Chapter 10
Tef [*Eragrostis tef* (Zucc.) Trotter] Breeding

Solomon Chanyalew, Kebebew Assefa, and Zerihun Tadele

Abstract Tef or teff [*Eragrostis tef* (Zucc.) Trotter], a cereal crop which adapts to extreme climatic and soil conditions, is extensively cultivated in the Horn of Africa. It is also considered as nutritious and a life-style crop due to its richness in essential nutrients and health-related benefits. However, the productivity of the crop is extremely low due to little scientific improvement made globally. It is, therefore, in the category of *orphan crops*. Together with all cereal crops, tef belongs to the Grass or Poaceae family. The improvement of tef focuses on selection and hybridization techniques. However, recently, molecular and high-throughput techniques have also been implemented to a limited scale. Forty-two tef varieties were approved for release by the Ethiopian National Variety Release Committee in the past four decades. Due to the adoption of improved varieties and technologies, the national average yield of tef has more than doubled over the last 20 years. This review describes the progress in tef breeding and variety development as well as dissemination of the improved varieties to the farming community.

Keywords Accessions · Breeding · *Eragrostis tef* · Hybridization · Molecular breeding · Mutation breeding · Tef varieties

10.1 Introduction

Agriculture plays a key role in the economy of developing countries because a large number of their population engage in this sector. Smallholder farmers in these countries cultivate both major and minor crops such as cereals, legumes, root crops and vegetables. Major crops which include wheat, maize and rice are extensively

S. Chanyalew · K. Assefa
Debre Zeit Agricultural Research Center, Ethiopian Institute of Agricultural Research, Bishoftu, Ethiopia

Z. Tadele (✉)
Institute of Plant Sciences, University of Bern, Bern, Switzerland
e-mail: zerihun.tadele@ips.unibe.ch

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cultivated globally and have been given emphasis by the global research community. However, minor crops which are also known as underutilized, orphan, or disadvantaged crops, play a key role in the livelihood of a large proportion of the population in the developing world as they are the main source of nutrition and income. The importance of orphan crops is also due to the high adaptation of these indigenous crops to the prevailing extreme environmental conditions and to preference by consumers (Tadele 2010, 2017).

Tef or teff [*Eragrostis tef* (Zucc.) Trotter], a cereal crop extensively cultivated in the Horn of Africa, is the focus of this chapter. Tef is the most preferred crop among farmers and consumers in Ethiopia. Farmers choose to grow tef due to its resilience to extreme environmental conditions and high quality of bread, *injera*, made from its grain. Tef is the primary crop in Ethiopia in terms of the area under cultivation. It is annually grown on over three million hectares, which is equivalent to about 30% of the country's total area allocated to cereals (CSA 2015) (Fig. 10.1a). About 6.5 million smallholder farmers grow the crop every year. The importance of tef to the economy of Ethiopia is witnessed by the continuous expansion in the area under cultivation and also to the simultaneous increase in productivity. In the last 20 years, the area under tef cultivation has increased by 55% (from 1.8 million to 2.9 million mt) while productivity rose by 123% (from 0.7 to 1.56 mt ha^{-1}) (CSA 2002, 2015) (Fig. 10.1c). This demonstrates that the increase in the area was less than that of the increase in the productivity. Due to this significant increase in productivity, about 4.8 million mt of tef grain was produced in 2015, which is a 50% increase in production over two decades ago. However, the expected productivity level has not yet reached the national level due to little dissemination and adoption of improved varieties and cultural practices. As a result, the national grain yield of tef is the lowest among major cereals cultivated in the country (Fig. 10.1b).

The extensive cultivation of tef in Ethiopia is related to the high price of the tef grain compared to other cereals. The market price of tef and other cereals in Addis Ababa market was USD 600 mt^{-1} in 2015 (Minten et al. 2016) although the price of tef grain has doubled in early 2018. In general, the price of tef is higher than maize, sorghum and wheat by 37, 41 and 53%, respectively (FEWS-NET 2017). Consumers in Ethiopia pay the highest price for tef grain due to the good quality bread called *injera* which is made from tef flour. *Injera*, a spongy, flat bread baked after 2–3 days of fermentation, is considered the national bread eaten with all types of stews.

Large-scale cultivation of tef is also related to the resilience of the plant to several abiotic and biotic stresses, which include both excess and scarce moisture, pests and diseases. For instance, tef is the crop of choice in the poorly drained soils, especially Vertisols, which occupy about 10% of the arable land in the country, as it tolerates the stress, especially at the early growth stage, which coincides with heavy seasonal rainfall.

Tef is a very nutritious cereal grain. Its nutritional content is generally comparable to that of the major world cereals like wheat, rice, barley and millets (Table 10.1) (USDA 2018). Tef is superior in many aspects particularly in minerals such as calcium, iron, magnesium, phosphorus and potassium. Tef grains are also rich in essential amino acids, particularly in alanine, methionine, threonine and

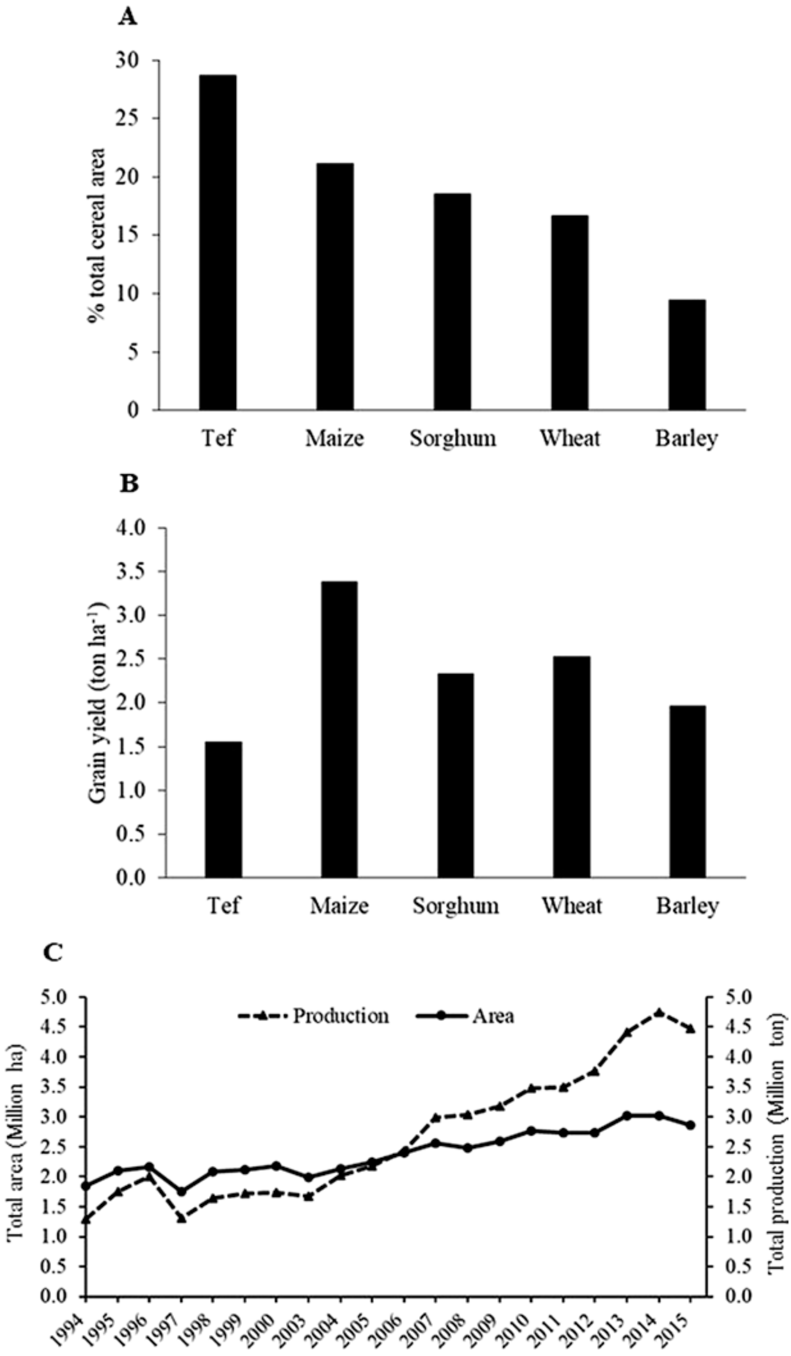

Fig. 10.1 The significance of tef in Ethiopia. (**a**) the proportion of area under tef and other major cereals in 2015. (**b**) The productivity of tef and other cereals in 2015. (**c**) The area under tef cultivation and total production from 1994 to 2015. (Source: Updated from CSA 2002, 2015)

Table 10.1 Nutritional composition of cooked tef grains (per 100 g) compared to wheat, rice, barley and millet

