Comprehensive REVIEWS in Food Science and Food Safety

Cultivated Ancient Wheats (*Triticum* spp.): A Potential Source of Health-Beneficial Food Products

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Abstract: A sustainable and wholesome food supply is the most important incentive that has led to an increasing interest in ancient wheats over the past few decades. Domestication of wheat, followed by breeding efforts, largely over the past 2 centuries, has resulted in yield increases but with grain quality deterioration due to the reduction of protein, vitamins, and minerals in grains. It has also resulted in a decrease in food diversity due to the loss of genetic variation in the cultivated wheat gene pool. Ancient hulled wheats, einkorn, emmer, and spelt are among the early cereals that were domesticated in their places of origin in the Fertile Crescent of the Middle East where their wild predecessors still grow. The ancient wheats had a long history as part of human diet, and played an important role as a major source of food for the early civilizations in that region. The risks of genetic erosion of crop plants and the associated likely consequences for agriculture now call for revitalization of the unrealized potentials of ancestral species like einkorn, emmer, and spelt wheat, the domesticated ancestors of modern durum and bread wheats. These ancestors need to be exploited to maximize the sustainable supply of grain protein, fiber, minerals, and phytochemicals. In addition, ancient wheat biodiversity can be utilized to ensure sustainable wheat production in the context of climate change and low-input organic farming systems. This review provides a holistic synthesis of the information on ancient wheats to facilitate a greater exploitation of their potential benefits.

Keywords: diversity, einkorn, emmer, flour, grain, nutrient rich food, spelt, *Triticum* spp

Introduction

Common wheat, bread and soft wheat (*Triticum aestivum* L. em Thell; AABBDD; $2n = 6x = 42$), was the world's most important crop in 2014 with a world production of about 730 million tons harvested from an area of over 220 million ha (FAOSTAT 2016). Used as a major staple food, as bread, in many countries, it has been the most abundant source of calories and protein in the human diet, supplying nearly 20% of the total dietary protein worldwide (Braun and others 2010). Durum or macaroni wheat (*Triticum turgidum* L. subsp. *durum* Desf.) is tetraploid wheat (AABB; $2n = 4x = 28$) which is widely used for the production of pasta. Common wheat is the most widely grown species accounting for 95% of the total with durum wheat representing the remaining 5%. Hulled wheats with nonfragile spikes and hulled grains were the earliest species domesticated, almost 10000 y ago during the Neolithic period. These played a key role in the phylogenesis of modern wheat. Easy cultivation, harvestability, and long-term storage capacity of wheat grains enabled man to establish his early settlements at the dawn of civilization as populations increased in the Babylonian and Assyrian empires over the area that encompasses the "Fertile Crescent." Wheat as a staple food was cultivated in ancient Persia, Greece, and Egypt in prehistoric times.

The global distribution and utilization of wheat is a consequence of its unique dough rheological properties and the bread-baking quality of its flour. A risen dough can be baked into a loaf of bread because of the characteristic physicochemical properties of gluten that provides the dough with the required elasticity. The gluten network can be stretched as a result of CO_2 gas bubbles trapped inside the fermenting dough, which is critical in the production of a variety of breads and fermented products. Pasta quality also largely depends on the gluten protein composition and content in durum wheat grains.

Ancient cultivated wheats (einkorn, emmer, and spelt) originated in the Fertile Crescent, an area in the Middle East spreading from Jordan, Palestine, and Lebanon to Syria, Turkey, Iraq, and Iran (Figure 1), where their wild ancestors are still found (Harlan and Zohary 1966). The ancient wheats have been recognized as a primary component of the human diet in the Old World during the Bronze and Neolithic ages. They represented a strategically important food crop among the ancient Assyrian, Babylonian, and Egyptian nations (Figure 1). These hulled (glumed) wheats comprise all 3 polyploidy levels of diploid ($2x$), tetraploid ($4x$), and

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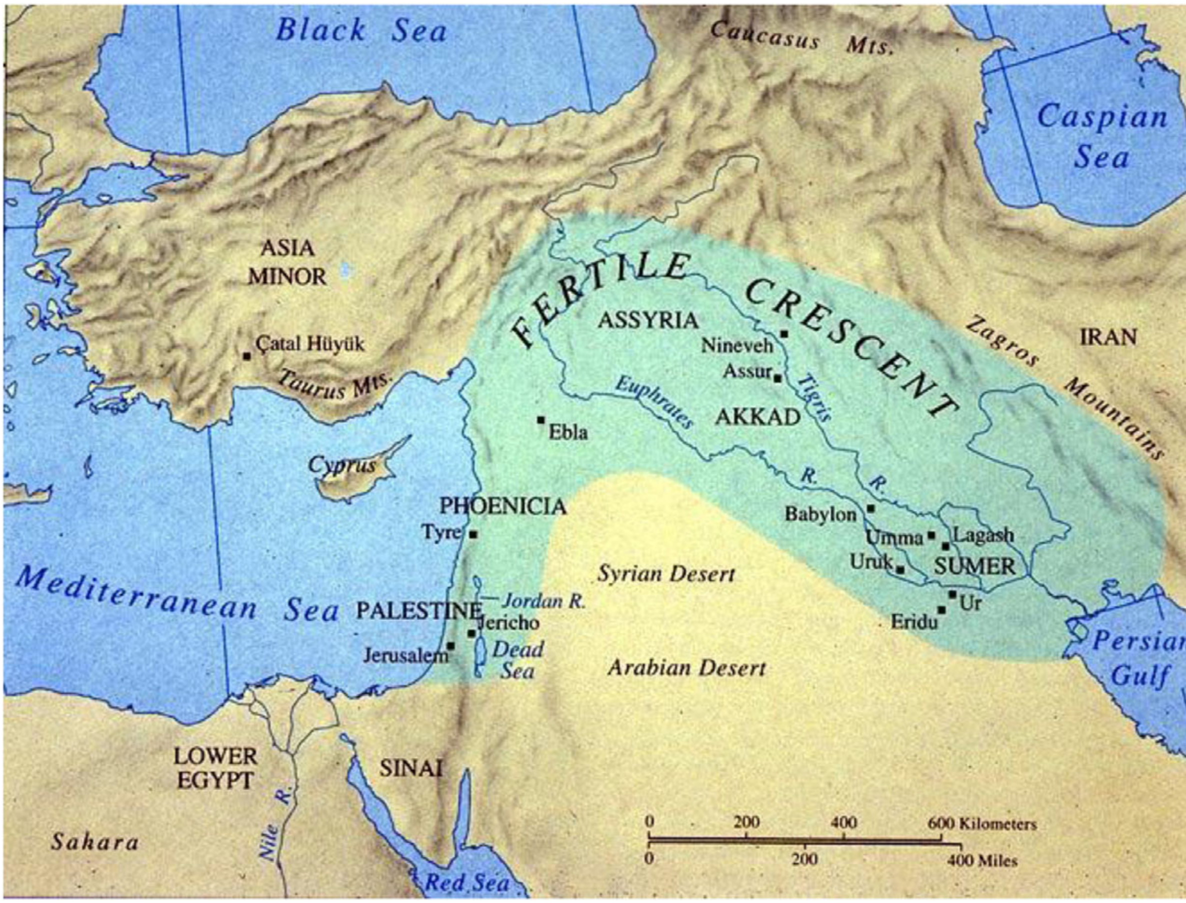

