Ethiop. J. Agric. Sci. 30(4) 1-27 (2020)

Genotypes and their Growing Environments Influence on Physicochemical Qualities of Tef Grain in the Highlands of Ethiopia

Anteneh Abewa[1,2*], Enyew Adgo[1], Getachew Alemayehu[3], Birru Yitaferu[4], Juan K. Q. Solomon[5], Kebebew Assefa[6], and William Payne[7]
[1] *Department of Natural Resource Management, Bahir Dar University, P.O.Box 5501, Bahir Dar, Ethiopia*
[2] *Amhara Agricultural Research Institute (ARARI), P.O.Box 527, Bahir Dar, Ethiopia*
[3]*Department of Plant Science, Bahir Dar University, P.O.Box 5501, Bahir Dar, Ethiopia*
[4]*Ethiopian Agricultural Research Council, P.0.Box 8125, Addis Ababa, Ethiopia*
[5]*Department of Agriculture, Veterinary & Rangeland Sciences, University of Nevada, Reno, 1664 North Virginia Street, Mail Stop 202, Reno, Nevada 89557, Nevada, USA*
[6]*Ethiopian Institute of Agricultural Research, Debre Zeit Agricultural Research Center, P.O.Box 32, Bishoftu, Ethiopia;* [7]*College of Agriculture, Biotechnology &Natural Resources, University of Nevada Reno, 1664 North Virginia Street, Mail Stop 221, Reno, Nevada 89557,Nevada, USA*
**Corresponding author: atenehabewa@yahoo.com, Tel: + 251918006680*

አህፅሮት

ከዋና ዋና የብርዕ አገዳ ሰብሎች መካከል አንዱ የሆነው የጤፍ ሰብል እና ከሱ የሚሰራው እንጀራ ለአብዛኛው የኢትዮጵያ ህዝብ ዋና ምግብ ሆኖ በማገልገል ላይ ይገኛል። የጤፍ ፍሬ አካላዊ/ቅርፃዊ ይዘት በተለይም ቀለሙ የበላተኛውን ቀልብ በመሳብ፣ የገበያ ዋጋን በመወሰንና በአልሚ ምግብ ይዘቱ ላይ ከፍተኛውን ድርሻ ይወስዳል። ይሁንና የጤፍ ፍሬ አካላዊና ኬሚካላዊ ባህርያት ልዩነቶች ከጤፉ ዝርያ ወይም ከሚበቅልበት አካባቢ ተፈጥሯዊ ሁኔታ ጋር የሚዛመድ ወይም የማይዛመድ መሆኑን እስከ አሁን በጥናት አልተረጋገጠም። በመሆኑም ይህ ጥናት የጤፍ ፍሬ አካለዊና ስነ-ምግባዊ/ኬሚካላዊ/ ይዘት በጤፍ ዝርያዎችና ጤፍ በሚበቅልበት ቦታ ያለው ከባቢያዊ ሁኔታ ሊያደርስ የሚችለውን ተፅዕኖ ውጤት ዳስሷል። በአስር የተለያዩ ሥነ-ምህዳር (የአየር ፀባይና የአፈር ዓይነት) ባላቸው የመካከለኛውና ሰሜን ምዕራብ ኢትዮጵያ አካባቢዎች እና ዘጠኝ የተለያዩ ባህርያት ያለቸው የጤፍ ዝርያዎች (የፍሬ ቀለማቸው ነጭ የሁኑ ሰባት እና ቀይ ሁለት) ለአንድ ዓመት (በ2009/10 ዓ.ም፣ የመኸር ወቅት) ተዘርተው የአካላዊና ኬሚካላዊ ባህርያታቸው ተጠንቷል። በጥናቱ መሰረት በአብዛኛው በጤፍ ፍሬ አካላዊም ይሁን ስነ-ኬሚካለዊ ባህርያት ላይ በዝርያዎች ዓይነት፣ በተዘሩበት ቦታ እና ዝርያዎች ከተዘሩበት ቦታ ጋር ባላቸው መስተጋብር መካከል ከፍተኛ ልዩነት (P ≤ 0.01) *አስመዝግበዋል። የነጭ ጤፍ ዝርያዎች በጤፍ ቀለም መለኪያ መስፈርት ማለትም የቀለም ጥግበት/ምጠት/* (saturation) *እና የቀለም ፍካት/ብሩህነት/* (brightnes) *ልዩነቶች የመጡት በአብዛኛው በሚበቅሉበት አከባቢ ተፅዕኖ* (43.9*በመቶ፤ እና* 66.8*በመቶ, በቅደም-ተከተል*) *እና ዝርያዎቹ ከሚበቅሉበት አካባቢ ያላቸው መስተጋበር* (33.7*በመቶ፤ እና* 24.5*በመቶ፤ በቅደም-ተከተል*) *ሲሆን የዝርያዎች ልዩነት በተናጥል ያመጣው ለውጥ ግን አነስተኛ* (22.5*በመቶ፤ እና* 8.7*በመቶ፤ በቅደም-ተከተል*) *ሆኖ ተገኝቷል። ጤፉ የተዘራበት አካባቢ የዝናብ መጠን ሲጨምር የፍሬው ቀለም ፍካት የመቀነስ ሁኔታዎች ነበሩት። በተጨማሪም ጤፍ የተዘራበቻው መሬቶች የአፈር ባህርያት ለምሳሌ ኮምጣጣነት፣ የንጥረ-ነገር ቅይይር ብቃት፣ ካልሽየም፣ ማግኒዝየም እና ፎስፎረስ የመሳሰሉት በቀለም ፍካት ላይ ቀጥተኛ/አወንታዊ እንዲሁም በቀለሙ ጥግበት ላይ አሉታዊ ተፅዕኖ ፈጥረውበታል። ይሁንና የጤፍ ፍሬ ንጥረ-ነገር ይዘት ከፍሬ ቀለሙ ጋር አጥጋቢ ተዛምዶ እንዳለው ጥናቱ አያሳይም። ጤፍ የበቀለባቸው ቦታዎች የአፈር*

ባህርያትና የአየር ፀባይ ከጤፍ ፍሬ ክብደትና መጠን ጋር ግን ዝምድና እንዳለቸው ይሳያል። የዝርያዎቹ ባህሪ ከጤፍ ፍሬ ክብደት ይልቅ መጠን ላይ ያላቸው ተፅዕኖ ይጎላል። ጤፍ የተዘራበት አካበባቢ ከባህር ወለል ከፍታው እና የዝናብ መጠን በጨመረ ቁጥር የጤፍ ፍሬ ክብደት እየጨመረ የመሄድ አዝማሚያ ታይቷል። ጤፍ የተመረተበት አካባቢ ሁኔታ እንዲሁም ዝርያዎች ከተዘሩበት አካባቢ ጋር ያለው መስተጋብር በጤፍ ፍሬ ንጥረ-ነገር (ፎስፎረስ፣ ፖታሽየም፣ ካልሽየም፣ ማግኒዝየም፣ ሶዲየም፣ አይረን፣ ዚነክ፣ ማንጋኒዝ፣ መዳብ፣ እና ሞሊቢዲነም) ላይ ያላቸው ተፅዕኖ ዝርያዎቹ በተናጥል ከሚያሳዩት ተፅዕኖ በእጅጉ በልጦ ተገኝቷል። የጤፍ ፍሬ የቃጫ፣ የቅባት፣ የፕሮቲን እና የስታርች መጠንም ጤፍ በበቀለበት አካባቢ 70.0በመቶ, 46.9በመቶ, 70.9በመቶ, እና 20.5በመቶ, በቅደም-ተከተል) እና የጤፍ ዝርያዎች ከበቀሉበት አካባቢ ያለው መስተጋብር (28.3በመቶ, 47.3በመቶ, 27.5በመቶ, እና 67.7በመቶ, በቅደም-ተከተል) ከፍተኛውን ልዩነት ያመጡ ሲሆን ዝርያዎቹ በተናጥል (1.7በመቶ. 5.8በመቶ, 1.6በመቶ, እና 11.8በመቶ, በቅደም-ተከተል) እምብዛም ተፅዕኖ አላደረሱም። የዝርያዎች ከበቀሉበት አካባቢ ጋር ያለው መስተጋብር ለጤፍ ፍሬ ንጥረ-ነገሮች እና ለቃጫ፣ ለቅባት፣ ለፕሮቲን እና ስታርች ያበረከተውን መጠን በትንተና ሲታይ በአስሩም አካባቢዎች አንድ ዝርያ ብቻውን ከሌሎች በልዩነት ገንኖ አልወጣም። የቀይ ጤፍ ፍሬ በንጥረ-ነገር ይዘቱ ከነጭ ይበልጣል የሚለው አስተሳሰብ በዚህ ምርምር ውጤት ተቀባይነት አላገኘም። ይለቁንም ሁለቱም ቀይ የጤፍ ዝርያዎች በስታርች ይዘታቸው ከሁሉም ያነሱ ሁነው ተመዝግበዋል። በአጠቃላይ የዚህ ምርምር ውጤት የሚያሳየው የጤፍ ፍሬ አካላዊና ኬሚካላዊ ባሕርያት ልዩነቶች የሚመጡት በአብዛኛው የተዘራበት አካባቢ እና ዝርያዎቹ ከተዘሩበት አካባቢ ያለቸው መስተጋብር የፈጠረው መሆኑን ነው። ስለዚህ በኢትዮጵያውያን ተፈላጊ የሆኑ የጤፍ ፍሬ አካላዊ ባህርያት እና ኬሚካላዊ ይዘት ማሻሻል ይቻል ዘንድ ለሰብሉ ተስማሚ የሆነ አካባቢ፣ የአፈር ኮምጣጣነትን የማስተካከል እና የአፈር ንጥረ-ነገሮችን መምረጥ አስፈላጊ ነው።

