

Tef: The Rising Ancient Cereal: What do we know about its Nutritional and Health Benefits?

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Abstract This review covers the nutritional significance of tef cereal as compared to other common cereals with emphasis on carbohydrate content and starch digestibility, protein content, iron and zinc bioavailability and antioxidant potentials. Tef is a gluten free cereal and contains the highest iron and calcium among other cereals. It has high micro- and macro-nutritional profile and is becoming globally popular in the healthy grain food chain. Tef starch has a high gelatinization temperature, an essential precondition in the preparation of low glycemic index foods. There are significantly conflicting reports of iron content of tef ranging from 5 to 150 mg/100 g dm. The traditional fermentation of *injera* reduced majority of the phytic acid but no significant change to mineral bioavailability was observed. This review indicated that studies on starch digestibility, protein characterization, amylase and protease inhibitors, mineral bioavailability and antioxidant potentials are needed to further explore the nutritional and health benefits of tef.

Keywords Tef · carbohydrate · protein · mineral · bioavailability · antioxidants

Abbreviations

AUC	Area under curve
dm	Dry matter
DPPH 2	2-diphenyl-1-picrylhydrazyl
FRAP	Ferric reducing antioxidant power
GAE	Gallic acid equivalent
GI	Glycemic index
PA	Phytic acid
RDS	Rapidly digestible starch
RS	Resistant starch
SDS	Slowly digestible starch
TEAC	Trolox equivalent antioxidant capacity

Introduction

Tef [*Eragrostis tef* (Zucc.) Trotter] is a tropical cereal crop belonging to the family of *Poaceae*, subfamily *Eragrostoidae*, tribe *Eragrosteae*, and genus *Eragrostis* [1]. It is adaptable to a wide range of agroecological conditions from as low as near sea level up to 3000 m above sea level (masl), however, it grows best at altitudes between 1500 and 2500 masl [2]. In Ethiopia where it is the primary center of origin and diversification, tef covers about 3 out of the 8 million hectares used for cereal crop production and its annual production is approximately 3.8 million tons and almost all of this is consumed within the country [3]. Compared to other cereal crops, tef is a lower risk crop to drought as it can withstand adverse weather conditions which make it a preferred crop by the rain fed substance agriculture Ethiopian farmers.

Tef kernel size is very small with an average length and width of 1.20 and 0.75 mm, respectively and due to its smallness, it is difficult to separate tef into its anatomical parts of germ, bran and endosperm [4]. Consequently, its consumption mode is as whole meal that may positively and/or negatively

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influences the nutritional value of the cereal. *Injera*, a soft pan cake made of a thin tef flour sourdough is a staple diet in Ethiopia, [5] and it is the major traditional food product made out of tef. This cereal is mostly preferred to make *injera* because of its excellent quality *injera* with very desirable texture which can last up to three days at room temperature without compromised organoleptic quality. Indeed, from a nutritional point of view, tef had been considered as an ordinary cereal in Ethiopian throughout history. Since there were no extensive studies on its nutritional and health benefits, it had been considered as the food of the poor while wheat based products got great deal of social value and a premium price until very recently. The nutritional and health importance of tef was started to be realized globally mainly after its feet touched in the Netherlands in 2003 and subsequently there were also groundbreaking research findings by Dekking [6] and Hopman [7] again from the Netherlands which proved tef actually was a healthy food at least for people with celiac diseases due its gluten free nature. Currently, it has a huge global recognition in its nutritional and health benefits and its price is skyrocketing compared to the other common cereals such as wheat, maize, rice, sorghum and oats. Due to an enormous imbalance of domestic tef market and weak purchasing power of the majority poor, the Ethiopian government had to ban tef export starting from 2006 but currently there are big efforts underway to intensify and mechanize production and revive the export trade.

Recently, tef has been included in the list of gluten free foods of 'Celiac Diseases Foundation' and 'Celiac Support Association'. The inclusion in these lists could have also boosted the chance of tef to get more niche market by the celiac diseases affected segment of population. However, it is not yet clear if tef has other unique nutritional or functional properties making it extremely expensive compared to other gluten free cereals such as maize, sorghum and rice in the Western countries. In fact, Abebe and Ronda [8] broadly stated that interest in the food application of tef has increased in the recent years because of its good nutritional qualities and absence of gluten.

Research on the nutritional, health and functional properties of tef has been increased probably due to its global acceptance and the interest among consumers to know more about the nutritional, health benefits and functional properties of this cereal has also increased. The purpose of this review was to summarize the existing literature on tef concerning its nutritional and health significance. It widely and critically examined the nutritional profile of tef in respect to glycemic properties, mineral contents and bioavailability and antioxidant potentials. The existing literatures dealing with tef grain proximate composition and nutritional benefits are presented and compared to the properties and contents of other common cereal grains and finally major research gaps are pointed out.

