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Tef *(Eragrostis tef (Zucc.) Trotter)* Breeding, Achievements, Challenges and Opportunities in Ethiopia; incase Southwestern Ethiopia: Review

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Abstract

Ethiopia is believed to be the center of origin and diversity of tef. The crop is highly evolved and diversified within the country and can grow in a variety of agro-ecological conditions, including marginal areas where other crops are more difficult to cultivate. Its nutritional and gluten-free value make tef very suitable as an ingredient for the increasing demand in healthy bakery, cereal and snack products. Southwestern part was major tef producing areas of Ethiopia but the productivity was very low. Productivity of tef in the region were highly influenced by diseases, soil acidity, poor soil fertility, lodging, labor intensive nature of crop husbandry and weak extension system. In addition, the small size of tef seed poses problems during sowing, weeding and threshing. In future to increase the productivity, the research must focus on solving especially disease and acidity problem by conducting adaptation trial of recently released varieties or by developing variety/ies/ was/were tolerant or resistant to challenges.

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Introduction

World food crops have been improved progressively since their domestication starting about 10,000 years ago. Progress was especially rapid after the rediscovery of Mendel's laws of inheritance when scientific principles could be applied to crop improvement. Modern varieties of wheat and rice which ushered in the green revolution and led to a doubling of cereal production in a 25-year period are examples of recent achievements in increasing crop productivity. The present world population of 5.9 billion is likely to reach 7 billion in 2010 and 8 billion in 2025.The increase in the global population, competition of food and biofuel for available land resources, and climate change are all threatening food security. One avenue to alleviate these pressures on our food supply is through better utilization of indigenous or 'orphan' crops. These crops have the advantages that they are already well-integrated in the socio-economics of the region, they are the preferred crops for both farmers and consumers, and they provide more stability under rapidly changing environmental conditions and demand. However, they have long been neglected both by commercial breeders and non-profit institutions. Harlan (1995) describes Africa as "modern crop evolution laboratory". It is characterized as such because the transition from wild and weed species to cultivated races can be traced through modern plant forms that exist in Africa today (Edwards, 1991). A small group of crops was domesticated in the Ethiopian highlands and adjacent regions, and these have been referred to as Ethiopian crop complex (Vavilov, 1926; Harlan, 1992a).

Harlan (1969) later established that most of the crops, Vavilov attributed to this complex are introduced species with secondary centers of diversity in Ethiopia. Although the concept of world centers of agricultural origin is now thought to be limited use (Harlan, 1971; Harris, 1990), the Ethiopian and adjacent highlands are still acknowledged as the region where a suite of indigenous crops known as the Ethiopian crop complex originated (Table 1).

Ethiopia is a country with varied a topography and a wide spectrum of habitats presenting a large number of endemic plants and animals. The country has about 6000 higher plant species of which about 10% are endemic (Hedberg *et al*., 2009). Ethiopia also harbours two of the 34 global biodiversity hotspots (CI, 2004) and is recognized as a Vavilov centre of origin and diversification for many food plants and their wild relatives (Edwards, 1991).

History and evolution of tef

The antiquity and origin of tef remain unclear.Ehret (1979; 1984) presents linguistic evidence suggesting that tef cultivation by Cushitic-speakers probably took place in Northern Ethiopia at least 7000 years ago. He suggests that tef is derived from the ancient Cushitic root *taf*,which is believed to be a generalized term for grain food of Northeast Africa, dating to the seven millennium BP (Ehret, 1979). The wild progenitor of *Eragrostis tef* has been identified as *Eragrostis pilosa* (Jones *et al*., 1978; Endashew and Lester, 1981). Although it has been suggested that *Eragrostis pilosa* is a weedy derivative of tef and not the progenitor (Barnnet, 1996), this statement is not supported by any new evidence. *Eragrostis pilosa* is wide spread throughout the warm temperate and old world and is a highly valued livestock fodder in the Ethiopian highlands (Phillips, 1995; Barnnet, 1996). Morphological and biochemical evidence suggests *Eragrostis pilosa* is a wild progenitor of tef, and both have a tetraploid chromosome number of 2n=40 (Jones *et al*., 1978; Endashew and Lester,1981).*E.pilosa* spikelets differ from those of *E. tef* in smaller size and the presence of shattering (Phillips,1995).

A biochemical study by Endashew and Lester (1981) examines the relationship of *E.tef* with several wild *E*.species. The results illustrate considerable chemical variation within tef and reveal its affinity with *E.pilosa*. Four additional species that may have been involved in the evolution of tef are also identified, including *Eragrostis aethiopica*, *E. barrelieri*, and to lesser degree *E.curvula* and *E.cilianesis*. The authors conclude that there is considerable difference in the amino acid composition of domesticated tef and wild *Eragrostis* species, however *E.pilosa* was found to be particularly similar to tef in its lysine content. Endashew and Lester (1981) also propose that *E.aethiopica* may have been the diploid ancestor of tetraploids *E.pilosa* and *E.tef*.

Tef illustrates three morphological changes in the inflorescence through domestication; uniform maturation, an increase in panicle size, and an increase in percent of seed set (Phillips, 1995; Seyfu, 1983). The tef panicle is very similar in the structure to that of *E.pilosa*, although uniform maturation establishes a more determinate growth pattern in the domesticate. The grains of the wild tef panicle ripen over a long period of time beginning at the base, where as tef grains ripen simultaneously on the plant and within the crop (Phillips, 1995).A second morphological change associated with domestication in *E.tef* is an increase in panicle size compared to *E.pilosa*. In *E.pilosa* the panicle measures 8 to 30cm in length, while in tef it measures 10 to 60cm (Phillips, 1995). Larger grain size and increased seed yields are probably related to an overall increase in panicle size (Harlan *et al*., 1973). Therefore, tef illustrates an increase in seed set or number of seeds produced per plant with an increase in overall inflorescence or panicle size.

