Planta (2019) 250:753–767
https://doi.org/10.1007/s00425-019-03209-z

REVIEW

Significance and prospects of an orphan crop tef

Solomon Chanyalew[1] · Setotaw Ferede[1] · Tebkew Damte[1] · Tsion Fikre[1] · Yazachew Genet[1] · Worku Kebede[1] · Kidist Tolossa[1] · Zerihun Tadele[2] · Kebebew Assefa[1]

Received: 26 October 2018 / Accepted: 5 June 2019 / Published online: 20 June 2019

Abstract

Main conclusion **Tef is a resilient crop from the Horn of Africa with significant importance in food and nutrition security, and currently gaining global popularity as health and performance food.**

Abstract Tef [*Eragrostis tef* (Zucc.) Trotter] is the most important cereal of Ethiopia in terms of production, consumption and cash crop value. In Ethiopia, tef is annually grown on about 3 million ha with total grain production of over 5 million tons. As such, it accounts for about 30% of the total cultivated area and one-fifth of the gross grain production of all cereals cultivated in the country. In spite of its supreme economic and agricultural significance in Ethiopia, its productivity is relatively low with national average yield of about 1.7 t/ha. This has primarily been due to the very little scientific improvement done on the crop. Tef has still been an "orphan crop" since it is globally a very much under-researched crop owing to its localized importance. Scientific research on tef in Ethiopia began in the late 1950s. The main objective of this paper is to provide an overview of the significance and major production constraints of tef, and the major achievements made to date in various tef research aspects including breeding, agronomy, crop protection, and agricultural economics and extension. Based on these reviews, the paper eventually concludes with remarks on the way forward by emphasizing on the identification of the major gaps and the improvement efforts required for realizing the ever-needed breakthrough in the productivity and production of the crop. The major focal areas of future efforts include increasing productivity of both grain and biomass, systematic conservation and mining of the genetic resources, tackling the lodging malady, mechanization of the crop's husbandry, understanding the overall physiology of the crop especially with respect to stress tolerance, unraveling the nutritional qualities, and development of recipes and value-added products.

Keywords Breeding · *Eragrostis tef* · Ethiopia · Genetic resources · Improved varieties · Tef

Introduction

Tef, *Eragrostis tef* (Zucc.) Trotter, is the most important cereal of Ethiopia in terms of area coverage, production volume, food and nutrition security as well as cash crop value. Over the millennia, the Ethiopian farmers who engineered domesticating the crop species have sustained the cultivation of tef with its area coverage expanding from time to time until to date. The continued extensive cultivation of tef in Ethiopia is accentuated by a multitude of its merits with respect to both husbandry and utilization (Ketema 1997; Tefera and Ketema 2001; Assefa et al. 2011a, 2017; Assefa and Chanyalew 2018). The peculiar meritorious features of tef crop that are of importance with respect to farming include: (i) broad and versatile agro-ecological adaptation under varied climatic, edaphic and socio-economic conditions; (ii) tolerance to both drought and water-logging conditions; (iii) fitness for various cropping systems and crop rotation schemes; (iv) usefulness as a reliable and low-risk catch crop at times of failures of other long-season crops such as maize and sorghum due to drought or pests; and (v) little vulnerability to epidemics of pests and diseases in its major growing regions.

On the other hand, the most important relative merits of tef in terms of utilization are as follows. First, tef grains

✉ Kebebew Assefa
Kebebew.Assefa@yahoo.com

[1] Debre Zeit Agricultural Research Center, P.O. Box 32, Debre Zeit, Ethiopia

[2] Institute of Plant Sciences, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland

give the best quality and most consumer-preferred "injera", a flat pancake-like soft bread, in terms of high water-holding capacity, long shelf-life, unique flavor (slightly sour but pleasant), pliability, and smooth and glossy texture. Second, the grains also give high returns in flour upon milling of 99% compared to 60–80% from wheat (Ebba 1969) and in injera upon baking. Third, tef suffers little from damages due to storage pests such as weevils and diseases, and the grains possess high storage longevity of 3–5 years without considerable loss of viability even under traditional storage conditions. Fourthly, the straw of tef called "chid" serves as invaluable fodder for cattle, as a binder of mud used for plastering walls of local houses, and as bedding and mulch material. In addition, tef serves as a cash crop for smallholder farmers since both the grains and straw fetch high market prices.

This paper provides an overview on the significance and major production constraints of tef crop, and the principal achievements and progress made to date in tef research with respect to breeding, agronomy, crop protection, and agricultural economics and extension. Based on the retrospect assessments, the paper eventually attempts to give highlights on the prospects of tef improvement with respect to the future directions based on identification of the major gaps and priority areas.

Taxonomy and origin

Tef belongs to the Grass Family, Poaceae (formerly Gramineae), sub-family Chloridoidae (Eragrostoidae), tribe Eragrostidae, sub-tribe Eragrosteae, and genus *Eragrostis*. The genus *Eragrostis* contains over 350 species (Watson and Dallwitz 1992) of which about 43% originated in Africa, 18% in South America, 12% in Asia, 10% in Australia, 9% in Central America, 6% in North America and 2% in Europe (Costanza et al. 1979). Among the 54 *Eragrostis* species found in Ethiopia, 14 (26%) are endemic to the country (Cufodontis 1974). Tef and finger millet [*Eleusine coracana* (L.) Gaertn.] are the only two species in the sub-family Chloridoidae cultivated as a cereal for human consumption.

Ethiopia is the center of origin and diversity of tef (Vavilov 1951). According to Ponti (1978), tef was introduced to Ethiopia well before the Semitic invasion of 1000–4000 BC. It was probably cultivated in Ethiopia around 6000 years ago, even before the ancient introduction of emmer and barley. Shaw (1976) argues that tef must have been domesticated before the introduction of wheat and barley to Ethiopia or else tef, sorghum and finger millet would have never been cultivated. However, this is arguable because even after the introduction of barley, wheat and maize, Ethiopian farmers have continued growing tef extensively with its area increasing from time to time.

According to Ebba (1975), tef seeds found by Unger (1866) in the Pyramid of Dashur (3359 BC) and from the ancient Jewish town of Ramses in Egypt (ca. 1300 BC) were probably *E. aegyptiaca* or *E. pilosa* and thus are not good evidence for the cultivation of tef in ancient Egypt. On the basis of linguistic, historic, geographic and botanical notes, tef is assumed to have originated in the highlands of Ethiopia (Costanza et al. 1979). The current area of cultivation is probably not the initial one of domestication, and the domestication probably occurred in the western area of Ethiopia, where agriculture is precarious and semi-nomad type (Ketema, 1997). The speculative model based on ethno-archeological and ethnographic studies suggested that tef might be domesticated by pastoralists in the northern parts of Ethiopia prior to the first millennium (D'Andrea and Wadge 2011).

Area of cultivation and production

Tef grows under varied moisture, temperature and soil regimes from sea level up to 3000 m above sea level (a.s.l.) (Ketema 1993). However, it performs best at altitudes between 1700 and 2200 m a.s.l., annual rainfall of 750-850 mm or growing season rainfall of 450–550 mm, and temperature range of 10–27 °C.

While the performance of the tef sub-sector still remains below its potential, tef production showed an increasing trend over the last 18 years. Tef production in Ethiopia increased from 1.74 million metric tons in 2000/01 to 5.28 million metric tons in 2017/18, which was equivalent to an average growth rate of 7.97% per annum (Fig. 1). More importantly, tef yield has been increased by 5.06% per annum during the same period to reach the current yield level of 1.73 metric tons/ha. On the other hand, the rate of tef area expansion was estimated at 2.91% per annum. During the same period, 63.5% of the total increase in tef production was due to improvement in productivity, while the remaining 36.5% was due to expansion in area under cultivation. The significant boost in productivity is mainly due to the development and wide dissemination of improved tef varieties through various development interventions in major growing areas of the country.

Consumption and nutrition

In Ethiopia, tef is primarily consumed in the form of *injera*, soft, porous, thin pancake-like bread that constitutes the major component of the favorite staple national dish of most Ethiopians. The "injera" diet culture is of invaluable significance to the nutrition of most Ethiopians since it is normally consumed with stew called "wot" made from various