Item	Unit	Tef	Wheat	Rice	Barley	Millet
Proximates						
Energy	Kcal	101.00	132.00	97.00	123.00	119.00
Protein	g	3.87	5.71	2.02	2.26	3.51
Fat	g	0.69	0.83	0.19	0.44	1.00
Carbohydrate	g	19.86	27.60	21.09	28.22	23.67
Fiber	g	2.80	4.30	1.00	3.80	1.30
Minerals						
Calcium	mg	49.00	9.00	2.00	11.00	3.00
Iron	mg	2.00	1.76	0.14	1.33	0.63
Magnesium	mg	50.00	48.00	5.00	22.00	44.00
Phosphorus	mg	120.00	147.00	8.00	54.00	100.00
Potassium	mg	107.00	164.00	10.00	93.00	62.00
Sodium	mg	8.00	8.00	5.00	3.00	2.00
Amino acids						
Alanine	g	0.22	0.21	0.12	0.09	0.31
Arginine	g	0.15	0.27	0.17	0.11	0.12
Aspartic acid	g	0.24	0.31	0.19	0.14	0.23
Cystine	g	0.07	0.12	0.04	0.05	0.07
Glutamic acid	g	0.98	1.88	0.39	0.59	0.76
Glycine	g	0.14	0.23	0.09	0.08	0.09
Histidine	g	0.09	0.15	0.05	0.05	0.08
Isoleucine	g	0.15	0.22	0.09	0.08	0.15
Leucine	g	0.31	0.43	0.17	0.15	0.45
Lysine	g	0.11	0.16	0.07	0.08	0.07
Methionine	g	0.13	0.10	0.05	0.04	0.07
Phenylalanine	g	0.20	0.30	0.11	0.13	0.19
Proline	g	0.19	0.62	0.10	0.27	0.28
Serine	g	0.18	0.30	0.11	0.10	0.21
Threonine	g	0.15	0.17	0.07	0.08	0.11
Tryptophan	g	0.04	0.05	0.02	0.04	0.04
Tyrosine	g	0.13	0.14	0.07	0.07	0.11
Valine	g	0.20	0.27	0.12	0.11	0.18
Vitamins						
Thiamin	mg	0.18	0.10	0.02	0.08	0.11
Riboflavin	mg	0.03	0.03	0.01	0.06	0.08
Niacin	mg	0.91	2.31	0.29	2.06	1.33
Vitamin B6	mg	0.10	0.07	0.03	0.12	0.11

Source: Adapted from USDA (2018)

tyrosine (USDA 2018). In recent years, tef has become popular as a health and performance food in the global market. Since the grain is gluten-free, it is useful as food for humans suffering from the gluten protein allergy ailment known as celiac disease (Spaenij-Dekking et al. 2005). Several studies have been done to investigate the application of tef in gluten-free bakery products (Nascimento et al. 2018). In these cases, the type of tef products tested include bread, cookies, *injera*, muffins and pasta. The low glycemic index characterized by slow release type starches, also make tef suitable for diabetic patients (Baye 2014).

In addition to its grain, tef straw is the most palatable livestock feed and, therefore, fetches a high price compared to straw from other cereals (Yami 2013). In general, this shows the significance of tef in the livelihood of both farmers and consumers in Ethiopia.

With an ultimate objective of providing an overview of tef breeding in Ethiopia, this chapter emphasizes, first, the significance of the crop and subsequently the status of the achievements made with respect to the various methods of breeding thus far employed in its improvement. To this end, attempts have been made to summarize the cultivation and traditional breeding, germplasm biodiversity and conservation and conventional, mutation and molecular-breeding approaches, including genetic engineering employed in tef. Finally, conclusions and prospects are made on the basis of the foregoing highlights and expectations.

10.2 Botanical Classification, Domestication and Distribution

Tef belongs to the Grass or Poaceae family, subfamily Chloridoideae, tribe Eragrostideae and genus *Eragrostis*. Among the cultivated cereals, tef and finger millet (*Eleusine coracana* (L.) Gaertn.) belong to the subfamily Chloridoideae. The relationship between tef and other cultivated cereals were reported by Assefa et al. (2017) and Cannarozzi et al. (2018).

The botanical name of tef has undergone several changes until it settled on the current one. Synonymous names for tef were *Poa tef* Zuccagni in 1775, *Poa abyssinica* Jacquin in 1781, *Eragrostis abyssinica* (Jacq.) Link in 1827, *Eragrostis pilosa* ssp. *abyssinica* (Jacq.) Asch. and Graeben. in 1900, and finally *Eragrostis tef* (Zucc.) Trotter in 1918 (Ebba 1975).

Ethiopia is the center of the origin and diversity for tef (Vavilov 1951). However, the exact date and location for the domestication of tef is not known. There is no doubt that it is a very ancient crop in Ethiopia, where domestication took place before the birth of Christ (Ketema 1997). According to Ponti (1978), tef was introduced to Ethiopia well before the Semitic invasion of 1000–4000 BC. It was probably cultivated in Ethiopia even before the ancient introduction of emmer and barley. Tef has been introduced to different parts of the world through diverse institutions and individuals. The Royal Botanic Gardens, Kew, London, obtained tef seeds from Ethiopia in 1866 and 1886 and distributed them to some of the British Colonies (India, Australia, the USA, South Africa and Guyana). According to Ebba

(1975), Burt Davy in 1916 introduced tef to California (USA), Malawi, Zaire, India, Sri Lanka, Australia, New Zealand and Argentina; Skyes in 1911 introduced it to Zimbabwe, Mozambique, Kenya, Uganda, and Tanzania; and in 1940, Horuitz introduced tef to Palestine. Tef makes excellent hay in all these places.

Ethiopia is the center of both the origin and diversity for tef due to the existence of large diversity in the crop and the presence of wild progenitors. Scientific evidence from archeological remains show that tef was domesticated in Northern Ethiopia during the pre-Axumite period from 800 to 400 BC (D'Andrea 2008). Farmers in Ethiopia deserve high praise for maintaining this hardy crop over generations; except for being grown on a limited scale in Eritrea, formerly part of Ethiopia, no other country produces tef for human food.

Over the years, tef has been improved in Ethiopia through natural selection and by farmers' selection for desirable traits. As a result, greater diversity in terms of agronomic characteristics has enhanced the value of the tef genetic resources found in Ethiopia.

10.3 Cultivation and Traditional Breeding

Tef is mainly grown by smallholder farmers in Ethiopia. Most cultural practices show little improvement over the last several centuries. Plowing is in most places done with a pair of oxen using a traditional plow called a *maresha*.

Farmers sow tef by broadcasting the seed on top of the soil at a rate of 25–30 kg ha^{-1}, which is 2–3 times higher than recommended by researchers. Weed control is mainly done by hand weeding, but in recent years, the broadleaf herbicide 2,4-D is also widely used. Harvesting is also done manually using a sickle, while threshing uses oxen. Postharvest loss is high since tef seeds are extremely small, predisposing seed loss.

Tef provides a number of benefits to smallholder farmers in Ethiopia as the crop is resilient to a variety of biotic and abiotic stresses, which more seriously affect other cereal crops leading to greater losses from these environmental difficulties. Farmers also use tef for income generation due to the higher price of the grain, compared to other cereal grains (Minten et al. 2016). Despite these benefits, the cultivation of tef faces a number of constraints among which the major ones are indicated below:

(a) Inherent characteristics of the plant: Tef possess a tall and weak stem which renders it susceptible to lodging, the shoot falling over onto the ground (Assefa et al. 2011b). The roots of tef have also poor anchorage in the soil (Van Delden et al. 2009). Hence, tef plants suffer from lodging which is exacerbated by rain and wind, and when nitrogenous fertilizers are applied to enhance growth and yield of the crop.
(b) Extreme environmental conditions: Compared to other cereals, tef is more tolerant of extreme soil and climatic conditions. However, tef also suffers from

severe abiotic stresses prevalent in different parts of Ethiopia including drought, waterlogging, frost and soil acidity (Tadele 2016a).

(c) Being an orphan crop: Similar to other understudied crops, tef has received very little attention by the global scientific community, which classifies the crop as an orphan or neglected crop (Tadele 2014; Tadele and Assefa 2012). However, a few donor organizations including the McKnight Foundation and Syngenta Foundation for Sustainable Agriculture have been providing support for both research and development which have improved varieties harboring traits of interest that have been disseminated to farmers.

Ethiopian farmers have maintained tef over millennia by selecting and preserving types with traits of their interest which include high grain yield, nonshattering and resilience to biotic and abiotic stresses. Scientific research on tef started in 1950s at the then Debre Zeit Experimental Station. Selection from natural accessions was the only improvement method until 1974 when the first crosses were successfully made (Berhe 1975), following the discovery of the chasmogamous behavior of tef flowers. Consequently, the development of an artificial binocular-aided surgical hand emasculation and pollination technique paved the way for improving tef using hybridization. Details on tef breeding regarding techniques and achievements are provided in the next sections.