Among the genera of the grass family *Poaceae*, *Eragrostis* is one the biggest with about 350 species that range from diploids (2n=2x=20) to hexaploids (2n=4x=60) (Watson and Dallwitz, 1992). About 43% of the species are believed to have 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 (Constanza *et al*.,1979). Ethiopia is believed to be the center of origin and diversity of tef (Vavilov, 1951).Fifty-four species are found in Ethiopia, out of which 14 are said to be endemic (Seyfu, 1993). Tef, *Eragrostis tef* (Zucc.) Trotter is the only cultivated species in the genus *Eragrostis*. Tef is arguably the world's smallest domesticated grain crop. The botanical designation of tef is said to come from *t'efa*', meaning "lost" in Amharic, a comment on the cereal's tiny grains (Rouk and Hailu, 1963).

Tef is preferred both by farmers and consumers. Farmers prefer cultivating tef to other cereals, due to i) Broad agro- ecological adaptation from below sea level up to 3000 meters above sea level under varied climatic, edaphic and socio- economic conditions; ii) Reasonable tolerance to both low (drought) and high (water- logging) moisture stresses; iii) Importance as a reliable and low- risk catch crop at times when other particularly long- season crops (such as maize and sorghum) due to natural calamities such as drought and pests (diseases and insect pests); iv) suitability to various cropping systems and crop rotation schemes; v) Relative resilience to serious epidemics of pests and diseases in at least the major tef production regions of the country; and vi) Minimal post- harvest losses since the grains suffer less from damage by storage pests such as weevils and diseases (Solomon *et al*.,2019). Normally, tef grains can be stored for 3–5 years without considerable loss of viability even under traditional storage conditions.

In addition, as a cash crop, both the grain and straw of tef fetch higher prices than the respective products from other cereals. Consumers prefer tef not only because it makes good quality ‘‘injera’’, a pancake-like soft bread, but also because it is nutritious due to its high protein and mineral content (Bultosa *et al*. 2002). Furthermore, the absence of gluten (Spaenij *et al*., 2005) makes tef an alternative food for people suffering from celiac disease. Due to this life-style feature of the crop, it has been heralded as a ‘super food’ or ‘super grain’ (Jeffrey 2015; Provost and Jobson, 2014). Overall, tef plays a vital role in food security, nutrition, and income generation to small-holder farmers in Ethiopia.

Tef is the most important cereal crop n Ethiopia accounting for about 28% of the total acreage and 21% of the gross grain production of all cereals. It is staple food for about 50 million people and grown by over 6 million small-scale farmers’ households, and constitutes the major staple food grain crop (Kebebew *et al*., 2015). Among the food crops grown in Ethiopia, tef is cultivated on about 3 million hectare producing 4.75 million tons. This implies that tef is very important in the overall national food security of the country (Kebebew *et al*., 2013).

Tef can be grown from low to high altitude, indicating that the crop has great flexibility and plasticity in growing over a wide range of agronomic and edaphic conditions and under various rainfall, temperature and soil regimes (Ayalneh *et al*., 2012). In Ethiopia, tef can grow under wide and diverse agro-ecologies. It is mainly produced in Amhara and Oromia, with smaller quantities in the Tigray and SNNP regions. There are 19 major tef producing zones in the country. The Central and South Tigray zones are the major tef producing zones in Tigray. Within the Amhara Region, East Gojjam, West Gojjam, North Gondar, South Gondar, North Wollo, South Wollo, North Showa and Awi Zones are the major producers of tef. In Oromia region, the major tef producing zones include the East Shoa, West Shoa, South West Shoa, North Shoa, East Wollega, Horo Guduroo Wollega, Jimma, Illubabor and Arsi (CSA, 2017).

Ethiopia is the largest tef producer in the world. In 2017, tef accounts for 24% of the grain area, followed by maize 17% and sorghum 15% (Table 2). Amhara and Oromia are the two major regions, and collectively, the two regions account for 85.5% of the tef area and 87.8% of the tef production (Table 3).

Despite its versatility in adapting to extreme environmental conditions, the productivity of tef is low in Ethiopia at 1.5 tons ha^{-1} as compared to 3.2 tons ha^{-1} for maize (CSA, 2015).The productivity of tef at Southwestern Ethiopia was below 1ton ha^{-1} (Tegegn *et al*., 2020).Poor genetic potential of the cultivars under wide spread production, and the problems of lodging and diseases are the major causes for yield reduction of tef. The extent of the problem of low productivity due to these constraints varies from place to place within the country. For instance, the problem of disease is aggravated in the southwestern parts of Ethiopia where there is high rainfall, and hot and humid climate. Therefore, this review gives insight on the tef production, achievements, challenges and opportunities in southwestern Ethiopia.

Major activities and achievements in tef breeding

Major activities in tef breeding

Development of improved variety

New tef varieties were developed through following different approaches. Conventional and Modern and Novel Approaches

Conventional approaches

Since genetic variation forms the fundamental basis for breeding, the first step in tef variety development anchors primarily upon 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 (Kebebew *et al*., 2017). i) Indigenous germplasm: The indigenous germplasm constitutes the major source of variability for tef breeding (Hailu, Kebebew *et al*., 2001) because, tef being a native and unique crop to Ethiopia, there have been no opportunities for introductions of germplasm and breeding materials from abroad.ii) Hybridization: This involves mainly intra- specific crosses and recently some inter- specific crossings especially with *E. pilosa*. A total of about 590 crosses have been made so far at DZARC. Subsequent segregating populations are handled using the modified bulk and modified pedigree methods of breeding. However, some varieties have been developed as recombinant inbred lines (RILs) through F2- derived single- seed descent (SSD) method.iii) other techniques: This includes modern and novel techniques such as induced mutation and marker- assisted breeding. Artificial induction of mutation creates variability for some important traits such as lodging resistance since sufficient variability in the existing germplasm is lacking (Kebebew *et al*., 2017).