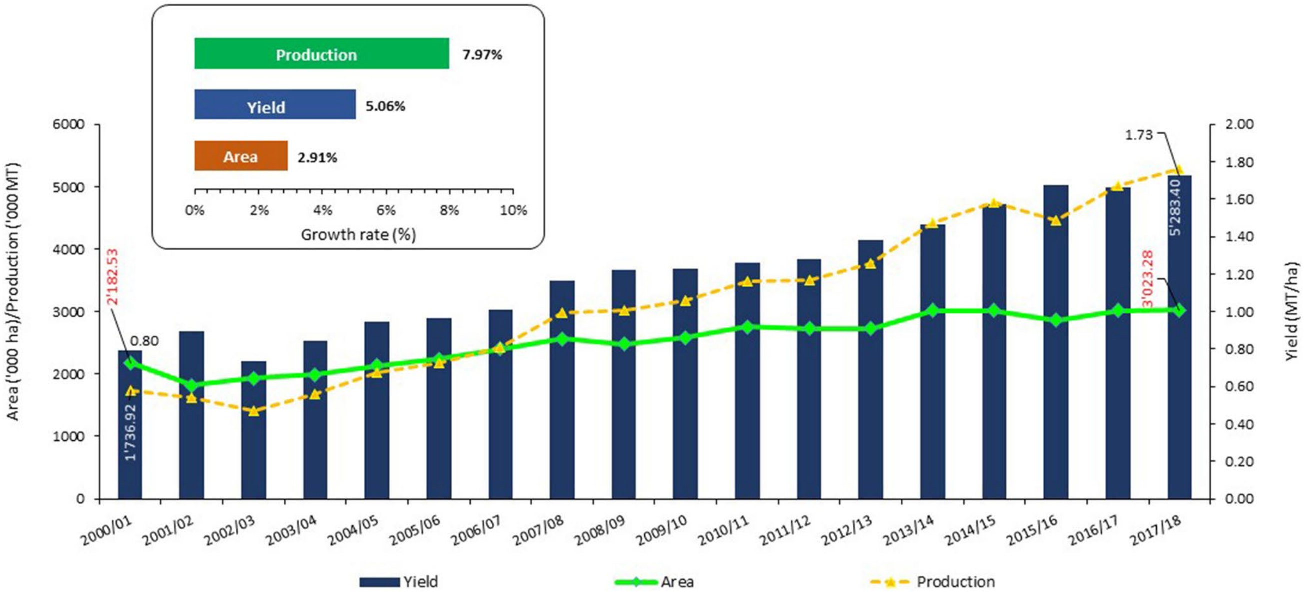

Fig. 1 Trend of tef cultivation and production in Ethiopia from 2000 to 2018. Note: Growth rates are calculated using *semi-log function* ($\ln X_t = a + bt$). Source: Computed from statistical reports of the Central Statistical Agency (CSA) of Ethiopia for the years 2000/01–2017/18

Table 1 Nutritional composition of tef as compared to the other major world cereals Source: Modified and compiled from Agren and Gibson (1968), Bultosa (2007) and Baye (2018)

Nutritional item	Tef	Finger millet	Barley	Maize	Wheat	Sorghum
Energy (cal.)	362.1	349.5	355.9	368.2	351.9	359.6
Moisture (%)	10.0	10.1	11.3	12.4	11.8	12.1
Protein (%)	11.0	7.2	9.3	8.3	11.2	7.1
Fat (%)	2.7	1.4	1.9	4.6	1.9	2.8
Carbohydrates (%)	71.0	73	72.4	71.2	70.6	74.1
Fiber (%)	3.0	5.0	3.1	2.2	3	2.3
Ash (%)	2.3	3.3	2.0	1.3	1.5	1.6
Ca (mg/100 g)	165.2	386.0	47.0	6.0	49.0	30.0
P (mg/100 g)	366.0	220.0	325.0	276.0	276.0	282.0
Fe (mg/100 g)	18.9	85.1	10.2	4.2	7.5	7.8

pulses and/or meat as well as vegetables. As such, tef provides about two-thirds of the dietary protein intake of most Ethiopians (ENS 1959). Generally, tef is the most important staple grain of Ethiopians and as such in 2011, for instance, it constituted 12.4% of the food expenditures with per capita consumption of 29 kg (Hassen et al. 2018).

As a cereal, tef is a very nutritious grain (Table 1). Since the minute grain is normally consumed as whole-grain including the bran and germ, it results in high fiber and nutrient content. Its nutritional content is generally comparable to or better than that of the major world cereals like wheat, barley and maize (NRC 1996; USDA 2015). Except for finger millet, tef is superior in many aspects particularly in minerals such as calcium, iron, magnesium, phosphorus and potassium. The grains of tef are also rich in essential amino acids particularly in alanine, methionine, threonine and tyrosine (USDA 2015).

Tef has become popular as a health and performance food in the global market. Since the grains are gluten free, it is useful as food for humans suffering from gluten protein allergy ailments known as celiac disease (Spaenij-Dekking et al. 2005). Its low glycemic index characterized by slow release type starches makes it particularly suitable for diabetic patients (Baye 2018). Moreover, its high iron content is associated with low prevalence of hookworm (ENS 1959) and pregnancy-related anemia in people consuming tef as staple food. In addition to this, recent studies have demonstrated the potentials of tef as a raw material for malting, brewing and manufacturing of gluten-free foods and beverages (Bultosa 2007; Zarnkow et al. 2008; Gebremariam et al. 2014).

Production constraints

The major challenges in tef production were recently reviewed (Assefa et al. 2017) where two categories of bottlenecks were identified. The two constraints are technical and socio-economic.

The main technical problems involve: (i) relatively low productivity coupled with widespread use of landraces and traditional husbandry practices along with minimal or sub-optimal inputs (Ferede 2013); (ii) susceptibility of the crop to lodging which poses direct and indirect deleterious effects (Ketema 1993); (iii) labor-intensive nature of tef's husbandry starting from land preparation to harvesting and threshing primarily due to the minute size of the seed with 100-kernel mass of only 19–34 mg (Assefa et al. 2017; Chanyalew et al. 2013) as well as poor competing ability of the crop with weeds; (iv) biotic stresses (i.e., diseases, weeds and insect pests) and abiotic stresses such as drought, soil acidity, frost and heat; and (v) scanty research on the improvement and development of tef coupled with limitations of basic scientific information on the crop. Lodging, which is defined as the permanent displacement of the crop from the upright position, substantially reduces the yield as well as the quality of both the grain and straw. Yield losses due to lodging under natural conditions range from 11 to 22% (with a mean of 17%), while it also reduces 1000-kernel weight by 35%, grain yield per panicle by 51%, and proportion and rate of seed germination by 41% and 44%, respectively (Ketema 1993). Application of nitrogenous fertilizers aggravates lodging incidence in tef since the stalks of the plants become large and eventually fall over on the ground irreversibly.

On the other hand, the major non-technical or socio-economic constraints include: (i) lack of attention to the research and development of tef both at the global and local level; (ii) limited availability of adequate quality and quantity of seeds of improved varieties; (iii) weak extension systems and research–extension linkages for dissemination of improved tef technologies; and (iv) lack of credit system for supporting smallholder farmers.

Research areas and achievements

Genetics

A number of studies have been conducted in the past three decades to investigate the extent of genetic diversity present among natural accessions of tef and improved varieties. Although over 5000 tef accessions were collected from diverse growing regions and are available at the seed depository of the Ethiopian Biodiversity Institute (EBI) (Tesema 2013), only a portion of them has been thoroughly evaluated and characterized. However, the limited studies made to date revealed the existence of substantial differences among tef genotypes for diverse traits investigated (Assefa et al. 2001, 2015; Chanyalew et al. 2013). The most recent studies in diversity involved 188 tef genotypes (including 144 landraces) using morphological traits (Jifar et al. 2018), 273 accessions using phenotypic traits (Ben-Zeev et al. 2018) and 82 accessions including wild *Eragrosti*s species using molecular markers (Girma et al. 2018).

Tef is an allotetraploid ($2n = 4x = 40$) plant whose diploid progenitor(s) is not yet known. *Eragrostis pilosa* which is also an allotetraploid is the closest relative and possibly the immediate wild progenitor of tef (Ingram and Doyle 2003). The close relationship between tef and *E. pilosa* was also evidenced by the successful hybridization between these two species (Tefera et al. 2003). Generation mean analyses in different crosses revealed additive and epistatic gene effects in controlling grain yield of tef, while triple-test cross analysis also showed epistatic gene interactions for the same trait (Tefera and Peat 1996, 1997a, b). Similarly, these studies also implicated epistasis gene actions for other important quantitative traits including grain yield per panicle, panicle mass, tiller number, harvest index, plant height, panicle length, and days to panicle emergence and maturity.

Based on these inheritance patterns, selection at early generations after crossing was not suggested (Tefera et al. 2001). Instead, delaying the selection to the later generations was recommended to increase the frequency of homozygous individuals in the population. Hence, segregating tef populations can be handled by a combination of modified bulk population method and modified pedigree breeding method. In this case, the F_2 and F_3 generations can be advanced by the bulk population method while the pedigree method of individual plant selection can start at F_4 to minimize the unfixable non-additive gene actions which are prevalent in the early generations.

Breeding

The principal objectives of the tef breeding program are to: (i) enhance the genetic resources base; (ii) develop suitable varieties for different agro-ecologies and cropping systems; and (iii) generate basic scientific information on the crop. To achieve these objectives, the tef breeding program focuses on enhancing the productivity (grain yield and biomass/straw), lodging tolerance, grain quality primarily in terms of farmer and consumer-preferred traits, and tolerance to biotic and abiotic stresses. Furthermore, the core strategies of the tef breeding are: (i) a shift from wide- to specific adaptation due mainly to high genotype × environment interaction