10.4 Germplasm Biodiversity and Conservation

10.4.1 Germplasm Diversity

Ethiopia is both the origin and center of diversity for tef, providing the country with a rich array of tef germplasm resources. Over 5000 tef germplasm accessions collected from diverse tef growing areas in the country are available at the Ethiopian Biodiversity Institute (EBI) (Tesema 2013). However, thus far only limited studies have been made to investigate the genetic diversity existing in these populations.

Diversity in tef has been studied for different traits, especially for important agronomic traits (Assefa et al. 2000; Chanyalew et al. 2009; Hundera et al. 1999; Jifar et al. 2015; Plaza-Wüthrich et al. 2013; Tefera et al. 1990). Although most diversity studies have been made on white-seeded tef germplasm, Jifar et al. (2015) reported diversity among 36 brown-seeded tef genotypes based on investigation at three tef growing areas in Central Ethiopia. This study of brown-seeded tef is important since food products from this type of grain are becoming popular due to its nutritional superiority over the white-seeded type. A recent review showed the extent of diversity in tef germplasm for diverse qualities, which included agronomic, nutritional and molecular traits (Assefa et al. 2015). The range of variability reported for selected traits is shown in Fig. 10.2. Traits with more than a six-fold higher value than the minimum include plant height, panicle length, peduncle length, kernel weight and harvest index. Traits with values 4–5 fold higher than the

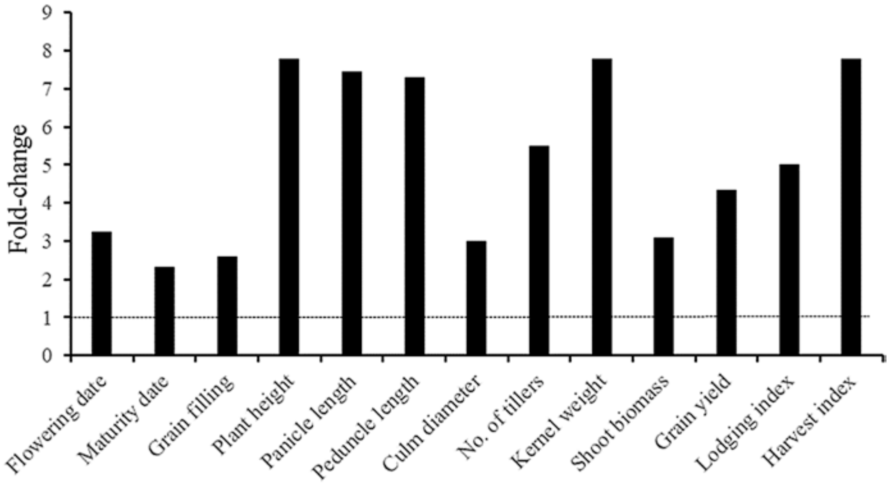

Fig. 10.2 Range of diversity for important agronomic traits in tef as shown in fold change between the minimum value (set to 1: dotted line) and maximum value shown in bar for each trait. (Source: Adapted from Assefa et al. 2000; Chanyalew et al. 2009; Hundera et al. 1999; Tefera et al. 1990)

minimum values were number of tillers, grain yield and lodging index. On the other hand, traits with modest diversity included days to flowering and maturity, and culm diameter. In general, this demonstrates that tef germplasm is rich in important agronomic and nutritional traits which can be exploited through selection and introgression.

10.4.2 Cultivar Characterization and Phylogeny

Ebba (1975) carried out the first scientific study of tef germplasm characterization and classification. It was based on morphological properties which include phenology, plant vigor, panicle form and ramification pattern, spikelet size, and lemma and caryopsis color. This detailed research identified 35 distinct tef cultivars or ecotypes which have been adopted in subsequent studies of germplasm characterization and groupings. A selection of 7 of the characters or traits used to characterize the 35 ecotypes are included in Table 10.2. These 35 ecotypes showed huge diversity in all of the characters studied. Among the ecotypes, the range for selected traits were plant height from 34 cm (Bunniye) to 95 cm (Murri), days to heading from 25 days (Gea-Lamie) to 60 days (Curati) and days to maturity from 60 (Gea-Lamie, Shewa Gemerra) to 120 days (Alba, Curati, Murri). These ecotypes also showed great diversity in the panicle form which ranged from very loose to very compact (Assefa et al. 2017). The variability among tef accessions for those indicated and other traits has been the focus of tef breeders in selecting genotypes of interest.

Table 10.2 Selected traits of 35 tef ecotypes representing tef germplasm

No.	Ecotype (cultivar) name	Plant height (cm)	Culm diameter (cm)	Panicle form[a]	Lemma color[b]	Seed color[c]	Days to	
							Heading	Mature
1	Ada	80	1.8	S-comp	PYG	yWh	45–50	95–115
2	Addisie	80	1.9	V-comp	PYG	yWh	45–50	95–110
3	Adoensis	70	1.6	V-loose	PYG	mBr	45–50	90–95
4	Alba	85	2.2	F-loose	PYG	yWh	45–50	95–120
5	Balami	88	1.8	V-loose	D-purple	yWh	40–45	90–110
6	Beten	70	1.6	V-loose	PYG	yWh	40–45	85–95
7	Bunniye	34	1.0	V-loose	PYG-green	mBr	35–40	75–85
8	Burssa	58	1.5	S-comp	G-green	yWh	45–50	85–90
9	Curati	88	2.3	S-comp	PYG	poW	50–60	95–120
10	Dabbi	70	1.6	V-loose	G-purple	mBr	40–45	80–95
11	Denkeye	60	1.5	S-comp	G-green	mBr	45–50	90–115
12	Dschanger	75	1.8	F-loose	G-green	mBr	40–65	90–110
13	Enatite	70	1.5	V-loose	PYG	yWh	40–45	90–100
14	Fesho	50	1.2	V-loose	D-purple	Br	38–45	75–85
15	Gea-Lamie	30	0.9	V-loose	G-green	Br	25–30	60–70
16	Gofarie	78	1.8	S-comp	PYG	yWh	45–50	90–100
17	Gommadie	75	2.0	S-comp	PYG	yWh	45–50	90–100
18	Gorradie	90	2.2	V-comp	PYG	yWh	50–55	95–120
19	Hamrawe Murri	75	1.8	V-comp	D-purple	yWh	50–55	90–100
20	Hatalla	90	2.1	V-loose	G-purple	yWh	50–55	90–115
21	Janno	75	2.0	F-loose	G-red	yWh	45–50	85–105
22	Karadebi	55	1.1	V-loose	Brown	Br	40–45	85–90
23	Kaye Agachem	77	1.8	V-comp	PYG	lBr	65–50	90–110
24	Kaye Murri	80	2.0	V-comp	D-red	yWh	45–50	90–105

(continued)

Table 10.2 (continued)

No.	Ecotype (cultivar) name	Plant height (cm)	Culm diameter (cm)	Panicle form[a]	Lemma color[b]	Seed color[c]	Days to	
							Heading	Mature
25	Manya	75	2.0	F-loose	PYG	yWh	40–45	90–110
26	Murri	95	2.3	V-comp	G-green	yWh	50–55	105–120
27	Purpurea	85	1.9	F-loose	D-red	Br	45–50	90–100
28	Rosea	75	2.0	F-loose	P-green	yWh	45–50	90–100
29	Rubicunda	85	2.4	F-loose	D-purple	yWh	45–50	90–115
30	Shawa-Gemerra	35	0.9	F-loose	PYG	Br	30–35	60–75
31	Trotteriana	70	1.6	V-comp	PYG	Br	50–55	90–95
32	Tullu Nasy	42	1.1	V-loose	PYG	poW	35–40	60–70
33	Variegata	70	1.8	F-loose	PYG	lBr	45–50	90–100
34	Viridis	75	2.2	F-loose	G-green	poW	45–50	85–95
35	Zuccagniana	65	1.3	V-comp	G-green	Br	45–50	90–100

Source: Adapted from Ebba (1975)

[a]Panicle form: *F-loose* fairly loose, *S-comp* semi-compact, *V-comp* very compact, *V-loose* very loose

[b]Lemma color: *D-purple* dark or deep purple, *D-red* dark or deep red, *G-Green* grayish, orange or olive green, *G-purple* grayish, orange or olive purple, *G-red* grayish red, *PYG* pale yellow green

[c]Seed color: *Br* brown, *mBr* medium brown, *lBr* light brown, *poW* purple orange white, *yWh* yellow white

Since this remarkable work, tef germplasm has been extensively studied using morphological, molecular and physiological parameters. As shown in Fig. 10.2, significant variabilities were reported for morphological and yield-related traits (Assefa et al. 2001b, 2003). Similarly, variabilities among diverse tef genotypes were studied using genetic markers such as microsatellites (simple sequence repeats (SSRs), genotyping by sequencing (GBS) and several other techniques (Chanyalew et al. 2013; Girma et al. 2018; Plaza-Wüthrich et al. 2013). Based on these studies, the relationships among tef germplasms were investigated using phylogenic trees constructed using morphological traits (Plaza-Wüthrich et al. 2013) and molecular markers, especially SSR markers (Assefa et al. 2015) (Fig. 10.3). Although phylogenetic trees constructed based on morphological traits provide useful information, due to inconsistencies in the values of some traits under field conditions, they are less accepted by researchers. On the contrary, those based on molecular markers provide consistent results as they are based on DNA sequences which are little altered by changes in environmental factors.

