042,619.65 quintals) of the grain production, in the same order [1].

Tef (*Eragrostis tef* (Zucc.) Trotter) is one of the dominant crops in terms of area coverage and production. *Tef* is the typical crop and staple food for Ethiopians. *Tef* straw is the preferred feed for animals and *Tef* has a fine stemmed straw which can be firmly stacked in such a way to minimize percolations of rain water and exposures to other inclement weather conditions [2]. *Tef* is a labor intensive crop, each activities/pre-harvest and post-harvest/mostly done by traditional practice. It is obvious that productivity of agriculture is strongly related to, among other factors, the timely and efficient pre-harvest and post-harvest operations.

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Most of the farmers in the country usually prepare their land either using human power or draught animals (personal observation).

Different researchers determined the mechanical and physical properties of different plants. Identifying the physical and engineering characteristics of cereal crop grains is very important to optimize the design parameters of agricultural equipment used in their harvesting, threshing, production, handling and storage processes.

Bending stress, young's modulus, shearing stress and shearing energy were determined for alfalfa (*Medicago sativa* L.) stem by Galedar et al. [3]. The experiments were conducted at a moisture content of 10, 20, 40 and 80% w.b. The bending stress decreased as the moisture content increased. The value of the bending stress at low moisture content was obtained approximately 3 times higher than at high moisture content. The average bending stress value varied from 9.71 to 47.49 MPa. The young's modulus in bending also decreased as the moisture content and diameter of stalks increased. The average young's modulus ranged from 0.79 to 3.99 GPa [3].

Shearing stress, bending stress and young's modulus were determined for canola (*Brassica napus* L.) stem by Hoseinzadeh and Shirneshan [4]. They studied three varieties of canola and the average values for the young's modulus were found to be 1.57, 1.71 and 2.04 GPa for Zarfam, Okapi and Opera varieties, respectively.

Measurement of the shear strength of six varieties of wheat straw by O'Dogherty et al. [5] showed mean values in the range 5.4-8.5 MPa. Kushaha et al. [6] reported mean values of shear strength of wheat straw from 8.6 to 13.0 MPa with some dependence on moisture content. Other workers have measured the energy require to shear materials.

Bending and shearing properties of safflower stalk was studied by Shahbazil and Galedar [7], the average bending stress value varied from 21.98 to 59.19 MPa. The Young's modulus in bending also decreased as the moisture content and diameter of stalks increased. The average Young's modulus varied between 0.86 and 3.33 GPa. The shear stress and the shear energy increased with increasing moisture content. Values of the shear stress and energy also increased from top to the bottom of stalks due to the structural heterogeneity. The maximum shear stress and shear energy were found to be 11.04 MPa and 938.33 mJ, respectively, both occurring at the bottom region with the moisture content of 37.16%. Chattopadhyay and Pandey [8] found that the bending stress for sorghum stalks at the seed stage and forage stage were 40.53 and 45.65 MPa, respectively.

The physical properties of cellular materials are importance in cutting, compression, tension, bending, density and friction [9,10]. Plants are rheological materials whose properties follow non-Newtonian laws as derived their behavior in terms of plasticity and elasticity [11].

The *tef* plant has different structure of the stem and the stem has different amount of panicles and contain different amount of *tef* seeds at each panicles. The lodging is the major problems of *tef* production. Several studies have shown morphological traits that are related to the lodging in *Eragrostis tef*/*tef* to be related to plant height, stem diameter of lower internodes, panicle length, biomass and seed weight [12]. In Ethiopia, lodging of *tef* is also a common phenomenon and one of the causes for the current low grain yields: the Ethiopian national average grain yield of *tef* is in the order of 800 kg ha^{-1} [13].

Tef's estimated yield loss due to lodging can be as high as 30% [12]. Lodging resistance related traits, such as plant height and culm thickness, diameter of the stem are related to the physical properties of the plant. van Delden et al. [14] studied the lodging cause of the two varieties of *tef* and come up with the conclusion that enhancing the anchorage strength of the roots has priority over stem enhancement. Nevertheless, breeding efforts should not only focus on a wider root plate diameter and more rigid horizontally growing roots but also on shorter and thicker stems, that means the breeding study should focus on the morphological behavior of *tef*.

According to Crook and Ennos [15], lodging susceptibility in cereals depends on three factors: first, the size and dynamics of the forces to which the plant is subjected; second, the bending strength of the shoot and its resistance to buckling; and third, the anchorage strength of the root system. Flexural rigidity (E × I) is not stem strength but is a measure of the stem's ability to bend. It is dependent on the geometry of the stem (stem radius and stem wall width), but is not dependent on the material component of the stem. The physical properties can influence the mechanical properties such as the tensile strength, shear stress and flexural rigidity of the stem (resistance to lodging). Prior to improve the physical properties of *tef* it is more crucial to determine the mechanical properties of the existing varieties (major produced varieties).

The mechanical properties are important not only to develop a new breed and genetically modified, but are equally important to use and generate different types of pre harvest like harvesting (cutting machine) and post-harvest like threshing and processing technologies in *tef* production. In order to harvest *tef* with combine or other harvester; to design appropriate threshing and cleaning unit, it is important to know the physical and mechanical property of *tef* stem. In other research works it is possible to found the mechanical properties of plenty crops, however there is limited information regarding the mechanical properties of *tef* stem. Hence, the objective of this research is to characterize and evaluate the mechanical and physical properties of *tef* stem.