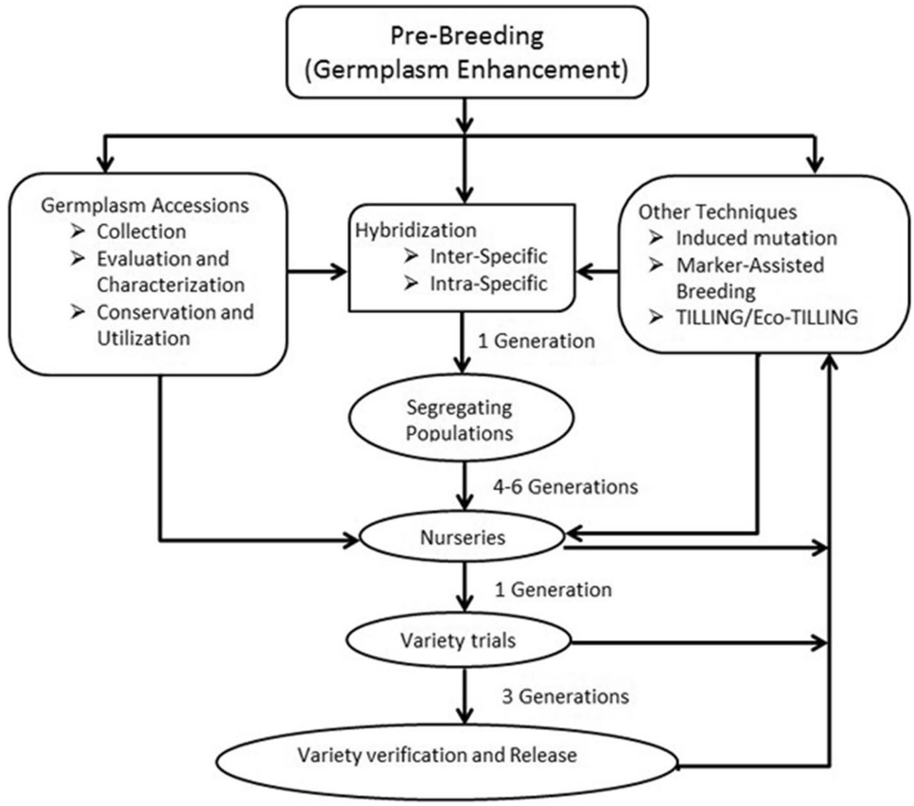

Fig. 2 Schematic diagram of the tef variety development process (Arrows indicate the direction of flow of the breeding materials)

(Kefyalew 2001) while still looking for broad adaptation; (ii) market orientation with respect to quality, quantity and food security; and (iii) expansion to previously non-tef growing areas and production systems (e.g., warm and irrigated places in the eastern parts of the country).

Figure 2 shows the general scheme and methodology employed in the tef variety development process. The first and fundamental step in this process involves pre-breeding aimed at germplasm enhancement through three complementary ways: (i) collection/acquisition, characterization, evaluation and conservation of germplasm; (ii) hybridization (intra- and inter-specific) among selected parents; and (iii) other techniques including novel methods and mutation breeding.

Studies in tef breeding are briefly discussed below under conventional breeding, molecular markers, high-throughput screening and omics studies.

Conventional breeding

The conventional breeding techniques have played major roles in tef breeding (Assefa et al. 2011a, 2013, 2017; Assefa and Chanyalew 2018). In the initial phase spanning from 1956 to 1975, the tef breeding was characterized by: (i) germplasm enhancement through focusing on collection, characterization and evaluation, and conservation of the indigenous tef germplasm; and (ii) reliance of the variety development solely on pure line and/or mass selection from farmers' varieties. Owing to the then belief that tef is not amenable to artificial hybridization, induced mutation techniques using gamma and X-ray radiation were also started in this phase to induce genetic variability.

The discovery of the chasmogamous floral opening behavior of tef flowers in the mid-1970s facilitated the development of the artificial crossing technique (Berhe 1975). Consequently, the genetic improvement efforts incorporated the development of varieties through intra-specific hybridization. So far, over 620 crosses have been made at Debre Zeit Agricultural Research Center in Ethiopia, but successful inter-specific cross has only been made with *E. pilosa* (Tefera et al. 2003). Subsequent segregating populations are handled using the modified bulk/pedigree method or F_2-derived single seed descent (SDD) method.

Materials emerging from the germplasm enhancement stage are entered into observation nurseries for initial screening and evaluation of selected genotypes. This is followed by a series of yield trials including preliminary and national variety trials. In the variety testing, genotypes are categorized into early set for terminal drought-prone areas and late set for optimum rainfall areas. At the last stage of the process, elite and promising genotypes selected as candidate varieties based on their performance in the variety trials are promoted to variety verification trials for evaluation by the National Variety Release Committee. At all stages, genotypes with poor performance or some desirable traits could be taken back to the early pre-breeding stage of the variety development process (Fig. 2).

Until the year 2017, 42 improved tef varieties were released in Ethiopia through the National Agricultural Research System (MoALR 2017) (Table 2). Of these, 24 varieties were released by Debre Zeit Agricultural Research Center, while the remaining 18 were released by other six research centers. Surprisingly, from all tef varieties released so far, only 45% were developed through hybridization, while 55% were developed using pure line selection from farmers' varieties.

Of the released tef varieties, the most adopted ones are *Quncho*, *Kora, Magna, Enatite, Dagim* and *Dukem* for optimum rainfall areas, while the relatively early maturing varieties like *Boset*, *Tsedey* and *Simada* are meant for terminal drought-prone areas.

Considering its large acreage, the general motto of the tef breeding program is "add a little, and it makes a difference". Studies of genetic gain in tef breeding showed linear grain yield increment of 0.8% per year under lodging controlled conditions until the year 1995 (Teklu and Tefera 2005), and 0.58% per year under lodging uncontrolled conditions until 2012 (Dargo 2013). In the latter study, biomass yield and grain yield per panicle also showed significant increments with annual genetic gains of 0.47% and 1.05%, respectively. No marked changes were noted in phenologic traits, harvest index, plant height, panicle length and weight, and hundred kernel weight. In conclusion, the genetic gain studies revealed that the grain yield potential of tef has not reached a plateau in Ethiopia; hence, the development of high yielding varieties should continue to increase tef grain yield.

Molecular markers

Molecular markers are important as tools for studying genetic diversity and relationships, classification of germplasm, construction of genetic linkage maps, and marker-assisted breeding. A recent review in which all major studies in markers and mapping are listed provides landmarks in tef genetics and genomics research (Cheng et al. 2017). The development of tef genomic SSR markers (gSSRs) alleviated the problem of low rate of polymorphism of EST-SSRs (Zeid et al. 2011). A total of 561 gSSRs were developed and 48% of the markers showed polymorphism among populations derived from crosses between tef (cv. Kaye Murri) and *E. pilosa*. This indicated twice as high rate of polymorphism of gSSRs over the EST-derived markers in tef (Yu et al. 2006). Presently, there are more than 1500 locus-specific tef markers available for use in genetic studies.

A study on 326 cultivated tef accessions and 13 wild relatives estimated the allelic diversity and identified markers associated with agronomic traits in tef germplasm (Zeid et al. 2012). The majority of the alleles detected in the above study were present in tef breeding lines and varieties suggesting that a broad range of germplasm has been used in the tef breeding programs. The markers documented in this study will be useful in identifying hybrids from crosses between promising lines that lack morphological differences, an approach that was not attempted before in the tef breeding programs.

The recent genotyping by sequencing (GBS) study involving 40 *Eragrostis* species and 42 tef lines showed that the wild *Eragrostis* species were more diverse than the tef cultivars indicating the usefulness of wild species in enriching the tef gene pools (Girma et al. 2018).

Five molecular tef linkage maps have so far been developed using different mapping populations and marker systems (Table 3).

Several attempts have been made to map QTLs for important agronomic traits especially lodging, yield and yield related traits in tef (Chanyalew et al. 2005; Yu et al. 2007; Zeid et al. 2011). However, validation of the QTLs has to be made before their use in marker-assisted selection. This is important especially for QTLs identified across multiple environments and those having high phenotypic variances.

High-throughput screening

As high-throughput techniques, TILLING (Targeting Induced Local Lesions IN Genomes) and Eco-TILLING are attractive methods for tef improvement since the products do not require biosafety regulations as they are free of transgenes. TILLING is a reverse genetic technique which uses traditional mutagenesis followed by high-throughput mutation detection. While TILLING is applied to the induced mutagenized population, Eco-TILLING is used in the natural population. The TILLING technique has been implemented on EMS (ethyl methane-sulfonate)-mutagenized tef populations at the University of Bern, Switzerland, mainly to develop semi-dwarf and lodging-tolerant cultivars (Tadele et al. 2010; Esfeld et al. 2013a, b). According to this, induced mutagenesis of tef involves three inter-related procedures, namely: mutation induction; mutation detection using TILLING; and mutation breeding (Tadele 2016). Since tef is a tetraploid, mutation in a single genome might not result in the expected phenotype. Hence, double crosses were made between two candidate mutant lines obtained from screening using TILLING technique. Ideally, the two candidate mutant lines harbor mutation for the gene of interest in different copy of the two tef genomes. The crossing and field testing of the breeding materials are done at the experimental site of the Debre Zeit Agricultural Research Center in Ethiopia. Unlike the above TILLING technique which uses a LiCOR machine to detect point mutations, next-generation sequencing was also applied to validate six

Table 2 Tef varieties released in Ethiopia until 2017. Source: MoALR (2017)