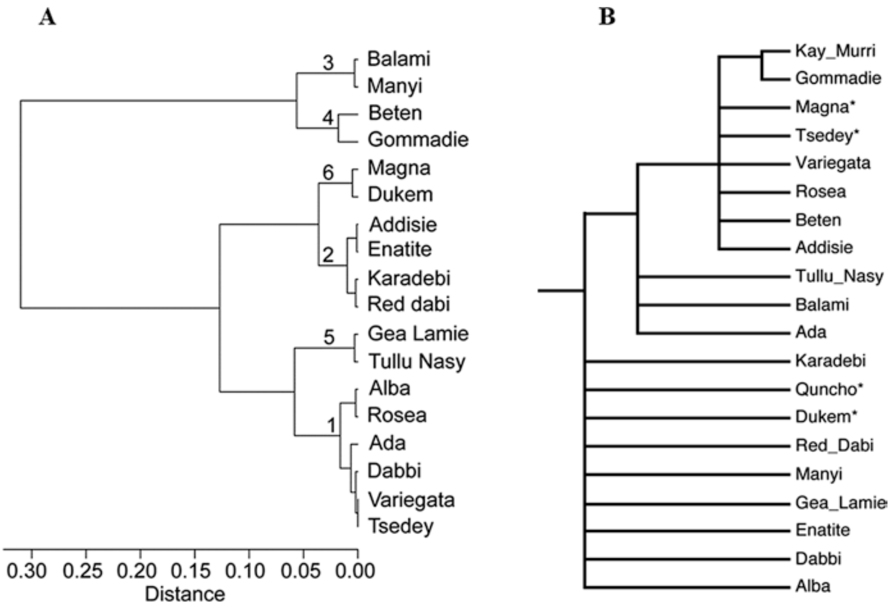

Fig. 10.3 Phylogenetic trees showing the relationship among natural accessions and improved varieties of tef. (**a**) Using morphological and yield-related traits. (Source: Plaza-Wüthrich et al. 2013). (**b**) Using SSR marker. (Source: Assefa et al. 2015)

10.4.3 Genetics and Cytogenetics

Studies involving key qualitative and quantitative traits in tef are briefly summarized as follows:

(a) Genetics of qualitative traits: Detailed studies were made to investigate the inheritance of three traits, namely lemma color, seed color and panicle form (Berhe et al. 1989a, b, c). These studies showed the involvement of multiple genes in the inheritance of the traits, and disomic inheritance patterns with no maternal effects.
(b) Genetics of quantitative traits: Several studies based on tef crosses showed that additive and epistatic gene effects controlled the inheritance of most yield and yield-related quantitative agronomic traits including grain yield (Tefera and Peat 1997a, b).
(c) Cytogenetics: Cytological studies showed that tef is an allotetraploid with 40 chromosomes ($2n = 4\times = 40$) (Jones et al. 1978; Tavassoli 1986) although the true diploid ancestors remain unknown. Despite all tef genotypes having the same level of polyploidy, two independent flow cytometric studies using ten improved varieties and four accessions showed a genome size range of 648–926 Mbp (Ayele et al. 1996a; Hundera et al. 2000).

10.4.4 Germplasm Conservation

Tef germplasm consisting of over 5000 accessions collected from diverse tef-growing regions are preserved at the Ethiopian Biodiversity Institute (EBI). The seeds of these accessions are periodically grown and rejuvenated in the fields of research institutes in Ethiopia before their viability is drastically reduced. Research centers in the country, particularly Debre Zeit Agricultural Research Center, regularly grow improved varieties of tef at its main- or sub-station sites. Research centers belonging to respective regional research institutes also multiply seeds of improved varieties to provide to farmers and extensions agents requesting the seeds. In addition to launching periodic new collecting missions, EBI has in recent years been fostering in situ conservation of tef genetic resources in farmers' fields.

10.5 Molecular Breeding

Molecular markers provide an invaluable tool for studying genetic diversity and relationships, classification of germplasm, construction of genetic linkage maps, and in marker-assisted selection for breeding. A number of tef marker systems including restriction fragment length polymorphism (RFLP) (Zhang et al. 2001), amplified fragment length polymorphism (AFLP) (Ayele and Nguyen 2000; Ayele et al. 1999; Bai et al. 1999a, b) and random amplified polymorphic DNA (RAPD) (Bai et al. 2000) have been developed and used for various purposes.

Mapping for quantitative trait loci (QTL) controlling key agronomic and morphological traits was made from 159 recombinant inbred lines derived from interspecific cross between *Eragrostis tef* and *E. pilosa*. The genetic map and list of traits investigated are indicated in Zeid et al. (2011). Although attempts were made in the past to develop a genetic map for tef (Yu et al. 2007), the map in Fig. 10.4 is the most comprehensive and up to date in terms of using more markers and including valuable traits. However, the resolution of this genetic map also needs to be substantially improved using additional markers already developed from recent studies. The availability of the tef genome sequence (Cannarozzi et al. 2014) enhances the discovery of new genetic markers, especially simple sequence repeat (SSR) markers. Genomic and proteomic tools have recently been employed to identify diversity and key traits in tef (Girma et al. 2018; Kamies et al. 2017).

By using expressed sequence tag (EST) from cDNA libraries, tef sequence specific markers have been developed such as expressed sequence tag derived simple sequence repeat (EST-SSR), intron fragment length polymorphism (IFLP), and single nucleotide polymorphism/insertion and deletion (SNP/INDEL) (Yu et al. 2006). Since these sequences were derived from the coding regions of genes, EST-derived markers are highly transferable to closely-related species. To that end, testing of 812 EST-derived markers from other grass species on tef revealed successful amplification of approximately 30% of the markers, and prominently EST-SSRs developed from sorghum and pearl millet (both belong to subfamily Panicoideae which is taxonomically close to the subfamily of tef, Chloridoideae) showed a transferability rate higher than 80% on tef (Assefa et al. 2017; Zeid et al. 2010).

The development of tef genomic SSR markers (gSSRs) alleviated the problem of low rate of polymorphism of EST-SSRs (Zeid et al. 2011). The genomic libraries were enriched for (AG) and (AC) dinucleotide repeats, and in tef the (AG) repeat occurs at a much higher frequency as compared to other grass species such as barley, rice and wheat. A total of 561 gSSRs were developed and 48% of the markers showed polymorphism on *Eragrostis tef* (Kaye Murri) and *E. pilosa* (Zeid et al. 2011). This indicates that the rate of polymorphism of gSSRS is twice as high as 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 (Assefa et al. 2017).

10.6 Biotechnology

Biotechnology is a broad topic, although there is a common understanding that if refers to genetically-modified organisms (GMOs) and tissue culture techniques. Except for few preliminary investigations (Gebre et al. 2013; Mekbib et al. 2001; Mengiste 1991; Plaza-Wüthrich and Tadele 2013) detailed genetic engineering studies which resulted in plants with phenotypes of interest have not yet been found for tef.