Following the pre- breeding germplasm- enhancement stage is the nursery for initial screening and evaluation of selected genotypes from the three germplasm- enhancement schemes. This, in turn, is followed by a series of yield trials including preliminary and national variety trials. In the variety testing, genotypes are categorized into early- and late- maturing sets depending on the period of maturity. The late types are mainly targeted for high potential or optimum environments, while the early sets are targeted for terminal moisture stress areas. At the last stage of the process, elite and promising genotypes selected as candidate varieties based on their performance in the various variety trials are entered into variety verification trials for evaluation by the National Variety Release Committee. At all stages, even after release as a variety, genotypes could be selected to be taken back to the earlier steps of hybridization and induced mutation schemes of germplasm enhancement (Kebebew *et al*.,2017).

Modern and Novel Approaches

The research achievement in tef molecular breeding approaches can be categorized into six parts as (i) molecular marker development, (ii) molecular analysis of genetic diversity and relationships, (iii) development of molecular marker linkage maps; (iv) identification of quantitative trait loci (QTL); (v) comparative genomics; (vi) regeneration and transformation techniques and (vii) high- throughput techniques such as Targeting Induced Local Lesion IN Genomes (TILLING) and eco- TILLING (Kebebew *et al*., 2017).

Improved management technologies

This involves different cultural or agronomic practices for increased productivity of the crop. The agronomic practices to cultivate tef have little changed, slowing improvement in tef productivity. Different agronomic practices to improve tef productivity were row planting with low seed rate, application of different fertilizer and agro-chemicals to improve fertility of the soil and protection from different pests.

Promotion of improved technologies

This entails the creation of awareness and subsequent demand by users for proven improved technologies through field demonstrations and limited level scaling up activities.

Research capacity building

Developing the capacity of research programs working on the improvement of tef was one of major step in the tef breeding program.. This includes formal training of staff assigned on tef research, supporting and strengthening linkage with regional and sub-regional research programs and increasing access to fresh germplasm sources.

Achievements in tef breeding

According to Tareke *et al.* (2000), efforts were made in the past to implement different techniques and tools in order to improve tef. The status of some of the techniques is indicated below: i) Inter-specific crossing was made between tef (*E. tef*) and *E. curvula* in an attempt to transfer the lodging tolerant trait of *E. curvula* to tef. However, so far, no viable hybrid was obtained from the crosses. ii) Application of plant growth hormone in order to obtain semi-dwarf plant. A chemical known as CCC significantly reduced the height of tef plant, but the panicles from these plants were also shorter. Hence, the use of this hormone did not increase the productivity of tef. iii) Spray application of foliar fertilizers containing major and micronutrients one to three times in a season did not improve the productivity of tef. iv) In attempts to develop doubled haploids using gynogenesis technique, some promising tef lines were obtained.

Until the year 2017, 42 improved tef varieties were released in Ethiopia through the National Agricultural Research System (MoA, 2017) (Table 4). Of these, 24 varieties were released by DZARC, 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 (Solomon *et al*., 2019).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 (Solomon *et al*., 2019).

Production of tef at Southwestern Ethiopia

In Ethiopia, Southwestern part of Ethiopia was one of major coffee growing regions and have climatic and edaphic factors that combine well to meet the requirements of both coffee and cereals (Paulos,1994) thereby strengthening the linkage between the two crops. This linkage has, in turn, enhanced the role of cereals in diversifying the coffee based farming system and the coffee industry as well. Currently, regional states of Oromia and Southern Nations, Nationalities and Peoples Region (SNNPR) and part of Amhara are high potential coffee growing regions also having tremendous potential for cereal production. Maize (*Zea mays* L.),sorghum (*Sorghum bicolor* Moench), tef (*Eragrostis tef* (zucc.) Trotter), rice (*Oryza sativa*. L), bread wheat (*Triticum. aestivum* L.) food barley (*Hordeum Vulgare* L) and finger millet (*Eluecine coracana* L) are the major cereal crops that are grown by coffee farmers as food and cash crops playing significant role in minimizing risks of dependence on coffee only.

Tef is an "orphan" crop meaning that it has not been subject of much research and development work. Scientific tef improvement research in Ethiopia was started in the late 1950's in Jimma Agricultural Technical High School, and later moved to Debre Zeit Agricultural Research Center (DZARC). DZARC began tef research in 1956-57 and presently it is the center of excellence for tef research in the Ethiopian Institute of Agricultural Research (EIAR). However, it has not been considered as an important crop by the international scientific community or funding agencies for a long period of time. In breeding program, the primary source of genetic variability for genetic improvement of tef is the indigenous germplasm. This is because, tef being native and unique crop to Ethiopia, there have been no opportunities for introductions of germplasm and breeding materials from abroad (Kebebew *et al*., 2011).

As in any crop improvement program, tef breeding also relies mainly upon the germplasm resources existing in the genetic stock. Diverse types of accessions are available in the country, and collection, evaluation, and utilization of tef germplasm by national and international groups began in Ethiopia in the late 1950s. However, organized collection at the national level was made after the establishment of the Plant Genetic Resources Center of Ethiopia (PGRC/E) in 1976. After several changes in its name and mandate, the institute responsible for germplasm collection and maintenance as well as distribution is currently called the Ethiopian Institute of Biodiversity (EIB). The institute with only 1067 tef accessions in Abebe (1991) has reached to 5169 accessions in 2011 (Alganesh, 2013). This fourfold increase in the collection size in just two decades shows the presence of both a wide diversity of germplasm in the country and also the commitment of institutes and individuals to collect and preserve these germplasm for future use. More than 10% of total tef accessions were collected from the southern and southwestern part of the country, of which 143, 127 and 37 tef accessions belongs to Wellega, Keffa and Illuababora in its order have been conserved at IBC (Abebe, 2001) in table 5.