Brief history and diversity of tef

The origin of tef is in Ethiopia, where it shows major diversity and highest production [9].

It has been introduced to different parts of the world through various institutions and individuals. The Royal Botanic Gardens, Kew, imported seed from Ethiopia in 1866 distributed it to India, Australia, the USA and South Africa [9]. Recently, about seven tef varieties from Ethiopia were also introduced to the Netherlands in 2003 by the Soil and Crop Improvements Company and currently Netherlands is the major producer and source of tef for the European markets.

Composition and Health Benefits

Carbohydrates

Total carbohydrate is the summation of monosaccharides, disaccharides, oligosaccharides, polysaccharides and total dietary fiber while that of available carbohydrate excludes the dietary fiber. As indicated in Table 1, the total carbohydrate content of tef grain ranges from 57 to 86 g/100 g dm. However, the relatively very low total carbohydrate content (57 g/100 g dm) reported by El-Alfy *et al.* [15] in a red type of tef seems unrealistic. Abebe and Ronda [8] have shown comparatively very high total carbohydrate content of different tef varieties in the range of 83–86 g/100 g. The total carbohydrate content of tef reported by El-Alfy *et al.* [15] is quite suspicious in that the starch content which is only part of carbohydrate alone accounted as much as 74–79% (w/w) in different tef varieties [8, 22]. Similarly, Shumoy and Raes [23] and Hager [24] also revealed starch contents that ranged from 66 to 76% (w/w) and 64% (w/w) dm in tef varieties grown in Ethiopia and in the Netherlands, respectively.

Starch Composition and Digestibility

Starch can be divided into linear polymers (amylose) and as macromolecules of shorter chains with α -1-6 branch linkages (amylopectin). The proportion amylose and amylopectin of a starch gives starch its typical functional properties during food processing. Bultosa *et al.* [25] revealed amylose content of 28.2% of the total starch of tef grain. Similarly, Shumoy and Raes [23] also showed amylose content of different tef varieties in the range of 29–31%. On the other hand, Hager *et al.* [24] and Abebe and Ronda [8] discovered a relatively lower amylose contents in the range of 20–22% in different tef varieties (Table 2).

Starches containing an amylose-amylopectin ratio $\sim$ 20:80 are categorized as normal starches and those having a higher ratio are called high amylose starch [33]. High amylose starches require temperatures of up to 150 °C in the presence

Table 1 Chemical composition (g/100 g dm) of tef grain compared with other cereals (all values are expressed or recalculated on dry matter)

Composition	Tef	Wheat	Rice	Maize	Sorghum	Oat	Quinoa	Buckwheat	Amaranth
Total carbohydrate	(83–86), 73.1–57.3	75.9	74.3	73.1	74.6	69.4	58.1	71.5	65.7
Crude Protein	12.84, 10.4, 13.2, 20.9	13.2	8.37	6.4	5.3	7.7	15.39	14	12.5
Crude fat	5.1, 4.9, 2.6, 2.4	1.6	1.0	1.4	3.9	7.5	3.9	2.9	5.8
Total dietary fiber	5, 12.2, 3.7	3.9	0.49	3.1	5.1	4.5	8.1	2.5	15.5
Insoluble dietary fiber	7.4, 4.3	1.5	4.11	9.9	8.0	4.5	10.4	6.7	9.0
Soluble dietary fiber	0.94, 4.8	1.5	0.2	0.7	0.8	0.4	2.0	7.1	6.5
References	[10–13, 8, 14–16]	[17, 10, 11]	[18, 19, 10]	[18, 19, 10]	[10, 17, 18]	[20, 10, 21]	[10, 11]	[17, 10, 17]	[17, 11]

of water to get fully gelatinized, which is not actually attainable under normal cooking and baking circumstances and thus results in foods with a lower digestibility. The linear chains of glucose in amylose are capable of forming a complex with fatty acids and become difficult for the access of hydrolytic enzymes during digestion while starches with higher proportion of amylopectin do not form glucose lipid complex which increase their vulnerability for easy access by the hydrolytic enzymes [34].