MATERIAL AND METHODS

Selected test materials (samples)

There are lot of *tef* varieties in the Country (Ethiopia), but for this research as test material the four varieties namely, Dz-Cr-387/RIL-355- local name Quncho, Dz-Cr-438- local name Kora, Dz-01-1880- local name Guduru and Local variety from farmers hand were selected; based on their productivity, quality of grain, acceptance among the farmers and dissemination rate in Ethiopia in consultation with *tef* researchers from Debreziet and Adet Agricultural Research Centers.

Test materials (samples) origin and site description

The samples were planted on individual plot at Adet Agricultural Research Center compound (test site, farm), on the main crop season in 2016/2017. The crops were planted by broadcasting on June and harvested on November by sickles after 120 days of planting. Adet Agricultural Research Center is located at 110 17'N latitude and 370 43'E longitude with an altitude of 2240 m a.s.l. It is situated in West Gojjam zone, Ethiopia, 43-km southwest of Bahir Dar town, Amhara Region capital, along the high way to Addis Abeba via Mota Town. The type of soil is clay loam.

Experimental design and test procedure

The test crops were harvested manually (by sickles) with minimum height of cutting (1-1.5 cm) and counted 60 stems (as a whole crop) in each varieties and packed with long plastic bags and cartoons, to avoid breakage of the stem. Then, the samples were transported to the controlled lab in Bahirdar University, Bahirdar Textile and Fashion Technology Institute and at Bahirdar School of Chemical and Food Engineering.

In this test *tef* stem shows its rheological properties, even so in each segments it is possible to have different elasticity and shear result, so the study has tried to get more reliable information by extending the sample size (20 samples in each segments) with different moisture levels.

The variables were moisture content, diameter of the stem, variety and position of the stem (segments where the measurements performed). Because of the morphological shape, the diameter of the *tef* stem decreases from the bottom of the plant to the top (upper); therefore, stem shows different physical and mechanical properties at different heights due to the variable cross sectional area. Then, prior to test the samples stems (the panicles lengths were excluded) were divided at three equal sections (measuring position) at bottom, middle and upper **(Figure 1)**. The segments' length were 170-200 mm (because of the plant height difference), hence the segments lengths were different, but the test was performed at the center of each segments and avoided to measure near to the nodes (measurement at the node and near the nodes had better strength to the shear and elasticity properties). The local variety has short stem length and the samples were prepared with two segments.

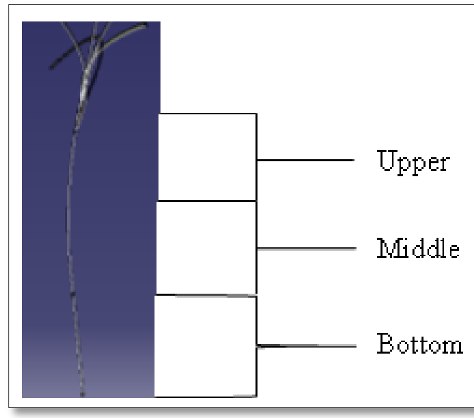

Figure 1. Specimens prepared at different position (segments) of the samples (stem sketch).

The grain straw ratio of the *tef* were 1:2.31, 1:3.59, 1:4.26 and 1:6.4 for Local, Kora, Quncho and Guduru varieties, respectively.

The moisture content of the stems was measured immediately after each test of each segment using the Infrared Moisture Genis Photometer **(Figure 2)** in (w.b.). To determine the mechanical properties of the *tef* stem within different moisture of the specimens, it was important to vary the amount of moisture in the stem. Though, the measured amount of water was sprayed using the syringe on the stem, which was packed with polyethylene material and it reserved for three days at controlled lab and refrigerator. During test the moisture differences were observed within the same stem at different positions, so the measurements of moisture were performed on the individual specimens. Before starting on each test, the required amounts of stems were allowed to warm up to the room temperature, in order to distribute equal moisture at the specimen (stem) as much as possible.

Figure 2. Infrared Moisture Genis Photometer (direct moisture tester).

The specimens had different moisture levels from 5%-35% (w.b.). During the harvesting and threshing of *tef* crop the m.c. is expecting from 18%-25% (w.b.) (consulting the farmers and researchers at *tef* producing areas). Though, the test represents the maximum and minimum range of the moisture. For each test, the samples were tagged and coded, the physical parameters like the diameter, thickness and length of the specimen were measured by appropriate equipment (micrometer and vernier caliper).

Instruments used for measurements were sensitive balance electronic scale. 2000 g/0.1 g, England; Micrometer/Moore Wright Sheffield (0-0.045) mm (0-2.5) cm, 0.01, England; Vernier caliper (0-150) cm, 0.01 scale; Infrared Moisture Genis Photometer (direct Moisture Tester); Texture analyzer TA.XTPlus Texture Analyzer and Tensile force measurements bench type Universal Testing Machine THE-Hounsfield England with 5 kN.