Variety	Releasing center	Year of release	Days to mature	Seed color	Grain yield (t/ha)	
					Research station	On-farm
I. Varieties for optimum rainfall areas (29)						
DZ-01-99 (Asgori)	Debre Zeit	1970	80–130	Brown	2.4–3.0	1.7–2.2
DZ-01-196 (Magna)	Debre Zeit	1970	80–113	Very white	1.8–2.2	1.4–1.6
DZ-01-354 (Enatite)	Debre Zeit	1970	85–130	Pale white	2.4–3.2	1.7–2.2
DZ-01-787 (Wellenkomi)	Debre Zeit	1978	90–130	Pale white	2.4–3.0	1.7–2.2
DZ-Cr-44 (Menagesha)	Debre Zeit	1982	125–140	White	2.4–3.0	1.7–2.2
DZ-Cr-82 (Melko)	Debre Zeit	1982	112–119	White	2.4–2.8	1.8–2.2
DZ-Cr-255 (Gibe)	Debre Zeit	1993	114–126	White	2.0–3.0	1.6–2.2
DZ-01-974 (Dukem)	Debre Zeit	1995	76–138	White	2.4–3.4	2.0–2.5
DZ-Cr-358 (Ziquala)	Debre Zeit	1995	75–137	White	2.1–3.6	1.8–2.4
DZ-01-2053 (Holetta Key)	Holetta	1998/99	124–140	Brown	3.4	2.5
DZ-01-1278 (Ambo Toke)	Holetta	1999/00	125–140	White	3.6	2.7
DZ-01-1285 (Koye)	Debre Zeit	2002	104–118	White	2.4–3.6	1.8–2.5
DZ-01-2054 (Gola)	Sirinka	2003	68–100	White	1.0–2.2	1.6
PGRC/E 205396 (Ajora)	Areka	2004	85–110	White	1.31	1.14
DZ-01-146 (Genete)	Sirinka	2005	78–85	Pale white	2.17	1.55
DZ-01-1821 (Zobel)	Sirinka	2005	78–85	White	2.07	1.51
DZ-01-1868 (Yilmana)	Adet	2005	108	White	2.32	1.63
DZ-01-2423 (Dima)	Adet	2005	105	Brown	2.46	1.68
DZ-Cr-387 RIL355) (Quncho)	Debre Zeit	2006	80–113	Very White	2.4–2.8	2.0–2.2
DZ-01-1880 (Guduru)	Bako	2006	132	White	1.5–2.3	1.4–2.0
23-Tafi Adi-72 (Kena)	Bako	2008	110–134	Very white	1.7–2.7	1.3–2.3
DZ-01-3186 (Etsub)	Adet	2008	92–127	White	1.9–2.7	1.6–2.2
DZ-Cr-438 RIL133 B (Kora)	Debre Zeit	2014	110–117	Very white	2.5–2.8	2.0–22
DZ-Cr-438 RIL91A (Dagim)	Debre Zeit	2016	112–115	Very white	2.6–3.2	–
DZ-Cr-438 RIL7 (Abola)	Adet	2016	110–118	Very white	2.1–2.8	1.5–1.7
DZ-Cr-429 RIL125 (Negus)	Debre Zeit	2017	112–116	Very white	2.0–2.6	–
DZ-Cr-442 RIL77C (Felagot)	Debre Zeit	2017	108 = 112	Brown	2.2–2.9	–
DZ-Cr-457 RIL181 (Tesfa)	Debre Zeit	2017	112–120	White	2.3–3.0	–
DZ-01-974 X DZ-01-2788 (Areka-1)	Areka	2017	112–119	White	2.0–2.6	–
II. Varieties for low rainfall (Terminal Drought-Prone) areas (Early Maturing) (11)						
DZ-Cr-37 (Tsedey)	Debre Zeit	1984	82–90	White	18–28	1.4–1.9
DZ-01-1281 (Gerado)	Debre Zeit	2002	73–95	White	2.2	1.0–.17
DZ-01-1681 (Key Tena)	Debre Zeit	2002	84–93	Brown	2.5	1.6–1.9
HO-Cr-136 (Amarach)	Debe Zeit	2006	63–87	White	0.13	1.2
Acc. 205953 (Mechare)	Sirinka	2007	79	Pale white	2.06	1.79
DZ-Cr-387 RIL127 (Gemechis)	Melkassa	2007	62–83	White	1.3–2.0	1.4
DZ-Cr-385 RIL295 (Simada)	Debre Zeit	2009	88	White	1.6	1.4
DZ-Cr-387 RIL273 (Lakech)	Sirinka	2009	90	Very white	2.24	1.3–1.8
DZ-Cr-409 Sel 50D (Boset)	Debre Zeit	2012	75–86	Very white	1.8–2.0	1.4–1.8
Acc. 214746A (Were-Kiyu)	Sirinka	2014	94	White	2.2	1.6
DZ-Cr-419 (Heber-1)	Adet	2017	112–124	Very white	2.2–2.7	–
III. Varieties for highland (Waterlogged) Areas (2)						
DZ-01-899 (Gimbichu)	Debre Zeit	2005	118–137	White	1.8	1.6
DZ-01-2675 (Dega Tef)	Debre Zeit	2005	112–123	White	1.8–2.8	1.6–2.0

Table 3 Description of five molecular genetic linkage maps developed for tef

Map description	Molecular tef linkage map				
	1	2	3	4	5
Mapping population	85 F_8 RILs of the intra-specific cross Kaye Murri × Fesho with polymorphism level of only 6.1% between the parents	116 RILs from the inter-specific cross *E. tef* (cv. Kaye Murri) × *E. pilosa* (30-5)	124 F_8 RILs from the inter-specific cross *E. tef* (DZ-01-2785) × *E. pilosa* (30-5)	94 F_9 RILS from the cross Kaye Murri × *E. pilosa* (acc. 30-5)	151 F_9 RILS of Kaye Murri × *E. pilosa* (acc. 30-5)
Marker system (s)	211 AFLP loci	149 RFLP loci and using tef cDNA probes and heterologous cDNA probes from rice, barley and oats	A combination of AFLP, ISSR, rice EST-SSR and tef-specific EST-SSR markers	A composite of RFLP, IFLP, EST-SSR and ISSR markers	A composite of RFLP, IFLP, EST-SSR and ISSR markers
No. of linkage groups	25	20	20	21	30
Genome coverage	2149 cM	149 cM	2112.3 cM	2082 cM	1277 cM
Reference	Bai et al. (1999)	Zhang et al. (2001)	Chanyalew et al. (2005)	Yu et al. (2006, 2007)	Zeid et al. (2010)

mutations in EMS-mutagenized tef population (Zhu et al. 2012).

Omics studies on tef

Research on tef genomics started very recently (Girma et al. 2014; Cannarozzi et al. 2018a). The first whole-genome sequence of tef contains 672 Mbp representing 87% of the total tef genome size (Cannarozzi et al. 2014). This would be important: (i) for elucidation of the sequence information of any gene which facilities primer designing and cloning of genes; (ii) in marker-assisted breeding, especially in developing genetic markers such as simple sequence repeats (SSRs) and single nucleotide polymorphisms (SNPs); and (iii) for identification of unique genes and shedding light on the pathways and mechanisms of the regulation for several desirable agronomic, nutritional and health-related traits. In addition, a transcriptome library from the roots and shoots of *Tsedey* variety resulted in 38,333 transcripts (Cannarozzi et al. 2014).

Since tef is resilient to extreme environmental conditions, differentially regulated genes were investigated under drought and waterlogging conditions. A recent study showed that under excess moisture, genes affecting carbohydrate metabolism, cell growth, response to reactive oxygen species, transport, signaling, and stress responses were differentially regulated (Cannarozzi et al. 2018b).

Similarly, the proteomics study from drought-stricken tef plants revealed that proteins associated with biotic and abiotic stress response, signaling, transport, cellular homeostasis and pentose metabolic processes were upregulated while those with photosynthesis and light harvesting reactions, manganese transport and homeostasis, the synthesis of sugars, and cell wall catabolism and modification were downregulated (Kamies et al. 2017).

Furthermore, the microRNA profiling using the next-generation sequencing of drought tolerant *Tsedey* variety and drought susceptible *Alba* landrace identified significantly modulated microRNAs in shoots and roots in response to drought (Martinelli et al. 2018). Based on this, putative targets of these miRNAs were predicted.

Physiology and agronomy

Similar to most tropical grasses such as maize, sorghum and sugarcane, tef is a C4 plant in which the first detectable photosynthetic product is a four-carbon compound as opposed to the C3 compound for C3 species such as rice, wheat and barley.

Tef is a versatile plant which performs better than cereal crops such as maize and wheat under both excess and scare moisture conditions. The physiological and anatomical mechanisms of response to waterlogging stress were recently investigated in three tef genotypes (Cannarozzi et al. 2018b). According to these findings, while waterlogged *Tsedey* variety grew better than normally watered *Tsedey* plants, the other genotypes (*Quncho* and *Alba*) were susceptible to the excess moisture stress. Such differential responses to waterlogging were also exhibited in the formation of aerenchyma in the roots. While *Tsedey* formed more aerenchyma than *Alba* and had accelerated growth under waterlogging, *Tsedey* and *Quncho* had constitutive aerenchyma (Cannarozzi et al. 2018b).

Generally, tef takes 25–81 days to emerge its panicle, 60–140 days to attain physiological maturity and 29–76 days from panicle emergence to seed maturity (Assefa et al. 2001;

Chanyalew et al. 2013). However, tef exhibits large phenologic plasticity depending on the growing conditions and genotype.

Farmers in some areas of Ethiopia practice pre-planting packing of tef seedbeds using animal trampling to minimize weed infestation and facilitate crop emergence. Although experimental results of DZARC (1989) showed that pre-planting seedbed packing improved crop establishment without significant effects on grain yield, the issue of seedbed packing still remains controversial.

Conventionally, farmers practice hand broadcasting of tef seeds at high seeding rates on the surface of the seedbeds. However, seed rates of 10–15 kg/ha would be appropriate and, in spite of the absence of significant differences between broadcasting and row sowing, the latter would be recommendable since it allows efficient utilization of fertilizers through application as row bands and facilitates subsequent cultural operations such as weeding and harvesting (Chanyalew et al. 2015).