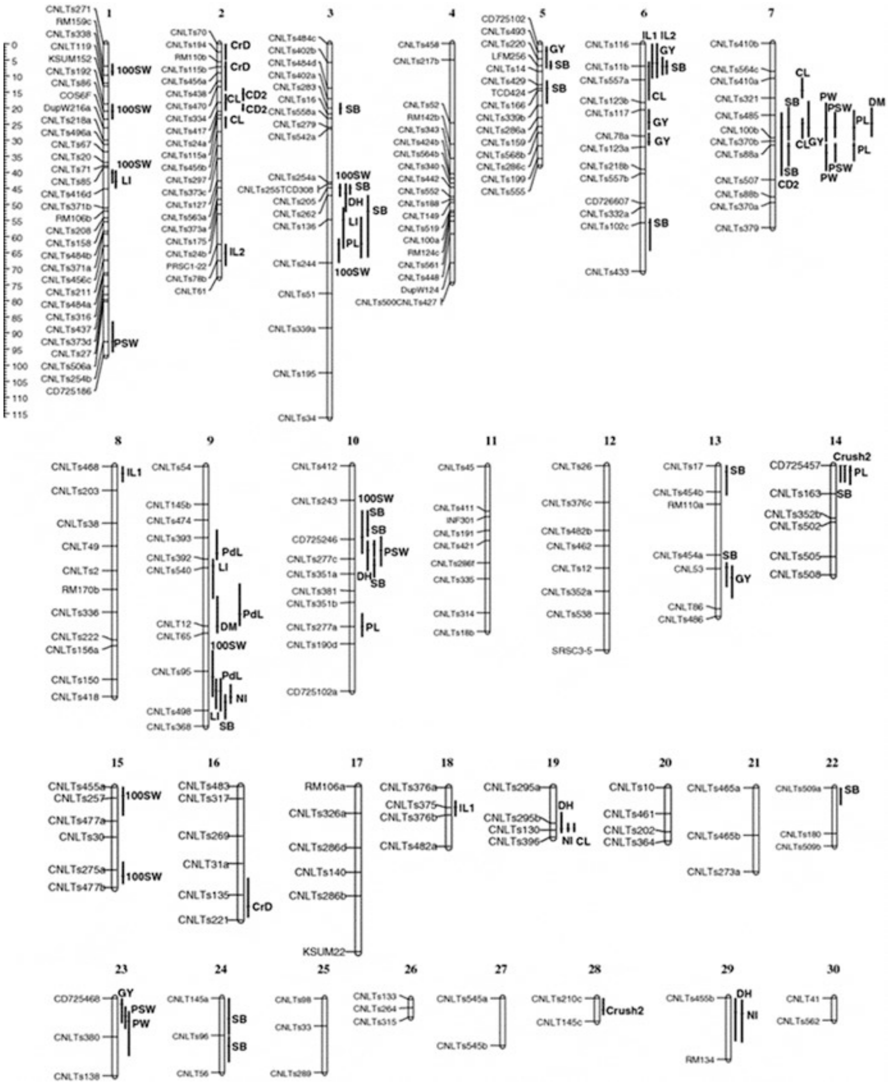

Fig. 10.4 Molecular linkage map of tef showing QTLs for important traits obtained from recombinant inbred lines *Eragrostis tef* × *E. pilosa*. Marker names are positioned equivalent to their cM distances on the left of the bars. Intervals for each QTL are indicated by the length of the vertical closed bars to the right of the linkage groups, and the name of the trait underlying each QTL is given to the right of the linkage map. Abbreviations. *100SW* 100 seed weight, *CD1* culm diameter at the 1st internode, *CD2* culm diameter at the 2nd internode, *CL* culm length, *Crush1* crushing strength at 1st internode, *Crush2* crushing strength at 2nd internode, *DH* days to heading, *DM* days to maturity, *GY* grain yield, *IL1* length of 1st internode, *IL2* length of 2nd internode, *LI* lodging index, *NI* number of internodes, *PL* panicle length, *PdL* peduncle length, *PSW* panicle seed weight, *PW* panicle weight, *SB* shoot biomass per plant. (Source: Zeid et al. 2011)

In vitro regeneration, or plant tissue culture, is an asexual method of propagation to produce clones in large quantities from an explant. This ability of the plant to develop from tissue into a whole plant after undergoing several regeneration steps is called totipotency. An efficient in vitro regeneration system is necessary for the genetic improvement of a crop which includes mutation breeding, somatic hybridization and genetic transformation. A number of in vitro regeneration studies were made on tef using a variety of explant types, genotypes and techniques. Explants from leaf parts, young seedling roots, mature seeds and immature embryos were investigated to determine the best explant for efficient regeneration (Ayele et al. 1996b; Bekele et al. 1995; Gugsa and Kumlehn 2011; Gugsa and Loerz 2013; Gugsa et al. 2006, 2009; Kebebew et al. 1998; Mekbib et al. 1997; Plaza-Wüthrich and Tadele 2012, 2013). Among these explants, immature embryos were found to be more efficient than the others (Gugsa and Kumlehn 2011; Plaza-Wüthrich et al. 2015). The procedure and the time required for each step of regeneration, starting from isolating immature embryos to obtaining fully-developed plants grown in soil are shown in Fig. 10.5. Immature embryos pass through either somatic embryos or callus before plantlets are formed. Fully-developed tef plants grown in soil can be achieved in 4 months after isolating immature embryos from tef flowers and placement on appropriate growth media.

The efficiency of regeneration is mainly dependent on the type of the genotype. Using the immature embryo technique, over 80% of explants from the natural tef accession Manya formed somatic embryogenesis while this was only 10% from the improved variety Tsedey (Plaza-Wüthrich and Tadele 2013). The proportions of explants developing into plantlets were also significantly low for Tsedey compared to Manya. Hence, it is important to first study the regeneration efficiency of diverse tef ecotypes or varieties before embarking on a large-scale study using a single or limited numbers of germplasm accessions.

Plant transformation refers to the introduction of genetic material into plant cells, tissue or organs in order to alter the trait(s) or phenotype of the plant. It is commonly

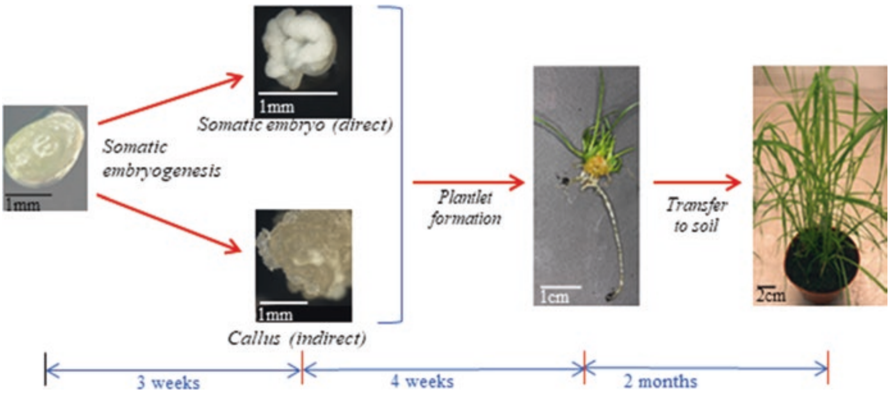

Fig. 10.5 Procedure and time taken for in vitro regenerated tef from immature embryo. (Source: Sonia Plaza-Wüthrich)

done using the *Agrobacterium* and the particle or microprojectile bombardment method. Similar to other monocot plants, tef tissue for transformation is recalcitrant to *Agrobacterium*-mediated transformation. However, an earlier study showed the attachment of *Agrobacterium* to the tef embryo, seed, seedling, leaf and callus explants, although the intensity of attachment was significantly different among the explants (Mekbib et al. 2001). Among three *Agrobacterium* strains investigated by another study, LBA4404 and EHA105 were more efficient or virulent in transient tef transformation compared to GV3101 (Plaza-Wüthrich and Tadele 2013). Stable transformation in tef was recently reported using gibberellic acid (GA) inactivating a gene under the control of triple 35S promoter (Gebre et al. 2013). According to the authors, despite inconsistencies in some results, semi-dwarf tef plants with a reduced level of endogenous GA were obtained.

Particle bombardment (also known as biolistic or gene gun) refers to delivery of the gene of interest into plant tissue using high-velocity microprojectiles that have the ability to penetrate the cell wall so that genetic material can be transferred into the cell. Only a few studies have investigated the potential of using particle bombardment in tef transformation. The efficacy of the methods were studied using a reporter gene under the control of different promoters. Transient expression of the reporter β-glucuronidase (GUS) gene using 35S promoter was noted in cell suspension cultures, callus tissue and zygotic embryos of tef (Mengiste 1991). On the other hand, an equal level of transient expression of GUS for three promoters (ubiquitin, actin, double 35S) was observed in tef callus derived from immature embryos (Plaza-Wüthrich and Tadele 2013). In general, despite some previous studies, an efficient and simple protocol for routine transformation of tef has not yet been established.

10.7 Mutation Breeding

Mutagenesis refers to the stable and heritable alteration of the genetic material of an organism. Although mutagenesis normally refers to the creation of a mutation, three categories are identified, especially in considering the utilization of mutations in crop improvement. These are mutation induction, mutation detection and mutation breeding (IAEA 2018). While mutations are induced or created using physical or chemical mutagens, the sites of mutations in the plant genome are detected using a number of molecular techniques (Tadele 2016b). The third and the most important part of mutagenesis is to incorporate the mutation into a breeding program in order to obtain a crop with enhanced trait(s) of interest.

Over the last 70 years, mutation breeding has contributed significantly to the improvement of many economically-important crops. Crops descended from using this technique were superior to the original cultivars in productivity and/or tolerance to biotic and abiotic stresses. The list of officially released and/or commercially available crop varieties originated from induced mutation are available in the Mutant Variety Database (MVD) of the Joint IAEA/FAO Program (IAEA 2018). According to this database, since the first variety was released in 1966 in China, 3275 crop varieties derived from mutation breeding have been officially released in a large number of countries, mainly in Asia and Europe. In Africa, only 69 crop varieties were released through mutation breeding, and of these 25 are rice varieties in Cote D'Ivoire, and 15 are rice and sorghum varieties in Mali. On the other hand, Asian countries were advanced in mutation breeding by releasing 61% of the total released varieties. The three leading countries in releasing high numbers of varieties are China (810), Japan (479) and India (335). This shows that Africa benefited little from mutation breeding in improving its indigenous crops.