Figure 1–This is the region where some of the most ancient agricultural communities in the world came into being in the Fertile Crescent. The domestication of wheat and barley occurred thousands of years ago in this region. It also comprises Sumer, the birthplace of the 1st civilization and the Bronze Age; and Mesopotamia consisting of Sumerian, Babylonian, Akkadian, and Assyrian empires (Adapted from: http://resourcesforhistoryteachers.wikispaces.com/7.7).

hexaploid (6*x*) present in *Triticum* spp. Einkorn (*T. monococcum* L.) is a diploid wheat (AA; $2n = 2x = 14$) which is now cultivated in limited regions in the world (Arzani 2011). Emmer (*T. turgidum* L. spp. *dicoccum* Schrank ex Schübler) is a tetraploid wheat (AABB; $2n = 4x = 28$) which is a domesticated form of *T. turgidum* spp. *dicoccoides* (wild emmer wheat). *Triticum turgidum* ssp. *durum* (Desf) Husn. (durum wheat) originated from the domesticated emmer (Figure 2). Spelt (*T. aestivum* subsp. *spelta*) is a hexaploid wheat (AABBDD; $2n = 6x = 42$) and is most likely the ancestor of the free-threshing common wheat. Thus, einkorn, emmer, and spelt represent the 3 cultivated species of hulled wheat which include a bridging species between the cultivated (bread wheat and durum wheat) and wild wheats (Figure 2). Einkorn, emmer, and spelt wheat types are the earliest cultivated ones; hence, designated as ancient wheats.

Over the centuries, desirable bread quality was achieved through a variety of traditional methods effectively using available raw materials. In some places, the traditional craft of bread-making has been conserved, while in others it has undergone substantial change. For example, steamed breads in China and flat breads in the Middle East are still traditionally baked in large quantities upholding ancestral cultural traditions. North America, in contrast, has witnessed the development of new wheat cultivars since its introduction by European settlers, while innovative developments introduced by the bread-making industry have replaced maize as the traditional staple crop.

The whole wheat grain is milled and usually only the endosperm is used to make white flour, while the bran and germ are removed as by-products (see review by Hemdane and others 2016). Paradoxically, it is the whole grain that is rich in protein, minerals, and vitamins, with the refined grain largely consisting of starch. Both the common and durum wheats have the free-threshing forms in which the glumes are fragile and the rachis tough. On the other hand, the grains of the 3 ancient domesticated species of wheat (einkorn, emmer, and spelt) are covered by glumes (hulls) even after harvest. The disadvantage with these ancient cultivated wheats is that their grains are difficult to thresh because the hulls remained attached upon threshing so that further processing is required to remove the hulls or husks and make them ready for milling or pounding. The toughened glumes provide protection against pests of stored grain since these types of wheat are usually stored as spikelets.

Nutritional Qualities of Modern and Ancient Wheats

Evidence shows that the proportion of the global human population facing malnutrition due to inadequate micronutrients has risen over the past several decades (Miller and Welch 2013; Kumar and others 2016). This is believed to be partly the consequence

