Chapter 15

NUTRIENT COMPOSITION AND HEALTH BENEFITS

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Teff (*Eragrostis tef*) is an ancient tropical cereal that has its center of origin and diversity in the northern Ethiopian highlands from where it is believed to have been domesticated (Ketema 1997a and 1997b; Demissie 2001). Teff is an underused cereal crop worldwide, whereas in Ethiopia, it is a major food grain, mainly used to make injera, a traditional fermented Ethiopian pancake. In other countries, like Australia, South Africa, and the United States, it is principally used as a forage crop for animal feed. Relative to more common cereals like wheat, rice, and maize, little is known about the nutritional composition and potential health benefits of teff. This, along with technological limitations in processing teff, has long restricted its more widespread consumption from its center of origin, Ethiopia. Although teff is the preferred grain for making the staple injera (Yetneberk, Rooney, and Taylor 2005), the limited information available to the general public and the lack of global interest in teff has prolonged thinking by Ethiopians that their grain is of inferior nutritional quality. However, the recent recognition that teff is gluten-free has spurred global research interest by nutritionists and food scientists. Consequently, studies on the nutritional composition of teff and its processing qualities have grown, and the development of new teff-based products has accelerated.

This chapter looks at the physical and chemical characteristics of teff and its nutrient composition. The use of teff and teff-based products for human nutrition in Ethiopia are described, along with the food-processing challenges impeding teff's worldwide consumption. Recent research advances to solve these challenges are discussed. Finally, the potential health benefits that could be associated with higher consumption of teff are highlighted.

Physical Characteristics of Teff Grain

Teff is possibly the smallest cereal grain with an average length of about 1 millimeter (Table 15.1) (Umeta and Parker 1996; Lacey and Llewellyn 2005;

TABLE 15.1 Teff grain characteristics

Average of 12 teff varieties
Length (millimeters) = 1.17
Width (millimeters) = 0.61
Percentage of sample that passes through sieves of different mesh size:
710 microns – 1.1
600 microns – 52.7
300 microns – 45.3
250 microns – 0.1
Thousand kernel weight (g) = 0.264

Source: Bultosa 2007.

Bultosa 2007; Adebowale et al. 2011). The average thousand kernel weight of 12 teff varieties tested by Bultosa (2007) was 0.264 grams. The minuteness of teff grains has nutritional and technological implications. For instance, as teff grains are difficult to decorticate, the cereal is consumed as a whole grain, improving nutrient intake for consumers.

The color of teff can vary from white (ivory) to dark brown (black) depending on the variety. In Ethiopia three major categories can be identified: white (nech), red (quey), and mixed (sergegna). It is also common for wholesalers to further subdivide white teff into very white (magna) and white (nech). However, given that these classifications are imprecise and subjective, what may be referred to as magna by some may be considered nech by others. White teff generally grows only in the Ethiopian highlands and require relatively good growing conditions. This, along with its higher consumer preference, may justify why white teff is the most expensive type of teff. However, in recent years, red teff, which is believed to be more nutritious, is gaining popularity among health-conscious consumers in Ethiopia.

Nutritional Composition of Teff Grain

Carbohydrates

Carbohydrates are the major source of energy for human nutrition and play an important role in metabolism and homeostasis. Based on the molecular size and degree of polymerization, carbohydrates can be classified into sugars, oligosaccharides, starch (amylose, amylopectin), and nonstarch polysaccharides.

Complex carbohydrates make up 80 percent of the teff grain. It has a starch content of approximately 73 percent, making teff a starchy cereal. The amylose content of 13 teff varieties tested ranged from 20 percent to 26 percent, comparable to other grains, such as sorghum (Bultosa 2007). The extent to which carbohydrate is digested and absorbed in the small intestine determines its health effect. Rapidly digested and absorbed carbohydrates (glycemic carbohydrates) have greater impact on blood glucose levels, as they lead to greater metabolic perturbation (Lafiandra, Riccardi, and Shewry 2014). Such perturbations have been associated with metabolic diseases such as type-2 diabetes and cardiovascular diseases (Ludwig 2002). Hence, from a health standpoint, slowly digesting carbohydrates are preferred over rapidly digesting ones.