Abstract

Tef is one of the main cereal crops and its injera is the major staple food for the majority of Ethiopians. Tef grain physical quality especially color is an important attribute influencing preference of consumers, the market prices and nutritional quality. However, the effect of the growing environment and the genotype on its physicochemical quality is not yet investigated. The study was, therefore, aimed at assessing the effects of genotypes (G) and growing environments (E) on physicochemical quality of tef grain. Ten diverse locations and nine tef genotypes were selected based on soil and climatic variability as well as variation in grain color [seven white and two brown). Most of tef grain physicochemical contents significantly ($P \leq 0.01$) different between genotype, environment and G x E interaction effects. The environment, wherein tef was grown, accounted for the greatest proportion of variation in S (saturation), and V (brightness) values of the white grain genotypes (16.8%, 43.9%, and 66.8%) and G x E interaction effects (33.7%, and 24.5%) as compared to genotype alone (22.5%, and8.7%). Growing areas of greatest precipitation will reduce the brightness value of tef grain. Soil parameters such as soil pH, Ca, Mg, and P play a positive and negative role~~s~~ in grain brightness and saturation values of tef, respectively. However, grain minerals had no influential role on the color of tef grain in this study. Tef growing areas tied to both climatic and edaphic factors are critical in governing both grain density and size. The role of genotype was more influential in the grain size of tef than the grain density. The raise of growing locations altitudes and precipitation increased tef grain density. The environment and genotype by environment interaction effects accounted a greater *proportion of the variation of grain P, K, Ca, Mg, Na, S, Fe, Zn, B, Mn, Cu, and Mo minerals concentrations, while the genotype effect was relatively low. The variability of grain fiber, fat, protein, and starch compositions were also due to environment (70.0%, 46.9%, 70.9%, and 20.5%, respectively), and genotype by environment interaction (28.3%, 47.3, 27.5%, and 67.7%, respectively), while genotype played a minor role (1.7%. 5.8%, 1.6%, and 11.8%. respectively). With location by genotype interactions, there was no consistency in the dominance of any single genotype across all 10 locations in most of the tef grain mineral concentration and proximate compositions. The brown grain color genotype superiority in grain mineral and proximate composition is not supported by this research, rather the brown color genotypes were the lowest in grain starch concentration on the majority of the locations in this study. Generally, most physical and chemical quality variables of tef grain were markedly influenced by tef growing environments and their interactions with a minuscule role of genotype. Therefore, selection of suitable teff growing environments and proper soil pH and nutrient management would be so important for harnessing the maximum potentials of tef with the desired physicochemical quality of tef grain in Ethiopia.*

Keywords: Climatic factors, grain color, density, grain mineral, proximate composition, grain size, soil properties, tef,

Introduction

Tef [*Eragrostis tef* (Zucc.)] Trotter] has been cultivated for more than a century in Ethiopia primarily for its grain as the main staple food and its straw for animal feed (Seyfu Ketema, 1997). Tef grain in Ethiopia has traditionally been used to make *injera; a large pancake-like bread with many honeycomb-like eyes on the top surface* (Geremew Bultosa, 2007). Indeed, the use of tef grain in other countries has been extended to a variety of products including soups, stews, gravies, puddings, casseroles, and as a thickening agent (Wood, 1997). The high nutritional content of tef grain has augmented its widespread use in infant nutrition in developing nations, and due to its gluten-free nature, it is also recommended as healthy food for celiac patients (Spaenij-Dekking *et al.*, 2005). The grain of tef is also rich in both macro- and micro-nutrients including, among others, P, K, Mg, Fe, and Zn along with a high concentration of carbohydrates, fiber, and protein, and excellent amino acids proportion and concentration (Vohwinkel *et al.*, 2002).

Tef grain color is an important physical property that varies from very white (*Magna*), white (*Nech*), mixed (*Sergegna*) and brown (*Key*) (ESA, 2012), and dictates market prices. The white grain tef fetches a premium price and is more preferred by consumers compared to brown grain. Even within the white grain category, the very white tef grain is valued a greater price than other shades of white grain, and it is considered superior quality by Ethiopian consumers (Tadessa Daba, 2017). Based on nutritional analysis, the brown grain tef had greater nutritional value (Tadessa Daba, 2017) with higher Fe, Zn, and Ca contents, and generally greater crude fiber composition compared to mixed or white grain tef.

Grain color of cereal crops is not only influenced by genotype, but it is also modified by the environment and agronomic management practices used during field cultivation (Lukow *et al.*, 2013). For example, Hussain *et al.* (2010) reported that location of wheat cultivation does not only influence the grain color and yield, but it also influences its grain nutritional quality. Soares *et al.* (2019) found that climate change alters not only the growth and productivity of crop plants, but it also affects directly the grain physical and chemical quality of many crops. According to Jat *et al.* (2018), scarcity of water, unpredictability of precipitation patterns, and rising temperatures are major hindrances to crop quality uniformity under rain-fed agriculture). Furthermore, continuous cultivation and agricultural intensification of production areas in order to ensure food security have led to serious soil degradation due to accelerated erosion resulting in poor soil health with low fertility (Lal, 2009) that also has implication on grain quality of crops.

Although a number of studies have reported the nutritional profile of tef grain in Ethiopia (cite few and recent studies), none of them comprehensively addressed the effects of genotypes and growing environments on its physical and chemical quality. Lack of environmental predictability on grain color has curtailed the profitability of farmers since tef grain color dictates prices in the country. Furthermore, in the main tef market places like Addis Ababa (capital of the country), tef grain prices are determined more by their production areas rather than the physical appearance of the grain, which signifies the importance of the production area (soils and climate). However, this traditional belief has not been validated scientifically. Therefore, this study was aimed at validating the local knowledge of tef grain quality by assessing scientifically the influence of genotypes and their growing environments on the physical and chemical quality of the grain in the major tef growing regions of central and northwestern Ethiopian highlands.

Materials and Methods

Experimental locations and season

The field experiment was conducted during the 2017 main cropping season at 10 representative locations of the major tef growing areas in the central and northwestern highlands of Ethiopia. In the central highlands, the locations were Akaki, Alemtena, Debre Zeit and Minjar, while the other six locations in the northwestern highlands wereAdet-1, Adet-2, Bichena, Motta, Wondata and Zenzelima (Table 1). Soil types of all four selected locations in the central highlands of the country were black colored soils (Vertisols) while in the northwestern highlands, three locations were red-colored soils (Nitisols) and the other three locations were Vertisols (Table 1). Environmental variability in both climatic factors and soil properties was considered in the selection of the testing sites (Table 1).

Table 1. Soil type, altitude, rainfall and temperature of the testing locations

Locations	Soil type	Altitude (masl)	Rainfall (mm)		Mean maximum temperature. (°C)		Mean minimum. temperature (°C)	
			Annual	Growing season	Annual	Growing season	Annual	Growing season
Adet-1[1]	Nitisols[1]	2207	1209	783	26.7	24.7	11.2	12.2
Adet-2[1]	Vertisols[1]	2174	1209	783	26.7	24.7	11.2	12.2
Akaki [2]	Vertisols	2205	877	617	29.5	27.7	8.5	7.7
Alemtena[2]	Vertisols	1652	1016	489	30.0	29.5	13.2	14.9
Minjar[2]	Vertisols	2000	1118	773	31.1	29.1	13.5	13.5
Bichena[3]	Vertisols	2543	1316	862	24.7	23.5	11.3	10.9
Debre Zeit[2]	Vertisols	1887	792	545	26.9	24.6	11.3	13.5
Motta[3]	Nitisols	2419	1600	1219	25.0	22.9	10.4	9.4
Wondata[4]	Vertisols	1816	1599	1333	27.9	26.5	13.3	14.9
Zenzelima[4]	Nitisols	1920	1599	1333	27.9	26.5	13.3	14.9

[1] = EIAR, 2006; [2] = Yihenew G/Silasie, 2002; [3] = Yfru Abera and Mesfin Kebede, 2013;. [4] = personal observation.
Source of the climatic data is the National Meteorology Agency of Ethiopia and Debre Zeit Agricultural Research Center

Planting materials used and experimental design

Nine released tef varieties (*Boset, Dima, Etsub, Keytena, Kora, Magna, Quncho, Tsedy, and Simada*) were selected as testing varieties. These varieties differed in their grain color, duration to physiological maturity and suitability to the test locations (Table 2).

Table 2. Descriptions of tef varieties used for the study

Varieties	Grain color	Required Altitude (m)	Required rainfall (mm)	Days to maturity	Productivity (t ha-1)	
					On-farm	On station
Magna (DZ-01-196)	Very white	1500-2400	200-700	80-113	1.4-1.6	1.8-2.2
Tsedy (DZ-Cr-37)	White	1500-2200	150-200	82-90	1.4-1.9	1.8-2.8
Keytena (DZ-01-1681)	Brown	1600-1900	300-500	84-93	1.6-2.0	2.0-2.2
Dima (DZ-01-2423)	Brown	2000-2600	> 600	105	1.68	2.46
Quncho (DZ-Cr-387/RIL-355)	Very white	1500-2500	300-700	80-113	2.0-2.2	2.4-2.8
Etsub (DZ-01-3186)	Pale white	1800-2600	1230	92-117	1.6-2.2	1.9-2.7
Simada (DZ-Cr-385 RIL295)	White	1300-1700	300-700	73-88	1.7-2.0	1.8-2.2
Boset (DZ-Cr-409/RIL50d)	White	1500-2200	400-800	75-86	1.6-2.0	1.9-2.8
Kora (DZ-Cr-438)	White	1700-2400	700-1200	110-117	1.8-2.2	2.5-2.8

At each testing location, the experiments were laid out in a randomized complete block design with three replications. The gross plot size was 16 m^2 (4m × 4m) with a net plot area of 13.68m^2 (3.8m × 3.6m). Tef seeds were drilled in plots at the recommended seeding rates of 10 and 15 kg ha^{-1}on Nitisols and Vertisols, respectively. Based on the recommended sowing time, as well as following farmers' sowing dates at each specific testing location, tef sowing was done in 20cm spaced rows from early July to the first week of August. Nitrogen and phosphorus fertilizers were applied uniformly at the recommended rates of 40kg N and 60kg P_2O_5 ha^{-1} for Nitisols, and 60kg N and 60kg P_2O_5 ha^{-1} for Vertisols. The whole Di-ammonium phosphate (18-46-0) was applied at the time of sowing, while Urea (46-0-0) was split applied i.e. half at sowing and the remaining half at the early tillering stage. All other agronomic practices were done based on the recommendations for tef production of the respective test locations.