Similar to other crop improvement program, tef breeding relies mainly upon the germplasm resources existing in the genetic stock. It can provide valuable information for plant breeders who are interested in introgressions of agronomically desirable traits into established cultivars or to select lines from the existing diversity. To this end, there had been efforts in tef germplasm collection and characterization in the country. Thus, the national tef improvement program has so far released about 42 tef varieties by following different breeding methods for different agro-ecologies of Ethiopia (Table 3) (MoA, 2017).

However, the grain yield performance of improved varieties is limited with agro-ecological difference except the most accepted Quncho variety. Jimma Agricultural Research Center is one of the longest serving tef varieties testing location for the national tef improvement programs, and has experienced that almost all materials being evaluated in the research site resulted less or equal performance with the local checks so far (JARC progress report of different years, 2012-2019) and productivity was less than one ton per hectare (Table 6). In line with the national tef improvement program, Jimma Agricultural Research Center (JARC) has long history of variety development trial for the areas, but yet no improved varieties that can significantly beat the local varieties were developed.

In Southwestern Ethiopia, Jimma (Dedo, Omonada, Somodo (Mana), Gooma, Tiro Afeta, Kersa and Sekoru) and Buno bedele (Gechi and bedele town around banshure kebeles) were major tef producing areas of Jimma and Buno bedele zones of southwestern Ethiopia.In Jimma and Buno Bedele zones highland agro ecologies cover 18 and 10% of the total area, respectively.Dedo was one of the highland (above 2000m a.s.l.) area of Jimma zone and located in 20 km from Jimma town. Tef varieties produced in these area were locally called Yigga, Gomojore, Hawilo, Goomo and Fokore. Goomo and Yigga were early maturing types in the area. The time of tef sowing varies depending upon climatic conditions of the location, soil type and maturity period of the variety (Seyfu, 1989). Most of them were planted at half of july and harvested after half of October. Omonada, Tiro afeta and Kersa wereda were belt area for different cereals and pulses crops. Tef was produced in large amount and the major production constraints at the weredas were occurrence of tef diseases especially head smudge. Buno bedele zone also major producer of tef and other cereal crops. Most produced farmer cultivar in the area was 'Gerao'. Our breeding program (JARC) popularized the new released variety ´Kora´ but, it was popularized not that much expected due to weak extension system and collaboration (Table 7).

Method of sowing and seed rate have impact on the productivity of tef. Hand broadcasting is the usual method of sowing tef. In most cases, the seeds are left uncovered; however, tree branches may be pulled on the surface when there is dry spell after sowing. Uncovered seeds are prone to erosion (water and wind) and bird attack. Farmers locally used tef cultivars, use high seed rates due to unclean seed with problem of germination and low seed rate with white type (names unidentified). The tillering capacity of low seed rate tef cultivars was vary and agronomic practices such as high fertility and increased number of plowing exposed the crop for lodging. The observed area, major challenge for low productivity of tef was lodging which was occurring after heading. Labor intensive nature of crop husbandry (weeding), post harvest loss was also cause for yield reduction in tef production.

Jimma research center identified additional tef varieties (Melko and Gibe were nationally released varieties for southwestern part especially, Jimma and similar agro-ecologies) of broad adapted and high yielding for different agro-ecologies of Jimma and Buno bedele zones (Table 8). Variety Quncho and Kora were recently released and extension system was not that much pushed.

Major challenges of Tef productivity

Some of major challenges of tef production at national and southwestern level were listed below.

Head smudge

Tef head smudge caused by *Helminthosporium myaikai Nisikado* is one of the most serious fungal diseases threatening tef production in southwestern Ethiopia. It attacks the inflorescence of tef plants and a dense mate of dark brown fungus spores cover the infected spikelet's (Sewalem *et. al* 200l). Date of sowing its own influence on the incidence of the head smudge disease. Comparing to early planted tef, disease seriously affected the late planted ones. The disease can cause considerable damage to both yield and quality of tef grains in humid and warm areas of south west Ethiopia (Dagnachew 1967). Lack of basic information (biology and means of transmission) made the study challenging. In southwestern part of Ethiopia; the productivity of tef was very low due to diseases, lodging, low yielding varieties, soil acidity and inappropriate use of cultural practices.

Jimma Agricultural Research Center was one of implementing center of breeding activities for many years to develop varieties which were tolerant or resistant to head smudge. A large number of tef genotypes collected from southwestern and other parts of Ethiopia were screened for resistance to tef head smudge caused by *Helminthosporium miyakei Nisikado* in the farmers' field under natural condition for 3 consecutive years at Bulbul in Kersa Woreda of Jimma Zone. The disease has been a serious problem causing up to100% damage to the crop (Unpublished, 2004). The screening activities were done starting from 2002-2004 for three consecutive years at hot spot areas of Jimma zone using 250 tef genotypes and 2009 to 2010 (some of the experimental materials was lost due to diseases and the second phase remaining were lost due germination as unfavorable condition during the trial planted) and using 169 tef genotypes for two project years.

The result in both cases was discouraging and the disease was seen catastrophic. However, since the country is center of origin and diversity of tef (*E. tef*), it is essential to conduct further collection and screening at least to develop tolerant variety. Moreover, the disease seems to be highly tied with the cool and foggy weather that appear after the crop flowering which is also influenced by topographical situation of the locality. Therefore, studying alternative disease management strategies such as alternation of sowing date and influence of topographical situation on the diseases development is imperative for improving tef production and productivity in such disease hot spot areas of southwestern Ethiopia.