The degree of starch gelatinization is also highly dependent on the starch size, shear force and extent of processing temperature among others. Starch granule could be categorized as large (>25 µm), medium (10–25 µm), small (5–10 µm) and very small (5–10 µm) [15] and based on this, tef starch is categorized as very small in diameter (Table 2). However, in addition to amylose/amylopectin proportion of native starch and starch granule size, other factors that determine the rate of starch enzymatic hydrolysis includes, but not limited to, the feature of granular morphology that determines the mechanism by which the enzyme attacks the starch either by surface erosion or digestion via pore route, arrangement of crystalline and amorphous regions in the granule, size of blocklet that contains both amorphous and crystalline lamella, the structure of amylose and amylopectin which explains the distributions of branch (chain) lengths in both amylose and amylopectin and the crystalline types, 'A' or 'B'. In tef native starch, the

'A' type of crystal accounts for about 37% [25] and this could mean that tef starch will have higher digestibility but it was proved that the α -amylase degradation of tef starch granules occurs by surface erosion, probably due to the absence of surface pores in the granules which obviously result in a very slow starch digestion [35]. Therefore, starch digestion is a function of all the properties mentioned above and it is not possible to predict the rate of starch digestion if all of the above factors are not taken into consideration. Starch fractions based on digestibility are classified as resistant starch (RS), slowly digestible starch (SDS) and rapidly digestible starch (RDS). Tef starch's RS, SDS and RDS as reported in Soil & Crop biodiversity [36] - tef information map version were 20, 50 and 30%, respectively. On the other hand RS, SDS and RDS, respectively in the range of 7–11%, 31–41% and 29–33% [37] and 12–30%, 19–53% and 17–68% [23] were also reported in different tef varieties grown in Ethiopia.

The high RS and SDS of the flour could be an indication for slower starch digestibility which eventually result in a mild to lower glycemic index (GI). An *in vitro* study on the native starches of tef flour indicated that only 4.7% of the starch was digested after incubation with alpha-amylase for 0.5 h, while it increased up to 32.6% after 5 h [35]. However, prediction of digestibility and/or GI merely on based a flour's starch fraction content may not be adequate as the starch digestibility of a food product is largely dependent on the properties and

Table 2 Starch properties of tef compared to other cereals

Cereal	Starch granule	Amylose%	Gelatinization temp. [°C](T_O , T_P , T_E)	Pasting properties (cP) PV, BV, FV, SV	References
Tef	(2–6), (3–8)	(28.4), 19.7, (21–22)	(68, 74, 80), (66, 71, 77)	(735, 49, 1406, 680), (2690, 790, 2920, 1010)	[22, 16, 8, 24, 25]
Wheat	(10–35)	21.10	(55, 61, 66)	(1599, 588, 2094, 504)	[26, 10, 16, 25]
Rice	(2.3–6.5)	21.38	(70.7, 75.7, 86.7)	(2706.7, 286.7, 4815.4, 239.54)	[21, 10, 27, 28]
Maize	(3–20)	29.5	(65, 73, 80)	(2058, 1345, 758, 86)	[29, 22, 30]
Sorghum	(6–18)	18.18	(64, 69, 73)	(2258.5, 709.2, 2422.5, 872.9)	[25, 10, 28]
Oat	(3–10)	20.42	(51, 56, 62)	(2189, 608, 3010, 820)	[16, 10, 25]
Quinoa	1.3	4.62	(52, 58, 64)	(3322, 439, 3725, 843)	[16, 10, 31]
Buckwheat	3	15.95	(59, 66, 72)	(975.6, 188.5, 622.8, 966)	[25, 10, 16, 32]

contents of the starch fractions after cooking and /or at the point of consumption. The same flour may result different contents of the starch fractions and their content could be highly affected by the way they were cooked (temperature, time, shear force, water content), the type and contents of other accompaniments. In addition to the contents of starch fractions, the rate of starch digestion or GI of a food product can also be determined by the contents of other constituents such as proteins, fat, and the interaction of SDS and RDS, interaction between fat and RS. Each of these food components and their interaction have different magnitude of impact on GI of a food product and it has been shown to follow a decreasing order of $\text{SDS} > \text{RS} > \text{fat} > \text{interaction between SDS and RDS} > \text{interaction between fat and RS} > \text{RDS}$ [38].