At physiological maturity, each plot was harvested separately. Harvesting of tef was done manually in the net plot area with the exclusion of border rows and plants to avoid the border effects. The harvested tef plants were labeled and air-dried in polypropylene bags. After sufficient drying, threshing was done manually inside the polypropylene bags on the concrete surface to avoid contamination.

Data Collection

Soil physico-chemical properties

Soil samples were randomly collected to a depth of 20cm in all ten experimental locations prior to sowing using a 10cm diameter soil auger. The collected soil samples from each location were then composited to represent the study location. Further, independent undisturbed core soil samples were taken at each location for bulk density determination.

The soil samples were air-dried for laboratory analysis of pH, cation exchange capacity (CEC), organic carbon (OC), total nitrogen (TN), available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), and sodium (Na). The soil CEC was measured by the ammonium acetate method of Schollenberger and Dreibelbis (1930). The soil organic carbon (OC) was analyzed using Walkley and Black (1934). The soil pH was determined the soil-water suspension method as per Rayment and Higginson (1992) method. Total nitrogen (TN) content was analyzed and determined by using the Kjeldahl method (Iswaran and Marwaha, 1980). Mehlich 3 extraction methods (0.2M CH_3COOH, 0.25M NH_4NO_3, 0.015M NH_4F, 0.013M HNO_3, and 0.001M EDTA) adjusted to pH of 2.5 were used for the extraction of the rest macro- and micro-minerals (Mehlich, 1984). The minerals determined with inductively coupled plasma atomic emission spectroscopy Spectro CIROS ICP–AES, Spectro Analytical Instruments, Kleve, Germany).

Physico-chemical properties of grains

Clean tef grains harvested from each net-plot area were bagged after thorough sifting and winning manually to remove dust, chaff, and other debris and used for subsequent analyses.

Grain color

Tef grain color images were captured using a Tecno-Camon mobile 24 mm pixel camera (Tecno Mobile, Hong Kong). The images were first analyzed using RGB (red, green, blue) color detector online free software. The RGB color was then converted to HSV (hue, saturation, and value) by RGB to HSV color converter software. The preference for HSV color space was difficult to apprehend with the human eyes from colors(Ibraheem *et al.*, 2012; Deswal and Sharma, 2014). Ibraheem *et al.*(2012) and Deswal and Sharma (2014) described HSV color space as H (hue) that measures the purity of a particular color, S (saturation) that measures the degree of white color embedded in a specific color and V (value or brightness) that detects the intensity of colors. They also noted that V can be used as a luminance thatdetects color brightness (brightness/lightness or darkness). The value of H is represented in degree and the S and V values are represented in percent.

Grain density and size

The grain density was determined by measuring the volume of a measured mass of grain in a graduated cylinder. This was done by filling a 5cm diameter cylinder with seeds from a height of 15cm at a constant rate (Singh and Goswami, 1996; Gupta and Das, 1997). Bulk densities were calculated as the ratio of the mass of the sample to the volume of the container and expressed in g cm^{-3}.The tef grain sizes were determined by mechanical sieve shaker model A-060. A 100 g tef grain sample was poured into the sieve (0.6-mm mesh screens (U.S. standard testing sieve #30 mesh) and shook for 5 minutes by the mechanical sieve shaker. The grain sample under the sieve (>0.6mm) and over the sieve (<0.6mm) were measured and converted to a percentage.

Grain mineral contents

For nutrient analysis, 100 g of tef grain from each genotype and site per replication was ground separately using a Rihong high-speed multifunction rotary grain grinder (Shanghai Yuanwo Industrial and Trade Co. LTD, Shanghai, China). Half of the ground tef flour (50 g) was used for nutrient or mineral contents analyses at Horticoop Soil and Water Laboratory (Bishoftu, Ethiopia). The grain mineral elements determination was carried out using Mehlich 3 extraction method (0.2M CH_3COOH, 0.25M NH_4NO_3, 0.015M NH_4F, 0.013M HNO_3, 0.001M EDTA and adjusted to pH 2.5) (Mehlich, 1984). The samples were analyzed using inductively coupled plasma atomic emission spectroscopy (Spectro CIROS ICP–AES, Spectro Analytical Instruments, Kleve, Germany). Proximate composition and amino acids.

The proximate analyses were done at the Food Science and Nutrition Lab of the Ethiopian Agricultural Research Institute (Addis Ababa, Ethiopia). The proximate composition analyses [crude fiber (CF), fat, crude protein (CP) and starch] were analyzed using 3 grams of homogenized teff flour in duplicate. The flour samples were scanned using a Near Infrared Reflectance Spectrophotometer (NIRS) spinning system (FOSS, Model: NIRS system 5000, Denmark). Samples were placed in ring cups and their spectra were recorded in reflectance mode in the range from 400 to 2500 nm, at 2 nm intervals as described by Agza *et al.* (2018).

The prediction for the collected spectra was carried out using plant-based and aqua feed calibrations developed by the International Livestock Research Institute in collaboration with Ethiopian Institute of Agricultural Research. As described by Agza *et al.* (2018) the coefficient of determination (R^2) for the calibration and validation ranged between 0.93-0.99 and 0.93–0.98 with corresponding standard error values ranging between 0.03-0.25 and 0.04–0.37.

Data analyses

Grain HSV color values, density, size grades, mineral, and proximate composition data were subjected to analysis of variance (ANOVA) SAS 9.4 statistical package (SAS, 2017). A combined (across sites) analysis of variance was also performed for those tef grain physicochemical parameters using a mixed ANOVA model (SAS, 2017). To separate the total variation into genotypes (G), environments (E) and their interactions (G×E), tef genotypes and environments (locations) were considered as fixed and replication as random sources of variation. Whenever the ANOVA results showed significant differences among genotypes, environments and/or their interactions for a variable, mean separation was further carried out using Fisher’s LSD method. The Pearson's simple correlation analysis was used to examine the relationships of grain HSV color space values, mineral contents and proximate composition parameters with soil and climatic factors.

Results and Discussions

Like the major global cereal crops, the physical attributes of tef grain color and size, and the chemical composition are key qualitative traits influencing consumers' demand (Peterson *et al.*, 2001) hence a major focus on grain color. Since studies of this nature have not been reported on the global scale for tef, the discussion of our results was done with major reference to the other well-studied cereal crops wheat, rice, and maize.

The grain sizes, grain minerals (P, K, Ca, Mg, S, Na, Fe, Zn, B, Cu, Mn, and Mo), and grain proximate compositions (Crude fiber, crude fat, crude protein, and starch) contents of tef were highly significantly ($P < 0.0001$) different for genotype, environment/location and genotype by location interactions (Table 3). Most of the grain HSV color space values and density of tef were highly significantly ($P < 0.0001$) different on genotype, environment and G x E interaction effects (Table 3). However, form these parameters, grain density and grain S color value of the brown colored genotypes were significantly ($P > 0.00$ and $P > 0.05$, respectively) different. On the other hand, H and V value of the white and brown colored genotypes respectively, were not significant ($P > 0.05$) for the main effect of genotype (Table 3). Interaction effects of genotype by environment were not significantly (*P* > 0.05) different for the H and S color space value of the white and brown colored genotypes respectively (Table 3).

Table 3. Mean squares from the analyses of physico-chemical properties of grains of nine tef genotypes across 10 locations in central and northwestern Ethiopia in 2017

	Mean squares					
Grain physico-chemical properties	Location(L) (DF= 9)	L*Rep (DF = 20)	Genotype(G) (DF = 8)*	L x G Interaction (DF = 72)	Error (DF = 160)	CV %
H (WGC)	45.7***	2.0	21.2***	21.2	4	4.97
S (WGC)	705.6***	7.6	536.6***	74***	4	6.02
V (WGC)	362.5***	1.1	82.9***	19***	1.5	1.51
H (BGC)	21.5***	1.7	7.0	36***	2.1	6.16
S (BGC)	129.9***	2.5	401.7*	71	2.6	1.80
V (BGC)	126.9***	1.9	0.18	12.5***	1.3	2.30
Grain density	0.03***	0.01	0.01**	0.02*	0.01	1.28
Grain size > 0.6mm	1042***	38.3*	849.3***	51.2***	20.1	7.75
Grain size < 0.6mm	1042***	38.3*	849.3***	51.2***	20	7.75
Fiber	8.48***	0.05	0.5***	0.3***	0.01	3.68
Fat	0.53***	0.03	0.1***	0.0***	0.05	2.42
Crude protein	15.7***	0.01	0.3***	0.6***	0.08	0.89
Starch	23.1***	0.14	36***	9.1***	0.3	0.94
P	2385855***	6867	331812***	394417***	1328	1.181
K	6575626***	1121	906327***	859342***	773	0.72
Ca	22047.5***	241	20201.4***	50386***	201	1.15
Mg	418555.6***	212.9	78526.9***	8001591***	19	1.30
S	2248.7***	155.9***	8224.6***	4166***	34	2.59
Na	10767.1***	0.6	518.7***	1236***	0.4	0.67
Fe	110509.6***	6.8	19828.6***	27290**	4.9	1.183
Zn	156.9***	0.07	17.6***	259**	0.04	0.943
B	14***	0.055***	1.31***	2.5***	0.01	5.09
Cu	4.3***	0.04	1.64***	1.2***	0.04	4.85
Mn	50818**	1.65	4518.11***	2900**	1.21	1.35
Mo	0.758***	0.007**	0.047***	0.12***	0.003	12.66

*, **, ***, and ns indicate significance at P ≤ 0.05, P ≤ 0.0.1, P ≤ 0.001, and not significantly different (P >0.05), respectively; H, S, and V denotes hue, saturation and brightness color space values respectively

Soil physicochemical properties

There were variations in soil physicochemical parameters across the 10 locations (Table 4). The bulk density of the soil varied from 1.15 g cm^{-3} for Alemtena to 1.46 g cm^{-3}for Minjar (both of them are black soils), while soil pH ranged from 5.3 for the red soils at Zenzelima to 7.8 for the black soils at Akaki (Table 4). Generally, the lower pH values were found for the Nitisols and higher for the Vertisols.