Tensile test

The tensile measurements were performed using Universal Testing Machine THE-Hounsfield England **(Figure 3)**. The speed of the test was 75 mm/min. The specimen measured with constant length of segments and to avoid the skidding and squeezing of the stem, the stem ends were plastered (rolled) with the drawing scotch tape at each end and tightened on the upper and lower jaw of the instrument. The breakage of the specimens was not performed exactly at the center of the specimen it happened because of the rheological properties of the stem and the breakage acts at any position of the specimens, to avoid the jaws effect for this test, the breakage distance from the upper and the lower jaws decided to be from 30-40 mm, the specimens which had breakage lower than the specified gap were discarded. The test result data and graphs were recorded **(Figure 4)**. The moisture of each specimen was measured immediately after performing each test/using the Infrared moisture Genis Photometer.

Figure 3. The universal test machine (UTM) THE-Hounsfield.

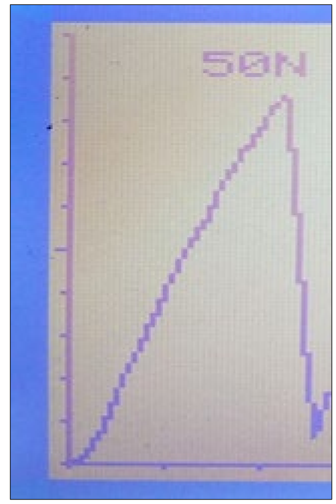

Figure 4. A typical load-deformation curve of *Tef* stem under vertical tension load (tensile test) from UTM.

It is possible to determine the modulus of elasticity of different varieties of *tef* from the tested and/or measured parameters using the following empirical and derived formulas.

Area of each variety was calculated for elliptical shape the area of the stem, most of the *tef* stem shape is elliptical and this formula used in each calculation.

$$A = \frac{d_1^{\ 2} - d_2^{\ 2}}{4}\pi \quad (1)$$

Modulus of elasticity was calculated with

$$E = \frac{PL}{A\Delta l_{\max}} \quad (2)$$

Where;

A=Cross section area of the stem in mm^2; d_1=Major diameter of the stem in mm; d_2=Minor diameter of the stem in mm; P=The maximum tensile force measured by the testing instrument in N; L=The length of the specimens (stem to be tested) from the upper jaw to the lower jaw of the instruments in mm; Δl_{max}=The maximum elongation of the specimens in mm

Fluxural rigidity (F_r) of the stem calculated using

$$F_r = EXI \quad (3)$$

$$I = \frac{\pi}{4}\left| d_1 d_2^{\ 3} - (d_1 - t)(d_2 - t)^3 \right| \quad (4)$$

Where,

I=Moment of inertia in mm^4; d_1=Major diameter of the stem in mm; d_2=Minor diameter of the stem in mm; t=thickness of the stem in mm

Shear test

The shear force measurements were performed using texture analyzer TA-XTPlus **(Figure 5)**. The blade is knife type with sharp edge (0.1 mm). The test mode was compression; pre-test and test speed was 2 mm/s, the target mode was displacement with trigger type auto, break mode rate and break detect auto. The specimen was plastered on the table of the analyzer without squeezing the stem and lied on the center of the knife (blade) and applies the cutting force using proper setup of the texture analyzer. The moisture of each specimen was measured immediately after performing each test, using the Infrared moisture Genis Photometer. The shear stress with its force and displacement graphs were registered by the testing instruments (texture analyzer attached with computer and accessories).

Figure 5. Texture analyzer TA.XTPlus Texture Analyzer with full computer accessories.

It is possible to determine the shear stress of different varieties of *tef* from the tested and/or measured parameters using the following empirical and derived formulas.

Shear stress calculated

$$\tau = \frac{F_{s\max}}{A} \qquad (5)$$

Area of each variety can be calculated using equation 1

Where;

A=Cross section area of the stem in mm^2; d_1=Major diameter of the stem in mm; d_2=Minor diameter of the stem in mm; F_{smax}=maximum cutting/shearing/force in N; τ=Shear stress in Mpa

STATISTICAL ANALYSIS

In this study the following four factors were studied, they are moisture, diameter, thickness and variety. The effects of stem moisture content, diameter and thickness of the *tef* stem, stem region as segments (at upper, middle and bottom regions) and variety of *tef* (Dz-Cr-387/RIL-355 – Quncho, Dz-Cr-438- Kora, Dz-01-1880- Gudru and Local) shows the mechanical properties (modulus of elasticity, shear strength (shear modulus), flexural rigidity of *tef* stem. Based on the preliminary result and analysis, it was found that the main and most determinant position (segments) was the bottom segments; hence the detail analysis for this paper is focusing and describing on the bottom position of the *tef* stem.

A factorial test with four factors and twenty replications based on completely randomized experimental design was used. Experimental data were analyzed using analysis of variance (ANOVA) linear modeling, correlated with multi linear modeling and the means were compared with different range tests and graph construction in R i386.3.0.1 software.

RESULTS AND DISCUSSION

Using the proper set up of the testing equipment and the empirical formulas for determination of the mechanical and physical properties four *tef* varieties of stem results (at bottom segment) are depicted in the **Tables 1 and 2**. The summary of results for modulus of elasticity and flexural rigidity of each variety are presented in the **Table 1** and the summary results for the shear stress of each varieties are indicated in the **Table 2**.