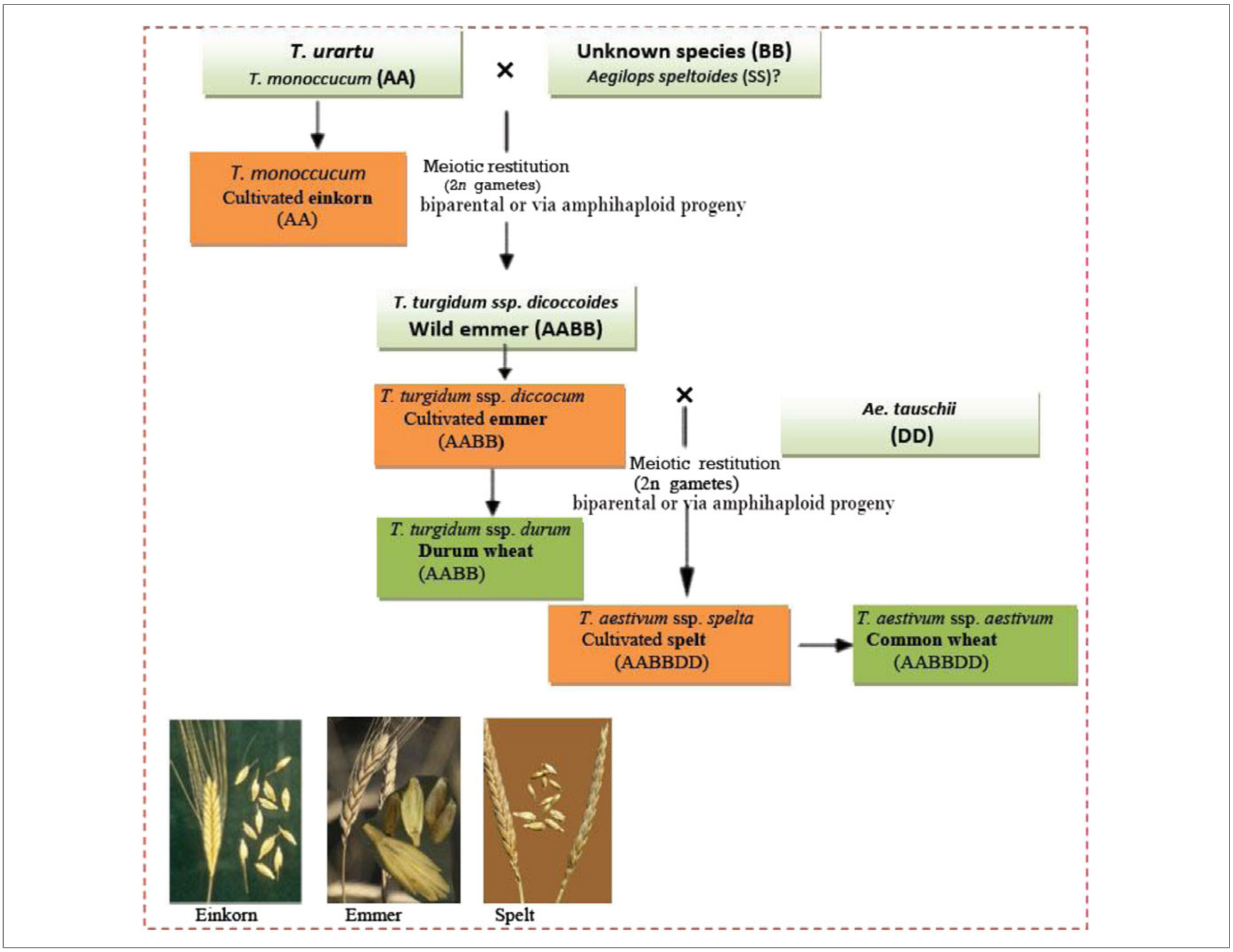

Figure 2–Phylogeny of domesticated species of the *Triticum* spp., including einkorn, emmer, spelt, durum, and common wheat.

of replacement of not only "ancient" but also "old" crop cultivars. It is well known that modern and old common wheats (*T. aestivum*) differ significantly from each other in terms of their micronutrients, with zinc and iron specifically being lower in modern cultivars (Fan and others 2008). The most commonly quoted evidence supporting this claim comes from a long-term study, of more than 160 y, conducted at Rothamsted Research (Harpenden, U.K.), which is further confirmed by several other studies evaluating old and modern wheat cultivars/lines in modern field trials. Although some evidence indicating the superiority of the old wheat over the modern one in terms of other grain quality components is scant, it is believed that intensive breeding might have led to lower concentrations of minerals in modern wheat grains due to the "yield dilution phenomenon" (Shewry and others 2016). Therefore, in the light of current evidence, there is no doubt that old common wheats are superior to modern ones due to their higher micronutrient contents (Garvin and others 2006; Fan and others 2008; Shewry and others 2016). Also, increased starch content may lead to the reduction of other grain components in modern wheat cultivars. This is further supported by the fact that increased grain yield is clearly associated with a rise in harvest index as a result of employing modern short-straw cultivars. The semi-dwarf wheat phenotype in common wheat (*T. aestivum* L.) was developed by the introduction of functionally constitutive growth repressor (*Rht*) genes which resulted in enhanced efficiency of partitioning photosynthetic assimilates into grain.

An alternative or supplementary hypothesis would be the smaller root system due to the dwarfism that may have negatively influenced the capacity of the plant to absorb micronutrients from the soil, or its capacity to store them in the vegetative organs before being remobilized to the grain. Nonetheless, the importance and improved health benefits of wheat in the dietary chain of many people in the world imply that wheat breeders should target the concentration of beneficial ingredients in the grain of novel cultivars ideally using ancient wheat species. However, both ancient and old wheats need to be exploited to achieve biofortification aimed at enhancement of micronutrient contents and their bioavailability in grains.

Malnutrition, or nutritional deficiency, is one of the main reasons underlying the high morbidity and mortality rates especially in poor households that, compared with those with higher incomes, are more likely to eat more starch than protein from meat or other sources. The need for crop diversification, the increasing demand for nutritionally healthy food products, and the asserted therapeutic properties of foodstuff have led to a renewed interest in ancient wheats such as einkorn (*T. monococcum* L.), emmer (*T. turgidum* ssp. *dicoccum*), or spelt (*T. spelta*). The global increasing incidences of obesity and metabolic diseases related to diet have resulted in a great interest in the ancient food diet. Recent evolutionary diet studies have suggested that our present-day diets should somehow bear resemblance to those of the Palaeolithic human diets containing carbohydrate-rich food derived from both underground starchy tubers like potatoes and starchy grains such as wheat, barley, oats, rye, millet, and maize (Hardy and others 2015; Solon-Biet and others 2016).

The common wheat most likely originated from spelt wheat through hybridization between the emmer wheat and the diploid goatgrass (*Aegilops tauschii*, DD genome) (Figure 2; Arzani and others 2005). However, domestication of wheat clearly occurred as a result of selecting 2 traits of reduced shattering of the spike at maturity and free-threshing. While grain shattering is undoubtedly an essential trait of the wild species responsible for the effective dispersion of seeds, nonshattering through a "tough rachis" is governed by the *br* (brittle rachis) gene in wheat (Nalam and others 2006). Governed by a recessive gene *tg* (tenacious glume), a modifier dominant gene *Q* and several other mutations in other loci (Dvorak and others 2012), the free-threshing trait of wheat due to the loss of strong glumes is one of the most important factors contributing to the domestication of wheat. This trait not only helps discriminate between "spelt and common" or between "emmer and durum" wheats but also facilitates the management, harvest, and use of the grains.