The soil CEC values are generally high for all locations but varied across locations ranging from 28 mg 100 g^{-1}soil at the red soils of Zenzelima to 66 mg 100 g^{-1} at the black soils of Bichena (Table 4). The soil organic carbon across the 10 locations varied from 0.33% at the black soils of Wondata to 0.14% at the red soils of Motta. Soil TN, available P, K, Ca, Mg, S, Fe, Zn, Cu, Mo, Co, and Na all varied across the 10 locations. For example, the P content at Debre Zeit (43 ppm) was more than five folds than that of Adet 2 (7.7 ppm). However, the magnitude of variations among the 10 locations was low in the contents micronutrients (Table 4).

Table 4. Important soil physico-chemical properties of the 10 experimental locations in central and northwestern Ethiopian highlands before sowing in 2017

Soil Properties	Adet1	Adet2	Akaki	Alem-tena	Biche-na	Debre Zeit	Minjar	Motta	Wond-ata	Zenze-lima
Soil type †	NS‡	VS	VS	VS	VS	VS	VS	NS	VS	NS
BD (g cm^{-3})	1.22	1.21	1.38	1.15	1.17	1.24	1.46	1.26	1.31	1.34
pH	5.4	6.6	7.8	6.9	6.4	6.8	7.7	5.4	6.5	5.3
CEC mg 100 g^{-1})	31.2	58.8	41.7	34.84	65.96	49.78	60.46	31.28	58.66	28.12
SOC (%)	1.07	1.34	0.43	0.8	1.21	0.88	1.28	1.38	0.33	1.33
TN (%)	0.1	0.07	0.06	0.17	0.09	0.08	0.09	0.12	0.07	0.13
P (ppm)	7.9	7.7	8.6	23.8	11.5	43	29.7	8.2	9.4	8.2
K (ppm)	226	293	452	851	349	540	647	267	225	231
Ca (ppm)	2302	6032	1065	2863	6966	5495	8544	1851	5670	1297
Mg (ppm)	518	1302	1259	415	1362	1135	869	408	1469	324
Su (ppm)	21.6	8.2	8.6	12.9	11.4	12.3	9	19	10.1	21.3
Na (ppm))	13	31	42	44	35	45	23	13	25	13
Fe (ppm)	124	154	81	106	168	158	59	165	158	75
Mn (ppm))	150	106	123	279	96	246	247	154	141	113
Zn (ppm)	1.36	1.38	1.78	2.75	1.13	1.96	1.52	1.54	1.9	0.89
Cu (ppm)	4.8	4.09	3.56	1.51	5.06	3.73	3.93	4.4	4.76	2.37
Mo (ppm))	0.29	0.28	0.32	0.41	0.32	0.29	0.3	0.29	0.27	0.3
Co (ppm)	3.84	3.42	3.22	2.61	3.26	4.29	4.3	4.43	4.8	2.76

† Sources (references) = EIAR, 2006, Yihenew G/Silasie, 2002, Yfru Abera and Mesfin Kebede, 2013.
‡ NS = Nitisols, VS = Vertisols;
BD= bulk density; CEC= Cation Exchanging Capacity; SOC= Soil Organic Carbon; TN= Total Nitrogen

Grain color

Pertaining to tef grain color characterization using the HSV color space, four of the seven white grain genotypes, namely *Boset*, *Etsub*, *Magna*, *Simada*, and *Tsedey* showed the highest grain H color space value (Table 5). Grains of white colored tef varieties produced at Adet 1, Adet 2, Motta, and Wondata showed consistently highest grain H color space value while that of from Akaki, Alemtena, Bichena, and Debre Zeit locations ranked consistently lowest (Table 5). The tef grain H color space value did not show consistency for genotype by environment interactions. *Tsedey* and *Kora* genotypes at Adet-1 and Adet-2 locations showed the highest rank on grain H color value (Table not shown). *Kora* genotype at Bichena and Akaki locations and *Tsedey* genotype at Bichena locations consistently showed the lowest rank in grain H value (Table 5).

From the white color grain genotypes *Etsub* was the highest in grain S color value, while *Quncho* was the lowest. The highest grain S color value was found from Zenzelima, while the lowest at Adet-2 and Minjar. *Etsub* genotype grown at Adet-1 and Zenzelima locations had the highest grain S color value, while *Quncho* genotype at Debre Zeit and Minjar locations followed by *Magna* genotype at Minjar and *Simada* at Adet-2 locations ranked the lowest score on grain S color value (Table 5). From the white color grain genotypes *Quncho and Magna* had the highest grain V color value, while *Etsub* had the lowest. The highest grain color V value was found at Minjar followed by Debre Zeit and Bichena locations, while the lowest at Zenzelima location. The G*E interaction result showed that *Tsedey, Quncho*, and *Boset* genotypes at Minjar location; *Quncho* at Bichena and; *Tsedy* at Akaki locations were ranked highest in grain V color value, while *Quncho, Magna,* and *Etsub* genotypes ranked lowest at Zenzelima location (Table 5).

Considering the soil types, there were significant differences between HSV color values of the white color tef grain. Grain H (color purity) value was significantly highest at the Vertisols of Adet-2, Wondata, and Nitisols of Adet-1 followed by the Nitisols of Motta and Zenzelima. It was lowest at Vertisols of Bichena, Alemtena, Akaki, and Debre Zeit (Table 5). The three Nitisols (Zenzelima, Motta, and Adet-1) were the highest in grain S (saturation) color value, while the mean value was significantly lowest at the Vertisols of all locations (Table 5). The highest grain V color value produced on the Vertisols of Minjar, Debre Zeit, and Bichena, while the Nitisols of Zenzelima followed by Motta and Adet-1 showed the lowest. The Vertisols of Alemtena, Wondata and Adet-2 locations also had the lowest grain V values (Table 5).

Regarding the HSV color values of the brown grain tef varieties, there was significant differences only in S (saturation) color values between the two varieties. The genotype *Keytena* had the highest S color value. Their mean H and V color values of all locations differ significantly ($P < 0.001$) across locations (Table 6). The location Adet-2 followed by Alemtena and Bichena ranked highest, while Motta, Wondata and Zenzelima were the lowest in grain H color value on the brown color tef grain. The G*E interaction effects showed that grain H color value of *Dima* was highest at Adet-1, Akaki, Alemtena, Bichena, Wondata, and Zenzelima, but lowest at Debre Zeit, Motta, and Minjar locations. For the genotype *Keytena,* the grain H color value was the greatest at Adet-2, Alemtena, Bichena, Debre Zeit, and Minjar locations but least grain H value at Zenzelima and Wondata locations (Table 6).

Bichena location was the highest in S color values on the brown color tef grain, while Motta and Wondata were the lowest. Partitioning the G*E interaction effects, the genotype *Dima* grain S color value was highest at Minjar and lowest at the Adet-1 followed by Motta location . For the genotype *Keytena,* the grain S color value was the highest at Adet-2 and Zenzelima locations but lowest at Motta and Wondata locations (Table 6).

The grain color V value of the brown color grain tef was highest at Bichena location, while lowest at Minjar Zenzelima locations. Grain V color value across locations was highest for both genotypes *Dima* and *Keytena* at Bichena location, lowest for *Dima* at Zenzelima and *Keytena* at Adet-1 location. Only at Adet-1 and Motta locations were the differences in grain V color value between genotype and it was greater for *Dima* at Adet-1 but at Motta location, *Keytena* had greater V value than *Dima* (Table 6).

Table 5. Means of H S, and V color space values of the white grain color tef genotypes and environment main effctes and their interactions (G x E) effect at different testing locations in 2017 in central and northwestern Ethiopian highlands