Table 1. Summary of measured and calculated data to determine different parameters of *tef* crop for the 4 varieties at bottom position of the stem; standard deviation in parentheses.

Variety	Moisture content (wb), %	Diameter mm	Thickness mm	Modulus of elasticity E, in Gpa	Fluxtural rigidity (E x I)
Local	15.42 (6.23)	1.87 (0.17)	0.30 (0.07)	0.65 (0.38)	2.99 (2.43)
Guduru	17.86 (4.18)	2.01 (0.28)	0.38 (0.10)	0.69 (0.31)	6.41 (4.36)
Kora	17.51 (7.64)	1.98 (0.29)	0.35 (0.09)	1.75 (1.19)	7.69 (5.13)
Quncho	16.65 (5.67)	2.31 (0.37)	0.47 (0.09)	0.95 (0.27)	9.83 (4.61)

Table 2. Summary of data measured and calculated to determine different parameters of *tef* crop for the 4 varieties at bottom position of the stem; standard deviation in parentheses.

Variety	Moisture content (wb), %	Diameter Mm	Thickness Mm	Shear stress Mpa
Local	19.21 (3.60)	1.91 (0.14)	0.32 (0.04)	27.77 (7.78)
Guduru	19.44 (8.25)	2.05 (0.41)	0.28 (0.08)	23.19 (8.23)
Kora	15.55 (10.05)	1.79 (0.41)	0.29 (0.06)	20.24 (8.65)
Quncho	15.01 (8.18)	2.23 (0.39)	0.37 (0.08)	18.40 (11.40)

SHEAR STRESS

The effect of moisture, stem diameter, thickness and variety for shear stress

The statistical analysis with multi linear regression shows the thickness of the stem has low effect in shear, but the moisture content and diameter are the most dominant factor for shear stress. The shear stress value indicated in a mean value for comparison at the bottom segments of each stem with the range of all moisture, the result shows with their level of shear force value were the Local (check) is 1st, Guduru (Dz-01-1880.) 2nd, Kora (Dz-Cr-438) 3rd and Quncho (Dz Dz-Cr-387/RIL-355) 4th **(Figure 6)**. Most of the *tef* varieties have closely solid stem and its diameter decrease from bottom towards upper position with minimum difference; and the minimum and maximum value of the shear stress at different m.c. was 8.58 and 32.12 Mpa; 6.30 and 28.40 Mpa; 10 and 26.30 Mpa and 2 and 29.60 Mpa at upper and bottom position for Local, Kora, Quncho and Guduru varieties, respectively. When comparing the shear stress among *tef* varieties **(Figure 7)**, the Local varieties has higher value, this is due to its compactness and more nodes with limited length of the stem and has more strong fiber than that of others varieties. Based on the test result the *tef* shear stress is better than any other cereal crops for instance, wheat 3.8-6.8 Mpa, barley 7.2-9.2 Mpa and rice 5.4-10.2 Mpa (Miu, 2016). The shear stress of safflower stalk was studied by Shahbazi and Nazari [7] and their result shows in the bottom region the shear stress increased from 5.48 to 11.04 MPa by increasing moisture content from 8.61 to 37.16%.

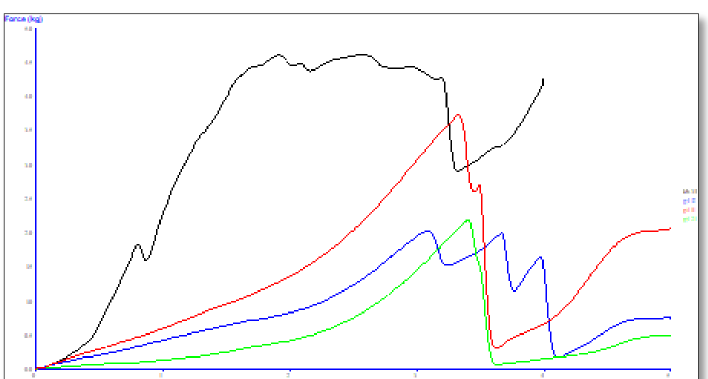

Figure 6. A typical shear (cutting) curve (graph) on the shearing strength test by texture analyzer.
1st Kora (black), 2nd Local (red), 3rd Quncho (green), 4th Guduru (blue)

The position (segment) of the *tef* stem has effect on the shear stress within the same moisture content for each variety. Comparison of each variety with the maximum, average and minimum values of shear stress through the measured moisture content and diameter was plotted by R-software and shows at **Figure 7**. The relation between the moisture content and diameters on the result of shear stress for each variety at different position is indicated as on the **Figure 8** (It is particularly for the variety of Kora (Dz-Cr-438) and the same condition was applied for all varieties of *tef*).