When starch is heated in the presence of water, it tends to lose its crystallinity due to gelatinization. Ostman [39] revealed that gelatinization of starch increases the availability of the starch for enzymatic hydrolysis, facilitating digestion and thus increasing blood glucose levels. Similar score of gelatinization temperatures of onset (T_O), peak (T_P) and ends of gelatinization (T_E) (Table 2) of tef starch were reported by Bultosa *et al.* [25]. Tef starch showed the highest onset (T_O) and end of gelatinization (T_E) temperatures (Table 2) as compared to wheat, quinoa, oat, buckwheat and sorghum. High gelatinization temperatures were positively correlated to a lower GI [16]. Indeed, it has been indicated that less gelatinized native starches are less susceptible to amylase hydrolysis, resulting in a slower digestion [40]. Gelatinization of starch is a change of form of the native starch into a rapidly digestible starch form that is easily accessible for enzymatic hydrolysis. Therefore during starchy foods cooking, the starches get gelatinized and as a result the RDS content increase tremendously while the SDS and RS contents of the native starches decrease. The formation of the RDS is highly dependent on the amount of water used for cooking among others factors as water is the key factor for starch to swell, melt of the crystal forms and finally burst leaching the amylose contents. In the work of Shumoy and Raes [23] the RDS content of different tef varieties showed an increase that ranged from 60 to 85% and 3–69% when processed into traditional *injera* and porridges, respectively while a significant decrease both in the contents of SDS and RS.

The few reports on the predicted GI of tef food products are by Wolter *et al.* [16] who indicated that conventionally baked frozen tef bread had a GI of 74 which is lower than GI of breads from buckwheat (80), quinoa (95), and wheat (100) but similar to those of oat (71) and sorghum (72). The GI of foods is a term used to classify and categorize foods according to the classification of the international table of GI which shows the glycemic response of foods whether foods eaten release glucose rapidly or in a slow and sustained fashion for a period of time. Predicted GI of 32, 45, and 67 of oat, tef and wheat based egg pastas, respectively were also reported by

Hager *et al.* [41]. Furthermore, relatively higher GI that ranged from 79 to 99 and 94–137 for traditional fresh porridge and *injera*, respectively in seven tef varieties were also reported [23].

According to Ferng [42] foods are classified into three categories depending on their GI as: $\text{GI} \leq 55$ low, $\text{GI}(56\text{--}69)$ medium and $\text{GI} \geq 70$ high if glucose is used as a reference material in calculating the area under curve (AUC) on the other hand, if fresh white wheat bread is used as a reference material in the calculation of AUC, the standards of low GI, medium and high GI foods are defined as $\text{GI} < 60$, $\text{GI}(60\text{--}85)$ and $\text{GI} > 85$. Based on this classification, as all of the GI specified here were calculated based on fresh white wheat bread, the second classification standard will be taken into consideration to compare the GI of the food products and in this regard, the GI of egg based tef pasta are categorized as low, the frozen tef breads as medium, the fresh porridges in the range of medium to high while those fresh *injera* as high GI food products.

A possible explanation of the lower GI of the tef based bread and pasta food products as compared to the similarly prepared food products of other cereals could be attributed to the starch properties of tef and the presence of higher amounts of antinutritional factors such as PA and phenolic compounds in tef [43] which will be discussed more in detail further in this review. It is also known that the presence of catechin or tannic acid and/or PA can reduce protein and starch digestibility. As explained above, tef is processed as whole meal and its high fiber content may reduce starch digestibility. The presence of fibers, the physical form of starch, cooking/gelatinization and natural amylase inhibitors (e.g. phytate, phenolic compounds) could have an effect on the starch hydrolysis rate, and thus influencing the GI of tef-based foods. Tef contains high total phenolic content and phenolic compounds in general and specially flavonoids are potent α -amylase and α -glucosidase inhibitors [44]. The justification for the higher GI in both porridge and *injera* contrary to the lower GI of tef based bread and egg pasta could be attributed to the higher water content of the prior food products which was in the range of 71–73% and 59–66%, respectively in porridge and *injera* of the seven tef varieties [23]. It was shown that high water content significantly increases the rate of starch gelatinization which eventually increases the GI of the resulting food [45]. Thus, GI of a food product is also dependent on the way the food was processed in addition to the nature of the starting material. This could be the reason why the same starting material, in this case tef, resulted very wide range of GI when processed into different foods.

Fiber is mostly concentrated in the bran of cereals. As tef is known as the smallest cereal, it is expected to have a higher surface area and thus the higher fiber proportion could be associated to its higher surface area. Collar and Angioloni [11] reported a higher total, soluble and insoluble dietary fiber

of tef (Table 1) compared to other common cereals except for amaranth. Even though Hager *et al.* [24] reported relatively lower values of total and soluble dietary fiber of tef compared to the report by Collar and Angioloni [11], the values still remained higher than many of the common cereals (Table 1). As the consumption mode of tef is as a whole meal, it may significantly contribute to a higher dietary fiber intake which is highly associated with many health benefits. Human subjects with high intakes of dietary fiber seem to have considerably lower prevalence of developing coronary heart disease, diabetes, obesity, stroke, hypertension, duodenal ulcer, diverticulitis, constipation, hypercholesterolemia and certain gastrointestinal diseases [46]. Looking more into detail in the fiber composition of tef could help to explain the specific possible health effects of tef consumption. The higher fiber content as compared to other cereals could be one of the blessings of tef that would make it uniquely beneficial in the current trend of human nutritional Baye [10].