Lodging

Lodging defined as the permanent displacement of crop plants from their vertical position because of root or shoot failure, is a major yield reducing factor**.** Lodging susceptibility is the most significant production problem for tef. In an average year, 17% of tef grain is lost nationally as the result of lodging, whereas some areas routinely experience losses greater than 50% (Seyfu, 1993). In general, lodging reduces grain yield through reduced canopy photosynthesis, increased respiration, reduced translocation of nutrients and carbon for grain filling, and greater susceptibility to pests and diseases (Hitaka,1969).Lodging in tef is usually attributable to the bending of the thin stalk rather than by breakage of the stalk or uprooting of the plant. This causes the grain to rest on the ground, where it may spoil or be missed during harvest. It is likely that lodging also inhibits crop improvement in the direction of panicles with more or larger seed, as larger panicles cause plants to be more prone to lodging. Lodging reduces tef grain yields by up to 23% (Seyfu, 1983, 1993b). It also decreases straw yield and deteriorates the quality of both grains and straw produced. Furthermore, it imposes restrictions to the use of high rates of nitrogen fertilizers and other high input husbandry technologies, and creates difficulties in harvesting operations. In tef research, most attention has been devoted to relate the degree of lodging to shoot properties (Yu *et al*., 2007; Kebebew *et al*., 2011).

Soil acidity

Tef is versatile crop able to grow under a wide range of soil types, climatic conditions and at differing altitudes ranging from 1000 to 2500 m a.s.l (Mulu, 1999). The major abiotic stress factors affecting its growth and production include soil acidity, drought and salinity (Tadele *et al*., 2010). Aluminum toxicity and other acidity-related soil fertility problems are among the major constraints affecting tef production in Ethiopia (Dubale 2001; IFPRI, 2010). The most important cause of soil acidity is the leaching of basic cations to the lower profiles of the soil by percolating rain water. The acidifying effect of acid forming nitrogen fertilizers, poor nutrient recycling and the continuous removal of basic cation through harvested crops, runoff loss and acid rain also contribute to the development of soil acidity and Al-toxicity. The overall effects of Al-toxicity are stunted growth and low productivity (Rao *et al*., 1993).Aluminum toxicity is an important growth-limiting factor for plants in many acid soils, particularly in pH of 5.0 or below.

Generally, Al interferes with cell division in root tips and lateral roots, increases cell wall rigidity by cross linking pectins, reduces DNA replication by increasing the rigidity of the DNA double helix, fixes phosphorous in less available forms in soils and on root surfaces, decreases root respiration, interferes with enzyme activity governing sugar phosphorylation and the deposition of cell wall polysaccharides, and the uptake, transport, and also use of several essential nutrients (Ca, Mg, K, P and Fe) (Anderson,1998).The problem is widespread in the high rainfall areas of the southwestern, western and southern, and parts of the country (Schlede, 1989; Abebe, 2007).

Labor intensive cultural practices

All the cultural operations in tef husbandry including land preparation, planting, weeding, harvesting and threshing are all labor requiring. This is mainly associated with the minute size of the tef seeds with 100-kernel mass amounting to 19-34mg (Kebebew *et al*., 1999). This, in turn, necessitates the preparation of fine and smooth seed bed, poses difficulties in optimizing plant method and plant population density, and imposes drudgery in harvesting and threshing.

Besides, tef crop are generally poor competitors with weeds particularly at the early stages and country-wide yield losses in tef due to weeds varied from 23 to 65% (Rezene and Zerihun, 2001; Zewdie and Damte, 2013), hence, weed control has been one of the most labour-demanding and back-breaking activity in tef husbandry.

Weak seed and Extension system

Presently, lack of adequate quality and quantity of planting seeds of improved varieties has become a constraint due to the limitation of the existing seed system. Although the government of Ethiopia has in recent years established the most robust public agricultural extension systems in Africa. In terms of structure, this extension system hardware still suffers from serious drawbacks in terms of efficiently discharging the dissemination of improved agricultural technologies, innovations and knowledge to the farming communities. Factors such as expensiveness and unavailability of seeds 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). Lack of awareness was reported by 34% of the farmers as the most important factor for the non-adoption of improved tef varieties. There has been a wider consensus that the weak seed system in Ethiopia is the major limiting factor the slow dissemination of improved tef varieties. Since the formal seed sector which consists of both the private and public seed enterprises is driven by profit, it is virtually engaged in the production of seeds of hybrid maize and of the self pollinated crops almost solely for wheat. In Ethiopia, the formal seed sector covers only 5% of the tef, but 53% of the maize and 20% of the wheat seed requirement (Alemu *et al*., 2007).

Government attention

Even though, tef has enormous potential for growth, it has been neglected for centuries in research, development and promotion compared to major cereals. The very low productivity of the crop is as a result of the limitations in the full exploitation of the existing potential of the crop (Viswanath, 2013). The absence of major breakthrough, to increase the productivity of tef, coupled with the misguided notion that "a low yielding crop is occupying too large an area'', has even led Ethiopian government to consider policies that facilitates its replacement by other crops (Seyfu,1993). During the dictatorial military regime of Mengistu (former Ethiopian military ruler), there was a strong campaign and enforcement of farmers for shifting of tef with other high productive staple crops especially with tritiale (Tareke *et al*., 2000; Narrowing the rift). However, due to its high preference by the consumers and fetching high price for the farmers, the area under tef cultivation has even been increasing (Hailu *et al*., 2001).Similarly, the late prime minister of Ethiopia Meles Zenawi also said, if something miracles will not happen, tef will disappear from Ethiopian dish. The exerted political pressures were not totally abandon farmers from growing of tef. Perhaps, due to the fact that it is not easy break old tradition, at least not so acutely, of Ethiopian farmers and consumers, alike, the production of tef has taken an opposite direction, increased acreage. This becomes a compelling reason to necessitate scientific research aimed at understanding the fundamental biological aspects of tef, which may have implications for increasing its productivity.