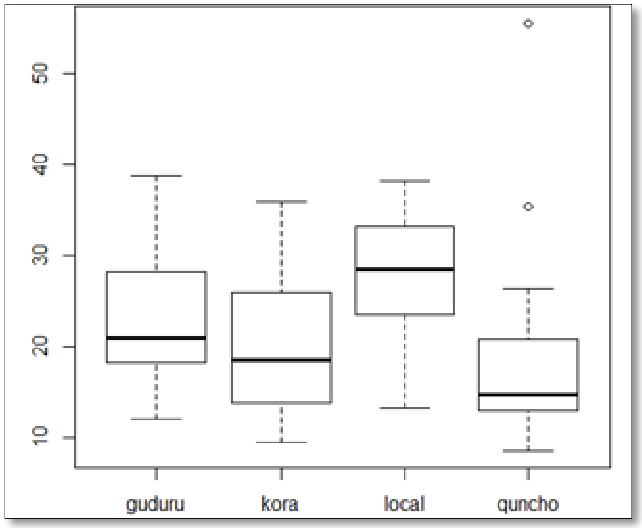

Figure 7. Comparison of *tef* varieties on their maximum, minimum and mean value of shear stress at bottom position (segments).

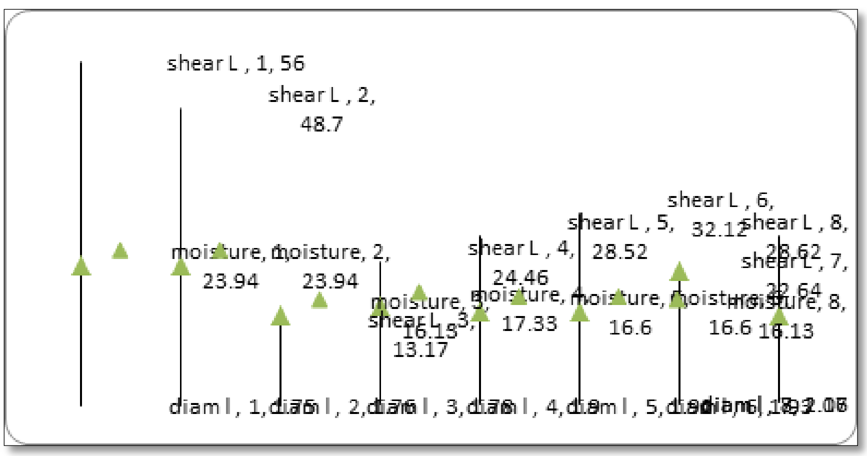

Figure 8. Moisture, diameter of specimens vs. shear stress for Kora variety at bottom position.

The ANOVAs result indicated the interactions of all factors on the shear stress at bottom position. Among the factors, the diameter and moisture content are highly significant for the shear stress under the 99% confidence interval, whereas the variety and thickness of the segments had significance for the shear stress under 95% confidence interval at bottom position of the stem. In regard of interaction, diameter with moisture is highly significant for the shear stress at the 99% confidence interval; the interaction between variety with diameter and between varieties with thickness had significance for the shear stress under 95% confidences. The 3D plot **(Figure 9)** shows the shear stress increase with increase moisture content and local variety has greatest values of shear stress than other three varieties.

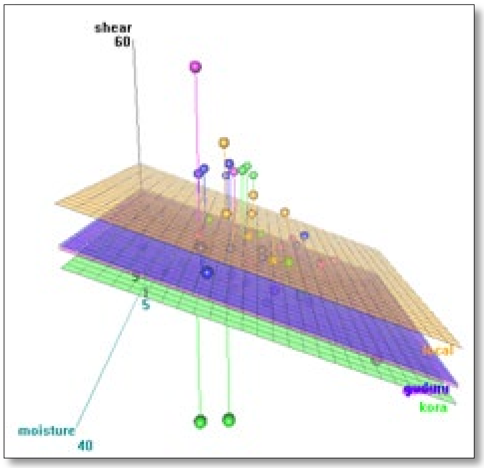

Figure 9. The effect of moisture and diameter of each varieties on shear stress at bottom position (3D plot).

Similarly, the ANOVAs result shows the interaction of all four factors at middle and upper segments of *tef* stem and the result indicated the independent variables variety and moisture had significance effect for the shear stress under 95% confidence. Under the interaction, variety with diameter and variety with thickness shows significance for the shear stress under 95% confidences at the middle position of the *tef* stem. The other factors interaction has no significance for the shear strength.

At the upper position of the stem only moisture content has significance for the shear stress under 95% confidence and the diameter has significance for the shear stress under 90% confidence. The effect of the moisture and diameter of the stem on the shear stress at all segments shows moisture content is the most dominant factor in shear strength of the stem in all varieties of *tef*. However, after a certain amount of increments of moisture above 35% (w.b.) the cutting force trend is decreasing, so it requires optimization of the moisture level on which the harvesting could perform with minimum cutting force and minimum harvesting loss.

Multi linear regression analysis was used to find and fit the best general models to the experimental data. Results showed that the *tef* stem shear stress was a linear function on the stem moisture content, diameter and thickness. The linear equations for all segments are as follows:

$$\tau = 31.143 + 0.41X_1 - 5.78X_2 - 12.43X_3$$

R^2=0.76 for upper segments (position)

$$\tau = 43.64 + 0.154X_1 - 3.82X_2 - 15.56X_3$$

R^2=0.71 for middle segments (position)

$$\tau = 47.16 + 0.144X_1 - 8.13X_2 - 9.29X_3$$

R^2=0.56 for bottom segments (position)

Where;

τ=Shear stress in (Mpa); X_1=moisture content (%) (w.b.); X_2=diameter of the stem in (mm); X_3=thickness of the stem in (mm)