Soil fertility management

Tef is grown in a wide range of agro-ecologies having diverse types of soils. Although tef prefers a neutral soil pH, it can grow on soils with slightly acidic to slightly alkaline pH. The most important soil-related constraints in tef husbandry are poor soil fertility, waterlogging, acidity and salinity (Negassa and Abera 2013).

In Ethiopia, DAP (diammonium phosphate) and urea were the most commonly used inorganic fertilizers for over four decades because of the initial understanding that nitrogen (N) and phosphorus (P) are the major limiting nutrients in Ethiopian soils (EhioSIS 2014). Accordingly, the recommended fertilizer for tef production on different soil types ranged from 15 to 90 kg/ha for nitrogen and from 0 to 30 kg/ha for phosphorus (Negassa and Abera 2013). However, the blanket recommendation for the major tef growing areas was 60 kg/ha N and 26 kg/ha P for heavy clay soils and 40 kg/ha N and 26 kg/ha P for light soils.

On the other hand, recent studies carried out in different parts of the central highlands of Ethiopia showed limitations in essential nutrients such as N, P, K, S, B, Zn and Mo (Hailu et al. 2015). Due to this, blended fertilizers containing different levels of NPS (nitrogen, phosphorus and sulfur) and other nutrients are recommended depending on the soil type (EthioSIS 2014).

Crop protection

Insect pests

Two species in storage (Damte and Belay 2011) and more than 44 species in the field have been reported as insect pests of tef, but the majority of these are with little economic significance (Damte 2013). The tef shoot fly is the only insect pest that occurs throughout tef growing regions in Ethiopia, although it causes sporadic damage only in dry areas.

Shoot fly infests tef plants either at three to six leaf stages especially when plants are sown densely or at six leaf stage and continue up to the heading stage. Tef has the ability to compensate from damages by shoot flies when control measures are taken at early growth stage. However, it does not compensate from the damage once the plants start flowering since this period coincides with the end of the rainy season, which makes the plant more susceptible to the pest damage as the plants become weaker during moisture scarcity (Gudeta 1997). The presence of several alternative grass species as a host, intra- and inter-species competition among tef shoot flies, and the existence of natural enemies and wide genetic bases of tef are the likely reasons for the minor status of tef insect pests in general and tef shoot flies in particular.

Other field insect pests that may cause sporadic damage to tef in localized areas include tef red worm (*Mentaxya ignicollis*), Wello bush cricket (*Decticoides brevipennis*), and termites (*Macrotermes subhyalinus* and *Odontotermes* spp.). The tef grasshopper (*Aiolopus longicornis*), which at one time was a major pest of tef in the central parts of Ethiopia, has been relegated to the minor status.

The bulk of research on tef pests focused on the selection of the right type and doses of insecticides for which recommendations are available to control shoot flies, tef red worm, tef grasshopper, and Wello bush cricket.

Diseases

About 24 fungal pathogens and two nematodes are known to attack tef plants. However, no bacterial or viral diseases are known to infect tef (Amogne et al. 2001). Among the fungal diseases, tef rust (*Uromyces eragrostidis*) and damping-off (*Drechslera* spp. and *Epicoccum nigrum*) occur throughout tef growing regions of the country, while the head smudge (*Helminthosporium miyakei*) is prevalent in the warm and humid tef growing areas in the western and southwestern parts of Ethiopia.

The tef rust mostly attacks the upper side of leaves and to a limited extent the leaf-sheath, culm and rachis of spikelets. It infects the plant beginning from the vegetative stage to crop maturity, but it causes economic damage if it occurs before or at the heading stage. Yield losses caused by tef rust ranged from 10 to 41% (Dawit and Andnew 2005).

Tef fields sown at reduced seed rate had lower damping-off incidence than those sown at high seed rate of 35–50 kg/ha, whereas tef rust was less affected by plant density (Amogne et al. 2001). On the other hand, early sowing and/or use of early maturing varieties significantly reduced both the incidence and the severity of tef rust than the late sowing

(Dawit and Andnew 2005). According to these workers, fungicides such as propiconazole and Triadimefon were effective in reducing tef rust severity, although there were no significant yield advantages due to their application.

Weeds

Weeds are one of the major yield limiting factors in all tef growing regions. Tef has a poor capacity to compete with weeds because of its shallow root system, slender stem, and small and narrow leaf-blade. Consequently, yield losses in tef due to weeds can reach up to 65% (Kinfe and Megenassa 1984).

The composition and abundance of weeds vary greatly depending on the type of cropping system, the growing seasons, agro-ecologies, soil types, and weed management practices. However, weeds prevalent in major tef growing areas are *Gallinsoga parviflora, Guizotia scabra, Cyperus* spp., *Plantago lanceolata, Digitaria spp.*, *Setaria* spp., *Commelina benghalensis, Cynodon dactylon, Oxalis corniculata, Argemone ochroleuca*, and *Echinocloa* spp. (Zewdie and Damte 2013). Interestingly, *Convolvulus arvensis*, which was inadvertently introduced to Ethiopia with seeds, has established and invaded many Vertisol areas in East, West and Southwest Shewa Zones in the central parts of Ethiopia, where premium tef is produced. *Striga hermonthica* is the only parasitic weed that grows within tef fields. However, it was not possible to confirm the susceptibility of tef plant to this parasitic weed under laboratory condition (Reda 1996).

Research on weed management of tef focused on tillage, hand weeding, and herbicide use. Hand weeding is still the dominant and widely used method in tef husbandry. Farmers who apply herbicides also hand weed their tef field to remove weeds that escape herbicide treatment. Currently, herbicides labeled for use in tef are 2,4-D, Mecoprop and Flurasulam + Flumetsulam for broad leaf weed control; Pyroxsulam for grass weed control; and Glyphosate-Isopropyl Ammonium and PALLAS 45-OD for annual and perennial weed control (MoA 2015).

Agricultural economics and extension

Adoption studies of improved tef production technologies were conducted in major tef growing areas of Ethiopia to generate pertinent information for research and policy design. These studies provide important information on patterns of adoption and dis-adoption of several improved tef varieties. An evaluation of the national extension program in 1999 showed that 15% of the farmers adopted the full package of improved tef technologies which consisted of varieties, fertilizer, and herbicides, while 58% of them applied both fertilizer and herbicide on the local tef cultivar (Tesfaye et al. 2001). A study in Lume and Minjar-Shenkora Districts unveiled that 84% of the tef farmers planted *Magna* variety, while only 5% of the farmers grew *Quncho* in the 2008/09 cropping season (Ferede 2012). These two varieties accounted for 71% and 4% of the total tef acreage in the two districts, respectively.

Since its release in 2006, the most popular and mega tef variety, *Quncho*, has been rapidly expanding to most tef growing areas of the country. In line with this, adoption survey made in 2011 in three districts (namely: Minjar-Shenkora; Ada, and Lume) in the central highlands of Ethiopia revealed that *Quncho* was the most widely (76%) adopted improved variety followed by *Magn*a (40%) (Ferede 2012). Compared to the results of a similar survey conducted in the same area in 2008, the adoption of *Quncho* in 2011 by far exceeded the expectation. For instance, its adoption rate has increased from 5% in 2008 to 76% in 2011. On the contrary, the adoption rate of *Magna* has dropped from 84% in 2008 to 40% in 2011 (Fig. 3a) (Ferede 2013). It is to be noted that the adoption rates for the different varieties would not add up to 100% because the sampled farmers commonly grow more than one tef variety in the same season.

In terms of intensity of adoption, *Quncho* was the most widely adopted variety covering 66% of the total tef acreage followed by *Magna* accounting for 26% of the total tef area (Ferede 2012). Similarly, the intensity of adoption for *Quncho* increased from 4% in 2008 to 66% in 2011, while that of *Magna* dropped from 71% to 26% in the respective years (Ferede 2013) (Fig. 3b).

Factors such as limited access to improved seeds (availability and affordability) and lack of awareness have commonly been cited as the major constraints contributing to the low level of tef technology adoption (Tesfaye et al. 2001). There has been a wider consensus that the weak seed system in Ethiopia is the major limiting factor for the slow dissemination of improved tef varieties. The profit driven from the formal seed sector is mainly engaged in the production of seeds of hybrid maize and wheat with better market size. Interestingly, the formal seed sector covers only 5% of the tef but 53% of the maize and 20% of the wheat seed requirement in Ethiopia (Alemu et al. 2007). This shows that smallholder tef producers mainly depend on the informal seed system involving farmer-to-farmer seed exchange and use of their own recycled seeds.

Tef is an important cash crop for smallholder farmers in most cereal-based farming systems of the country (Minten and Taffesse 2018). So, it is the priority crop among cereals in the use of commercial inputs such as fertilizer and other agro-chemicals. Tef is the leading crop that accounts for 29% of the total annual fertilizer consumption in Ethiopia followed by maize (25%) and wheat (22%) (CSA 2015).