Tef has mainly been used in traditional food production like *injera* but recently the interest is growing to use tef in the breads and pasta making alone or mixed with wheat. When mechanization of tef food product processing is needed, the rheological properties of tef dough are mandatory as rheological data are required in product quality evaluation, engineering calculations, and process design. There is limited literature on tef rheology, nonetheless Bultosa and Taylor [25] showed pasting, breakdown, hot past, cold paste and setback viscosity in the range of 126–191, 11–48, 115–157, 203–284 and 84–132 BU (brabender units), respectively in 13 tef varieties. Tef flour has a high water absorbance capacity, a high shear tolerance and its starch has slow retrogradation tendencies which are all good traits in food processing [47]. Abebe and Ronda [48], also showed that tef flour can form a gel with a minimum flour concentration ranging from 6 to 8%. They revealed that tef flour is suitable as a food ingredient in the formulation of gel-like foods. Further studies of rheology on the suitability of tef for regular pasta, bread and other common food products would be paramount.

Protein

The reports on crude protein level of tef flour varies widely from 10.4–20.9 g/100 g calculated based on 6.25 conversion factor [12, 15, 24, 25]. Tef crude protein level is similar to other cereals such as wheat, quinoa, buckwheat and amaranth but higher compared to rice, maize, oat and sorghum (Table 1). However, the protein content reported by El-Alfy *et al.* [15] is exceptionally higher compared to the other reports of tef protein content, or of other cereals. The reports of El-Alfy *et al.* [15] are nuance as no other results match to it and it is unlikely that cereals could have this much protein unless they are genetically modified. However, the type of tef used in the study of El-Alfy *et al.* [15] was not described

as genetically modified. Indeed these authors also reported unusually very low total carbohydrate content (57%) of the same tef.

Nutritionally, tef could be one of the best source of dietary proteins due to its high contents of all the essential amino acids as shown in Table 3. Most of the essential amino acid contents of tef protein is slightly higher or similar to other common cereals, however, lysine, the most limiting essential amino acid in cereals, seems to be specifically higher in the case of tef than the other common cereals except that of quinoa (Table 3). Tef based food products could fulfill the daily protein requirement in that all the essential amino acid contents of tef are at least equal to the FAO scoring patterns (Table 3). However, tef is known to contain both higher mineral (Table 4) and phytic acid [43] and the formation of a triple ‘protein-mineral-phytate complex’ is believed to inhibit enzymatic degradation thereby decrease the bioavailability of proteins. Literature on the effect of different food processing steps on the content, digestibility and bioavailability of tef protein is not available. The fact that tef is consumed as a whole meal and the location of both the minerals and phytic acid in cereals is in the outer grain covers makes it important to study the different processing effects on the digestibility and bioavailability of tef protein and its nutritional significance to consumers.

The reports on the Osborne solubility based fraction of tef protein are very few and they contradict to one another. The Osborne protein fractions decreased in the order of glutelins 44.6% > albumins 36.6% > prolamin 11.8% > globulins 6.7% [9]. Similarly, Bultosa [4] reported protein fractions of tef in the decreasing order of glutelins 40% > albumin 36% > globulins 18% > prolamins 10%. On the contrary, Adebawale [49] revealed tef protein fraction in the decreasing order of prolamin 40% > glutelins 22% > (albumins + globulins) 11%. The difference in the content of the Osborne fraction could be attributed in part to the use of different solvents. Tert-butanol 60% (v/v) with DTT as reducing agent was used to extract prolamin in the work of Adebawale [49] while only 60% ethanol was used by ketema [9]. Based on these few and conflicting available results, it remained difficult to know the major storage protein of tef, solubility characterization and their nutritional implications, thus further studies are paramount to determine tef protein solubility characteristics. Also it has to be confirmed if the Osborne method is valid in gluten free cereals protein fractionation.