Modulus of elasticity

The modulus of elasticity for each variety was computed on the **Figure 10**. The rheological properties of *tef* indicate on the tensile test. The typical tensile graph is depicted on the **Figure 4**. The varieties has maximum and minimum values of elasticity 0.13 and 2.6 Gpa at moisture level 8.82% and 16.6%; 1.02 and 3.6 Gpa at moisture level 10.32% and 13.79%; 0.85 and 3.22 Gpa at moisture level 7.65% and 12.72%; 1.27 and 3.88 Gpa at moisture level 5.5% and 19.70% at upper and bottom position for Local; Kora; Quncho and Guduru varieties, respectively. The modulus of elasticity at harvesting moisture was determined that for wheat 2-6.7 Gpa, barley 11.06 Gpa, rye 11.50 Gpa and rice 0.39-1.2 Gpa [11]. Shahbazi and Nazari [8] studied the modulus of elasticity for safflower stalk and they concluded the average value was between 0.86 and 3.33 GPa. Bahram and Alireza [4] found the young's modulus of the canola stem were 1.57, 1.71 and 2.04 GPa for Zarfam, Okapi and Opera varieties, respectively. Based on the test result all varieties of *tef* stem had better modulus of elasticity than other cereals.

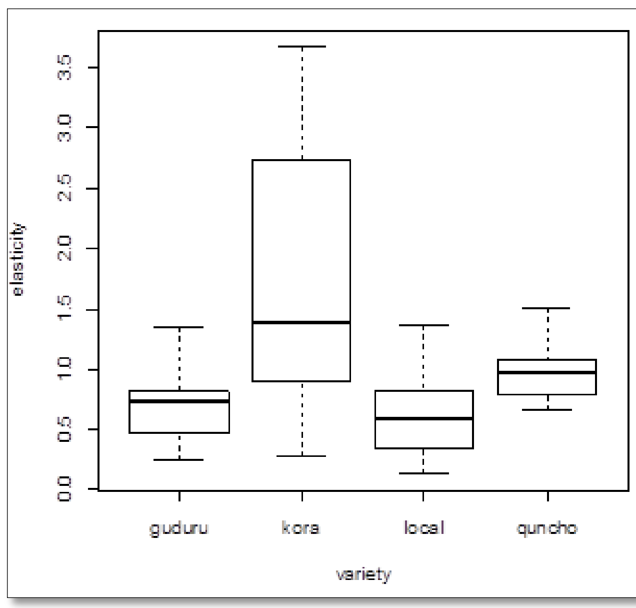

Figure 10. Comparison of *tef* varieties on their maximum, minimum and mean value modulus of elasticity at bottom position.

In the test, the number of nodes per segments was observed directly proportional for the elasticity properties, when the segment had 2 (two) nodes the modulus of elasticity was better than the segment which has one node, so the numbers of nodes on the stem are very important properties of *tef* for the strength and this property could help to generate lodging resistant variety. In all varieties the moisture variations depicted in inversely relation with the elasticity, on the increment of moisture above 25% the tensile force is decreasing, but most specimens tested below 25% and required greater tensile force, though it requires determining the optimum moisture content of the stem on which it gives the maximum value of the elasticity.

The ANOVAs' **Table 3** shows the interaction of all four factors at bottom segments of *tef* stems. The result indicated the independent variables diameter had significance impact for the modulus of elasticity fewer than 99% confidences at bottom position. Among the factors diameter and thickness and the interaction between variety with diameter and variety with thickness shows significance for the elasticity under 90% confidences at the middle position of the *tef* stem. The other factors interaction has no significance for the modulus of elasticity.

Table 3. Results of ANOVA (mean square error) for the tensile properties of *tef* stem at bottom position.

Source	Df	Sum Sq	Mean Sq	F value
Diameter	1	1.5824	1.58243	5.9598*
Moisture	1	0.4691	0.46915	1.7669
Thickness	1	0.5507	0.55071	2.0741
Variety	1	0.5578	0.55776	2.1007
Diameter × Moisture	1	0.1710	0.17103	0.6441
Diameter × Thickness	1	0.1153	0.11533	0.4344
Moisture × Thickness	1	0.3648	0.36477	1.3738
Diameter × Variety	1	0.0052	0.00521	0.0196
Moisture × Variety	1	0.0371	0.03709	0.1397
Thickness × Variety	1	0.4599	0.45992	1.7322
Diameter × Moisture × Thickness	1	0.0399	0.03991	0.1503
Diameter × Moisture × Variety	1	0.0061	0.00614	0.0231
Diameter × Thickness × Variety	1	0.0107	0.01074	0.0405
Moisture × Thickness × Variety	1	0.5095	0.50952	1.9190
Diameter × Moisture × Thickness × Variety	1	0.1100	0.11004	0.4145
Residuals	1	8	4.7793	0.26551

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

The graphical relation of the moisture and diameter of the stem at all segments were depicted on the 3D plot **(Figure 11)**; and it shows diameter is the most dominant factor in modulus of elasticity of the stem in all varieties of *tef*.