The rate of carbohydrate digestion of a food can be characterized by its glycemic index (GI) (Harris and Geor 2009).[1] The GI of a food depends on endogenous factors of the food matrix, such as starch susceptibility to α-amylase, protein and lipid content, and the macroscopic structure of the food (Fardet et al. 2006). Starch susceptibility to α-amylase is in turn determined by its structure, encapsulation, crystal structure, degree of gelatinization, the proportion of damaged granules as well as the retrogradation of the starch granules (Fardet et al. 2006). Using a scanning electron microscope (SEM), the size of teff starch was found to be 2–6 μm (Bultosa, Hall, and Taylor 2002; Wolter et al. 2013). This makes teff starch granules smaller than those of wheat (A type 20–35 μm), sorghum (20 μm), and maize (20 μm) (Delcour et al. 2010). Given their larger surface area, smaller starch granules are more susceptible to enzymatic attack (Tester, Karkalas, and Qi 2004). Nonetheless, in comparison to wheat, which has larger starch granules, the in vitro starch digestibility of teff was found to be significantly lower (Wolter et al. 2013).

In line with this, the predicted glycemic index of teff (74) was significantly lower than that of white wheat (100) but comparable to that of sorghum (72) and oats (71) (Wolter et al. 2013). This somewhat lower GI for teff than expected may be explained by its amylose content, lower starch damage, and the possible formation of amylose-lipid complexes that can hinder enzymatic access and thus starch digestibility (Singh, Dartois, and Kaur 2010; Wolter et al. 2013). In addition, the high gelatinization temperature of teff (68–80°C)

1 The glycemic index (GI) is a measure of how carbohydrate-containing foods raise blood glucose. Foods are ranked based on how they compare to a reference food, either glucose or white bread, which has a GI of 100. The consumption of high GI foods leads to a rapid and large release of glucose into the blood.

(Bultosa 2007; Wolter et al. 2013) can hinder gelatinization and thus decrease susceptibility to enzymatic attack by α-amylase (Fardet et al. 2006).

Protein

The average crude protein content of teff is 11 percent, similar to other more common cereals such as wheat (Table 15.2). Teff's fractional protein composition suggests that glutelins (45 percent) and albumins (37 percent) are the major protein storages, while prolamins are a minor constituent (about 12 percent) (Bekele et al. 1995; Tatham et al. 1996). In contrast, more recent studies report that prolamins are the major protein storages in teff (Adebowale et al. 2011). The different methods of extraction between these studies may explain the contradictory findings. By examining the amino acid profile, the higher contents of glutamine, alanine, leucine, and proline and the relatively lower content of lysine further suggests that prolamins are the major storage proteins (Adebowale et al. 2011). Teff's amino acid composition is well balanced (Table 15.2). A relatively high concentration of lysine, a major limiting amino acid in cereals, is found in teff. Similarly, compared with other cereals, higher contents of isoleucine, leucine, valine, tyrosine, threonine, methionine, phenylalanine, arginine, alanine, and histidine are found in teff.

Another important feature of teff is that it has no gluten (Hopman et al. 2008). Spaenij-Dekking, Kooy-Winkelaar, and Koning (2005) investigated the presence or absence of gluten in pepsin and trypsin digests of 14 teff varieties. The digests were analyzed for the presence of T-cell–stimulatory epitopes.[2] In contrast to known gluten-containing cereals, no T-cell stimulatory epitopes were detected in the protein digests of all the teff varieties assayed, thus confirming the absence of gluten in teff. This makes teff a valuable ingredient for functional foods destined for celiac patients who are gluten intolerant.

Fat

Cereals are not the best source of fat, but as they are often consumed in large quantities, cereals can contribute a significant amount of essential fatty acids to the diet (Michaelsen et al. 2011). Fatty acids are potentially beneficial to growth, development, and long-term health. Consequently, there has been significant interest in recent years in their inclusion in diets. For instance,

2 T-cell stimulatory epitopes are defined as peptide sequences that, in association with proteins on antigen-presenting cells (APC), are required for recognition by specific T-cells.

TABLE 15.2 **Macro, amino acid, and fatty acid composition of teff grain compared with maize, sorghum, wheat, and rice**