Wheat grains mostly contain carbohydrates, proteins, lipids, and minerals (Table 1). In what follows, each of these ingredients is explored.

Proteins

Wheat proteins can be classified into the 2 major gluten (glutenin and gliadin) and nongluten (globulin and albumin) fractions. The polymeric glutenins have the ability to impart strength and elasticity to dough, whereas the gliadins are monomeric proteins responsible for dough viscosity (D'Ovidio and Masci 2004). Based on electrophoretic mobility at low pH, glutenins are further subdivided into low-molecular-weight (LMW) and high-molecular-weight (HMW) proteins. According to the repetitive amino acid sequence patterns, gliadins are classified into the 4 types of α-, β-, γ-, and ω- (Barak and others 2015). When subjected to gastrointestinal digestion, each component of wheat grain protein breaks down into a vast variety of peptides with variable lengths. Since gluten is rich in proline, compact and tough structures are generated that commonly pose difficulties in digestion and elimination (Arentz-Hansen and others 2000). Some of these digestion-resistant peptides are believed to be involved in unfavorable immune processes in susceptible persons. For example, one of the key immunotoxic peptides for celiac patients is gliadin 33-mer peptide of gluten which is resistant to digestion (Shan and others 2002).

Grain quality attributes, including its protein content, not only vary within and across species but are strongly influenced by the environment as well (Ashraf 2014; Arzani and Ashraf 2016). Comparisons of ancient and common wheats in Table 1 reveal that grain protein contents (whole grain flour) of the ancient wheat are commonly superior to those of the modern counterpart (Abdel-Aal and others 1995; Ranhotra and others 1996; Loje and others 2003; Marconi and Cubadda 2005; Brandolini and others 2008; Shewry and others 2013). Grain size and weight are important determinants in many qualitative and compositional constituents such that a big and heavy grain, for instance, yields a larger endosperm as well as smaller proportions of aleuronic layers and external pericarp. A wheat grain includes 3 main components of germ (embryo), endosperm, and outer layers (pericarp, seed coat and, aleurone). The endosperm accounts for approximately 90% of the dry weight of the grain. Compared to the ancient wheat, the lower protein content of modern wheat may be explained by its bigger and heavier grain that yields a larger starchy endosperm which, in turn, lessens its protein content.

Carbohydrates

Carbohydrates account for the most abundant fractions (about 65% to 75%) of the wheat grain, with starch being the main constituent of wheat grain and flour (approximately 60% to 70%) (Lineback and Rasper 1988). Starch is composed of amylose and amylopectin which are α-D-glucose polymers of different structures intertwined to form a starch granule. Amylose is easily hydrolyzed by amylase enzymes (α-amylase and β-amylase) to maltose, while amylopectin is degraded to maltose (approximately 60%) and dextrins (approximately 40%). Despite the fact that amylose accounts for only around one-quarter of the starch granule, the frequency of its molecules is almost 150 times greater than that of amylopectin ones. This is due to the much smaller size of amylose compared to amylopectin. On the other hand, its higher resistance to hydrolytic enzymes, due to the more tightly packed amylose chains than amylopectin ones, leads to the low postprandial levels of glycemic and insulinemic responses which, in turn, give rise to reduced postmeal blood insulin and glucose, yielding longer satiety.

A number of studies (including the present one as reported in Table 1) show either a comparable or even lower starch content of ancient wheat compared with that of bread wheat (Mohammadkhani and others 1998; Rodriguez-Quijano 2004; Brandolini and others 2008; Caballero and others 2008; Haghayegh and Schoenlechner 2010). The enhanced grain yield of modern wheat results in the so-called "yield dilution phenomenon" coupled with the higher ploidy level may explain the higher starch content of modern wheat.

Most of the starches from white bread and white rice are readily digested in the small intestine, leading to a fast rise in blood glucose, which may be linked to the risk of developing obesity. Type-2 diabetes has been documented in people who frequently eat starch-based diets such as the Asian ones (Hu and others 2012). In addition, ample evidence from both human and animal investigations support a link between wheat gluten and type-1 diabetes (for a review, see Barbeau 2012). However, a fraction of starch, namely, the resistant starch (RS), resists digestion or breakdown by α-amylase in the stomach and may be delivered from the small intestine to the colon where it undergoes fermentation to yield small-sized fatty acids, such as butyrate, which may be beneficial to health because it can lower colorectal cancer risks (Topping 2007).

In 2011, global human consumption of wheat was estimated to be 65 kg per head per annum, with the highest estimate of 210 kg observed in Azerbaijan (Bilgic and others 2016). Considering the fact that wheat is the primary staple food for over one-third of the world population, the reintroduction of ancient wheat species can be pondered for a variety of reasons including the nutritional enrichment and diversification of food. A plethora of literature sources has been published in recent years expounding the employment of genetic resources in plant breeding. Recently, Arzani and Ashraf (2016) addressed the need for the sustainable use of

Table 1–Mean or range of macronutrients of whole-grain flour in cultivated einkorn, emmer, spelt, and bread wheats.