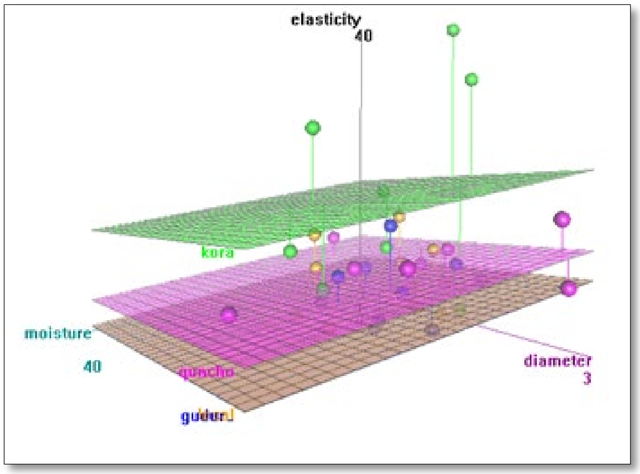

Figure 11. The effect of moisture and diameter of each varieties on elasticity at bottom position (3D plot).

Multi-linear regression analysis was used to find and fit the best general models to the experimental data. Results showed that the *tef* stem modulus of elasticity was a linear function on the stem moisture content, diameter and thickness. The linear equations for all segments are as follows:

$$E = -1.117 + 0.904X_1 + 0.940X_2 - 0.007X_3$$

R^2=0.64 for bottom segments (position)

$$E = 0.142 + 0.256X_1 + 1.820X_2 - 0.012X_3$$

R^2=0.73 for bottom segments (position)

$$E = -4.650 + 3.338X_1 + 24.642X_2 + 0.005X_3$$

R^2=0.67 for bottom segments (position)

Where;

E=Modulus of elasticity in (Gpa); X_1=Diameter of the stem in (mm); X_2=Thickness of the stem in (mm); X_3=Moisture content (%) (w.b)

FLEXURAL PROPERTIES

The effect of moisture content, diameter and thickness of the *tef's* stem on flexural properties

The lodging effect is highly related with the flexural rigidity of the *tef's* stem. Flexural was calculated using the (Equation 4) and value of modulus elasticity (Equation 3). It is directly proportional to the modules of elasticity and moment of inertia. The value of flexural on a heterogeneous cross-section based on bending theory regarding an elastic behavior was reviewed, and also a calculation method of flexural rigidity for materials with heterogeneous cross-section was inspected. Based on the ANOVAs result variety has significant effect for the flexural rigidity. The value depicted in **Table 4 and Figure 12**. Since the flexural rigidity is directly proportional to the elasticity all relation and value comparison among each variety is similar to the modulus of elasticity. The varieties has maximum and minimum values of flexural rigidity 1.3 and 26 kNmm^2 at moisture level 8.82% and 16.6%, 10.18 and 36 kNmm^2 at moisture level 10.32% and 13.79%, 8.48 and 32.2 kNmm^2 at moisture level 7.65% and 12.72%, 12.78 and 38.84 kNmm^2 at moisture level 5.5% and 19.70% at upper and bottom position for Local, Kora, Quncho and Guduru varieties, respectively. The graphical relation of the moisture and diameter of the stem at all segments were depicted on the 3D plot **(Figure 13)**; and it shows diameter is the most dominant factor in flexural rigidity of the stem in all varieties of *tef*.

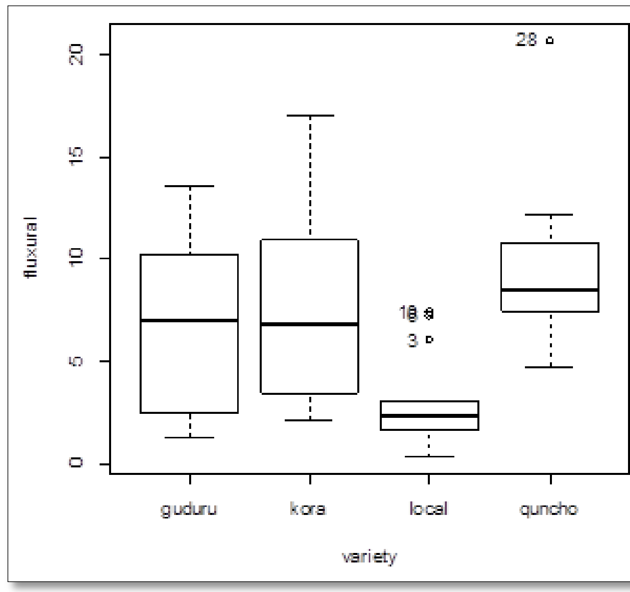

Figure 12. Comparison of *tef* varieties on their maximum, minimum and mean value of flexural rigidity at bottom position.

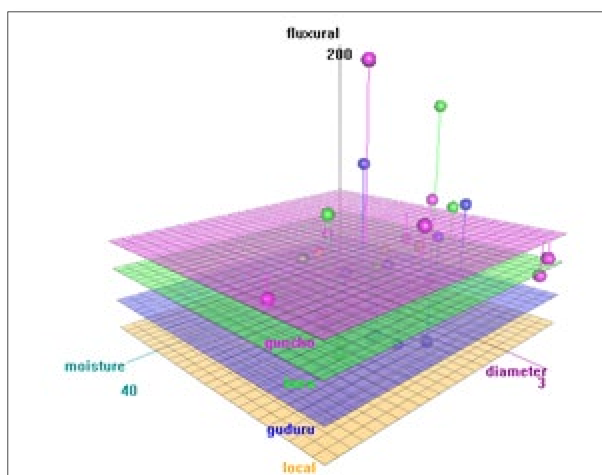

Figure 13. The effect of moisture and diameter of each varieties on flexural rigidity at bottom position (3D plot).