	Teff	Maize	Sorghum	Wheat	Rice
Energy (kcal)	357	375	370	359	357
Starch (%)	73	72	63	71	64
Crude protein (%)	11	8–11	8.3	11.7	7.3
Amino acid (g / 16 g N)					
Lysine	3.7	3.6	0.3	2.1	3.7
Isoleucine	4.1	3.8	0.7	3.7	4.5
Leucine	8.5	13.8	2.1	7.0	8.2
Valine	5.5	5.0	0.8	4.1	6.0
Phenylalanine	5.7	5.1	0.9	4.9	5.5
Tyrosine	3.8	3.3	0.7	2.3	5.2
Tryptophan	1.3	0.6	0.2	1.1	1.2
Threonine	4.3	3.2	0.5	2.7	3.7
Histidine	3.2	3.0	0.4	2.1	2.3
Arginine	5.2	4.3	0.6	3.5	8.5
Methionine	4.1	2.2	0.3	1.5	2.7
Cystine	2.5	2.2	0.3	2.4	1.8
Asparagine	6.4	—	—	5.1	9.0
Serine	4.1	4.0	0.8	5.0	5.0
Glutamine + Glutamic Acid	21.8	19.7*	—	29.5	17.0
Proline	8.2	9.2	1.3	10.2	5.0
Glycine	3.1	3.8	0.5	4.0	4.5
Alanine	10.1	8.0	1.6	3.6	5.5
Crude fat (%)	2.5	4.9	3.9	2	2.2
Total polyunsaturated fatty acids	1.1	1.8	1.4	0.5	0.8
Linoleic acid (LA)	0.9	1.7	1.3	0.5	0.78
α-linoleic acid (ALA)	0.14	0.05	0.07	0.03	0.03
LA:ALA ratio	7:1	34:1	20:1	17:1	26:1
Crude fiber (%)	3.0	—	0.6	2.0	0.6–1.0
Total dietary fiber	4.5	2.6	—	—	—
Soluble dietary fiber	0.9	0.6	—	—	—
Ash (%)	2.8	1.4	1.6	1.6	1.4

Source: Agren and Gibson 1968; Bultosa and Taylor 2004; FAO 1992; Gebhardt et al. 2006; Gebremariam, Zarnkow, and Becker 2012; Hager and Arendt 2013; Juliano 1993; Ketema 1997a and 1997b; Khoi et al. 1987; Mbuya, Nkongolo, and Kalonji-Mbuyi 2011; Michaelsen et al. 2011; Mossé, Huet, and Baudet 1985; Shoup et al. 1969; and Wolter et al. 2013.

Note: *Glutamic acid only; — = data not available.

increased intake of n-3 fatty acids (α-linoleic acid) were found to reduce biological markers associated with cardiovascular disease, cancer, inflammatory and autoimmune diseases, among others (Simopoulos 2001).

The crude fat content of teff is higher than that of wheat and rice, but lower than maize and sorghum (Table 15.2). Rice, wheat, and maize contain negligible amounts of linoleic acid (LA) and only traces of α-linoleic acid (ALA). Furthermore, these widespread cereals are consumed after decortication and further refining, which reduces their amount of crude fat and n-6 and n-3 poly-unsaturated fatty acids. By maintaining whole grains, as in the case of teff, this provides a better source of fatty acids than refined ones. Teff grains are rich in unsaturated fatty acids, predominantly oleic acid (32.4 percent) and linoleic acids (23.8 percent) (El-Alfy, Ezzat, and Sleem 2012). Although a clear consensus has not been reached on the optimal ratio between LA and ALA fatty acids, the Codex standards for infant formula recommends an LA-to-ALA ratio in the range of 5 to 15 (Koletzko et al. 2005). In this regard, the LA-to-ALA ratio of 7:1 for teff can be considered favorable and is comparable to legumes that are good sources of fatty acids, such as soybean.

Fiber

The American Association of Cereal Chemists defines dietary fiber as the "edible parts of plant or analogous carbohydrates resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine" (DeVries 2003). The most recent Codex definition further added that dietary fibers should have "proven physiologic effects of benefit to health" (Cummings et al. 2009). Some of these physiologic effects include fecal bulking (laxation), lowering blood glucose levels after eating, and lowering plasma LDL-cholesterol (Champ et al. 2003). The crude fiber, total, and soluble dietary fiber content of teff is several folds higher than that found in wheat, sorghum, rice, and maize (Table 15.2). There may be several reasons for this. First, whole grains have higher fiber content than decorticated ones. Second, small grains have a relatively high proportion of bran, which is high in fiber (Bultosa 2007). Therefore, higher dietary fiber intake and the associated health benefits are expected with increased consumption of teff.

Minerals

The difference in mineral content between and within teff varieties is wide ranging. Red teff has a higher iron and calcium content than mixed or white teff (Abebe et al. 2007), while white teff has a higher copper content than red

TABLE 15.3 Mineral content of teff grain compared with other cereals (milligrams per 100 grams)

Minerals	White teff	Red teff	Mixed teff	Maize	Sorghum	Wheat	Rice
Iron	9.5–37.7	11.6– >150	11.5– >150	3.6–4.8	3.5–4.1	3.7	1.5
Zinc	2.4–6.8	2.3–6.7	3.8–3.9	2.6–4.6	1.4–1.7	1.7	2.2
Calcium	17–124	18–178	78.8–147	16	5.0–5.8	15.2–39.5	23
Copper	2.5–5.3	1.1–3.6	1.6	1.3	0.41	0.23	0.16

Source: Abebe et al. 2007; Baye et al. 2014; Gebremariam, Zarnkow, and Becker 2012; Kebede 2009; and USDA 2013.

and mixed teff (Table 15.3). Ketema (1997a and 1997b) analyzed 12 genotypes of teff grown in different agroecologic settings and 5 varieties grown in a greenhouse in Great Britain and reported that genetic and environmental factors affect the iron content of teff. This may partly explain the high variability in the mineral content reported in different studies.