Component (dry matter)	Einkorn	Reference[@]	Emmer	Reference	Spelt	Reference	Bread wheat	Reference
Digestible carbohydrate (% or g per 100 g)	64.5	(1)	71	(2)	65.9*	(1)	73*	(3)
Starch (%)	62.3*	(1; 4; 5)	65	(2)	63.8*	(1)	68.5	(4)
Amylose (% starch)	23.8*	(4; 6)	25.1	(6)	–	(–)	28.4*	(7)
Dietary fiber (%)	9.8*	(8; 9)	9.8	(9)	12	(9)	13.4	(10)
Protein (%)	15.5–22.8	(4; 11)	13.5–19.05	(8; 11)	16.3–17.5	(1)	12.9 –19.9	(12)
Lipid (%)	3.5*	(13; 14)	2.16*	(11; 14)	2.39*	(1; 14)	2.8	(13)
Ash (%)	2.3	(8; 13)	2.3	(8)	2.1	(8)	1.9	(8)
Phosphorus (g kg^{-1})	5.2	(15)	5.12	(15)	4.70	(15)	4.18	(15)
Potassium (g kg^{-1})	4.29	(15)	4.39	(15)	4.17	(15)	5	(15)
Sulfur (g kg^{-1})	1.90	(1; 15)	1.88	(15)	1.8	(15)	1.4	(15)
Magnesium (g kg^{-1})	1.63	(15)	1.67	(15)	1.5	(15)	1.44	(15)
Calcium (g kg^{-1})	0.42	(15)	0.36	(15)	0.39	(15)	0.43	(15)
Iron (mg kg^{-1})	49	(15)	49	(15)	50	(15)	38	(15; 16)
Zinc (mg kg^{-1})	53	(15)	54	(15)	47	(15)	35.0	(15)
Manganese (mg kg^{-1})	28	(15)	24	(15)	27	(15)	26	(15)
Copper (mg kg^{-1})	4	(15)	4.1	(15)	5	(15)	3.9	(15)
Sodium (mg kg^{-1})	7	(15)	12	(15)	10	(15)	10	(15)

*By taking an average value either from the genotypes reported in a reference or taking an average from the listed references.
[@] References: 1. Abdel-Aal and others (1995); 2. Lacko-Bartosova and Curna (2015); 3. Davis and others (1981); 4. Brandolini and others (2008); 5. Brandolini and others (2011); 6. Mohammadkhani and others (1998); 7. Regina and others (2015); 8. Loje and others (2003); 9. Gebruers and others (2008); 10. Andersson and others (2013); 11. Grausgruber and others (2004); 12. Shewry and others (2013); 13. Hidalgo and others (2009); 14. Suchowilska and others (2009); 15. Suchowilska and others (2012); 16. Zhao and others (2009).
–: not available for whole grain flour.

natural genetic resources toward: (1) developing cultivars with sustainable tolerance to both abiotic and biotic stresses, (2) reducing the risk of loss of biodiversity and foreseeing problems associated with global climate change, and (3) ensuring the recreation of ecological integrity as well as sustainable exploitation of biological diversity.

The most comprehensive comparative investigation to date was undertaken in Europe (as part of the EU HEALTHGRAIN project; Shewry and Hey 2015) on 5 wheat species (einkorn, emmer, spelt, durum, and bread wheat). The study determined the total dietary fiber levels in wholeflour of 151 bread wheat cultivars, 10 durum wheat cultivars, and 5 lines of each of einkorn, emmer, and spelt (Gebruers and others 2008). The agronomic practices and associated inputs (nutrient and irrigation) have shown relevance to the adaptation of bread wheat plants. A considerable variation has also been found in the dietary fiber constituents among the wholegrains of 129 bread wheat genotypes from the HEALTHGRAIN diversity screen (Andersson and others 2013).

Phytochemicals, vitamins, and antioxidants

In addition to the major components of protein, carbohydrate, and lipid, wheat grain is an important source of other health-related ingredients, notably phytochemicals, vitamins, and antioxidants as well as macro- and micro-nutrients (Arzani 2011). The health-promoting vitamins, antioxidants, and phytochemicals of the ancient wheats have been compared with those of the common wheat in a number of studies. However, these studies suffer from being mostly focused on limited numbers of attributes and genotypes under agronomic conditions favorable to the common wheat, or from quality assessment impediments as regards samples, replications, tools, or methods.

Wheat grain is comprised of numerous health-promoting compounds including phenols, which are the most diverse and abundant "phytochemicals" (plant components with biological functions). Polyphenols are comprised of phenolic acids, flavonoids, and lignans. Recently, they have received considerable attention because of their potential antioxidant activity and protective ability to counteract oxidative damage and diseases such as coronary heart disease, stroke, and cancer (Quinones and others 2013). One of the major polyphenols present in whole grain wheat products is alkylresorcinol. A comprehensive study by Ziegler and others (2016) using whole grain flours of 15 genotypes each of einkorn, emmer, spelt, durum, and bread wheats grown in 4 locations found that the overall mean concentrations of alkylresorcinol in the species were comparable, whereas they varied greatly among the genotypes within each species. On the other hand, the results of the HEALTHGRAIN study showed higher alkylresorcinol contents in small-seeded ancient wheats (einkorn, emmer, and spelt) than in large-seeded modern wheats (durum and bread wheat) (Andersson and others 2008; Shewry and Hey 2015). Andersson and others (2008) reported alkylresorcinol mean values of 581, 595, and 605 $\mu g\ g^{-1}$ in the dry matter of emmer, einkorn, and spelt, respectively. Ferulic acid is one of the most important phenolic acids found in wheat bran which has antioxidant and antiinflammatory effects. Similar phenolic components including ferulic acid have been reported for bread wheat and ancient wheats (Abdel-Aal and Rabalski 2008; Li and others 2008; Serpen and others 2008).

The highest variations among wheat species were reported for grain carotenoid content. In wheat, the predominant carotenoid is lutein, which is also the major yellow-colored pigment; only insignificant amounts of other carotenoids such as β-carotene have been detected in wheat grain (Abdel-Aal and others 2007). Among the wheat species, einkorn has been reported to have the highest lutein content, implying a high antioxidant quality (Abdel-Aal and others 2007; Abdel-Aal and Rabalski 2008; Lachman and others 2013; Ziegler and others 2016). Einkorn contains up to 10-fold higher lutein than does bread wheat with durum wheat containing intermediate amounts of lutein (Ziegler and others 2016). The higher amounts of carotenoids in durum than in bread wheat may be ascribed to the selection of yellow-colored grains for the production of yellow-tinted pasta (Hentschel and others 2002).