Limited basic information

A very rich natural genetic diversity exists in tef and this has been identified and described (Melak Mail *et al*., 1965; Tadesse, 1969; Seyfu, 1993). However, two main constraints had hampered a successful tef improvement program through conventional breeding. First, the very early morning and brief pollination period of tef remained a mystery until discovered in 1975 (Tareke, 1975). Secondly, the minute size of its florets requires a 20-30 times magnification and microsurgery needles and forceps in order to manipulate and effect cross-fertilization. Now that artificial crossing of tef is possible (Tareke, 1975), a prerequisite to developing a sound breeding program is knowledge of the basic genetics (Source: Narrowing the rift).

Tef belongs to the *Chloridoideae* subfamily, a lineage of grasses (*Poaceae*) that has been given very little research attention until recently, with publication of the first linkage maps of tef (Bai *et al*., 1999) and preliminary genetic mapping of finger millet (*Eleusine coracana*) (Dida *et al*. 2007). Because of the foregoing importance of tef to Ethiopia in particular, and potentially to the world in general, a public tef improvement programme has been undertaken in Ethiopia since 1956 (Hailu and Mulu, 1995). Both the rate and amount of progress in tef research has been low due to lack of basic information on the biology of the crop. This is particularly true for information on the molecular genetic aspects of the crop. It is widely accepted that the construction of a linkage map in many species greatly increases the efficiency of genetic improvement.

Localized importance

The most common utilization of tef in Ethiopia is the fermented flatbread called injera (Seyfu, 1997). This traditional flatbread as a soft, thin pancake with a sour taste. The most preferred form of the injera is one made from pure tef flour. Injera mixed with other flour such as wheat or sorghum is considered inferior. Other utilizations of tef include local alcoholic beverages called *tela* and *katikala*, and porridge (Seyfu, 1997).

Collaboration of local and international food companies would add more value to tef by developing new and improved tef based products for both domestic and international consumers.

Opportunities

Some of the different opportunities for tef improvement were;

Wealth of resources

Ethiopia is the origin and center of diversity for tef (Vavilov, 1951), and the country harbors landraces with a wide array of phenotypic diversity, and also wild progenitors and related wild species. This genetic diversity is the capital for current and future improvement of the crop since options for introduction of genetic stocks from abroad are almost none-existent.

Number of researchers in Tef breeding

Different progenies of the crosses are evaluated for several generations at DZRAC in Ethiopia. Once initial screenings of the genotypes have been completed, those with enhanced performance are promoted for multi-location evaluation at sites representative of traditional tef growing areas. This increased the number of tef researcher participating to conduct the trials at different sites were increased. For example, in 2016, 16 experiments, each containing 80 genotypes were tested at 24 representative sites. The sites belong to several research and higher learning institutions and range in altitude from 1400 m a.s.l. at Wolenchiti to 2500 m. a.s.l. at Bichena and Shambu. Hence, they represent the huge diversity in the agro-ecology of the country (Gina *et al*., 2018).

Table.1 Plants of the Ethiopian Crop Complex (Harlan, 1992a)

Scientific Name	Common name and use
Avena abyssinica	Oats, weeds in barley and emmer fields, or cultivated alone
Cath edulis	Chat,a mild narcotic, chewed fresh
Coffea Arabica	Coffee
Eleusine coracana	Finger millet, domesticated in the East African highlands
Ensete ventricosum	Ensete or “false banana” stem base eaten, not fruit
Eragrostis tef	Tef,the primary staple cereal of Ethiopia used to make *injera*
Guizotia abyssinca	Noog,the primary edible oil crop of Ethiopia

Table.2 Production of tef in Ethiopia

Crops	Area in ha	Yield in ton / ha
Grain crops	12,574,107	-
Maize	2,135,571	3.675
Sorghum	1,881,970	2.525
Tef	3,017,914	1.664

Source: (CSA, 2017)

Table.3 Major tef producing regions

Producing regions	Area in ha	Production in ton	Yield /(ton / ha)
Oromia	1,441,030	19,328,573	1.717
Amhara	1,137,844	19,328,573	1.699
Tigray	167,584	2,410,116	1.438
SNNPR	246,099	3,412,547	1.387
Benishangul-Gumuz	24,433	303,184	1.241
Others	924	12,014	-
Total	**3,017,914**	**50,204,400**	

Source: (CSA, 2017)