Notwithstanding the differences described in Table 15.3, teff has a higher iron, calcium, and copper content than other common cereals (Mengesha 1966). The zinc content of teff is also higher than that of sorghum and wheat. However, the very high mineral content of teff (that is, iron) has been contested and in many instances attributed to soil contamination (Ketema 1997a and 1997b; Abebe et al. 2007). For example, Hallberg and Björn-Rasmussen (1981) reported that teff's iron content is not different from other cereals by showing that iron content drops from 39.7 milligrams per 100 grams to 3.5 milligrams per 100 grams when grains are washed with dilute hydrochloric acid. However, washing with acid is likely to lead to loss of acid-labile intrinsic iron and thus may underestimate the iron content. For instance, Areda et al. (1993) reported that acid-washing of teff grains led to a 50 percent greater loss of iron than washings with de-ionized water. Comparing uncontaminated teff to barley, wheat, maize, and sorghum, Mengesha (1966) reported that teff is superior in its mineral content, particularly in calcium and iron. More recently, Baye et al. (2014) examined the content of iron, zinc, and calcium in teff, barley, wheat, and sorghum before and after washing with de-ionized water. Mengesha (1966) found that washing the grain significantly decreased the iron content as well as the variability between replicates. Despite this decrease, the variability between replicates for teff remained relatively high, suggesting that soil contamination in teff is relatively high compared with other cereals.

The mineral contamination of teff is probably due to its small size, which suggests increased contact with soil over a larger area (Baye et al. 2014). The contamination of cereal grains in Ethiopia, particularly in teff, has often been associated with traditional methods of threshing grain under the hooves of cattle (Bezwoda et al. 1979). More recently, Ambaw (2013) compared the iron content of the same teff variety after laboratory (manually) and traditional threshing. Traditional threshing led to 30 percent to 38 percent increase in iron content, mainly due to soil contamination. The iron content of the lab-threshed teff was 16 milligrams per 100 grams dry matter, which was still higher than what is found in many cereals. This suggests that although the intrinsic iron content of teff may not be as high as previously thought, teff is still a better source of iron than other cereals like wheat, barley, sorghum, and maize.

In contrast to iron, Baye et al. (2014) showed that under the same conditions the values reported for calcium and zinc are consistent and are less affected by washing. This suggests that soil contamination contributes little to the content of these minerals in teff.

Phytochemicals in Teff

For minerals to be used for normal metabolic functions (bioavailable), they need to be absorbed through the small intestine (Fairweather-Tait 2002). The bioavailability of minerals depends on subject/host and dietary factors (Hurrell and Egli 2010). Among dietary factors, phytochemicals, such as polyphenols and phytates, constitute major mineral absorption inhibitors and hence were, for a long time, referred to as "antinutritional factors." However, in recent years the recognition of their health-promoting effects including antidiabetic, anticancer, and antioxidative (Shamsuddin 1995) properties made the term "antinutritional factor" obsolete (Schlemmer et al. 2009).

Phytates

Phytates are a common constituent of cereals and legumes (Schlemmer et al. 2009). It is the primary form of phosphorus storage in seeds and accounts for 60 percent to 90 percent of the total phosphorus. It can constitute as much as 1.5 percent of the dry weight of cereals (Loewus 2002; Bohn, Meyer, and Rasmussen 2008). Teff contains high amounts of phytate (Table 15.4) with a wide range of variability, probably due to differences in varieties and growing conditions. Teff's phytate content is comparable to values reported for whole grain cereals (Schlemmer et al. 2009). Such high values in phytate are likely to impair the absorption of iron and zinc (Hurrell and Egli 2010). The mechanism by which phytate inhibits mineral absorption is based on the formation of insoluble phytate-mineral or peptide-mineral-phytate complexes in