In the early phase of tef breeding, until the discovery of the hybridization technique in the mid 1970s (Berhe 1975), genetic improvement relied solely upon pure line or mass selection. Because of this, induced mutation techniques were introduced into the tef breeding program in 1972 through the cooperation of the International Atomic Energy Agency (IAEA) and the Food and Agriculture Organization (FAO) of the United Nations. From this work, gamma irradiation dose of 250 Krad, X-ray dose of 100–130 Krad and ethyl-methane sulfonate (EMS) concentrations of 2.5–4.0%, were recommended for seed treatment to induce mutations in tef (Ketema 1993). However, desirable mutants were not identified from either the earlier works or the consequent latter efforts made with the application of conventional induced mutation techniques.

Targeting induced local lesions in genomes (TILLING): High-throughput techniques, such as TILLING and Eco-TILLING, are attractive methods for tef improvement, since the products from these techniques 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, EcoTILLING is used in the natural population. The TILLING technique has been implemented on EMS (ethyl methanesulfonate) mutagenized tef population at the University of Bern, Switzerland, mainly to develop semi-dwarf and lodging-resistant cultivars (Esfeld et al. 2013a, b; Tadele et al. 2010). Since tef is a tetraploid, mutation in a single genome might not result in the expected phenotype, hence double crossings were made between candidate lines harboring point mutation in the two copies of the tef genome. 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 technique which uses a LiCOR machine to detect point mutations, next-generation sequencing was also applied to validate six mutations in EMS mutagenized tef population (Zhu et al. 2012). TILLING and mutation breeding enabled tef researchers to discover mutant lines with desirable traits such as semi-dwarf, lodging resistance, drought tolerance and acid soil tolerance, which were later incorporated into the national breeding program to enhance productivity (Cannarozzi et al. 2018; Desta et al. 2017; Jifar et al. 2017; Jöst et al. 2015; Zhu et al. 2012).

10.8 Hybridization and Breeding

10.8.1 Floral Biology

The paniculate tef inflorescence varies in form ranging from very compact whip-like or rat-tail-like type, with the branches appearing fused to the rachis to very loose open and laterally-spreading types (Assefa et al. 2017). Broadly, four major panicle forms are distinguished: very compact, semi-compact, fairly loose and very loose. The panicle branches bear numerous spikelets varying from 30–1070 per panicle (Assefa et al. 2001a). The spikelets are laterally compressed with a flexuous rachilla (with 3–18 nodes and about 1 mm long internodes) borne on a pedicel up to 2 mm long (Ebba 1975). The spikelets are generally linear, oblong to lanceolate in shape and each 3.0–15.0 mm long and 1.0–3.0 mm wide at the broadest part (Assefa et al. 2017). Each spikelet has 2 unequal-sized glumes at the base and a number of florets above. The color of the young glumes can generally be grayish-olive green, dark red, purple, yellow-green or variegated flecked with dark purple or dark red on a grayish yellow-green or grayish olive-green background. The tef florets (3–17 per spikelet) are characterized by asynchronous development which is basipetal on a panicle basis and acropetal on a spikelet basis. Each floret comprises a 3-nerved lemma, a 2-nerved bow-shaped palea, 3 stamens arising from near the ovary base and having very fine slender filaments apically bearing 2-celled length-wise opening anthers, and a pistil or an ovary (Assefa et al. 2017; Ebba 1975) Fig. 10.6. The ovary has 2 or in a few exceptional cases 3 styles, each ending in a plumose (feathery) yellowish white stigma. In addition to genotypic differences, the number of florets or kernels per spikelet and the size of the spikelet vary depending on the particular position along the panicle, the highest and the largest at the top and diminishing toward the base of the panicle.

Fig. 10.6 The morphology of tef flower indicating 3 stamens and a pair of hairy stigmas. (Source: Regula Blösch)

10.8.2 Breeding Behavior

As described above, the tef floret is a hermaphrodite with 3 stamens and 2 stigmas. As a result, tef is an autogamous species, and as such it was thought to be entirely cleistogamous (closed flowers) with no options for outcrossing until the discovery by (Berhe 1975) of its chasmogamous nature that revealed the opening of the florets early in the morning (about 0645–0745 h). The rate of natural outcrossing in tef is 0.2% in the field and 0.05–1.37% in the greenhouse (Kedir et al. 1992). Hence, due to this very low level of outcrossing, tef is considered as a strictly self-pollinated crop. Based on the breakthrough discovery of the chasmogamous nature of tef florets, (Berhe 1975) developed the artificial surgical hybridization method for tef which is still in use in the hybridization program. Accordingly, the conventional binocular-aided tef crossing involves emasculation of the maternal parent (by removal of the 3 stamens) the day before at about 1600–1900 h, storage of the paternal and maternal parents separately under dark and cold conditions in a refrigerator (4 °C) overnight, and collection of pollen from the paternal parent and subsequent brushing of the pollens over the stigma of the previously emasculated florets of the maternal parent. Other methods for inducing male sterility using male-selective gametocidal chemical treatments such as ethephon (ethrel) at flag leaf stage, although phytotoxic at a high concentration has shown some promise (Berhe and Miller 1978; Ketema 1983, 1993). In spite of attempts made to find alternative methods of emasculation, however, the most practicable method for tef hybridization remains the surgical binocular-aided hand emasculation and pollination technique.

10.8.3 Hybridization

In tef, hybridization involves mainly intraspecific crosses and recently some interspecific crossings, especially with *Eragrostis pilosa*. A total of about 620 crosses have been made at the Debre Zeit Agricultural Research Center. Subsequent segregating populations are handled using the combination of modified bulk population (F_2–F_5) and modified pedigree (starting from F_5) methods of breeding. However, some varieties have been developed as recombinant inbred lines (RILs) through the F_2-derived single seed descent (SSD) method. The tef breeding scheme from hybridization to variety development and dissemination is shown in Fig. 10.7.

In the SSD method, the starting materials at the F_2 generation are 500 seeds obtained from an individual F_1 plant. Promotion of a single seed to the next generation is made until the F_6 generation. This is followed by an observation nursery (ON) where selected plants at F_6 are grown, each in a single row. Selected lines from ON are promoted to PVT (pre-variety trial) where a limited number of lines are tested each on 1 m^2 plot at a minimum of 5 locations using 2 replications. At the NVT (national variety trial), 10–20 lines selected from PVT are grown, each on