Table 4. Results of ANOVA (mean square error) for the flexural properties of *Tef* stem at bottom position.

Source	Df	Sum Sq	Mean Sq	F value
Diameter	1	252.918	252.918	16.7255**
Moisture	1	2.922	2.922	0.1933
Thickness	1	126.543	126.543	8.3683*
Variety	3	51.896	17.299	1.1440
Diameter × Moisture	1	9.082	9.082	0.6006
Diameter × Thickness	1	11.093	11.093	0.7336
Moisture × Thickness	1	2.750	2.750	0.1819
Diameter × Variety	3	99.677	33.226	2.1972
Moisture × Variety	3	42.714	14.238	0.9416
Thickness × Variety	3	22.901	7.634	0.5048
Diameter × Moisture × Thickness	1	4.897	4.897	0.3238
Diameter × Moisture × Variety	3	18.011	6.004	0.3970
Diameter × Thickness × Variety	3	63.542	21.181	1.4007
Moisture × Thickness × Variety	3	30.321	10.107	0.6684
Diameter × Moisture × Thickness × Variety	3	5.807	1.936	0.1280
Residuals	8	120.973	15.122	

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

The ANOVAs **Table 4** result indicated the independent variables diameter has significance effect for the flexural fewer than 99% confidences and thickness has significant impact for the flexural under the 95% confidence at bottom position. The other factors interaction has no significance for the flexural. The interaction variety with diameter and variety with thickness shows significance for the flexural fewer than 90% confidences at the middle position of the *tef* stem. On the upper position of the segments the diameter is the most dominant factor for the flexural rigidity and on the interaction with other factors shows the diameter has significant for the flexural under the 95% confidence.

The effect of moisture and diameter at flexural rigidity at bottom position (segment) depicted in the **Figure 13** and the increment of all factors increase the flexural rigidity, while in middle position the increment of diameter increase the flexural and increment of moisture decrease the flexural rigidity.

Multi linear regression analysis was used to find and fit the best general models to the experimental data. Results showed that the *tef* stem flexural rigidity (ExI) was a linear function on the stem moisture content, diameter and thickness. The linear equations for all segments are as follows:

$$ExI = -10.343 + 3.363X_1 + 20.946X_2 + 0.0091X_3$$

R^2=0.79 for bottom segments (position)

$$ExI = -13.721 + 10.511X_1 + 11.712X_2 - 0.219X_3$$

R^2=0.55 for middle segments (position)

$$ExI = -50.698 + 31.983X_1 + 46.250X_2 + 0.314X_3$$

R^2=0.53 for upper segments (position)

Where;

E=Modulus of elasticity in (Gpa); I=Moment of inertia in mm^4; X_1=Diameter of the stem in (mm); X_2=Thickness of the stem in (mm); X_3=Moisture content (%) (w.b)

CONCLUSION

The ability to track significant differences between the varieties and their individual mechanical and physical properties provides a path forward for tailoring harvesting (cutting) and post harvesting operations. The result revealed the modulus of elasticity 0.13 and 2.6 Gpa at moisture level 8.82 and 16.6%, 1.02 and 3.6 Gpa at moisture level 10.32 and 13.79%, 0.85 and 3.22 Gpa at moisture level 7.65 and 12.72%, 1.28 and 3.88 Gpa at moisture level 5.5 and 19.70%; the flexural rigidity 1.3 and 26 $kNmm^2$, 10.18 and

36 $kNmm^2$, 8.48 and 32.2 $kNmm^2$, 12.78 and 38.84 $kNmm^2$ and the shear stress at different moisture content 8.58 and 32.12 Mpa, 6.30 and 28.40 Mpa,10 and 26.30 Mpa; and 2 and 29.60 Mpa at upper and bottom position for Local, Kora, Quncho and Guduru varieties, respectively. Generally, the minimum and maximum value of mechanical properties of tef stem with different factors (moisture, diameter and thickness of the stem) shows 5 and 32 Mpa, 0.13 and 3.8 Gpa, 1.30 and 40 $kNmm^2$ for shear stress, modulus of elasticity and flexural rigidity, respectively. For all moisture content that were studied the shear stress and modulus of elasticity decreased from bottom towards the upper region of the stem. The shear and tensile test result indicated on the maximum test moisture (between 30-40% w.b.) the shearing and tensile force decreased, that means there is an optimum level of moisture to keep the stem strong, so there is a need to determine the optimum moisture content.

To tackle the problem of lodging it is better to see the morphological structure of each varieties of *tef* stem which has better modulus of elasticity and diameter of the stem. *Tef* stem has better elasticity and shear strength than some cereals and needs more attention for designing harvesting and threshing machines. The length of *tef* stem has effect in lodging and *tef* straw is useful for animal feed, thus it is a must to compromise its length towards the stem morphology.

Since, the *tef* stem has better mechanical properties than some cereals it is recommended to identify the fiber properties and use as material for composite.

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