TABLE 15.4 Phytochemical composition of teff grain

Phytochemicals	Quantity
Phytate (milligrams per 100 grams dry matter)	682–1,374
Tannin (milligrams catechol equivalent per 100 grams dry matter)	16
Total polyphenols (milligrams gallic acid equivalent per 100 grams dry matter)	140
Iron-binding phenolics	
Galloyls (milligrams tannic acid equivalent per 100 grams dry matter)	210
Catechols (milligrams catechin equivalent per 100 grams dry matter)	200
Phenolic acids (µg per milligrams)	
Protocatechuic	25.5
Gentisic	15
p-OH Benzoic	—
Vanillic	54.8
Caffeic	3.9
Syringic	14.9
Coumaric	36.9
Ferulic	285.9
Cinnamic	46

Source: Abebe et al. 2007; Baye 2013; Baye et al. 2014; Dykes and Rooney 2006; McDonough, Rooney, and Derna-Saldivar 2000; and Umeta, West, and Fufa 2005.

Note: Most analyses did not use the same method and thus comparison among cereals would be misleading; — = data not available.

the gastrointestinal tract (Weaver and Kannan 2002). Furthermore, phytates form complexes with endogenously secreted minerals such as zinc (Sandström 1997; Manary et al. 2002) and calcium (Morris and Ellis 1985), making these minerals unavailable for reabsorption into the body.

Phytate can be degraded by endogenous phytases, which can be activated by food-processing techniques like soaking, fermentation, and germination and to a lesser extent during cooking. For instance, fermentation of injera has been shown to result in phytate degradation through the activation of endogenous phytases (Umeta, West, and Fufa 2005; Baye, Mouquet-Rivier et al. 2013; Baye et al. 2014). However, the application of exogenous commercial enzymes can be more effective in degrading phytates (Troesch et al. 2009; Baye, Guyot et al. 2013). On a positive side, phytates have been shown to prevent kidney stones by serving as crystallization inhibitor of calcium salts in biological fluids (Curhan et al. 2004). They also have glucose-lowering (Lee et al. 2005, 2006) and anticancer properties (Singh, Agarwal, and Agarwal 2003). Given these positive effects of phytates, it remains unknown as to whether there is an optimal concentration of phytate where the beneficial effects can be appreciated with little or no compromise to mineral bioavailability. Further investigations are needed to find more conclusive results.

Polyphenols

Polyphenols are secondary metabolites of plants involved in the defense against pathogens or ultraviolet radiation (Manach et al. 2004). Polyphenols similarly protect cell constituents against oxidative damage, limiting the risk of diseases associated with oxidative stress (Scalbert et al. 2005). Baye (2013) reported the total polyphenol content of teff, wheat, barley, and sorghum whole grains using the modified Folin-Ciocalteu's method. Red sorghum has the highest content of total polyphenols expressed as gallic acid equivalents (GAE) per 100 grams of flour (1,607 milligrams), followed by barley (310 milligrams), wheat (143 milligrams), teff (140 milligrams), and white sorghum (81 milligrams). However, only one variety of teff, sergegna, was analyzed; thus, to what extent varietal differences in teff influence polyphenol contents remains to be investigated.

Polyphenols can hamper iron absorption from plant-based foods (Hurrell and Egli 2010). Consequently, reducing polyphenol contents in predominantly plant-based diets has been encouraged (Matuschek and Svanberg 2002). The iron-binding properties of polyphenols are associated, however, with the catechol (ortho-dihydroxy benzene) and galloyl (trihydroxy-benzene) functional groups. Hence, not all polyphenols possess inhibitory effects (Brune, Rossander, and Hallberg 1989). The galloyl content of teff was similar to that of wheat, white sorghum, and barley, whereas the catechol content was comparable to that of barley but higher than that of wheat and white sorghum (Baye 2013).

The polyphenol profile of teff was reported by McDonough, Rooney, and Derna-Saldivar (2000) (Table 15.4). Ferulic acid is the major constituent of phenolic acid in teff. Vanillic, cinnamic, and coumaric are also important constituents of the phenolic acids. These major constituents of phenolic acids in teff do not have galloyl and catechol functional groups and thus are less likely to hamper iron absorption. This suggests that it may be possible to benefit from the antioxidative properties of the polyphenols in teff while not compromising on iron bioavailability. Indeed, Alaunyte et al. (2012) showed that by supplementing wheat bread with 30 percent teff flour, it was possible to significantly increase the total antioxidant capacity from 1.4 to 2.4 mM trolox equivalent antioxidant capacity (TEAC) per 100 grams.