Genotypes	Adet 1	Adet 2	Akaki	Alemtena	Bichena	D/Zeit	Minjar	Motta	Wondata	Zenzelima	Main effect	LSD (0.05)	SEM(±)
H [Hue color space value (°)]													
Boset	45.7	40.3	43.6	43.7	39.0	40.9	41.2	40.7	46.0	46.0	42.71^{a}†		
Etsub	39.7	44.7	44.0	35.7	42.7	42.3	45.5	42.3	41.7	41.2	41.96^{abc}		
Kora	37.3	46.7	36.0	37.0	35.3	39.3	39.9	42.3	44.0	43.7	40.16^{d}		
Magna	43.0	45.3	38.1	42.7	36.7	39.8	45.1	42.7	44.7	42.9	42.10^{abc}		
Quncho	45.7	45.3	39.4	43.3	37.3	40.1	37.9	41.0	43.7	42.1	41.58^{bc}		
Simada	44.3	43.0	41.7	41.3	44.0	41.5	40.1	46.3	41.3	39.2	42.29^{ab}		
Tsedey	46.7	40.3	40.2	39.7	41.3	39.6	41.2	41.7	43.7	37.3	41.17^{cd}		
LSD (0.05)						3.23					0.63		
SEM(±)											0.338		
Main effect	43.19^{a}†	43.67^{a}	40.43^{de}	40.48^{de}	39.48^{e}	40.51^{cde}	41.56^{bcd}	42.43^{ab}	43.57^{a}	41.77^{bc}		1.26	0.226
S [Saturation value (%)]													
Boset	42.5	27.2	29.9	32.1	41.6	41.4	34.8	35.4	27.7	49.4	36.19^{b}		
Etsub	61.0	38.9	43.1	32.1	40.3	39.0	36.5	48.6	41.9	60.0	44.15^{a}		
Kora	43.0	26.8	36.4	39.1	30.0	34.2	38.3	36.6	36.5	45.2	36.61^{b}		
Magna	37.5	31.9	32.2	32.8	28.9	32.6	23.5	43.7	29.2	43.0	33.53^{c}		
Quncho	39.0	32.7	29.3	27.3	32.6	21.8	20.0	40.2	27.4	34.1	30.44^{d}		
Simada	31.9	24.0	29.5	35.9	29.0	35.6	31.2	43.7	36.2	49.0	34.59^{c}		
Tsedey	45.9	34.3	34.7	35.9	37.5	25.7	33.6	49.5^{a}	26.6	49.0	37.27^{b}		
LSD (0.05)						3.65					1.11		
SEM(±)											0.571		
Main effect	42.95^{b}	30.84^{g}	3358^{cd}	33.59^{cd}	34.27c	32.88^{de}	33.14^{fg}	42.52^{b}	32.24^{ef}	47.09^{a}		1.33	0.571
V [Value/brightness (%)]													
Boset	79.7	87.1	83.5^{b}	77.8	83.4	87.8	89.5	82.3	82.0	72.8	82.60^{b}		
Etsub	78.5	78.7	79.2	78.2	82.6	76.9	85.1	79.1	77.6	71.4	78.72^{d}		
Kora	77.7	85.1	81.6	82.5	84.2	87.7	82.9	77.9	80.3	75.4	81.52^{c}		
Magna	82.1	82.6	83.9	86.2	88.6	88.2	87.7	82.5	84.0	71.5	83.74^{a}		
Quncho	78.3	85.8	87.7	84.3	90.3	88.4	89.3	79.1	82.1	69.1	83.43^{a}		
Simada	81.7	82.1	86.9	78.3	83.6	86.7	85.9	76.6	79.3	75.6	81.68^{c}		
Tsedey	79.9	82.4	88.1	78.3	83.9	81.7	90.4	76.9	80.0	74.8	81.63^{c}		
LSD (0.05)					1.96						0.63		
SEM(±)											0.33		
Main effect	79.71^{f}	83.39^{d}	84.43^{c}	80.79^{e}	85.23^{b}	85.34^{b}	87.26^{a}	79.20^{f}	80.77^{e}	72.93g		0.755	0.0338

† within the columns, means followed by small lowercase letter superscripts are not different (P > 0.05).

Table 6. Means of H S, and V color space values of the brown grain color tef genotypes, environment and by their G x E Interaction effects in the central and northwestern Ethiopian highlands in 2017

	Locations												
H [Hue color space value (°)]													
Genotype	Adet-1	Adet-2	Akaki	Alemtena	Bichena	Debre Zeit	Minjar	Motta	Wondata	Zenzelima	Main effect	LSD (0.05)	SEM(±)
Dima	22.3	25.3	25.9	24.7	24.3	18.9	20.3	19.3	24.0	25.7	23.08		
Keytena	24.0	27.3	22.8	26.7	26.3	26.3	25.2	23.3	18.7	17.0	23.77		
LSD (0.05)					2.29						NS		
SEM(±)											0.41		
Main effect	23.17^{c}†	26.33^{a}	24.35^{bc}	25.67^{ab}	25.33^{ab}	22.63^{cd}	22.77^{cd}	21.33^{d}	21.33^{d}	21.33^{d}		1.74	0.415
S [Saturation color space value (%)]													
Dima	79.7	87.1	90.6	93.2	89.8	91.0	96.1	81.9	85.1	87.1	78.88		
Keytena	95.7	98.5	89.5	96.4	95.2	92.1	96.7	83.4	83.0	100.0	93.00		
LSD (0.05)					2.66						0.87		
SEM(±)											0.81		
Main effect	86.32^{f}	92.78^{cd}	90.07^{e}	94.80^{ab}	92.50^{cd}	91.57^{de}	96.42^{a}	82.62^{g}	84.02^{g}	93.53^{bc}		1.96	0.81
LSD (0.05)						2.66							
V [Value/brightness color space value (%)]													
Dima	49.3	52.6	48.8	51.9	60.0	51.5	50.9	49.8	49.0	40.4	50.41		
Keytena	42.5	52.2	47.1	51.1	60.5	51.4	51.5	51.1	50.6	45.0	50.30		
LSD (0.05)					2.11						NS		
SEM(±)											0.61		
Main effect	45.90^{f}	52.36^{b}	47.92^{e}	51.50^{bc}	60.27^{a}	51.44^{bc}	51.18^{bcd}	50.47^{cd}	49.81^{d}	42.68^{g}		1.39	0.611

† within the columns, means followed by small lowercase letter superscripts are not different (P > 0.05).

For the white-colored genotypes, highest V (brightness) color value represented for the very white and the lowest V value for pale white (Table 5). Our result is in line with Abebe and Ronda (2014) who found that the flour of *Quncho* (Cr-387) genotype had a better brighter color value as comparable to wheat flour than other two tested genotypes of tef (*Tsedy* (Cr-37), and Asgori (Dz-99)). The color value was also in line with the inherent color of the genotypes as described by Kebebew Assefa *et al.* (2011).They reported that the *Magna* and *Quncho* genotypes a very white, *Simada* and Tsedy as white. Esub is also recorded as white in the Ethiopian variety registry book (MoANR, 2008). Based on variance component analysis of the white grain color genotypes, hue (H color value) was mostly influenced by G×E interaction (83.2%), while environment 16.8% only. The grain S and V color values of tef grain was strongly affected by the growing environment (43.9% and 66.9%) and G X E interaction effect (33.7% and 24.5%, respectively). Independently, the role of genotype was relatively small in altering tef grain H (0%), S (22.5%), and V (8.7%) color space values. Similar to the results of this study, Lukow *et al.* (2013) reported a strong influence of the environment on the kernel color of wheat.

Based on Pearson's correlation analysis, the altitude of cultivation has no influential role ($P > 0.05$) on the white color tef grain HSV color space value. However, while the correlation values were not strong, variation in grain H and S values were positively influenced ($P \leq 0.05$) by rainfall ($r = 0.24$; $r = 0.36$), while a negative strong association was observed with grain V value ($r = -0.52$). Therefore, in areas of relatively high rainfall, grain brightness may more likely to decline and influencing the market value of the tef grain. Furthermore, the V has also negative correlation with temperatures ($r = -0.24$; $P = 0.05$). Kebebew Assefa *et al.* (2011), stated that field observations in areas of high rainfall, there is persistent lodging of tef and consequently, the grain may be in contact with dirt or change of color due to moisture and humidity (Kebebew Assefa *et al.*, 2011).

Even though, there were significant ($P \leq 0.05$) soil K and Na concentrations $r = -0.28$ and $r = -0.31$, respectively), the correlation is poor and do not express best relationship with grain H color value. Our study indicates that grain S value had a strong positive linkage to the soil sulfur and total nitrogen, but negatively correlated by black soil color, pH, CEC, Ca, Mg, Na, and Zn (Table 7) Brightness (V) of tef grain is positively ($P \leq 0.05$) associated with black soil color, pH, CEC, Ca, Mg, K, Na, P, Mn, Cu, Zn, Mo, and Co, but negatively with TN ($r = -0.47$; ≤ 0.001), and Su ($r = -0.65$; ≤ 0.001) (Table 7). This implies that tef grown in areas of relatively high soil pH, CEC, available P and exchangeable cations like Ca, Mg, K, and Na may have bright tef grain color values and thus more demanded product in the market. High soil total N that will generally increase grain production and soil nitrogen and sulfur have negative effects on grain brightness (V value) and this may augment the need for management intervention aimed at discerning the optimum N and S needed to optimize grain production and grain brightness value. Additionally, tef grown on slightly acid to alkaline soils (pH: 6.4 to 7.8) and higher CEC soils (34,84 mg 100 g^{-1} to 65.96 mg 100 g^{-1}) are more likely to result in brighter grain color. Liming of acidic soils to raise their pH value may be beneficial in producing whiter tef grain color. Anteneh Abewa *et al.* (2019) reported that the tef genotype *Quncho* collected from 24 locations in Amhara and Oromia regional states in Ethiopia, generally had low saturation value and brighter grain color (very white) from the Vertisols which have relatively highest pH, CEC, available P, and exchangeable cations as compared to Nitisols with relatively low pH, CEC, available P, and exchangeable cations which concurred with this study. Our study is in line with Lukow *et al.* (2013), who stated that grain chemical composition of tef is strongly linked to the concentration of available mineral elements present in the soil and is known to influence cereal grain color.

There was no significant ($P > 0.05$; data not shown) correlations among grain HSV color space values and grain mineral concentration on the white color grain genotypes in this study. This suggests that mineral concentration in tef grain has no/little connection to its color. However, increased grain fiber concentration has a positive relationship with grain hue (color purity) ($r = 0.37$; $P = 0.001$), and saturation (S value) ($r = 0.44$; $P = 0.001$) but decreased the grain brightness value of tef ($r = - 0.29$; $P = 0.01$). Further, greater grain starch concentration decreases the grain saturation value ($r = -0.45$; $P = 0.001$) thus resulting in whiter tef grains. However, based on correlation coefficients, neither grain fat nor CP concentrations altered grain HSV values (data not shown).

Grain density and size

There were significant effects ($P \leq 0.01$ - $P \leq 0.05$) of genotype, environment, and genotype by environment interaction on grain density and size grades (Table 3). Five out of nine genotypes (*Dima*, *Magna*, *Tsedy*, *Keytena*, and *Simada*) produced their greatest grain density (0.853 - 0.849 mg cm^{-3}). The genotypes; *Boset*, *Etsub*, *Kora*, and *Quncho* were generally ranked consistently among the lowest in grain density. Across environments, the mean of the nine tef genotypes; Akaki followed by Motta showed highest grain density; while Alemtena followed by Minjar and Debre Zeit the lowest (Table 7).