Vitamins are classified into water-soluble and fat-soluble compounds. The B vitamin groups comprise various compounds: B1 (thiamine), B2 (riboflavin), B3 (niacin), B6 (pyridoxine), B9 (folate), and B12 (cobalamin) (Gerdes and others 2012). Wheat, its whole grain in particular, is a valuable source of B1, B2, B3, B6, and B9 (Shewry and Hey 2015). Folate (B9), also known as folic acid or folacin, serves numerous functions including its involvement in the metabolism of protein, formation of red blood cells, and lowering the risk of neural tube birth defects (Scott and others 2000). Only folate has been studied in the HEALTHGRAIN project using ancient and modern wheat species to observe minor variations in its concentration, with higher concentrations observed in durum (0.74 μg g^{-1} dry weight) and emmer (0.69 μg g^{-1} dry weight) than in the other species studied (0.56 to 0.58 μg g^{-1} dry weight) (Piironen and others 2008). However, it should be noted that further studies are required to determine in detail the amounts and functions of this vitamin to compensate for the shortcomings of previous studies that focused only on a single growth environment and on limited numbers of genotypes/species other than bread wheat.

Wheat grains are also a valuable dietary source of vitamin E, comprised of 2 tocopherol and tocotrienol groups (each with α-, β-, γ-, and σ- isomers), collectively known as tocochromanols (Falk and Munne-Bosch 2010). Vitamin E compounds are considered the most important lipophilic radical-quenching antioxidants in cell membranes, hence, they are considered vital for human health (Schneider 2005). Ancient and modern wheat species have been compared for their tocochromanol contents to detect the highest total tocol content in einkorn (Lampi and others 2008; Ziegler and others 2016).

From the above observations, it may be concluded that einkorn wholegrain has several advantages over the other cultivated ancient and modern wheats with higher ploidy levels (tetraploid and hexaploid). The higher levels of some of the macro- and micro-nutrients as well as the antioxidant compounds (conjugated polyphenols, carotenoids, tocols, alkylresorcinols, and phytosterols) contribute to the excellent nutritional properties of this diploid ancient wheat.

Other grain components

The high yields of durum and bread wheat cultivars have given rise to their extensive cultivation and their substantial replacement for einkorn, emmer, and spelt wheats. However, a growing interest has more recently been shown in these underutilized crops because of the advantageous attributes of hulled wheat species such as their greater amenability to sustainable agriculture and superior health-related properties over the bread wheat and durum wheat species (Abdel-Aal and others 1998; Longin and Wurschum 2016). Hulled wheats can be grown under unfavorable soil and climate conditions (Arzani 2011). Moreover, they are superior to modern wheat because of their tolerance to abiotic and biotic stresses such as diseases, pests, drought, heat, cold, salinity, pollution, and soil nutrient shortage. In addition they show greater competitiveness against weeds and tillering ability (Loje and others 2003; Arzani 2011; Hidalgo and Brandolini 2014).

The presence of functional foods in the human diet plays an important role in both disease prevention and therapy. Although cereal-based products are rich sources of starch, proteins, and minerals, the presence of antinutritional factors reduces the bioavailability of these essential nutrients, in particular minerals, thereby hampering their nutritive values. It is, therefore, crucial to seek means of counteracting the antinutritional factors in favor of the nutritional values. Clearly, lowering the antinutrient (phytate, saponins, tannins, oxalates, and cyanogenic glycosides) content in the wholemeal wheat flours will lead to enhanced nutritional value of the final products. While the quality of ancient wheat grain components remains largely unknown, it may be hypothesized that they benefit from less antagonistic interaction(s) between health-beneficial ingredients and the antinutrients. In addition, cultivated ancient wheats may contain certain biocompounds with protective functions against insects and pathogens. A good example is the trypsin/α-amylase inhibitor family found in the endosperms of ancient wheats that provides defense against animal predators, insects, and bacteria (Fontanini and others 2007). Such biocompounds can function as immunomodulators or enzyme inhibitors.

The modern wheat species (durum and bread wheat) have been developed from old wheats using modern breeding techniques such as hybridization and subsequent selection of recombinants with high yield potentials. This process has bestowed grain yield advantages to the modern wheat over its ancestral ancient wheats. However, not only have some grain quality constituents, phytochemicals, and nutritional elements declined or been lost in modern offspring, but some antinutrients have also been enhanced. Relatively few long-term, comprehensive studies have been conducted to determine whether ancient wheat species grown under traditional (subsistence and low-input) or modern (high-input) production systems have greater positive health advantages and lower antinutritional composition than modern wheat (see review by Shewry and Hey 2015). The evidence from a decade of work by German researchers (Longin and others 2016; Longin and Würschum 2016; Ziegler and others 2015, 2016) on einkorn, emmer, and spelt wheats as well as those by others (D'Antuono and others 1998; Cubadda and Marconi 2002; Galterio and others 2003; Loje and others 2003; Serpen and others 2008; Charmet 2011; Giambanelli and others 2013; Hidalgo and Brandolini 2014;) have revealed the health benefits of ancient wheats. Based on a preliminary screening of germplasm in the field, 15 superior accessions for each of the einkorn, emmer, and spelt wheats along with 15 commercial cultivars from each of the durum and bread wheats (to make a total number of 75 genotypes) were tested at 4 different locations in Germany (Ziegler and others 2015; 2016; Longin and others 2016). Their results showed that, although both einkorn and emmer were promising, einkorn whole grains contained higher minerals and lipophilic antioxidants (lutein, vitamin E, and steryl ferulates). This suggests that these properties could be exploited for functional foods and nutraceutical applications with favorable aroma and color.