In summary, compared with grain of other more common cereals, teff is superior in its nutrient composition. Its starch is slowly digestible and consequently has a low GI; it has a favorable amino acid composition and contains no gluten. Teff is also a good source of unsaturated fatty acids and has a favorable LA-to-ALA composition. Teff is high in minerals, especially iron and calcium. Furthermore, the high dietary fiber along with the relatively good concentration in phytochemicals makes teff a good contender for a functional food for health promotion and disease prevention. Nevertheless, the use of teff for human consumption is limited to only a few countries in the world (Ethiopia and Eritrea).

Use of Teff for Human Consumption

Teff is cultivated in a few countries such as South Africa, India, the United States, Eritrea, and Ethiopia, but it is primarily used for human consumption only in the latter two. Although teff has been used for food in Ethiopia for many centuries, it is only recently that its use as a food ingredient has gained interest in other parts of the world. As technological challenges are overcome in processing teff to make bread and other food products, demand for teff is likely to increase globally.

Forms of Consumption

Teff is mainly used for the making of injera. Injera is made by mixing cereal flour with water to make dough and then triggering the fermentation process by inoculating with ersho, a starter obtained from previous fermentations (Baye, Mouquet-Rivier et al. 2013). The fermentation lasts on average two to three days, after which the dough is thinned into a batter before steam baking. Teff is the preferred grain for making injera, primarily for its better sensory attributes (taste, color, smell) and shelf life (Zegeye 1997; Yetneberk et al. 2004). Besides the ability to easily roll injera, softness is an important quality attribute since this allows easy wrapping of the sauces (wot) consumed with it. In this regard, the superiority of teff was demonstrated by the minimal force required to bend fresh, 24-hour- and 48-hour-stored injera relative to injera made from other grain (Yetneberk et al. 2004). Similarly, incorporating teff flour into the sorghum flour has been shown to improve the sensory attributes of sorghum in injera (Yetneberk, Rooney, and Taylor 2005). Moreover, blending teff with wheat, as is often observed in less-privileged households (Piccinin 2002), has been found to be nutritionally beneficial, as it allows higher phytate degradation due to the higher endogenous phytase activity in wheat (Egli et al.

2004; Good 2009). Although used to a much lesser extent than for injera, teff can also be used for the making of porridges, unleavened breads (kitta), gruels (atmit), and traditional alcoholic beverages like tella and arake (Gebremariam, Zarnkow, and Becker 2012).

Teff: A Future Global Food

There has been a growing global interest in the use of teff as a food ingredient.[3] This interest is mainly attributed to the growing Ethiopian diaspora community but also to teff being gluten-free and thus a candidate ingredient for food products destined for people with celiac disease (Hager et al. 2013; Wolter et al. 2013). The relatively high nutrient content (that is, minerals) of teff is also likely to be well suited for celiac patients who usually suffer from mineral malabsorption (García-Manzanares and Lucendo 2011).

The incorporation of whole grains in bread making is often challenging. This is further complicated when gluten-free ingredients are used, since gluten plays an essential role in producing leavened bread with a fine open structure (García-Manzanares and Lucendo 2011). In relation to this, the addition of teff flour to bread dough in higher quantities has been shown to negatively affect the sensory properties of the bread. For instance, the replacement of wheat flour with greater than 10 percent teff flour has been associated with lower sensory scores, lower specific volumes, and higher crumb firmness than wheat bread (Ben-Fayed, Ainsworth, and Stojceska 2008; Mohammed, Mustafa, and Osman 2009).[4]

The use of enzymes provides an alternative strategy to improve the texture and sensory properties of teff-enriched breads. Alaunyte et al. (2012) have shown that the application of a combination of enzymes, including xylanases, amylase, glucose oxidase, and lipase improved the quality of teff-enriched breads. In contrast, treatment with glucose oxidase or protease did not show any improvement in the sensory and textural attributes of teff breads (Renzetti and Arendt 2009). This suggests that the type, dose, and combination of the enzymes used determine their effects on the quality

3 For a discussion of injera exports from Ethiopia, see Chapter 2. No data are available on teff exports given that there is still an export ban in place (except for a limited number of commercial farmers who have recently been granted an exemption).

4 Sensory evaluation consists in giving scores for sensory attributes such as taste, color, mouthfeel, odor, and texture. The scores are given using hedonic scales with a maximum score of 5, 7, or 9. Specific volume and crumb hardness are among the major sensory attributes for bread.

of teff-enriched breads. Further studies are needed to determine the optimal doses and conditions needed to improve the processing and sensory attributes of teff-enriched breads. Another alternative is to use hydrocolloids such as xanthan gum and hydroxypropylmethylcellulose (HPMC). Hager and Arendt (2013) have shown that the addition of HPMC in gluten-free cereals, including teff, reduced crumb hardness, whereas xanthan increased it. Further research in this regard is needed to determine optimal water and hydrocolloid addition levels.