For the grain size grades, *Magna* and *Dima* genotypes were from the big grain size grade category (greater than 0.6mm) (>64%). *Boset* and *Kora* genotypes were the lowest (< 52%) from the big grain size grade category (> 0.6mm). The genotypes *Kora* and *Boset* were the highest in the small grain size category (<0.6mm), while *Dima* and *Kora* had low percentage from the smallest size grade (< 0.06mm) category (Table 7). From the locations Adet-2, Minjar, and Zenzelima locations produced a greatest proportion of (> 64.5%) tef grain in larger size category (greater than 0.6 mm), while Alemtena and Debre Zeit locations produced relatively the lowest proportion (<35.5%) in this category. Akaki and Debre Zeit locations produced the greatest proportion of tef grain size of less than 0.6 mm while Adet-2, Minjar, and Zenzelima produced the lowest proportion in this category (Table 7).

Table 7: Mean vales of grain size distribution (%) and grain density (g cm-1) of tef grain at different testing locations in 2017 in central and northwestern Ethiopian highlands

Treatments	Grain size distribution (%)		Grain density (g cm^{-3})
	>0.6mm	< 0.6mm	
Means of genotypes (over all 10 locations)			
Boset	51.6^{e}†	48.4^{a}	0.847^{bc}
Dima	64.9^{a}	35.1^{e}	0.853^{a}
Etsub	58.2^{c}	41.8^{c}	0.847^{bc}
Keytena	56.6^{cd}	43.4^{bc}	0.851^{ab}
Kora	50.8^{e}	49.2^{a}	0.845^{c}
Magna	65.6^{a}	34.4^{e}	0.852^{ab}
Quncho	54.5^{d}	45.5^{b}	0.845^{c}
Simada	61.5^{b}	38.5^{d}	0.849^{abc}
Tsedy	57.00^{c}	43.0^{c}	0.852^{ab}
LSD >0.05	2.285	**2.286**	0.006
SEM(±)	**0.572**	**0.572**	**0.002**
Means of environments/locations (over 9 tef genotypes)			
Adet-1	58.9^{bc}†	41.1^{de}	0.86^{d}
Adet-2	65.4^{a}	34.6^{f}	0.87^{c}
Akaki	52.3^{e}	47.7^{b}	0.91^{a}
Alemtena	48.9^{f}	51.1^{a}	0.79^{g}
Bichena	57.1^{cd}	42.9^{cd}	0.87^{c}
Debre Zeit	49.9^{ef}	50.1^{ab}	0.81^{f}
Minjar	65.1^{a}	34.9^{f}	0.80^{f}
Motta	61.2^{b}	38.8^{e}	0.88^{b}
Wondata	55.2^{d}	44.8^{c}	0.86^{d}
Zenzelima	64.5^{a}	35.5^{f}	0.85^{e}
LSD >0.05	2.515	1.701	0.006
SEM(±)	**0.570**	**0.390**	**0.002**

† within the columns, means followed by small lowercase letter superscripts are not different (P > 0.05).

For each tef genotype across locations (G*E interaction), the location Akaki produced consistently greater grain density than most other locations, while the Alemtena location ranked among the lowest in grain density of different varieties (data not shown). Within each location, the genotypes *Dima*, *Etsub*, *Keytena*, *Magna*, *Tsedy*, and *Simada* produced greater grain density at majority of the locations relative to *Boset*, *Kora*, and *Quncho* .However, at Akaki location grain density did not differ ($P > 0.05$) among the nine genotypes (data not shown). Tef genotypes differed in the proportion of both grain size categories produced at nine out of the 10 locations The nine genotypes evaluated were the same in both grain size categories on the Nitisols of Motta location. Among genotypes within each location, *Magna*, *Dima*, and *Simada* were consistently ranked among the highest while *Boset* and *Kora* among the lowest in the proportion of grain size of > 0.6 mm (data not shown).For the small grain size category < 0.6 mm, the reverse occurred.

Grain density and size are important components of cereal crop quality (Wang *et al.*, 2019). The majority of variations in grain density that occurred in this study was attributed to the growing environment (98.5%) with only a minuscule role for genotype (0.3%), and G × E interaction (1.1%). However, the role of environment (50.2%), genotype (36.4%), and G × E interaction (13.4%) was relatively more evenly distributed in altering tef grain size. Yet, environment plays dominant roles in altering both grain density and size. Grain density increased with increasing altitude and precipitation with $r = 0.41$; $P = 0.001$, $r = 0.31$; $P = 0.001$, respectively. Locations such as Akaki, Motta, Bichena, and Adet-2 will be favorable for producing tef of relatively greater grain density compared to the lower elevations of Alemtena, Minjar, and Debre Zeit (Table 7). Soils with relatively higher soil bulk density, Ca, Cu, and Co will impact grain density positively ($r = 0.58$; $P = 0.001$, $r = 0.36$; $P = 0.001$, $r = 0.34$; $P = 0.001$, $r = 0.24$; $P = 0.05$), conversely soil TN, and available Mo, P, Mn, K, Na, Zn, Fe, and, SOC had negative correlations with grain density increases ($r = -0.55$; $P = 0.001$, $r = -0.53$; $P = 0.001$, $r = -0.50$; $P = 0.001$, $r = -0.44$; $P = 0.001$, $r = -0.40$; $P = 0.001$, $r = -0.37$; $P = 0.001$, $r = -0.29$; $P = 0.01$, $r = -0.26$; $P = 0.01$, $r = -0.24$; $P = 0.05$). Based on the calculated correlation coefficients, altitude, precipitation, and temperature have no role in tef grain size (>0.6-mm). However, based on the strength of the correlation, soil OC ($r = 0.44$; $P \leq 0.001$) plays an impactful role in grain size with minuscule roles for sulfur ($r = 0.27$; $P \leq 0.05$), soil pH, Ca, K, Na, Zn, and Mo ($r = -0.28$; $P = 0.01$, $r = -0.23$; $P = 0.05$, $r = -0.28$; $P = 0.01$, $r = -0.26$; $P = 0.01$, $r = -0.29$; $P = 0.01$, $r = -0.34$; $P = 0.001$). The reverse trend was obtained for the smaller grain size category (< 0.6-mm). Higher rainfall and temperature in some growing areas might have possibly led to a longer maturation period and thus more effective grain filling. The environment main effect highest contribution for the variability of grain density and both environment and genotype for grain size are in confirmation of the influential role of genotype and environment on grain density and size reported by Benincasa *et al.* (2017).

Grain minerals

The mean values of the grain mineral contents are presented in Table 8. Tef grain P, K, Mg, and Zn concentrations of variety *Tseday* ranked highest, but not significantly different ($P > 0.05$) from that of *Kora* genotype in grain Mg concentration. The genotypes *Simada* and *Kora* for Ca contents, *Magna* for Na, *Kora* for S, *Keytena* for Fe, *Etsub* and *Magna* for B, *Quncho* for Mn, *Kora* for Cu, and *Boset* and *Dima* for Mo contents were superior than other genotypes (Table 8).

Grain K, Mg, Fe, Cu, Mo, and Fe concentrations were highest at Debre Zeit location. Similarly, Alemtena location on grain contents of Ca, Zn, and B; and Adet 1, Adet-2, Alemtena, and Motta locations on tef grain P, Ca, S, and Mn concentrations, respectively ranked highest. The lowest grain P, K, Mg, and Zn concentrations were found at Zenzelima location (Table 8).

Table 8: Mean values of grain mineral content (mg kg-1) of tef at different testing locations in 2017 in central and northwestern Ethiopian highlands

Treatments	P	K	Ca	Mg	Na	S	Fe	Zn	B	Mn	Cu	Mo
Means of genotypes (over all 10 locations)												
Boset	3021^{f}†	3699^{f}	1202^{d}	1509^{b}	96^{e}	207^{e}	168^{h}	21.20^{e}	2.42^{bc}	86^{d}	3.64^{e}	0.471^{a}
Dima	2996^{g}	3826de	1187^{e}	1400^{g}	98^{c}	217^{c}	206^{c}	23.17^{b}	2.39^{bcd}	77^{e}	4.10^{c}	0.47^{a}
Etsub	3048^{e}	3817^{e}	1252^{a}	1443^{e}	97^{d}	222^{cb}	186^{f}	22.04^{d}	2.64^{a}	67^{h}	3.84^{d}	0.40^{e}
Keytena	3071^{d}	3846^{c}	1223^{c}	1483^{c}	92^{g}	216^{c}	231^{a}	22.41^{c}	2.37^{cd}	89^{c}	4.23^{b}	0.467^{ab}
Kora	3231^{b}	4068^{b}	1250^{a}	1525^{a}	99^{b}	269^{a}	151^{i}	22.34^{c}	2.36^{d}	97^{b}	4.45^{a}	0.451^{abc}
Magna	3115^{c}	3840^{cd}	1204^{d}	1466^{d}	106^{a}	221^{bc}	192^{e}	23.11^{b}	2.63^{a}	74^{g}	4.21^{b}	0.351^{f}
Quncho	3022^{f}	3846^{c}	1209^{d}	1410^{f}	92^{g}	208de	181^{g}	21.93^{d}	2.26^{e}	101^{a}	4.10^{c}	0.415^{de}
Simada	2989^{g}	3522^{g}	1257^{a}	1416^{f}	97^{d}	21.5^{cd}	201^{d}	23.07^{b}	2.43^{b}	65^{i}	4.09^{c}	0.44^{bcd}
Tsedy	3284^{a}	4101^{a}	1242^{b}	1535^{a}	94^{f}	227^{b}	209^{b}	23.66^{a}	1.93^{f}	76^{f}	4.17^{bc}	0.424^{dce}
LSD (0.05)	19.06	1.49	7.33	9.43	0.38	7.90	1.17	0.179	0.062	0.49	0.101	0.03
SEM(±)	26.96	42.6	8.94	11.86	1.62	2.82	6.55	0.22	0.66	3.11	0.05	0.02
Means of locations (over 9 tef genotypes)												
Adet-1	2959^{g}†	3579^{g}	1149^{ef}	1435^{e}	77^{h}	200^{h}	240^{c}	21.7^{f}	2.24^{e}	178^{a}	4.08^{d}	0.24^{g}
Adet-2	3500^{a}	4196^{d}	1248^{d}	1605^{ab}	114^{c}	249^{c}	173^{e}	25.0^{b}	2.85^{c}	83^{d}	4.43^{d}	0.41^{d}
Akaki	2837^{h}	3679^{f}	1141^{g}	1376^{f}	78^{g}	217^{e}	165^{f}	19.8^{h}	2.15^{f}	53^{h}	3.64^{fg}	0.47^{c}
Alemtena	3143^{e}	4317^{c}	1378^{a}	1507^{d}	116^{b}	252^{bc}	141^{h}	27.5^{a}	3.35^{a}	61^{g}	4.47^{b}	0.69^{b}
Bichena	2997^{f}	3869^{e}	1142^{fg}	1314^{h}	91^{f}	224^{d}	135^{i}	20.9^{g}	2.80^{cd}	84^{c}	3.73^{ef}	0.33^{e}
Debre Zeit	3245^{d}	4400^{a}	1346^{b}	1614^{a}	133^{a}	255^{b}	324^{a}	23.1^{c}	1.31^{g}	50^{i}	4.77^{a}	0.74^{a}
Minjar	2983^{f}	3190^{h}	1248^{d}	1356^{g}	100^{e}	189^{i}	200^{d}	22.7^{d}	1.11^{h}	31^{j}	4.22^{c}	0.46^{c}
Motta	3300^{c}	4343^{b}	1291^{c}	1541^{c}	101^{d}	279^{a}	111^{j}	23.0^{c}	2.97^{b}	133^{b}	3.78^{e}	0.35^{e}
Wondata	3404^{b}	3862^{e}	1152^{e}	1603^{b}	78^{g}	207^{g}	242^{b}	22.4^{e}	2.75^{d}	65^{e}	3.57^{g}	0.34^{e}
Zenzelima	2493^{i}	2972^{i}	1156^{e}	1299^{i}	77^{h}	212^{f}	157^{g}	19.3^{i}	2.28^{e}	78^{f}	4.21^{c}	0.27^{f}
LSD >0.05	1.96	15.68	7.73	9.940	0.40	3.92	1.23	0.19	0.065	0.61	0.11	0.031
SEM(±)	26.96	42.6	8.94	11.86	1.62	2.82	6.55	0.22	0.066	3.11	0.05	0.02