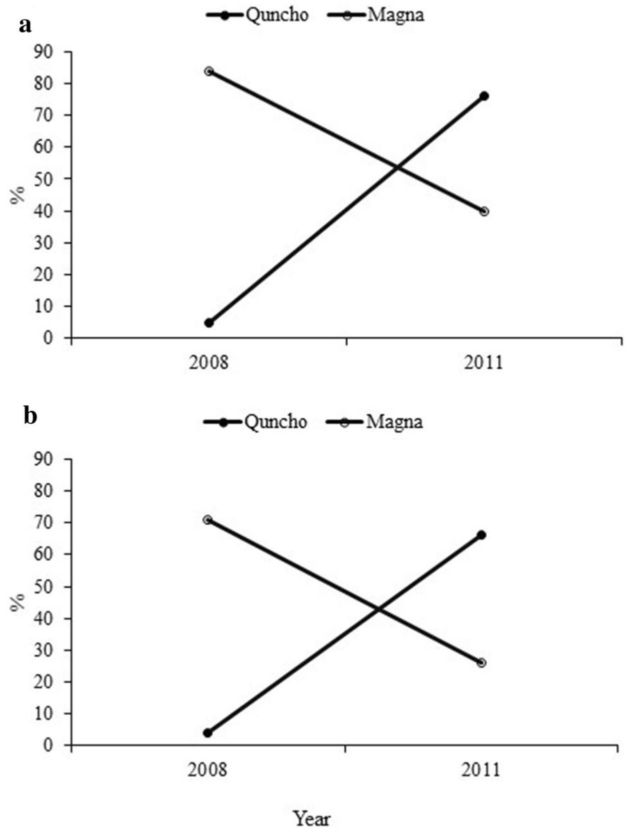

Fig. 3 The Adoption of two widely cultivated tef varieties (*Quncho* and *Magna*) in three *Weredas* (Minjar Shenkora, Ada and Lume) in the central highlands of Ethiopia. **a** The Adoption rate, **b** the Adoption intensity. Source: Modified from Ferede (2013). Note: The adoption rates for the different varieties would not add up to 100% since the sampled farmers commonly grow more than one tef variety in the same season

The Ethiopian Institute of Agricultural Research (EIAR) introduced a new technology pre-scaling up approach with the major objective of addressing technology gaps in unaddressed agro-ecologies while in due course revitalizing the formal and informal seed systems. The implementation of this intervention is based on multi-stakeholder partnership approach involving packaging of technologies, training and technical backstopping supplemented with continuous monitoring and evaluation (Assefa et al. 2011a, b; Assefa and Chanyalew 2018). Evidences showed that this technology pre-scaling up program has greatly contributed to the wider dissemination of improved technologies for local crops like tef with very limited seed supply from the formal seed sector. Based on this, over 1600 tons of improved tef varieties were distributed to over 65,000 farmers covering about 15,000 ha of land through the pre-scaling up program during the period between 2011/12 and 2013/14 (Alemu et al. 2016).

Research partnerships

A number of local as well as international institutions have contributed to tef improvement through conducting independent research, collaborations, partnerships, training of researchers, and provision of grant or loan. In Ethiopia, the national agricultural research system for tef involves the Ethiopian Institute of Agricultural Research (EIAR) with its Debre Zeit Agricultural Research Center (DZARC) as the National Tef Research Program coordinator. Regional Agricultural Research Institutes (RARIs) actively involved in tef research include Amhara Region Agricultural Research Institute (ARARI), Oromia Agricultural Research Institute (OARI), Southern Agricultural Research Institute (SARI) and Tigray Agricultural Research Institute (TARI). Similarly, among higher learning institutions, substantial amount of studies have been made on tef at Addis Ababa University, Haramaya University, Jimma University, Hawassa University, Debre Markos University, and Mekelle University.

Future directions

Globally, owing to its localized importance, tef still remains to be under-researched "orphan" crop. In Ethiopia, however, tef is the most important crop by all measures of acreage, production as well as consumption and nutrition (Hassen et al. 2018). Consequently, transformative agricultural development in the country can never be anticipated without addressing tef which accounts for over one-fifth of the total cultivated area of the country, and constituting not only the major element of food and nutrition security but also the biggest cash crop for the smallholder farmers. On the other hand, the demand for tef in Ethiopia is increasing from time to time due to: (i) the ever-increasing population which presently is estimated at over 100 million and projected to reach over 130 million by the half of this century; (ii) the shift of the staple diet preference of the people from other grains to tef with increased incomes and livelihoods; (iii) the opening of an additional demand and market for tef due to the current peaceful reconstitution between Ethiopia and Eritrea, and (iv) the recent global popularity of tef as health and performance food or "super-grain" because of its gluten-free grains, nutritional value and health benefits as a consequence of which there is an increasing global market for export of tef and its products.

However, to satisfy the increasing demand, the major production constraints such as low productivity, lodging, biotic and abiotic stresses, minute seed size and labor intensiveness of the cultural practices need to be addressed. Therefore, areas of focus in future tef improvement and development should include: (i) improving productivity of tef; (ii) overcoming the lodging malady; (iii) developing climate-smart and appropriate crop and soil management options; (iv) developing tolerance to abiotic stresses such as drought and soil acidity; (v) developing suitable pre- and post-harvest mechanization technologies suitable for smallholder farmers as well as commercial farms; (vi) food processing and nutrition aspects with special attention to the development of different food recipes and value-added products; (vii) developing crop protection measures against diseases, insect pests and weeds; and (viii) improving or strengthening socio-economics and agricultural extension services.

Most importantly, the problem of lodging in tef needs the highest priority since lodging inflicts substantial yield loss on tef. Modern biotechnological techniques including genome editing techniques need to be employed to solve the lodging problem. The Green Revolution genes that marked the breakthrough in the control of lodging in wheat and rice appear difficult to work in the same analogy with tef. A modified dwarfing ideotype in tef has to be envisaged with the height reduction restricted to the culms so as not to compromise with yield by shortening the length of the panicles, while the shortening with respect to the panicles needs to be for a more dense type with reduced length between the panicle branches. Lodging resistant varieties do not only avoid yield losses but also open a new avenue for revolutionizing the management aspects of the crop in terms of using high input husbandry.

On the other hand, the collection, characterization and conservation of the tef genetic resources have not yet been comprehensive and systematic. Consequently, rigorous conservation, characterization, and utilization of tef genetic resources would be necessary for sustainable improvement of the crop. Furthermore, the physiology of tef is almost untouched. For instance, the tef plant is generally believed to have important traits in terms of tolerance to abiotic stresses such as drought, waterlogging, soil acidity and salinity. But the physiological mechanisms of tolerance to these stresses and the traits associated with these stress tolerances are little known.

To date, tef husbandry remains to be very culture- and labor-intensive starting from land preparation to harvesting and threshing. However, if tef production in Ethiopia is to sustain, the cultural operations need to be transformed into the use of improved machineries and implements.

As indicated earlier, tef is highly nutritious and has recently gaining global popularity as a life-style crop. If Ethiopia is to exploit the newly opened global export market for the crop, due attention must be given to the development of diverse and consumer-demanded value-added products instead of exporting raw grains or flour.

Despite the wide-ranging challenges that require appropriate attention, there have also been ample opportunities for tef improvement and development as indicated below.

1. Availability and accessibility of diverse genetic resources: The tef genetic resources contain tremendous diversity in phenological, agronomical and morphological traits, coupled with unexploited aspects in terms of traits associated to nutrition, and biotic and abiotic stress tolerance. This ample source of diversity offers opportunities for genetic improvement of the crop to develop suitable varieties for diverse cropping systems, agro-ecologies, and utilization.
2. Advanced research approaches: Advances in bio-sciences have unlocked new understandings into how to effect crop improvements through employing coordinated strategies involving classical breeding, contemporary techniques including genomics and in vitro cultures, and crop and soil and water management, food science and processing, and mechanization.

Conclusions

Integrated use of conventional breeding with modern tools will speed up genetic improvement of tef. Improved cultural practices including seed pelleting techniques for even and easy distribution of seeds at planting, and appropriate use of farm machinery would further improve productivity and production of the crop. Appropriate crop, soil and water, and pest management practices commensurate to the genetic improvement efforts would be imperative if the genetic gains are to be realized at the farm level. Equally, it would be necessary to strengthen the seed as well as the extension systems in order to hasten wider dissemination and utilization of the research outputs. In summary, modernizing the tef breeding program in particular and the overall tef research and development undertakings in general in terms of personnel, infrastructure and facilities, and scientific techniques and tools would be invaluable and required in order to bring about breakthrough in tef improvement instead of the merely incremental changes in tef varieties registered to date.

Author contribution statement SC, ZT, KA: conceived the idea; SC, SF, TD, ZT, KA: wrote the paper; all authors read the paper and approved.

Acknowledgements We thank Syngenta Foundation for Sustainable Agriculture for financing currently ongoing important tef research projects in Ethiopia as well as Switzerland. We are also grateful to the McKnight Foundation's Collaborative Crop Research Program for supporting fruitful collaborative research projects for over a decade and a half from 1995 until 2014. In addition, the support of the Alliance for Green Revolution in Africa (AGRA) through a project on seed systems is very much acknowledged. Furthermore, the substantial contributions of the Ethiopian Agricultural Transformation/DANIDA sub-grant Tef Improvement Project (TIP) are highly appreciated and greatly acknowledged.