Although the addition of enzymes and hydrocolloids can improve the sensory attributes of teff-enriched or teff-based breads, there is a growing interest in reducing the use of food additives. A good alternative is sourdough technology, which can lead to improvements in the texture and shelf life of breads (Arendt, Ryan, and Dal Bello 2007; Schober, Bean, and Boyle 2007; Moore, Dal Bello, and Arendt 2008). However, much work is needed to evaluate the robustness of this approach, particularly for teff-enriched or teff-based breads. The possibility of using teff for food products other than bread has begun to be evaluated. Coleman et al. (2013) confirmed the suitability of teff flours for biscuits and cake making. Similarly, studies evaluating the possibility of using teff in pasta formulations (Hager et al. 2013), beer making (Gebremariam, Zarnkow, and Becker 2012), and gel-like food formulation (Abebe and Ronda 2014) have shown promising results. These efforts show that teff can be used in various products familiar to Western culture, especially in the formulation of gluten-free products.

Health Benefits of Teff and Teff-Based Products

Iron Deficiency

Iron-deficiency is the most widespread micronutrient deficiency globally, affecting more than 2 billion people (Zimmermann and Hurrell 2007). Growth retardation, impaired mental and psychomotor development, child and maternal morbidity and mortality, and decreased immunity and work performance are among the adverse effects of iron deficiency (Georgieff 2011). The etiology of iron deficiency includes diseases that induce excessive loss or cause malabsorption of dietary iron, low intakes of bioavailable iron, or increased requirements due to physiologic status (for example, pregnancy, infants, and young children) (Pasricha et al. 2013).

Inadequate iron intake is common in low- and middle-income countries, particularly among infants and young children (Gibson et al. 2010) and pregnant women (Clark 2008). Food fortification and nutritional supplements may constitute effective strategies to prevent iron deficiency (Stoltzfus 2011). However, these strategies are not without side effects, especially when applied to environments where malaria and infections are prevalent (Sazawal et al. 2006; Zimmermann et al. 2010). Therefore, adjusting iron intakes with iron-rich foods may be preferred. Teff can be a good alternative (Gebre-Medhin et al. 1976; Adish et al. 1999). Alaunyte et al. (2012) showed that by supplementing wheat bread with 30 percent teff flour, the iron content of the bread more than doubled. By assuming an average daily consumption of 200 grams of teff-enriched bread, it is possible to cover between 42 and 81 percent and 72 and 138 percent of daily intake requirements for iron in women and men, respectively (Alaunyte et al. 2012).

The bioavailability of iron in teff is likely to vary depending on processing. For instance, during the fermentation of injera, significant decreases in phytate content results in an ideal phytate-to-iron molar ratio (Umeta, West, and Fufa 2005; Baye et al. 2014). Given that part of the iron in teff has been attributed to soil contamination, to what extent molar ratios accurately predict iron bioavailability has been questioned (Baye et al. 2014). However, Bokhari et al. (2012) showed that consumption of 30 percent teff-enriched wheat breads can help maintain serum iron levels in pregnant women. The study also suggested that degradation of phytates may lead to better iron bioavailability. Given the high iron content of teff and its potential contribution to food-based approaches to improve nutrition, further investigations on the iron bioavailability of teff are required.[5] Indeed, if the bioavailability of iron in teff can be confirmed, teff can be a very good ingredient for celiac patients not only due to the absence of gluten but also for its high iron content.

Celiac Disease

Worldwide, 0.6 percent to 1.0 percent of the population is affected by celiac disease (CD) (Gujral, Freeman, and Thomson 2012). The prevalence of the disease in populations at risk of CD is as follows: 3 to 6 percent in type 1 diabetic patients, up to 20 percent in first-degree relatives, 10 to 15 percent in those with symptomatic iron-deficiency anemia (IDA), 3 to 6 percent in those with asymptomatic IDA, and 1 to 3 percent in individuals with

5 Food-based approaches are strategies to prevent and control micronutrient deficiencies. They consist of dietary improvement or fortification using inorganic forms of vitamins and minerals. Dietary improvement includes strategies like food-to-food fortification, dietary diversity, and household processing with the aim of improving the micronutrient content.

osteoporosis (Dubé et al. 2005). CD is caused by aberrant T-cell responses to glutens and gluten-like proteins found in wheat, barley, rye, and possibly oats (Vader et al. 2003; Arentz-Hansen et al. 2004). The symptoms include diarrhea, abdominal pain, and disturbances in nutrient absorption caused by histological alterations of the small bowel. Extraintestinal complications such as osteoporosis, infertility, and cancer have also been reported (Alaedini and Green 2005).