† within the columns, means followed by small lowercase letter superscripts are not different (P > 0.05).

From the above Table, one can conclude that the varieties *Kora* and *Tsedey* ranked the highest in terms of their contents of investigated minerals while *Simada* and *Quncho* were ranked the least in most of the minerals. On the other hand, genotypes grown on the Vertisols of Debre Ziet and Alemtena sites were superior in terms of mineral contents for most of the elements. The lowest values were registered for most varieties grown on the Nitisols of Adet-1 and Vertisols of Akaki.

Regarding the interaction effects, the genotype *Tsedy* at Adet-2 followed by *Etsub* at Wondata (3947 mg kg^{-1}), and at Adet-2locations (3889 mg kg^{-1}) had their highest P concentration (4123mg kg^{-1}, 3847 mg kg^{-1}, and 3889 mg kg^{-1}, respectively (data not shown). The genotypes *Tsedy, Simada,* and *Keytena* had greater P concentration at more locations than all other genotypes. However, for the majority of the genotypes, the Zenzelima location consistently produced tef grain with low P concentration. The genotype *Keytena* at Alemtena and *Dima* at Debre Zeit locations, respectively ranked highest in grain K concentration (5502 mg kg^{-1} and 5465 mg kg^{-1}) while the genotype *Quncho* at Zenzelima location had lowest tef grain K content (2201 mg kg^{-1}). The genotype *Simada* at Motta, *Tsedy* at Debre Zeit,and *Tsedy* at Alemtena locations ranked highest in grain Ca content (1648 mg kg^{-1}, 1533 mg kg^{-1}, and 1533 mg kg^{-1}), respectively. The genotype *Magna* at Bichena and Akaki location ranked lowest in tef grain Ca content (950 mg kg^{-1} and 954 mg kg^{-1}), respectively (date not shown).

The genotypes *Dima* at Debre Zeit, *Keytena* at Alemtena, and *Tsedy* at Debre Zeit locations ranked highest (534 mg kg^{-1}, 522 mg kg^{-1}, and 516 mg kg^{-1}) in grain Fe concentration and the genotype *Tsedy* at Alemtena, *Simada* at Motta, and *Dima* at Alemtena locations, respectively produced the highest contents (36.1 mg kg^{-1}, 31.8 mg kg^{-1}, 30.5 mg kg^{-1}, and 30.2 mg kg^{-1}) of Zn respectively. The lowest tef grain Fe (46 mg kg^{-1} and 62 mg kg^{-1}) and Zn (15.35 mg kg^{-1} and 15.96 mg kg^{-1}) produced on the genotype Tsedy and *Dima* at Bichena location and , and *Magna* at Bichena and *Quncho* at Zenzelima locations, respectively. The genotype, *Simada* at Adet-2, and *Kora* at Minjar ranked highest (5.99 mg kg^{-1} and 1.32 mg kg^{-1}) in tef grain Copper; and Molybdenum contents, respectively. The genotype *Boset* at Wondata and *Kora* at Alemtena locations produced the lowest copper (2.8 mg kg^{-1}) and molybdenum (0.12 mg kg^{-1}), concentrations, respectively.

Grain mineral concentration in our study was influenced by the interaction effects of genotype by environment similar to the results reported by Koppell and Ingver (2008) on wheat. Pertaining to the differences that occurred in grain mineral concentrations among environment alone and G × E interaction accounted for a greater proportion of the variation up to a maximum of 76% and 63.5% and minimum 21.6% and 34.6%, respectively relative to genotype with a maximum of 4.2% to minimum 0.1% (data not shown). Similar to our study, there was substantial variation among the tef genotypes in grain mineral concentrations of spelt wheat, while the environmental and the G × E interaction effects were the most important sources accounting for the variation in grain mineral concentration (Gómez-Becerra *et al.*, 2010).

Precipitation has been reported to alter grain minerals like Ca and Mg in wheat (Zhao *et al.*, 2009) and in our study, precipitation was negatively correlated with tef grain Ca, K, Mg, and Zn concentrations similar to the study by Ge *et al.* (2010). The variation in grain mineral concentrations of rice, wheat, oats, and barley, and tef genotypes (Kebebew Assefa *et al.*, 2001) is closely linked to the soil properties of the cultivation site.

There were significant positive correlation among Grain Ca with soil TN, K, Na, P, Mn, Zn, and Mo ($r = 0.31$; $P < 0.01$; $r = 0.40$; $P < 0.001$, $r = 0.23$; $P < 0.05$, $r =$

0.39; $P < 0.001$, $r = 0.46$; $P < 0.001$, $r = 0.39$; $P < 0.001$) and negative relation with soil Cu ($r = 0.31$; $P < 0.01$). There were significant ($P \leq 0.05$) positive correlations among available grain K and soil Na, Fe, and Zn ($r = 0.34$; $P < 0.01$, $r = 0.50$; $P < 0.001$, and $r = 0.40$; $P < 0.001$, respectively). There were also a significant positive association between grain P with soil CEC, Mg, Fe, Cu, Zn, and Co ($r = 0.27$; $P < 0.01$, 0.27; $P < 0.01$, 0.45; $P < 0.01$, 0.23; $P < 0.01$, 0.26; $P < 0.01$, and 0.34; $P < 0.01$, respectively), while negatively with soil sulfur ($r = 0.28$; $P < 0.01$) (data not shown).

Grain Fe had a positive association with soil P and Co ($r = 0.33$; $P < 0.01$ and $r = 0.28$; $P < 0.01$, respectively), while negatively soil TN and Mo (r, 0.21; $P < 0.05$ and 0.24; $P < 0.01$, respectively). The strong to poor negative correlation of grain Mn with soil minerals were positively correlated with grain Mo, and the vies-versa. For example grain Mn was negatively correlated to soil pH, Ca, Mg, K, Na, P, Mn, and Zn ($r= -0.63$; $P < 0.001$, $r = -0.39$; $P < 0.001$, $r = -0.49$; $P < 0.001$, $r = -0.34$; $P < 0.01$, $r = -0.47$; $P < 0.001$, $r = -0.50$; $P < 0.001$, $r = -0.43$; $P < 0.001$, and $r = -0.30$; $P < 0.01$), respectively, while soil pH ($r = 0.38$; $P < 0.001$) and minerals like K, Na, P, Mn, and Zn were positively correlated ($r = 0.53$; $P < 0.001$, $r = 0.52$; $P < 0.001$, $r = 0.54$; $P < 0.001$, $r = 0.50$; $P < 0.001$, and $r = 0.33$; $P < 0.01$, respectively) with grain Mo. Whereas, soil sulfur and Cu were positively associated ($r = 0.59$; $P < 0.001$ and $r = 0.31$; $P < 0.01$, respectively) with grain Mn and negatively ($r = -0.29$; $P < 0.01$, and $r = -0.33$; $P < 0.01$,) with grain Mo. The grain Zn was also positively correlated with soil TN, K, Na, P, Mn, Zn, and Mo ($r = 0.28$; $P < 0.01$, $r = 0.38$; $P < 0.001$, $r = 0.23$; $P < 0.05$, $r = 0.22$; $P < 0.05$, $r = 0.40$ $P < 0.01$, $r = 0.46$; $P < 0.01$, and $r = 0.31$, respectively), while poor negative association with soil Cu ($r = -0.22$; $P < 0.05$). Apart from the soil K with grain Cu and Zn relationship; soil Fe with grain Mg, S. B and Mn, soil Zn with grain P, Mo, and Zn association, all the other soil mineral to grain mineral relationships were relatively strong and indicate the critical role of soil nutrient availability in grain mineral nutrition of cereal crops like tef. For example, Zn deficiency is a global nutritional problem but more so in developing nations and similar to our study, Tuyogon *et al.* (2016) reported a significant correlation between soil Zn and grain Zn concentration in rice. Therefore, improving soil Zn availability will be a good strategy in improving grain Zn concentration of tef across the tef cultivation regions of Ethiopia. Our study concretized that no one genotype was superior in grain mineral concentrations across the 10 locations unlike the Zenzelima location that showed consistently lower grain mineral concentration.