Einkorn and emmer wheats are especially promising for the production of grains with low immunotoxic effects (Gianfrani and others 2012). However, doubts have been raised as to the safety of some ancient wheat cultivars for celiac patients (Suligoj and others 2013), thus suggesting that the immune toxicity for celiac patients might be genotype-dependent. More recently, serological and histological studies have shown that the einkorn cultivar "Monlis" is toxic to celiac patients, but that it is well tolerated by the majority of patients with gluten sensitivity (Zanini and others 2015). On the other hand, spelt wheat possessing the D genome was found to be similar to common wheat in terms of cytotoxicity as the D genome was found to be related to celiac epitope expression. Vincentini and others (2007) found no difference between common and spelt wheats. They, however, noted that the other ancient wheats were poor in cytotoxic prolamins thereby having potential as healthy food crops.

The effects of whole grain flour obtained from modern and ancient (spelt, emmer, and einkorn) wheats on the development and course of diabetes in the Zucker diabetic fatty (ZDF) rats were assessed (Thorup and others 2014). Results showed that the disorder was less pronounced with ancient grains fed to the ZDF rats than with the modern wheat; this was ascribed to a down-regulation of the expression of important regulatory genes in the liver.

Health-promoting properties of ancient wheat have been credited to its superior levels of phytochemicals such as carotenoids, flavonoids, phytosterols, and phenolic compounds (lignans and ferulic acid) compared with the modern wheat species (Charmet 2011; Giambanelli and others 2013). However, the potential health-promoting benefits of ancient wheat species await further detailed research, particularly under low-input environmental growing conditions.

Type of Food Consumption and Dietary Diversity

Einkorn, emmer, and spelt possess hulled grains enclosed by tough glumes (husks) in a semi-brittle rachis. After threshing, the hulled wheat spikes break into spikelets and uphold the attached glumes to the grain and the semi-brittle rachis. Either particular dehullers are used for dehulling or milling/pounding is employed to remove the glumes from the grains. The ancient wheat is primarily used for human food, but it is also utilized as animal feed. It is used in making bread and various dishes, some of which have a long history of cultural dependence, particularly in rural areas (Hansson 1994; Stallknecht and others 1996). In addition to the different types of fermented bread, unleavened bread such as chapatti and some types of pancake are produced from the ancient wheat. A porridge is prepared with milk or water or by stirring in crushed grains, decorticated flour, or extracted starch until it is fully gelatinized (Hansson 1994; Stallknecht and others 1996).

Einkorn and emmer were initially used as porridge by ancient civilizations before being used to bake bread. Bread has a long history dating back to the New Stone Age (Neolithic times) commencing at about 10000 to 8000 BC. Hand-crushed grains mixed with water were used to bake early bread by laying the dough on heated stones. The 1st leavened bread was made by people from Sumeria around 6000 BC by mixing sour dough with unleavened dough (Belderok 2000). The procedure of preparing bread was passed down to the Egyptians about 3000 B.C. The Egyptians started the use of yeast as a potential source of dough rising to make the bread lighter (Samuel 1996). Nowadays, a wide range of breads made across the globe come in different sizes, shapes, textures, colors, crusts, elasticity, eating qualities, and flavors.

Bread made from the emmer wheat flour is widely used in Switzerland. It is also known as *pane di farro* in Italy and is available in some bakeries. Pasta is also produced from emmer wheat in limited quantities in central Italy at the domestic level but has been largely rejected by consumers owing to its unappealing texture (D'Antuono 2013). Bulgur (cracked grains) of emmer is also used to prepare hard porridge by mixing it with boiled water and butter. In addition, bulgur whole grains of emmer wheat have traditionally been used to make different types of soup worldwide. In some rural areas in Italy and Iran, emmer is used as carbohydrate source in meals in the same way as rice (Arzani 2011).

Ancient wheat is likely rich in protein, amino acids, antioxidant compounds, carotenoids, vitamins, and minerals. In combination with pulses (legumes), it can produce an optimal dietary protein level for vegetarians, or for those eager to consume a plant-based food source with a balanced-quality protein.

Ancient and Modern Wheat Flour Blends

Some of the ancient wheats have a distinctive composition such as resistant starch, carotenoids, phytochemicals, and antioxidants which offer numerous health benefits. Although ancient wheat flour may produce a relatively satisfactory loaf of bread, the quality is not comparable to that made with bread wheat (Arzani 2011; Brandolini and Hidalgo 2011). Wheat protein is deficient in some essential amino acids (AA), especially lysine (the 1st limiting AA) and threonine (the 2nd limiting AA). This naturally results in foods poor in protein and consequent protein deficiency (Endo and others 2002; Pichardo and others 2003). Although few studies have investigated the amino acid composition of ancient wheat proteins, a wide variation has been observed in the lysine content of einkorn wheat, some accessions of which have exhibited greater lysine contents than bread wheat (Loje and others 2003; Hidalgo and Brandolini 2014). Quantifying the protein content and quality in ancient and modern wheats, Konvalina and others (2008) observed a reasonably high amount of protein in the emmer grain; they, however, found its gluten quality inferior to that of bread wheat. The poor gluten quality of emmer wheat has been ascribed to its lack of D genome. Bread-baking with ancient wheat flour could be more appealing if a blend of flours from ancient and bread wheats were used. In this way, the high lysine content and the other health-promoting compounds of ancient wheat could supplement those of bread flour to achieve a better dietary balance.

Much interest has recently been shown to linking phytonutrients to reducing the incidence of aging-related and chronic human diseases. It is well established that, from among the numerous antioxidant compounds found in foods, lipid-soluble antioxidants play an important role in disease prevention. Curiously, the natural antioxidant activity of phytonutrients may be associated with their functional properties contributing to the shelf-life and freshness of food products. Wheat is an important staple food for a large proportion of the human population, and it is a source of protein and energy as well as a source of phytochemical compounds for human nutrition. As already mentioned, the concentrations of phytonutrients, however, appear to be lower in bread wheat than in ancient wheat.