Phenolic Contents and Antioxidants Potentials

Whole grain cereals naturally contain high amounts of phenolic compounds. Indeed, phytochemicals, such as phenolic acids, phytosterols, alkylresorcinols, lignans and folate are predominantly found in the outer layers than in the interior parts of grains [62]. Shumoy and Raes [63] reported a total

Table 3 Amino acid profile of tef compared to other common cereals (g/100 g protein)

Amino acid	Tef	Wheat	Quinoa	Buck wheat	Oat	Rice	Maize	FAO Pattern
Histidine	2.9, 2.8	2.2	2.2	2.5	1.3	2.4	4.2	
Threonine	3.8, 3.6	2.9	5.7	3.7	3.8	3.8	3.2	2.8
Lysine	5.6, 3.0	2.7	2.4	5.9	3.1	3.1	2.1	4.2
Tyrosine	3.2, 3.0	1.6	1.2	2.7	2.4	5.5	4.6	
Methionine	1.8, 3.3	1.4	0.3	1.6	1.9	2.9	0.91	2.2
Valine	5.0, 5.9	4.5	1.0	4.8	6.2	5.9	5.2	4.2
Isoleucine	3.3, 4.0	3.5	0.8	3.7	4.1	4.5	2.6	4.2
Leucine	6.1, 8.1	7.4	0.8	6.2	7.6	8.3	13.3	4.8
Tryptophan	1.3	NA	NA	NA	2.9	1.5	NA	1.4
Phenylalanine	3.4, 5.0	4.9	1.5	5.3	4.3	5.7	4.9	2.8
Cysteine	1.8	1.2	0.1	3	2.8	2.2	0.91	
Serine	4.0, 4.1	4.9	1.7	5.5	6.6	5.1	4.8	
Arginine	7.7, 4.5	4.3	3.0	8.8	5.8	8.2	4.6	
Glycine	6.1, 3.1	4.5	3.0	6.0	6.1	4.6	2.7	
Aspartic acid	7.9, 6.4	4.9	3.7	10.5	8.8	9.0	5.3	
Glutamic acid	18.3, 21.8	33.8	8.8	20.2	20.7	18.0	18.3	
Alanine	5.9, 10.1	3.7	2.2	5.6	5.1	5.8	8.2	
Proline	3.7, 8.2	10.6	1.8	4.0	4.9	NA	11.2	
References	[49, 4]	[50]	[51]	[52]	[53]	[54]	[55]	[56]

NA- not available

phenolic content of seven different tef varieties grown in Ethiopia in the range of 263–448 mg gallic acid equivalent/100 g dm. Relatively lower total phenolic contents that ranged from 126 to 219 mg GAE/100 g were also reported [13, 64]. The low total phenolic content reported by Forsido *et al.* [13] only constituted methanolic phenolic extracts or only soluble form of phenolic compounds while the reports in both the studies of Shumoy and Raes [63] and Kotaskova *et al.* [64], it is as a summation of both soluble and bound phenolic extracts. In both of these two studies brown colored seed coat tef

varieties showed superior total phenolic content compared to the white varieties.

Unlike to report of Shumoy and Raes [63] that revealed more than 84% of the phenolic compound as bound, Kotaskova *et al.* [64] showed only 31% of the phenolic compounds as bound. However, similar to the reports of Shumoy and Raes [63], Adom and Liu [65] revealed higher proportions of bound phenolic contents in different cereals such as corn 85 and 91%, oats 75 and 61%, wheat 75 and 93%, rice 87 and 65%, respectively. The reason for the wide

Table 4 Mineral content (mg/100 g dm) and ash content (g/100 g dm) of tef corresponding to other cereals

Minerals	Tef	White Wheat flour	Whole wheat	Rice	Maize	Sorghum	Oat	Quinoa	Buckwheat
Ash	2.4, 2.5	1.0	1.5	0.60	0.50	1.3	0.90	2.7	2.0
Fe	31.6, 80.1, 9.4, >150, 37.0	3.7, 5.3 1.5	3.1	0.7	2.0,3.5	3.8, 11.1	1.9	6.3	2.2
Ca	78.8, 171	15.2	35.4	58.1	6.0	5.4	25.0	70.0	18.0
Cu	2.6, 1.0	0.20	0.50	0.30	1.8	0.40	0.30	0.70	0.60
Mg	170, 187	93.0, 26.0	89.6	37.8	127	95.6	43.9	161	231
K	380, 423	174	460	112	287	225	195	855	402
P	425, 400	104	235	105	241	263	165	462	319
Mn	3.8, 3.8	1.0	2.6	0.80	0.50	0.20	0.30	3.5	0.10
Na	15.9, 6.6	4.35	2.3	1.72	3.5	6.18	1.9	2.7	1.3
Zn	2.3, 4.6	1.68	2.07	2.07	2.5	1.53	1.23	3.2	2.2
Se*	12.0	1.0		2.6	2.7		23.5	6.6	3.2
References	[10, 47, 57, 43, 4, 58]	[10, 17, 43, 58]	[10]	[10, 58]	[10, 59, 60, 58]	[10, 43, 61, 58]	[10, 58]	[10, 29, 58]	[10, 29, 17, 58]