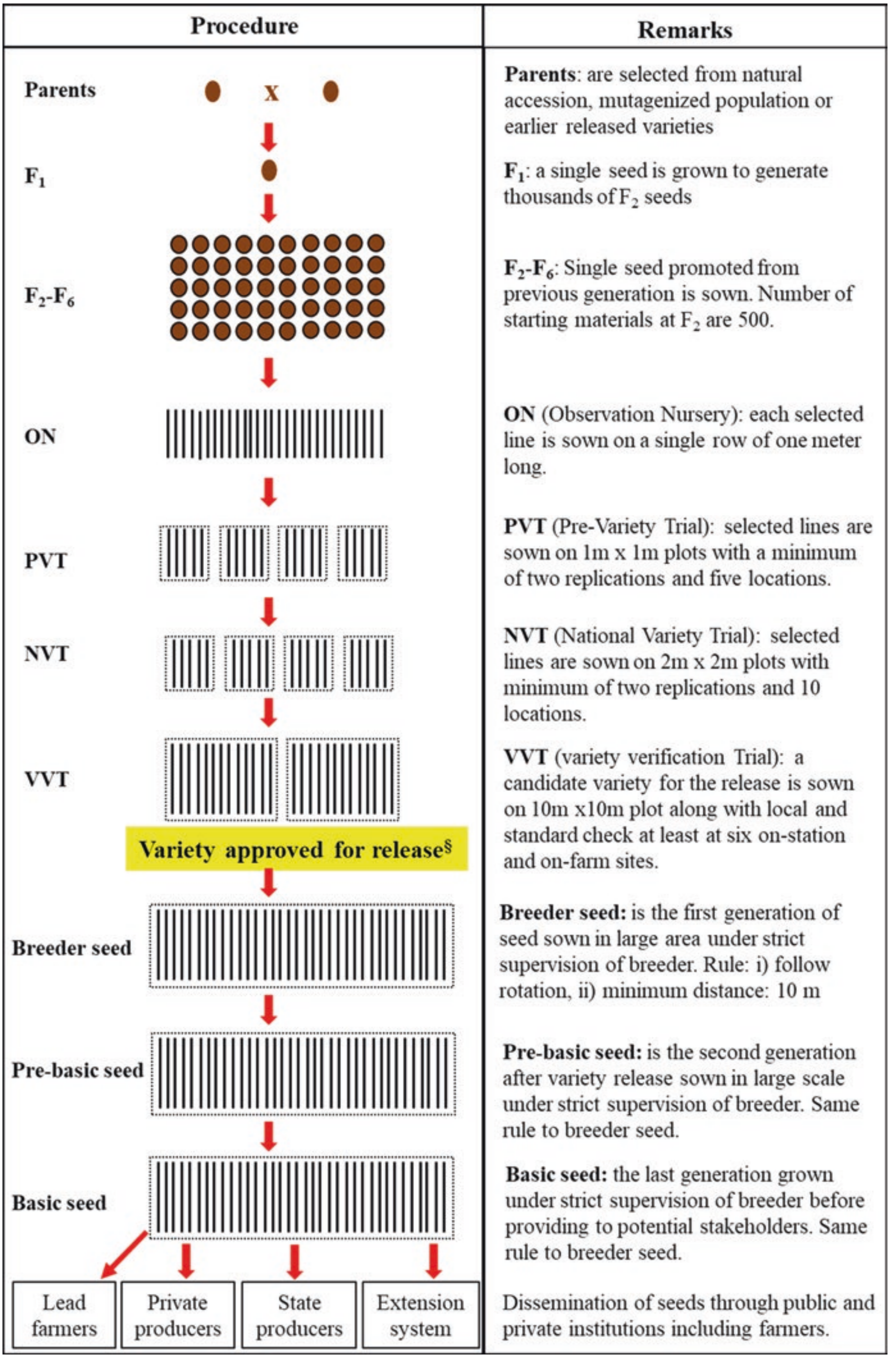

Fig. 10.7 Tef breeding scheme adopted by the National Tef Breeding Program through hybridization, early generation seed multiplication and dissemination of seeds. §Based on the field performance of the candidate variety at VVT and data from NVT and VVT, the National Variety Release Committee approves the new variety for distribution

4 m^2 plots located in at least at 10 representative tef-growing areas. Based on field performance of the candidate variety at VVT (variety verification) and data from NVT and PVT, the National Variety Release Committee approves the new variety for distribution.

10.9 Variety Development and Dissemination

10.9.1 Improved Tef Varieties

As shown in Fig. 10.7, new tef varieties are approved for release after evaluating the performance of the candidate variety at the PVT, NVT and direct field observation at VVT (variety verification). At the VVT, the candidate variety is grown along with the local and standard control varieties, each on 100 m^2 plot in at least five representative sites.

To date, 42 improved tef varieties have been released in Ethiopia through the National Agricultural Research System (MoANR 2017) (Table 10.3). Out of these, 18 were obtained through hybridization, while the remaining 24 were developed through direct selection from farmers' varieties. Except for the very early-maturing variety Simada, which resulted from the inter-specific cross of the tef line DZ-01-2785 and *Eragrostis pilosa* (accession 30-5), all the other varieties developed through hybridization are from intraspecific crosses. By center, 27 of the varieties were released by the federal research centers of EIAR, 24 by Debre Zeit, 2 by Holetta and 1 by Melkassa while those released by the regional centers were 6 by Sirinka, 5 by Adet and 2 each by Areka and Bako.

Of the total released tef varieties in the country, 30 were developed for optimum rainfall areas, 10 for terminal drought-prone areas and 2 for cool highland areas (Table 10.3). Among improved tef varieties so far, Quncho, Boset, Tsedey and Magna have received high acceptance by farmers. Quncho, with its very white seed color and high grain yield, is the most popular in almost all agro-ecological regions where tef is cultivated (Assefa et al. 2011a). Boset and Tsedey are early-maturing varieties that perform best in the vast drought-prone areas in the country, especially those which suffer from the drought during normal crop maturity. On the other hand, Magna is not a high-yielding variety but due to its extremely white seed color, the grain fetches the highest price in the market.

The genetic gain from tef breeding in Ethiopia was 0.8% per year under lodging-controlled condition by growing the varieties released up to 1995 through wire-mesh support (Teklu and Tefera 2005), while it was 0.58% per year under lodging-uncontrolled natural field conditions for the varieties released up to 2012 (Dargo and Mekbib 2017).

Increased biomass yield, plant height, panicle length, number of spikelets per panicle, grain yield per panicle and rates of phytomass production and grain filling were characteristic of improved tef varieties, while the varieties released through

Table 10.3 Improved tef varieties released in Ethiopia for different environmental conditions

Name		Variety release		Breeding method	Days to mature	Seed color	On-farm grain yield (mt ha^{-1})
Common name	Variety name	Year	Center				
Varieties for optimum rainfall areas							
Asgori	DZ-01-99	1970	Debre Zeit	Selection	80–130	Brown	1.7–2.2
Enatite	DZ-01-354	1970	Debre Zeit	Selection	85–130	Pale white	1.7–2.2
Magna	DZ-01-196	1978	Debre Zeit	Selection	80–113	Very white	1.4–1.6
Wellenkomi	DZ-01-787	1978	Debre Zeit	Selection	90–130	Pale white	1.7–2.2
Menagesha	DZ-Cr-44	1982	Debre Zeit	Hybridization	125–140	White	1.7–2.2
Melko	DZ-Cr-82	1982	Debre Zeit	Hybridization	112–119	White	1.8–2.2
Gibe	DZ-Cr-255	1993	Debre Zeit	Hybridization	114–126	White	1.6–2.2
Dukem	DZ-01-974	1995	Debre Zeit	Selection	76–138	White	2.0–2.5
Ziquala	DZ-Cr-358	1995	Debre Zeit	Hybridization	75–137	White	1.8–2.4
Holetta Key	DZ-01-2053	1999	Holetta	Selection	124–140	Brown	2.5
Ambo Toke	DZ-01-1278	2000	Holetta	Selection	125–140	White	2.7
Koye	DZ-01-1285	2002	Debre Zeit	Selection	104–118	White	1.8–2.5
Gola	DZ-01-2054	2003	Sirinka	Selection	68–100	White	1.6
Ajora	PGRC/E 205396	2004	Areka	Selection	85–110	White	1.14
Genete	DZ-01-146	2005	Sirinka	Selection	78–85	Pale white	1.55
Zobel	DZ-01-1821	2005	Sirinka	Selection	78–85	White	1.51
Yilmana	DZ-01-1868	2005	Adet	Selection	108	White	1.63
Dima	DZ-01-2423	2005	Adet	Selection	105	Brown	1.68
Quncho	DZ-Cr-387 RIL355	2006	Debre Zeit	Hybridization	80–113	Very white	2.0–2.2
Guduru	DZ-01-1880	2006	Bako	Selection	132	White	1.4–2.0
Kena	23-Tafi Adi-72	2008	Bako	Selection	110–134	Very white	1.3–2.3
Etsub	DZ-01-3186	2008	Adet	Selection	92–127	White	1.6–2.2
Kora	DZ-Cr-438 RIL133 B	2014	Debre Zeit	Hybridization	110–117	Very white	2.0–2.2
Dagim	DZ-Cr-438 RIL91A	2016	Debre Zeit	Hybridization	112–115	Very white	2.3–2-7

(continued)

Table 10.3 (continued)

Name		Variety release		Breeding method	Days to mature	Seed color	On-farm grain yield (mt ha^{-1})
Common name	Variety name	Year	Center				
Abola	DZ-Cr-438 RIL7	2016	Adet	Hybridization	98–112	Very white	1.5–1.7
Negus	DZ-Cr-429 RIL125	2017	Debre Zeit	Hybridization	102–118	Very white	2.3–2.6
Felagot	DZ-Cr-442 RIL77C	2017	Debre Zeit	Hybridization	94–102	Brown	2.0–2.6
Tesfa	DZ-Cr-457 RIL181	2017	Debre Zeit	Hybridization	99–120	White	2.0–2.7
Heber-1	DZ-Cr-419	2017	Adet	Hybridization	100–122	Very white	1.9–2.4
Areka 2		2017	Areka	Selection	84–110	White	1.6–2.0
Varieties for low rainfall (terminal drought-prone) areas							
Tsedey	DZ-Cr-37	1984	Debre Zeit	Hybridization	82–90	White	1.4–1.9
Gerado	DZ-01-1281	2002	Debre Zeit	Selection	73–95	White	1.0–1.7
Key Tena	DZ-01-1681	2002	Debre Zeit	Selection	84–93	Brown	1.6–1.9
Amarach	HO-Cr-136	2006	Debe Zeit	Hybridization	63-87	White	1.2
Mechare	Acc. 205953	2007	Sirinka	Selection	79	Pale white	1.79
Gemechis	DZ-Cr-387 RIL127	2007	Melkassa	Hybridization	62–83	White	1.4
Simada	DZ-Cr-385 RIL295	2009	Debre Zeit	Hybridization	88	White	1.4
Lakech	DZ-Cr-387 RIL273	2009	Sirinka	Hybridization	90	Very white	1.3–1.8
Boset	DZ-CRr-409 RIL 50D	2012	Debre Zeit	Hybridization	75–86	Very white	1.4–1.8
Were-Kiyu	Acc. 214746A	2014	Sirinka	Selection	94	White	–
Varieties for highland (waterlogged) areas							
Gimbichu	DZ-01-899	2005	Debre Zeit	Selection	118–137	White	1.6–2.2
Dega Tef	DZ-01-2675	2005	Debre Zeit	Selection	112–123	White	1.6–2.0

Source: Adapted from MoANR (2017)

hybridization generally exhibited 9% higher grain yield than those developed through direct selection from germplasm (Teklu and Tefera 2005).