Table.4 List of released tef varieties from 1970-2017

Local name	Variety Name	Year of release	Releasing center	Alt (m.a.s.l)	Rainfall (mm)	Maturity date	Source	Productivity (ton/ha)	
								On station	On farm
Asgori	DZ-01-99	1970	DZARC	2700	500	80–130	Selection	2.4-3	1.7-2.2
Magna	DZ-01-196	1970	DZARC	2700	450	80-113	Selection	1.8-2.2	1.4-1.6
Enatit	DZ-01-354	1970	DZARC	2800	500	85-130	Selection	2.4–3.2	1.7–2.2
Wellenkomi	DZ- 01- 787	1978	DZARC	2650	550	90–130	Selection	2.4-3.0	1.7-2.2
Dukem	DZ- 01- 974	1995	DZARC	1900	425	75–137	Selection	2.4-3.4	2-2.5
Holetta Key	DZ- 01- 2053	1999	Holetta	2300	NA	84–112	Selection	3.4	2.5
Ambo Toke	DZ- 01- 1278	2000	Holetta	2300	750	86–116	Selection	3.6	2.7
Gerado	DZ- 01- 1281	2002	DZARC	1850	>600	73–95	Selection	2.0-2.2	1.6-2.0
Key Tena	DZ- 01- 1681	2002	DZARC	1750	400	84–93	Selection	2.0-2.2	1.6-2.0
Koye	DZ- 01- 1285	2002	DZARC	2050	500	104–118	Selection	2.4-3.6	1.8-2.5
Gola	DZ- 01- 2054	2003	Sirinka	2200	842	82–90	Selection	1.0–2.2	1.6
Ajora	PGRC/E205396	2004	Areka	NA	1050	89–98	Selection	1.0-3.1	1.0-1.4
Dega Tef	DZ- 01- 2675	2005	DZARC	2150	1098	112–123	Selection	1.8-2.8	1.6-2.0
Dima	DZ- 01- 2423	2005	Adet	2300	>600	92–106	Selection	2.46	1.68
Genete	DZ- 01- 146	2005	Sirinka	1650	842	78–85	Selection	2.17	1.55
Gimbichu	DZ- 01- 899	2005	DZARC	2250	NA	118–137	Selection	1.8	1.6
Yilmana	DZ- 01- 1868	2005	Adet	1400	>600	98–110	Selection	2.32	1.63
Zobel	DZ- 01- 1821	2005	Sirinka	1650	842	72–87	Selection	2.07	1.51
Guduru	DZ- 01- 1880	2006	Bako	2900	1100	95–120	Selection	1.5–2.3	1.4–2.0
Mechare	Acc. 205953	2007	Sirinka	1650	842	78–85	Selection	2.06	1.79
Etsub	DZ- 01- 3186	2008	Adet	2200	1230	92-117	Selection	1.9-2.7	1.6-2.2
Kena	23- Tafi- Adi-72	2008	Bako	2125	1100	98–124	Selection	1.7-2.7	1.3-2.3
Werekiyu	Acc. 214746A	2014	Sirinka	NA	NA	94	Selection	2.2	1.6
Melko	DZ- Cr- 82	1982	DZARC	1850	500	112-119	Hybrid	2.4-2.8	1.8-2.2
Menagesha	DZ- Cr- 44	1982	DZARC	2150	550	95–140	Hybrid	2.4-3.0	1.7-2.2
Tsedey	DZ- Cr- 37	1984	DZARC	1850	175	82–90	Hybrid.	1.8-2.8	1.4-1.9
Gibe	DZ- Cr- 255	1993	DZARC	1850	500	114–126	Hybrid.	2.0-3.0	1.6-2.2
Ziquala	DZ- Cr- 358	1995	DZARC	1900	425	76–138	Hybrid.	2.1-3.6	1.8-2.4
Amarach	Ho- Cr- 136	2006	DZARC	1650	675	63–87	Hybrid.	1.3	1.2
Quncho	DZ- Cr- 387 RIL355	2006	DZARC	2000	500	80–113	Hybrid.	2.4–2.8	2.0–2.2
Gemechis	DZ- Cr- 387 RIL12	2007	Melkassa	1572	827	62-83	Hybrid.	1.3-2.0	1-1.4
Simada	DZ- Cr- 285RIL295	2009	DZARC	Low	500	75–87	Hybrid.	1.8-2.2	1.7-2.0
Lakech	DZ- Cr- 387RIL273	2009	Srinka	1650	842	90	Hybrid.	2.24	1.3–1.8
Boset	DZ- Cr- 409 RIL50d	2012	DZARC	-	-	75–86	Hybrid.	1.8–2.0	1.4–1.8
Kora	DZ- Cr- 438 RI133B	2014	DZARC	-	-	110-117	Hybrid.	2.5–2.8	2.0–2.2
Dagim	DZ-Cr-438 RIL91A	2016	DZARC	-	-	112-115	Hybrid.	2.6–3.2	-
Abola	DZ-Cr-438 RIL7	2016	Adet	-	-	110-118	Hybrid	2.1–2.8	1.5–1.7
Negus	DZ-Cr-429 RIL125	2017	DZARC	-	-	112-116	Hybrid.	2.0–2.6	-
Felagot	DZ-Cr-442 RIL77C	2017	DZARC	-	-	108 -112	Hybrid.	2.2–2.9	-
Tesfa	DZ-Cr-457 RIL181	2017	DZARC	-	-	112–120	Hybrid	2.3–3.0	-
Areka-1	DZ-01-974xDZ012788	2017	Areka	-	-	112–119	Hybrid	2.0–2.6	-
Heber-1	DZ-Cr-419	2017	Adet	-	-	112–124	Hybrid	2.2–2.7	-

Source: MoA, 2017, DZARC=Debre Zeit Agricultural Research Center, Hybrid=hybridization, NA=not available

Table.5 Number of tef accessions collected up to September 2000

Region	No. of collections
Arsi	65
Bale	60
Gamogofa	57
Gojam	408
Gonder	349
Hararghe	43
Illubabor	37
Kaffa	127
Shewa	532
Sidamo	101
Tigray	566
Wollega	143
Wollo	356