The only treatment for those with CD available to date is to follow a strict gluten-free diet (Fasano and Catassi 2001). This in practice is difficult given the abundance of food products containing wheat or other gluten-containing cereals. Consequently, inadequate intakes of essential nutrients such as folate and vitamin B12 (Hallert et al. 2002), calcium, iron, and fiber have been observed in those with CD (Thompson et al. 2005). Also, a higher percentage of energy intake in such patients was found to be from fat instead of carbohydrates. This has a negative impact on their nutritional status (Bardella et al. 2000). Therefore, nutrient-dense gluten-free alternatives are needed.

Teff, as discussed in previous sections, contains a good amount of minerals, fiber, and phytochemicals. Compared with gluten-free cereals and pseudocereals such as quinoa, amaranth, buckwheat, maize, brown rice, and sorghum, teff is more nutrient-dense (Alvarez-Jubete, Arendt, and Gallagher 2010; Gebremariam, Zarnkow, and Becker 2012). Furthermore, the low glycemic index of teff may help maintain good glycemic control. This is very important given the high incidence of diabetes in those with CD (Viljamaa et al. 2005).

Diabetes

The global incidence of diabetes is increasing alarmingly and has become a major public health problem (Danaei et al. 2011). In 2010 an estimated 285 million people worldwide were diabetic—a figure projected to rise to 439 million by 2030 (Shaw, Sicree, and Zimmet 2010). The socioeconomic and health implication of this disease, particularly in low- and middle-income countries, are enormous. The onset and progression of diabetes can be prevented by modifying lifestyle factors, of which diet constitutes a great part (Hu 2011). Several features of teff suggest that its consumption may prevent or control diabetes. Diets high in whole grains have been associated with a 20 to 30 percent reduction in the risk of developing type-2 diabetes (Hu 2011). Given that teff is consumed as a whole grain, similar effects can be expected from the consumption of teff. Although the mechanism by which whole grains help in the prevention of type-2 diabetes is not clearly elucidated, it is thought to be through the synergistic effects of the essential macronutrients and micronutrients as well as phytonutrients (Jonnalagadda et al. 2011).

Among macronutrients, the type of carbohydrate and its digestibility play a central role in glucose levels after eating and hence on the risk to diabetes (Sheard et al. 2004). Relative to wheat, teff has a low glycemic index and thus is better suited for diabetic patients (Wolter et al. 2013). In addition, the relatively high dietary fiber in teff relative to other common cereals can decrease fasting blood glucose levels and thus contribute to the prevention and management of diabetes (Post et al. 2012). The conditions of impaired antioxidant status and inflammation have been linked to the development of insulin resistance and type-2 diabetes (Wellen and Hotamisligil 2005; Folli et al. 2011). In this regard, the high phytate and polyphenol content in teff (Abebe et al. 2007; Baye et al. 2014) and the associated antioxidative property is likely to prevent and control diabetes (Lee et al. 2006; Munir et al. 2013). However, while studies to evaluate the antidiabetic property of teff consumption are of interest, so far such studies are very limited.

Conclusion

Teff, perhaps the world's smallest cereal grain, is composed of complex carbohydrates with slowly digestible starch. It has a similar protein content to other more common cereals like wheat but contains no gluten. Teff's amino acid composition is well balanced and contains relatively higher concentrations of lysine than what is commonly found in other cereals. Teff is a comparatively good source of essential fatty acids, fiber, minerals (especially calcium and iron), and phytochemicals, such as polyphenols and phytates. Despite having a very good nutrient profile, teff's consumption is limited to Ethiopia and Eritrea. The limited knowledge of teff's nutrient composition along with processing challenges faced in making teff-based food products adapted for international consumers has restrained its global use for human consumption.

However, in the recent past studies on the nutritional composition of teff and its processing quality and development of new teff-based food products have grown. These studies have confirmed the excellent nutrient composition of teff and demonstrated that through the use of enzymes, hydrocolloids, or sourdough fermentation that it may be possible to overcome food-processing challenges faced when using teff as an ingredient for bread making. Further research should investigate the variation in nutrient composition across teff varieties, the role of teff consumption on the management and prevention of diabetes, and the human absorption (bioavailability) of iron in teff and how it can contribute to the prevention of iron deficiency. Along with the possible health benefits in managing celiac disease, and a possible solution in preventing and controlling iron deficiency and diabetes, these all indicate the potential of teff to be a future global functional food for health promotion and disease prevention.

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