A notable observation in this study was the generally greater grain P concentration of tef grown on the lower available P soils of Adet-1 Adet-2, and Motta locations in the Nitisols and Wondata in the Vertisols compared to the greater available soil P of Minjar and Debre Zeit in the Vertisols. This could possibly be attributed to the natural colonization of tef roots with arbuscular mycorrhizal fungi (Ma *et al.*, 2019) or root morphological traits (like root length, diameter, number, and root hairs) of the different genotypes of tef. Some of the variation in Zn concentration among tef genotypes in this study may have also been a result of the date of release of the different genotypes. Zhao *et al.* (2009) suggested that wheat genetic improvement that increases grain yield of the newer wheat varieties may have led to the dilution of grain Zn concentration and the other minerals observed in this study. The range of each genotype grain mineral concentration in this study across the 10 locations was similar to those reported in a previous study (Tadessa Daba, 2017).

Grain proximate composition

Tef grain proximate composition just like other cereal crops is a primary quality component of cereals that confers benefits to human health (Shewry *et al.*, 2013). The proximate compositions of tef grain fiber and crude protein concentrations were highest for *Dima* and *Tsedy* genotypes over the10 locations (Table 9). Four genotypes (*Etsub, Quncho, Kora,* and *Magna*) consistently produced the highest crude fat concentration. Similarly, *Quncho, Simada, Etsub* and *Kora* genotypes ranked highest in starch contents, respectively out of the nine genotypes (Table 9). In terms of location, Zenzelima, Wondata, Debre Zeit, and Zenzelima, respectively showed the highest values of fiber, fat, crude protein, and starch concentrations.

The interaction results showed that no single genotype consistently ranked the highest in grain fiber concentration across all locations (data not shown). However, the genotype *Dima, Keytena, Kora, Tsedy,* and *Quncho* consistently had the greatest grain fiber concentration (44480 mg kg^{-1}, 43680 mg kg^{-1}, 43105 mg kg^{-1}, 43005mg kg^{-1}, and 42310mg kg^{-1}, mg kg^{-1}, respectively) at Zenzelima location. The genotype *Magna* produced the lowest grain fiber (16730 mg kg^{-1}) content at Bichena location. The grain fat content differed for each genotype across the 10 locations. The genotypes *Simada* and *Kora* at Wondata location had greatest grain fat (32095mg kg^{-1}, and 31810mg kg^{-1}), while the lowest values (20950 mg kg^{-1}, and 21935mg kg^{-1}) were found from *Quncho* and at Debre Zeit. The brown tef grain genotypes *Dima* and *Keytena* were generally among the lowest in grain fat concentration at all locations (data not shown). The genotypes *Quncho, Tsedy* and *Etsub* were ranked highest (126225 mg kg^{-1}, 123320 mg kg^{-1}, and 121320 mg kg^{-1}) in grain protein content at Debre Zeit location, while the genotype *Tsedy* and *Magna* produced the lowest concentration (83870 mg kg^{-1}, 83035 mg kg^{-1}, and 86670 mg kg^{-1}, respectively) at Motta location.

Table 9: Mean values of grain proximate composition (mg kg^{-1}) of tef grain at different testing locations in 2017 in central and northwestern Ethiopian highlands

Treatments	Crude Fiber	Crude Fat	Crude Protein	Starch
Means of genotypes (over all 10 locations)				
Boset	29181^{e}†	27500^{b}	98516^{e}	587650^{d}
Dima	32981^{a}	27554^{b}	98475^{e}	575890^{e}
Etsub	27226^{f}	28673^{a}	98428^{e}	607386^{a}
Keytena	32027^{b}	27473^{b}	99963^{b}	575392^{e}
Kora	31075^{c}	28449^{a}	96692^{f}	605455^{a}
Magna	29617^{e}	28420^{a}	99591^{bc}	598188^{c}
Quncho	30355^{d}	28521^{a}	98861de	608083^{a}
Simada	31439^{bc}	26793^{c}	99169^{cd}	608058^{a}
Tsedy	31372^{bc}	26574^{c}	101029^{a}	601623^{b}
LSD (0.05)	687.08	415.2	564.7	3416.3
SEM(±)	582.1	178.3	771.9	1917.7
Means of locations (over 9 tef genotypes)				
Adet-1	36459^{b}†	28947^{b}	92707^{d}	576667^{d}
Adet-2	35228^{c}	28709^{b}	97107^{c}	603087^{ab}
Akaki	23163^{h}	28171^{c}	91369^{e}	604120^{ab}
Alemtena	24394^{g}	27564^{d}	106704^{b}	583387^{c}
Bichena	21423^{i}	27502^{d}	91306^{e}	604038^{ab}
Debre Zeit	34241^{d}	23582^{f}	116564^{a}	601458^{b}
Minjar	26517^{f}	26964^{e}	106662^{b}	602689^{b}
Motta	27557^{e}	28763^{b}	91528^{e}	601584^{b}
Wondata	34691^{cd}	29932^{a}	89487^{f}	580778^{c}
Zenzelima	42183^{a}	27593^{d}	106257^{b}	606327^{a}
LSD >0.05	724.3	437.6	592.2	3601.1
SEM(±)	582.1	178.3	171.9	1917.7

† within the columns, means followed by small lowercase letter superscripts are not different ($P > 0.05$).

Tef grain starch concentration of the genotypes differed across locations by genotype interactions. *Simada* at Akaki, *Boset* at Motta, and *Simada* at Wondata locations ranked the highest (636575 mg kg^{-1}, 635440 mg kg^{-1}, 635235 mg kg^{-1}) in grain starch concentrations. The lowest tef grain starch content of 538375 mg kg^{-1}, 542230 mg kg^{-1}, and 545595 mg kg^{-1} were found from the genotype *Keytena* at Adet-1, *Dima* at Adet-1, and Magana at Wondata locations, respectively. Generally there was no genotype showing consistently higher grain proximate composition across environments. However, the brown genotypes *Dima* and *Keytena* were generally amongst the lowest in grain starch concentration on the majority of the locations.

The proximate composition parameters of crude fiber, fat and protein compositions were highly influenced by the growing environment (70.0%, 46.9%, and 70.9%) and by G x E interaction effect (28.3%, 47.3%, and 27.5%), while minuscule contribution by the genotype (1.7%, 5.8%, and 1.6%, respectively) (data not shown). The variability of starch composition was governed by G x E interactions (67.7%), genotype (20.5%), and environment (11.8%) in the respective order from high to low. Similar to our result, Dupont and Altenbach, (2003) reported that the proximate composition parameters are strongly influenced by environmental variables during the grain filling process. Environmental variables such as temperature, rainfall, and soil nutrient status influence protein accumulation and starch deposition (Dupont and Altenbach, 2003) in ways that alter the concentration in their grain.

Positive associations were found between grain fiber and precipitation ($r = 0.49$; $P = 0.001$), and minimum temperature ($r = 0.48$; $P \leq 0.001$), but negative values with altitude ($r = -0.36$; $P = 0.01$). There was significant positive association between precipitation and grain fat concentration ($r = 0.36$; $P\leq 0.01$), but altitude, minimum, and maximum temperature played no influential role. Higher growing elevations and increased precipitation resulted in tef grains with less crud protein (r = -0.47; r = - 0.30; $P\leq 0.01$ respectively), while higher temperature seems to be associated with increased grain CP concentration ($r= 0.47$). The soil parameters (pH, CEC, SOC, Ca, K, Na, S, Zn, and Mo) played an influential role in grain fiber concentration($r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$, $r = 0.36$; $P\leq 0.01$). Similarly, the grain fat concentration with available soil K, Na, P, and Mn was poor and negative. Soil organic carbon, TN, K, Na, P, Mn, and Zn positively influence tef grain CP concentration ($r = 0.22$ to 0.72) but increasing altitudes, and soil Mg, Fe, and Cu impacted negatively ($r=-0.24$ to -0.52) grain CP concentration (data not shown). The soil physicochemical properties were in not influencing tef grain starch concentration in this study. The results of G×E interaction on proximate composition in this study were similar to those of Adebowale *et al.* (2011).

Conclusion

Based on the results of the present study, within the same tef grain color range (white color grain genotypes), the color brightness and saturation values variability were changed by the growing environment/location.

Tef growing areas tied to both climatic and edaphic factors are critical in governing both grain density and size. The role of genotype was more influential in the grain size of tef than the grain density.

Tef growing environment/location and interaction effect of genotype by environment were more influential determinant of tef grain mineral concentrations and proximate compositions than the genotype alone.

The brown color genotypes superiority in grain mineral concentrations in previous research findings are not supported by this research finding. However, the brown genotypes *Dima* and *Keytena* were generally amongst the lowest in grain starch concentration on the majority of the locations in this study.

The growing location soil pH, CEC and other nutrients generally had significant relationship to tef grain physicochemical properties in this study together with climatic variables like precipitation and altitude.

Generally, most physical and chemical quality variables of tef grain were markedly influenced by tef growing environments and their interactions with a minuscule role of genotype. Therefore, soil chemical qualities and pH management of growing environments will be critical in harnessing the maximum potentials of tef with the desired grain physicochemical quality across the main tef cultivation areas of the country.

Acknowledgments

The authors acknowledge Amhara Agricultural Research Institute and AGP II project, Ethiopian Agricultural Research Institute quality lab, Debre Zeit Agricultural Research Center, Bahir Dar University, and University of Nevada, Reno College of Agriculture, Biotechnology, and Natural Resources (CABNR), on providing fund, experimental field, and facilitating the laboratory analysis.

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