Source: Abebe, 2001; Narrowing the rift,

Table.6 Productivity of tef at Southwestern Ethiopia, 2012-2019

No.	Cropping year	Traits						
		DH	DM	PH (cm)	PL (cm)	LI (%)	SHB (qt/ha	GY (qt/ha)
1.	2012	NA	NA	103.7	35.3	66.6	20.8	7.3
2.	2013	45.7	92.6	95.1	45.6	40.5	72.7	13.5
3.	2014	44.5	92.3	78	48	40.5	72.5	12.5
4.	2015	43.8	87.8	85	50.5	33.8	58.5	13.1
5.	2016	52.1	88	82	41	48.8	48.6	10.1
6.	2017	50.1	89	71.2	41.5	68.3	47.6	6.1
7.	2018	51.8	88.8	104.5	44.2	65.3	45.7	10.2
8.	2019	56.5	104.2	86.3	35.9	69.1	36.2	6.2
Mean		**49.2**	**91.8**	**86**	**42.7**	**54.1**	**50.3**	**9.8**

Source: JARC progress report of 2012-2019, DH=days to heading, DM=days to maturity, PH=plant height, PL=panicle length, SHB=shoot biomass, LI=lodging index, GY=grain yield, NA= not available

Table.7 Agro-ecological descriptions of major tef producing regions of southwestern Ethiopia

No.	Locations	Altitude (m.a.s.l)	Coordinates	RF (mm)	Temp	Soil type
1.	Dedo	>2350	7^0 25'N 37° 00' E	1850	18.6	Nitosol
2.	Mana (Somodo)	1770	$7^0$45′N 36°45′E.	1624	18.9	Nitosol
3.	Gooma	1,560	$7^0$51′N 36°35′E	1764	19.7	Nitosol
4.	Kersa	NA	NA	NA	NA	NA
5.	Omonada	1975	7^0 41'N 37°12''E	1600	20	Nitosol
6.	Sekoru	NA	NA	NA	NA	NA
7.	Tiro afeta	NA	NA	NA	NA	NA
8.	Jimma/Melko	1753	$7^0$47'N 360 47''E	1639	22	Nitosol
9.	Saja	1950	NA	1800	19	Nitosol
10.	Gechi	2087	$8^0$27′N 36°21′E	1800	20.7	Nitosol
11.	Bedele zuriya	NA	NA	NA	NA	NA

NA=not available

Table.8 High yielding and broadly adapted tef varieties identified for Southwestern part of Ethiopia.

Variety name	Local name	Year of release	Days to maturity	Released center	Rainfall (mm)	Altitude (m.a.s.l)	Grain yield (t/ha)	
							On station	On farm
DZ-01-354	Enatite	1970	85-130	DZARC	300-700	1600-2400	2.4-3.2	2.0-2.4
DZ-01-196	Magna	1978	80-113	DZARC	200-700	1500-2400	1.8-2.2	1.4-1.6
DZ-Cr-82	Melko	1982	112-119	DZARC	300-700	1700-2000	2.4-2.8	1.8-2.2
DZ-Cr-255	Gibe	1993	114-126	DZARC	300-700	1700-2000	2.0-3.0	1.6-2.2
DZ-01-974	Dukem	1995	76-138	DZARC	150-700	1400-2400	2.4-3.4	2.0-2.5
Dz-Cr-387	Quncho	2006	80-113	DZARC	300-700	1500-2500	2.0-3.2	1.6-2.6
DZ-Cr-438 RIL133 B	Kora	2014	110-117	DZARC	NA	NA	2.5 – 3.2	2.0 – 2.8

NA=not available

International attention

Ethiopia is the origin of the tef plant and it is grown throughout the country. Ethiopia does not import tef. Data from the 1990s indicate limited exports (Seyfu, 1997). Tef remains the favorite food crop for Ethiopians and is also becoming an important health crop in Europe and the USA especially due to the absence of gluten in its grain. The principle importers of niche cereals into Europe are Germany and the Netherlands. These countries imported respectively 3,000 and 2,200 tonnes. Together they represent almost 70% of the total European import. The United Kingdom and Belgium occupy a significant part of the remaining import (Ministry of foreign affairs, 2017) As an exporter you will find the largest consumer market for niche grains in Germany, thanks to a large cereal and bakery industry. The Netherlands re-exported over 37%, making the country an important hub for your niche grains. The United Kingdom has an interesting market for gluten-free products, which could explain its growth over the past years. Tef has become available in major UK retailers such as Sainsbury's and Holland & Barrett (Ministry of foreign affairs, 2017).

Molecular approaches

Tef breeding program have not exploited the genetic potential of the crop. The program was mostly dependent on the conventional improvement techniques such as selection and hybridization. Molecular techniques permit the visualization of molecular variation, which may allow a breeder to select the best possible parents for a crossing program. Useful gene variants may be present in plants with unpromising phenotypes, and molecular analysis of specific loci may allow cryptic, but potentially useful genes to be discovered. Both these situations undoubtedly contribute to the phenomenon long apparent to plant breeders as "transgressive segregation" (Frantz and Jahn, 2004; de Vicente and Tanskley, 1993). Only limited numbers of breeders implement modern techniques such as marker-assisted breeding. Genomic information such as whole-genome sequencing is not yet available for most orphan crops.

In conclusion, the increase in the global population, competition of food and bio-fuel for available land resources, and climate change are all threatening food security. One avenue to alleviate these pressures on our food supply is through better utilization of indigenous or 'orphan' crops.

Tef is staple food for many people and produced in different agro-ecologies of Ethiopia. Southwestern part of Ethiopia was one major producer of tef, but productivity was very low comparing to national average. The major causes for low productivity of tef were diseases, lodging, soil acidity and poor application of different cultural practices. To increase productivity in future, attention must be given to solve above mentioned problems.

Future line of work

7.1. Collection, characterization and evaluation of tef germplasm which were from south and southwestern part of Ethiopia to develop stress (diseases and acidity problems) tolerant or resistant varieties

7.2. Forming strong extension system and different agents to popularize recently released varieties and promote technologies

7.3. Agricultural Mechanization especially for harvesting and threshing to reduce post harvest loss

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