References

Agren G, Gibson R (1968) Food composition table for use in Ethiopia. Uppsala, Sweden, Swedish International Development Agency, Ethiopian Nutrition Institute, Addis Ababa

Alemu D, Mwangi W, Nigussie M, Spielman DJ (2007) An analysis of maize seed production and distribution systems in Ethiopia's Rift Valley, Research Report 72. EIAR, Addis Ababa

Alemu D, Kelemu K, Bezabih A, Zegeye F (2016) Transferring agricultural technologies: approaches, linkages and challenges. EIAR, Addis Ababa

Amogne S, Kassaye Z, Bekele E (2001) Tef pathology research in Ethiopia. In: Tefera H, Belay G, Sorrels M (eds) Narrowing the rift: tef research and development. Proceedings of the international workshop on tef genetics improvement, 16–19 October 2000, Debre Zeit, Ethiopia, pp 215–222

Assefa K, Chanyalew S (2018) Agronomics of tef. In: Minten B, Taffesse AS, Brown P (eds) The Economics of Tef, Exploring Ethiopia's Biggest Cash Crop. International Food Policy Research Institute (IFPRI), Wasington, DC, pp 39–70

Assefa K, Ketema S, Tefera H, Hundera F, Kefyalew T (2001) Genetic diversity for agronomic traits in tef. In: Tefera H, Belay G, Sorrells M (eds) Narrowing the rift, tef research and development, Proceedings of the international workshop on tef genetics and improvement, 16–19 October 2000, EIAR, Addis Ababa, Ethiopia, pp 33–48

Assefa K, Aliye S, Belay G, Metaferia G, Tefera H, Sorrells M (2011a) Quncho: the first popular tef variety in Ethiopia. Int J Agric Sustain 9:25–34

Assefa K, Fikre A, Alemu D, TekleWold A (eds) (2011b) mitigating crop technologies and seed gaps: addressing the unaddressed. EIAR, Addis Ababa

Assefa K, Chanyalew S, Metaferia G (2013) Conventional and molecular tef breeding. In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of tef improvement, Proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia, pp 33–51

Assefa K, Cannarozzi G, Girma D, Kamies R, Chanyalew S, Plaza-Wüthrich S, Blösch R, Rindisbacher A, Rafudeen S, Tadele Z (2015) Genetic diversity in tef [*Eragrostis tef* (Zucc.) Trotter]. Front Plant Sci 6:177

Assefa K, Chanyalew S, Tadele Z (2017) Tef, *Eragrostis tef* (Zucc.) Trotter. In: Patil JV (ed) Millets and sorghum, biology and genetic improvement. Wiley, Hoboken, pp 226–266

Bai G, Tefera H, Ayele M, Nguyen HT (1999) A genetic linkage map of tef [*Eragrostis tef* (Zucc.) Trotter] based on amplified fragment length polymorphism. Theor Appl Genet 99:599–604

Baye K (2018) Nutrient composition and health benefits. In: Minten B, Taffesse AS, Brown P (eds) The economics of tef, exploring Ethiopia's biggest cash crop. International Food Policy Research Institute (IFPRI), Wasington DC, pp 371–396

Ben-Zeev S, Bimro J, Barak V, Saranga Y (2018) Phenotypic diversity and heritability in *Eragrostis tef* under irrigated Mediterranean conditions. Isr J Plant Sci 65(3–4):222–231

Berhe T (1975) A break-through in tef breeding techniques, FAO Information Bulletin, Cereal Improvement and Production, Near East Project XII:11-13. FAO, Rome

Bultosa G (2007) Physicochemical characteristics of grain and flour in 13 tef (*Eragrostis tef* (Zucc.) Trotter) varieties. J App Sci Res 3:2042–2051

Cannarozzi G, Plaza-Wuthrich S, Esfeld K, Larti S, Wilson YS, Girma D, de Castro E, Chanyalew S, Blosch R, Farinelli L, Lyons E, Schneider M, Falquet L, Kuhlemeier C, Assefa K, Tadele Z (2014) Genome and transcriptome sequencing identifies breeding targets in the orphan crop tef (*Eragrostis tef*). BMC Genomics 15:581

Cannarozzi G, Chanyalew S, Assefa K, Bekele A, Blösch R, Weichert A, Klauser D, Plaza-Wüthrich S, Esfeld K, Jöst M, Rindisbacher A, Jifar H, Johnson-Chadwick V, Abate E, Wang W, Kamies R, Husein N, Kebede W, Tolosa K, Genet Y, Gebremeskel K, Ferede B, Mekbib F, Martinelli F, Pedersen HS, Rafudeen S, Hussein S, Tamiru M, Nakayama N, Robinson M, Barker I, Zeeman S, Tadele Z (2018a) Technology generation to dissemination: lessons learned from the tef improvement project. Euphytica 214(2):31

Cannarozzi G, Weichert A, Schnell M, Ruiz C, Bossard S, Bloesch R, Plaza-Wuethrich S, Chanyalew S, Assefa A, Tadele Z (2018b) Waterlogging affects plant morphology and the expression of key genes in tef (*Eragrostis tef*). Plant Direct 2:1–22

Chanyalew S, Singh H, Tefera H, Sorrels M (2005) Molecular genetic map and QTL analysis of agronomic traits based on a *Eragrostis tef* x *Eragrostis pilosa* recombinant inbred population. J Genet Breed 59:53–66

Chanyalew S, Assefa K, Metaferia G (2013) Phenotypic and molecular diversity in tef. In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of tef improvement , Proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia, pp 21–31

Chanyalew S, Genet Y, Asfaw M, Fikre T, Assefa K (2015) Effects of sowing methods, seed rates and sowing depths on growth performance and grain yield of tef [*Eragrostis tef* (Zucc.) Trotter]. Ethiop J Crop Sci 4(1):45–57

Cheng A, Mayes S, Dalle G, Demisse S, Massawe F (2017) Diversifying crops for food and nutrition security—a case of teff. Biol Rev 92:188–198

Costanza SH, deWet GM, Harlan GM (1979) Literature Review and Numerical Taxonomy of *Eragrostis tef*. (t'ef). Econ Bot 33:413–424

CSA (2015) Central Statistical Agency, Agricultural sample survey 2014/15 (2007 E.C.). Report on Farm Management Practices (Private Peasant Holdings, *Meher* Season). Volume III, Statistical Bulletin 578. Addis Ababa, Ethiopia

Cufodontis G (1974) Enumeration planetarium Aethiopiae spermatophyta. Jord. Bot, Bruseels

D'Andrea AC, Wadge P (2011) T'ef (*Eragrostis tef*): a legacy of Pastoralism? In: Fahmy AG, Kehlheber S, D'Andrea AC (eds) Windows on the African past: current approaches to African archeobotany. Reports in African archaeology 3, African Magna Verlag, Frankfurt, pp 225–241

Damte T (2013) Insect pest management research in tef. In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of Tef improvement , Proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia, pp 171–191

Damte T, Belay G (2011) New record of insect pest infesting stored tef (*Eragrostis tef* (Zucc.) Trotter) grains. Ethiop J Crop Sci 2:109–113

Dargo F (2013). Genetic Gain in Grain Yield Grain Yield Potential and Associated Traits of Tef [*Eragrostis tef* (Zucc.) Trotter] in Ethiopia, MSc. Thesis, Haramaya University, Haramaya, Ethiopia

Dawit W, Andnew Y (2005) The study of fungicides application and sowing date, resistance, and maturity of *Eragrostis tef* for the management of tef rust [*Uromyces eragrostidis*]. Can J Plant Path 27:521–527

DZARC (1989) Debre Zeit Agricultural Research Center, Annual Research Progress Report for 1988/89, Debre Zeit, Ethiopia

Ebba T (1969) Tef (*Eragrostis tef*): The cultivation, usage, and some of its known diseases and insect pests. Part I. Expt. Sta. Bull. No. 60, Haile Sellassie I University (HSIU), College of Agriculture, Dire Dawa, Ethiopia

Ebba T (1975) Tef (*Eragrostis tef*) Cultivars: Morphology and Classification, Part II, Expt. Sta. Bull.No.66, Addis Ababa University, College of Agriculture, Dire Dawa, Ethiopia

ENS (1959) Ethiopian Nutrition Survey. A Report by the Inter-Departmental Committee on Nutrition for National Defense, Addis Ababa

Esfeld K, Plaza-Wüthrich S, Tadele Z (2013) TILLING as a high-throughput technique of tef improvement. In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of Tef Improvement, Proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia, pp 53–65

Esfeld K, Uauy C, Tadele T (2013b) Application of TILLING for orphan crop improvement. In: Jain SM, Gupta SD (eds) Biotechnology of neglected and underutilized crops. Springer, Berlin, pp 83–113

EthioSIS (2014) Ethiopian soil information system, towards improved fertilizer recommendations in ethiopia—nutrient indices for categorization of fertilizer blends from EthioSIS *Woreda* Soil Inventory Data. Adis Ababa, Ethiopia

Ferede S (2012) Tef Seed system in Minjar-Shenkora and Lume-Ejere *woredas* of East Shewa. In: Wold AT, Fikre A, Alemu D, Desalegn L, Kirub A (eds) The defining moments in Ethiopian seed system. Proceeding of the international conference on sustainable seed systems in Ethiopia: challenges and opportunities, 01–03 June 2011, EIAR HQ, Addis Ababa, Ethiopia, pp 355–364

Ferede S (2013) Technological change and economic viability in tef production. In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of Tef improvement, Proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia, pp 255–273

Gebremariam MM, Zarnkow M, Becker T (2014) Tef (*Eragrostis tef*) as raw material for malting, brewing and manufacturing of gluten-free foods and beverages: a review. J Food Sci Technol 51(11):2881–2895

Girma D, Assefa K, Chanyalew S, Cannarozzi G, Kuhlemeier C, Tadele Z (2014) The origins and progress of genomics research on tef (*Eragrostis tef*). Plant Biotechnol J 12(5):534–540