* (µg/100 g dm)

difference of total phenolic content and the proportion of soluble and bound phenolics in tef could be attributed to the difference in tef varieties grown in different locations and methodological differences. Gallic acid, vanillic acid, caffeic acid, syringic acid, trans-*p*-coumaric acid, *m*-coumaric acid, ferulic acid, rutin, protocatechuic acid, cinnamic acid and quercetin were detected and quantified in tef flour [63, 64]. Trans-*p*-coumaric followed by ferulic acids and ferulic acid followed by catechin were the most dominant phenolic acid in the soluble and the bound extracts, respectively [64] whereas catechin followed by rosmarinic acid and ferulic followed by rosmarinic acids in the soluble and bound extracts, respectively [63].

There is scarce of information on how different food processing techniques affect the contents of total, soluble and bound phenolic contents of tef based food products. However, in the work of Shumoy *et al.* [66], it was reported that a traditional sourdough fermentation to make a pancake known as *injera* has significantly increased the total phenolic content by as much as 31–54%. In this study, the proportion of soluble phenolic extracts has increased while that of bound decreased after the fermentation. The increase of the soluble PCs could be owing to the action of endogenous and microbial enzymes initiated during the fermentation, which leads to the release of bound phenolics. Indeed several yeasts and LAB, which are also involved in tef fermentation, are capable of synthesizing enzymes like esterases, xylanases, and phenoloxidases that in turn are capable of breaking down ester linkages to release bound PCs in the form of soluble phenolic compounds [67]. The increase in the soluble phenolic proportion following the traditional fermentation would mean that an increase in the bioavailability of the phenolic compounds.

FRAP (ferric reducing antioxidant power) and DPPH (2,2-diphenyl-1-picrylhydrazyl) value in the range of 42–79 $\mu\text{mol Fe}^{2+}/\text{g dm}$ and 25–142 $\mu\text{mol trolox equivalent/g dm}$, respectively were reported in different tef varieties [63]. ABTS (2,2-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) and DPPH radical scavenging potentials that ranged from 3 to 6 and 2–5 $\mu\text{mol TEAC}/100 \text{ g dm}$, respectively were also revealed [64]. White wheat flour breads prepared by substitution of 10%, 20% and 30% by tef flour exhibited a significant increase of total antioxidant capacity from 1.4 to 2.4 mM TEAC/100 g [68] indicating that tef could be a good source of antioxidants which fight against free radicals which otherwise would cause chronic diseases.

Mineral Content and Bioavailability

Tef has the highest amounts of minerals compared to wheat, rice, maize, sorghum, oat, buckwheat and amaranth (Table 4). It specifically could be a very good source of the most important limiting minerals such as Ca, Se, Fe, and Zn. Tef certainly could be the most generous source of dietary Ca and Se

compared to other common cereals. The prevalence of selenium deficiency is high among celiac diseases patients, and tef was considered as the best gluten free cereal next to oat to mitigate this problem [58].

Although tef is known to have high mineral contents, there are concerns that the minerals in tef specifically iron is originating from direct soil contamination and due to this, researchers have tried to measure the inherent iron content by washing the grains with acid containing deionized water. However, the results obtained in different studies still vary significantly and contradict to one another. As presented in Table 4, Baye *et al.* [43] reported 80.1 and 31.6 mg/100 g of iron content for unwashed and washed tef, respectively. Iron content of >150 and 37 mg/100 g of unwashed red and white tef, respectively was also reported [57] while much lower iron contents (8.5 mg/100 g) of unwashed tef were revealed by Hager *et al.* [24].

If the higher iron content in tef is to be ascribed to soil contamination during threshing and other activities on the field, some questions should be clarified. Why is the difference of iron content so large between red and white tef [57] provided that they have similar size and passed through similar agricultural practice? Why are the results reported by different researchers contradict to one another like unwashed samples appear to contain less iron than the washed ones? For instance, there are reports of iron content (mg/100 g dm) 5.9 and 5.2 of unwashed white and red tef, respectively [69] and in that range of 12–19 in different tef varieties of unwashed but grown in a controlled system where at least the tef kernels were not in direct contact with soil [70]. On the other hands, acid containing deionized water washed tef resulted a relatively higher iron contents of 21.5 (white tef) and 21.5 (red tef) mg/100 g dm [71]. According to these contradictory reports, the iron content of tef is still controversial and it is difficult to conclude whether the higher iron content is derived from soil contamination or not. This may create fundamental uncertainties if tef has to be used to contribute in solving iron deficiency anemia and other iron deficiency related diseases.