10.9.2 Dissemination and Adoption of Improved Tef Varieties

The steady increase in the tef productivity in the last two decades (Fig. 10.1c), shows the advantages of disseminating improved varieties. The significant positive effect on productivity was observed after the year 2006 at which the yield of tef surpassed 1 mt ha^{-1}. That period coincided with the time when the popular Quncho variety was released and began to be disseminated to farmers (Assefa et al. 2011a). Widespread dissemination of improved varieties mainly depends on the commitment of the research and extension personnel in providing, not only improved varieties with high productivity, but also other essential inputs including fertilizer and herbicide. The use of lead farmers in disseminating improved tef varieties to other farmers has showed promising results (Bekele et al. 2016). A study on the adoption of improved tef varieties showed that while Quncho was adopted by 76% farmers, Magna was adopted by only 40% farmers in the Central Highlands of Ethiopia (Assefa et al. 2017). Quncho is grown on 66%, while Magna is on only 26% of the total tef area. This reflects the rapid adoption of the Quncho variety by farmers especially, by those in the Central Highlands of Ethiopia where tef is the major crop.

10.10 Conclusions and Prospects

In Ethiopia, tef improvement is carried out at federal and regional agricultural research centers, and the breeding program is chiefly at the Debre Zeit Agricultural Research Center, Ethiopian Institute of Agricultural Research. Breeding materials at different generations have been tested at over 20 sites in the country that represent diverse agro-ecological conditions. Since the scientific study of tef began about 5 decades ago, 42 improved varieties have been released. Outside Ethiopia, several academic institutions have been involved in basic and molecular studies. At present, researchers at the University of Bern, Switzerland are implementing genetic and genomic tools to identify candidate tef lines with traits of interest (Tadele 2013). Particular focus has been given to lodging resistance and drought tolerance, the two major constraints affecting tef productivity. Candidate lines obtained from the group have been introgressed into elite lines at the Debre Zeit Center where the first improved tef variety called Tesfa was recently released after several years of breeding (Cannarozzi et al. 2018).

Although tef is relatively more resilient to adverse climatic and soil conditions, the crop suffers from the prevailing extreme environmental conditions and is predicted to be severely affected from drought and other environmental conditions in the near future. In addition to boosting the productivity for this orphan crop, the

National Tef Breeding Program also focuses on developing tef varieties resilient to environmental constraints. Priority has been given to develop drought tolerant varieties. Several released varieties perform better than others in drought-prone areas (Table 10.3) mainly due to their early-maturity nature which allows them to escape from drought occurring during flowering time. A recent investigation based on climatic modelling and socioeconomic studies predicted a yield reduction of up to 0.46 mt ha^{-1} in tef by the year 2050. This magnitude of loss is equivalent to 1.19 million mt of grain and 5.4 million mt of straw for the entire country. In monetary terms, such losses are equivalent to USD 730 million for grain and USD 146 million for straw (Yumbya et al. 2014), indicating significant negative effects on even this hardy crop which normally tolerates environmental stresses better than other cereals. This calls for developing and adopting techniques which enhance the resilience of tef to expected the climate change.

Acknowledgments The tef research in Ethiopia and Switzerland is supported by Syngenta Foundation for Sustainable Agriculture, University of Bern and the Ethiopian government. We thank Sonia Plaza-Wüthrich for providing Fig. 10.5 and Regula Blösch for Fig. 10.6.

Appendices

Appendix I: Research Institutes Relevant to Tef

Institution	Specialization and research activities	Contact information and website
Ethiopian Institute of Agricultural Research (EIAR)	In addition to executing a number of research activities in the area of breeding, agronomy, crop protection, soil sciences, food sciences and economics, the Debre Zeit Agricultural Research Center of EIAR has a mandate to nationally coordinate the tef research in Ethiopia. Other EIAR centers involved in tef research include Melkassa Center on mechanization, and National Agricultural Biotechnology Research Center at Holetta	Dr. Kebebew Assefa, National Tef Research Coordinator, Debre Zeit Agricultural Research Center, P.O. Box 32, Debre Zeit, Ethiopia. Email: kebebew.assefa@yahoo.com EIAR website: http://www.eiar.gov.et/
Oromia Agricultural Research Institute (OARI)	Research on breeding, agronomy and socio economics of tef mainly at Bako Agricultural Research Center	Mr. Girma Gemeda, OARI, Bako Agricultural Research Center
Amhara Regional Agricultural Research Institute (ARARI)	Research on breeding, agronomy and socio economics of tef mainly at Adet Agricultural Research Center	Mr. Atinkut Fentahun, ARARI, Adet Agricultural Research Center
Tigray Agricultural Research Institute (TARI)	Research on breeding, agronomy and socioeconomics of tef mainly at Aksum Agricultural Research Center	Mr. Kidu Gebremeskel, TARI, Aksum Agricultural Research Center
Southern Agricultural Research Institute (SARI)	Research on breeding, agronomy and socio economics of tef mainly at Worabe Agricultural Research Center	Mr. Molalign Assefa, SARI, Worabe Agricultural Research Center
Crop Breeding & Genomics Group, Institute of Plant Sciences, University of Bern, Switzerland	Molecular and genomics studies on tef with particular focus on tackling major constraints affecting the productivity of tef	Dr. Zerihun Tadele, Tef Project Leader, University of Bern, Institute of Plant Sciences, Altenbergrain 21, 3013 Bern, Switzerland. Email: zerihun.tadele@ips.unibe.ch website: http://www.ips.unibe.ch/research/tef/index_eng.html or http://www.tef-research.org/

Appendix II: Tef Genetic Resources

Cultivar	Important traits	Cultivation location
Over 5000 tef accessions collected from diverse tef growing areas and deposited at the Ethiopian Biodiversity Institute	Huge diversity in agronomical, morphological and genomic traits	Different parts in Ethiopia
300 core tef germplasm available at Debre Zeit Agricultural Research Center, Ethiopia	For grain yield and yield related traits	Diverse tef growing areas
30 improved varieties for optimum growing rainfall areas: Abola (DZ-Cr-438 RIL7), Ajora (PGRC/E 205396), Ambo Toke (DZ-01-1278), Areka 2, Asgori (DZ-01-99), Dagim (DZ-Cr-438 RIL91A), Dima (DZ-01-2423), Dukem (DZ-01-974), Enatite (DZ-01-354), Etsub (DZ-01-3186), Felagot (DZ-Cr-442 RIL77C), Genete (DZ-01-146), Gibe (DZ-Cr-255), Gola (DZ-01-2054), Guduru (DZ-01-1880), Heber-1 (DZ-Cr-419), Holetta Key (DZ-01-2053), Kena (23-Tafi Adi-72), Kora (DZ-Cr-438 RIL133 B), Koye (DZ-01-1285), Magna (DZ-01-196), Melko (DZ-Cr-82), Menagesha (DZ-Cr-44), Negus (DZ-Cr-429 RIL125), Quncho (DZ-Cr-387 RIL355), Tesfa (DZ-Cr-457 RIL181), Wellenkomi (DZ-01-787), Yilmana (DZ-01-1868), Ziquala (DZ-Cr-358) and Zobel (DZ-01-1821)	Agronomic traits particularly yield and yield-related traits	Diverse tef growing areas
10 improved varieties for drought-prone areas: Amarach (HO-Cr-136), Boset (DZ-CRr-409 RIL 50D), Gemechis (DZ-Cr-387 RIL127), Gerado (DZ-01-1281), Key Tena (DZ-01-1681), Lakech (DZ-Cr-387 RIL273), Mechare (Acc. 205953), Simada (DZ-Cr-385 RIL295), Tsedey (DZ-Cr-37) and Were-Kiyu (Acc. 214746A)	Agronomic traits particularly yield, yield-related traits as well as drought tolerance.	Moisture scare areas
Two improved varieties for waterlogged areas: Dega Tef (DZ-01-2675) and Gimbichu (DZ-01-899)	Agronomic traits particularly yield, yield-related traits as well as waterlogging tolerance.	Waterlogged areas
Over 10,000 mutagenized tef populations available at the University of Bern in Switzerland	Diverse traits	
Kegne: semi-dwarf and lodging resistant tef line available at the University of Bern	Lodging tolerance	Universal
Kinde: semi-dwarf and lodging resistant tef line available at the University of Bern	Lodging tolerance	Universal
Dtt2 (Drought tolerant tef 2): available at the University of Bern	Drought tolerance	Drought-prone areas
Dtt13 (Drought tolerant tef): available at the University of Bern	Drought tolerance	Drought-prone areas

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