Girma D, Cannarozzi G, Weichert A, Tadele Z (2018) Genotyping by sequencing reasserts the close relationship between tef and its putative wild *Eragrostis* progenitors. Diversity 10(2):17

Gudeta S (1997) Biology of the tef shoot fly, *Atherigona hyalinipennis* van Emden in Eastern Ethiopia. Insect Sci Appl 17(3/4):349–355

Hailu H, Mamo T, Keskinen R, Karltun E, Gebrekidan H, Bekele T (2015) Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. J Agric Food Secur 4:19. https://doi.org/10.1186/s40066-015-0038-0

Hassen IW, Regassa MD, Berhane G, Minten B, Taffesse AS (2018) Teff and its role in the agricultural and food economy. In: Minten B, Taffesse AS, Brown P (eds) The economics of Tef, exploring Ethiopia's Biggest Cash Crop. International Food Policy Research Institute (IFPRI), Washington DC, pp 11–37

Ingram AL, Doyle JJ (2003) The origin and evolution of *Eragrostis tef* (Poaceae) and related polyploids: evidence from nuclear waxy and plastid rps16. Am J Bot 90(1):116–122

Jifar H, Dagne K, Tesfaye K, Assefa K, Tadele Z (2018) Agro-morphological traits diversity in tef [*Eargrostis tef* (Zucc.) Trotter] genotypes from various sources. Ethiop J Agric Sci 28(3):131–148

Kamies R, Farrant J, Tadele Z, Cannarozzi G, Rafudeen MS (2017) A proteomic approach to investigate the drought response in the orphan crop *Eragrostis tef*. Proteomes 5(4):32

Kefyalew T (2001) Genotype X environment interaction in tef. In: Tefera H, Belay G, Sorrels M (eds) Narrowing the rift: tef research and development . Proceedings of the international workshop on tef genetics and improvement, 16–19 October 2000, Debre Zeit, Ethiopia, pp 145–156

Ketema S (1993) Tef, *Eragrostis tef* (Zucc.) Trotter: breeding, Genetic Resources, Agronomy, Utilization and Role in Ethiopian Agriculture, Institute of Agricultural Research, Addis Ababa, Ethiopia

Ketema S (1997) Tef, *Eragrostis tef (Zucc.)* Trotter, Institute of Plant Genetics and Crop Plant Research Gatersleben/International Plant Genetic Resources Institute, Rome, Italy, p 52

Kinfe B, Megenassa T (1984) Frequency of hand weeding on weed control and yield of tef (*Eragrostis tef*). Ethiop J Agric Sci 6:88–101

Martinelli F, Cannarozzi G, Balan B, Siegrist F, Weichert A, Blösch R, Tadele Z (2018) Identification of miRNAs linked with the drought response of tef [*Eragrostis tef* (Zucc.) Trotter]. J Plant Physiol 224–225:163–172

Minten B, Taffesse AS (2018) Introduction. In: Minten B, Taffesse AS, Brown P (eds) The economics of tef, exploring Ethiopia's biggest cash crop. International Food Policy Research Institute (IFPRI), Washington, DC, pp 1–9

MoA (2015) Ministry of agriculture. List of registered pesticides as of June, 2015. Health Regulatory Directorate, MOA, Addis Ababa

MoALR (2017) Ministry of agriculture and livestock resource, plant variety release, protection and seed quality control directorate, crop variety Rehister, Issue No. 20, Addis Ababa, Ethiopia

Negassa W, Abera Y (2013) Soil fertility management studies on tef, In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of tef improvement, Proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia. pp 121–131

NRC (1996) Lost crops of Africa, National Research Council. Volume 1: grains. National Research Council, Washington DC

Ponti I (1978) The systematics of *Eragrostis tef* (Gramineae) and related species, PhD Thesis, University of London, UK

Reda F (1996) Parasitic weeds research in Ethiopia. . In: Arem Vol. 1 Fessehaie R (ed) Proceedings of the first annual conference of the ethiopian weed science society, 24–25, November 1993, pp 31–38, Addis Ababa, Ethiopia

Shaw T (1976) Early crops in Africa: a review of the evidence. In: Harlan JH, de Wet JMJ, Stemler ABL (eds) Origins of African plant domestication. Mouton Publishers, The Hague, pp 107–153

Spaenij-Dekking L, Kooy-Winkelaar Y, Koning F (2005) The Ethiopian cereal tef in celiac disease. N Engl J Med 353:1748–1749

Tadele Z (2016) Mutagenesis and TILLING to dissect gene function in plants. Curr Genomics 17(499–508):499

Tadele Z, Mba C, Till BJ (2010) TILLING for mutations in model plants and crops. In: Jain SM, Brar DS (eds) Molecular techniques in crop improvement, 2nd edn. Springer, Berlin, pp 307–332

Tefera H, Ketema S (2001) Production and importance of tef in Ethiopian agriculture. In: Tefera H, Belay G, Sorrells M (eds) Narrowing the rift: tef research and development, Proceedings of the International workshop on tef genetics and improvement, 16–19 October 2000, EIAR, Addis Ababa, Ethiopia, pp 3–7

Tefera H, Peat WE (1996) Gene action for some quantitative traits of tef [*Eragrostis* tef (Zucc.) Trotter]. Ethiop J Agric Sci 15:8–19

Tefera H, Peat WE (1997a) Genetics of grain yield and other agronomic characters in tef [*Eragrostis tef* (Zucc.) Trotter] I. generation means and variance analysis. Euphytica 96:185–191

Tefera H, Peat WE (1997b) Genetics of grain yield and other agronomic characters in tef [*Eragrostis tef* (Zucc) Trotter] II. The triple test cross. Euphytica 96:193–202

Tefera H, Assefa K, Hundera F, Kefyalew T, Teklu Y, Gugsa L, Ketema S, Adnew T (2001) Progress of tef breeding in Ethiopia. In: Tefera H, Belay G, Sorrels M (eds) Narrowing the rift: tef research and development, Proceedings of the international workshop on tef genetics and improvement, 16–19 October 2000, Debre Zeit, Ethiopia, pp 157–164

Tefera H, Assefa K, Belay G (2003) Evaluation of interspecific recombinant inbred lines of *Eragrostis tef* x *E pilosa*. J Genet Breed 57:21–30

Teklu Y, Tefera H (2005) Genetic improvement in grain yield potential and associated agronomic traits of tef (*Eragrostis tef*). Euphytica 141:247–254

Tesema A (2013) Genetic resources of tef in Ethiopia. In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of Tef improvement, Proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia, pp 21–31

Tesfaye T, Kelemework F, Deresa A, Zerfu E, Bedane K, Dadi L (2001) Tef technology transfer and adoption. In: Tefera H, Belay G, Sorrells M (eds) Narrowing the rift: tef research and development. Proceedings of the international workshop on tef genetics and improvement, 16–19 October 2000, EIAR, Addis Ababa, Ethiopia, pp 255–264

USDA (2015) National Nutrient Database for Standard Reference Release 27, United States Department of Agriculture, USA

Vavilov NI (1951) The origin, variation, immunity and breeding of cultivated plants. Translated from the Russian by K.S. Chester. Ronal Press Co., New York

Watson L, Dallwitz MJ (1992) The grass genus of the world. CAB International, Wallingford

Yu JK, Kantety RV, Graznak E, Benscher D, Tefera H, Sorrells ME (2006) A genetic linkage map for tef [*Eragrostis tef* (Zucc.) Trotter]. Theor Appl Genet 113:1093–1102

Yu JK, Graznak E, Breseghello F, Tefera H, Sorrells ME (2007) QTL mapping of agronomic traits in tef [*Eragrostis tef* (Zucc) Trotter]. BMC Plant Biol 7:30

Zarnkow M, Almaguer C, Burberg F, Back W, Arendt EK, Kreisz S, Gast M (2008) The use of response surface methodology to optimize malting conditions for tef (*Eragrostis tef* (Zucc.) Trotter) as raw material for gluten-free foods and beverages. World Brewing Congress, Honolulu

Zeid M, Belay G, Mulkey S, Poland J, Sorrells ME (2010) QTL mapping for yield and lodging resistance in an enhanced SSR-based map for tef. Theor Appl Genet 122:77–93

Zeid M, Belay G, Mulkey S, Poland J, Sorrells ME (2011) QTL mapping for yield and lodging resistance in an enhanced SSR-based map for tef. Theor Appl Genet 122:77–93

Zeid M, Assefa K, Haddis A, Chanyalew S, Sorrells ME (2012) Genetic diversity in tef (*Eragrostis tef*) germplasm using SSR markers. Field Crops Res 127:64–70

Zewdie K, Damte T (2013) Weed research in tef. In: Assefa K, Chanyalew S, Tadele Z (eds) Achievements and prospects of Tef improvement: proceedings of the second international workshop, November 7–9, 2011, Debre Zeit, Ethiopia, pp 199–207

Zhang D, Ayele M, Tefera H, Nguyen HT (2001) RFLP linkage map of the Ethiopian cereal tef [*Eragrostis tef* (Zucc) Trotter]. Theor Appl Genet 102:957–964

Zhu QH, Smith SM, Ayele M, Yang LX, Jogi A, Chaluvadi SR, Bennetzen JL (2012) High-throughput discovery of mutations in tef semi-dwarfing genes by next-generation sequencing analysis. Genetics 192:819–829