In most cereals, PA is the major phosphate storage compound and a major chelator of nutritionally indispensable micronutrients such as iron, zinc, calcium, magnesium and manganese [72]. The storage form of PA is known as phytate or phytin, which is mainly found in the aleurone layer of grains. High contents of PA 675–1544 mg/100 g dm of tef flour, similar to that of white sorghum, red sorghum, barley and wheat was reported [43, 57, 73]. The wide range of PA content in the reports could be attributed to differences of the source of tef as there is high positive correlation in the phosphorus content of the soil and phytic phosphorus in grains.

Several food processing steps has been described to lower the PA content. During fermentation and baking endogenous and exogenous microbial phytases degrade the PA and

increase the bioavailability of essential minerals [74]. Tef *injera* baked after 96 h of spontaneous fermentation showed a decrease in PA by 73–80% in white and red tef [75]. On the other hand, it was stated a decrease of PA of *injera* from 1050 to 340 mg/100 g representing a degradation 68% when inoculated with *L. buchneri* MF58 but 42% with that of spontaneous fermentations (25 °C, 48 h) [76]. Greffeuille *et al.* [77] reported that the adverse effect of PA on iron absorption of plant based food product can only be eliminated if the PA content is decreased to a level of less than 0.1 g/100 g dm.

Iron absorption can be improved in plant based foods, if the molar ratio of PA/Fe is reduced to <1 and preferably <0.4 [78]. According to WHO [79], 55% of Zn content of a food is expected to be absorbed (considered as highly available) if PA/Zn of the food is <5; but it would be 35% (moderately available) if the ratio is 5–15 and only 15% (low availability) if >15.

Umata *et al.* [73] revealed that spontaneously fermented tef *injera* showed a 3–4 times lower molar ratios of PA/Zn (10.8), and PA/Fe (0.3) compared to unfermented tef *injera*. Abebe *et al.* [57] also indicated that the PA/Zn and PA/Fe molar ratios of traditionally fermented tef *injer*as in the range of 7–9 and 0.1–1.3, respectively in white and red tef and speculated that those reduction of mole ratios could increase Fe and Zn bioavailability. On the other hand, Baye *et al.* [80] revealed destruction of more than 90% of the PA that led to a PA/Fe molar ratio of <1 of *injera* made from mixture of tef and white sorghum but saw only little or no improvement in iron bioavailability.

Catechol and galloyls containing groups of phenolic compound such as tannins, caffeic acid, gallic acid and catechin are also known to bind iron and reduce its bioavailability. Among the major catechol and galloyls groups containing phenolic compounds identified in tef includes gallic acid, *p*-coumaric acid, protocatechuic acid and ferulic acid [64, 66]. Umata *et al.* [73] reported condensed tannin contents of *injer*as made tef in the range of 45–65 mg/100 g. More study on the tannin contents of tef, its effect on mineral bioavailability, and strategies to reduce it by the food preparation steps could be important.

Research Gaps

A systematic study to prove whether the high iron content is inherent or is due to contamination is necessary as the current reports vary significantly. *In vitro* and *in vivo* protein and starch digestibility, characterizing and measuring the GI of traditional and modern tef based food products and rank them according the international GI table, of tef food products are needed. Immunogenicity studies on gluten if many of the tef varieties are safe for celiac diseases patients and the presence of other protein allergens in different tef varieties is lacking.

As tef is a good source of minerals, studies on mineral binding catechol and galloyls group bearing phenolic compounds, antinutrients such as tannins and phytic acid and their associated effect on minerals bioavailability is lacking. Literature concerning the presence and contents of amylase and protease inhibitors of tef is not available until now, therefore, this area is worth of studying to fully understand the nutritional and functional importance of this cereal.

Conclusions

Tef is claimed as gluten free cereal grain that contains magnificent nutritional components and becoming popular as a healthy cereal. It contains higher protein and mineral contents compared to other common cereals. Tef could be a good source of dietary fiber, phenolic compounds and minerals. The high Fe content of tef is still debatable as it is not yet completely confirmed whether it is intrinsic or comes from soil contamination. The Ethiopia traditional fermentation of *injera* preparation showed major reduction of phytic acid but no significant change in the *in vitro* iron and zinc bioavailability was observed. Tef starch has lower gelatinization properties compared to other cereal grains, which can result food products with lower glycemic index.

Compliance with ethical standards

Conflicts of Interest This work was financed by CARIBU project, an Erasmus Mundus Action 2 (EMA2) partnership program, as a PhD-grant for Habtu Shumoy. This article does not contain any studies with human or animal subjects.

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