Whole grain flour contains higher amounts of water-insoluble fibers but lower amounts of the water-soluble ones than white flour (Ranhotra 1994). Epidemiologists found a strong correlation between low fiber intake, particularly from the gastrointestinal tract, and many disease states (Birdsall 1985). In developing countries, there is a general belief among consumers that the greater plant fiber consumption by people from rural areas protects them against many diseases such as colon cancer, diverticular disease, cardiovascular diseases, hemorrhoids, appendicitis, and varicose veins common to people living in urban areas; in many cases this has been confirmed experimentally (Anderson and others 2000; Harris and Kris-Etherton 2010; Liu and others 2015). There is, however, some ambiguity in inferring a simple link between fiber intake and cancer risk because food that is rich in fiber may include other constituents that are linked to cancer prevention. Moreover, research findings show high-fiber diets to be associated with decreased blood pressure both in normal and hypertensive subjects (Keenan and others 2002; Behall and others 2006). This may be explained by the fact that a diet enriched with complex carbohydrates enhances glucose metabolism in diabetic individuals by elevating their insulin sensitivity, leading to reduced insulin dosage needs (Keenan and others 2002; Lutsey and others 2007; Freeland and others 2010; Tarini and Wolever 2010). Moreover, a high-fiber diet is positively associated with the control of obesity and physical gastrointestinal tract disorders.

High-fiber diets, in particular cereal-based fibers, clearly have certain health-beneficial effects on diet-related chronic diseases including obesity, diabetes, cancer, and cardiovascular diseases (Birdsall 1985; Anderson and others 2000). Accordingly, consumers are able to influence their health by choosing to consume high-fiber foods including functional cereal products. It should be noted that cereal product reception by consumers is grounded on their pleasant texture and flavor which are critical to the development of food items. Economic growth and urbanization have brought about dietary alterations in many countries that favor the utilization of energy-dense foods high in refined fat and carbohydrates with low dietary fiber (Bach Knudsen and others 2016). Consumers have replaced whole grain with refined wheat grain products, with the adverse consequences of reduced dietary fiber, micronutrient, and phytochemical intakes. As the biochemical mechanisms of the beneficial health effects of whole grain products are not yet fully understood, it is quite likely that the health problems stem from the combined action of low dietary fiber and the inadequacy of a wide variety of phytochemicals (Fardet 2010; Russell and others 2016). Nevertheless, the lower quantity of fiber in ancient wheats than in common wheat has been documented (see Table 1); hence, ancient wheat flour may partly be used as a substitute for wheat flour in bread and other cereal-based products to balance the dietary fiber components.

Ancient Wheat for Combating Malnutrition and Food Insecurity

The growing demand for nutritionally and phytochemically adequate food products has attracted growing attention to ancient wheat and this interest is likely to continue. One of the ultimate sustainable goals of wheat improvement is to combat micronutrient malnutrition in developing countries where billions of people consume staple cereals with inadequate supplies of essential micronutrients (Bouis 2003; Cakmak 2008). As reported in Table 1 and discussed earlier, ancient wheats, as nutritionally rich species, are better sources of micronutrients and phytochemicals than are their modern counterparts (Suchowilska and others 2012; Hidalgo and Brandolini 2014). To combat the global micronutrient malnutrition, it is, therefore, essential to fortify and enrich staple food crops with mineral elements as an immediate, but only temporary solution. International breeding efforts exploit biodiversity to improve the mineral nutrient levels in food crops. It is well established that modern high-yielding wheat cultivars have lower concentrations of mineral nutrients than low-yielding old ones do (Murphy and others 2008; Shewry and others 2016). Alone, the germplasm of modern wheat cannot provide the genetic diversity required to develop new wheat cultivars with sufficiently high grain mineral nutrient concentrations. On the other hand, ancient wheats, such as einkorn, emmer, and spelt, contain the germplasm resources that can be exploited to improve wheat grain micronutrient value (Genc and McDonald 2008; Suchowilska and others 2012; Hidalgo and Brandolini 2014).

Low-Input/Sustainable Cropping System

Sustainable food production calls for environmentally-friendly and ecologically sound farming practices. A potentially valuable measure that may be taken in response to consumer concern for food quality is to select appropriate crop species such as ancient wheats through breeding programs and to include them in organic and sustainable food production systems. Unfortunately, a drastic climate change is likely to have adverse effects on both yield and quality of wheat and an effective strategy for the bio-diversification of wheat varieties and their adaptation to the changing environment is essential. Global climate change has numerous adverse effects on food security. Most important are soil degradation and aggravation of biotic and, in particular, abiotic stresses (Lal 2014; Arzani and Ashraf 2016). Employing ancient wheat genetic resources as a component of sustainable use of agro-biodiversity may reduce the risks of climate change to food production. However, significant enhancements in crop yield stability may equally be achieved by deploying the less bred/modified species. In the meantime, such provisions as price adjustments must be made to compensate for the resulting economic losses to farmers due to changes in production systems or the use of lower yielding but nutritionally superior crops. A delicate balance must, therefore, be struck between the economic outcomes of the new farming practices at higher costs and a sustainable high-quality crop production. The focus should be on achieving greater harmony with nature through enhanced water, soil, and air quality as well as biodiversity. Furthermore, sustainable crop production should encompass an integrated management of natural resources and the environment as a whole. Smith and others (2000) noted that intensive agricultural practices lead to a loss of resilience in the ecosystem by altering such processes as productivity, nutrient cycling, and species diversity. The consequences of crop production in this new environment have an impact not only on farmers but also millers, bakers, processors, retailers, and consumers. Thus, it is not solely the farming system that must be in focus.

Public health and environmental concerns in some developed and developing countries have gradually resulted in a shift from more intensive cropping practices to more sustainable, low-input ones. However, one drawback associated with the current high-yield and high-protein wheat cultivars is that they require high agrochemical inputs such as nitrogen fertilizers, pesticides, and herbicides. Ancient wheats that have never been subjected to breeding programs and their landraces/original forms are presently available and may provide an important component in the development of low input/ high food nutritional food quality systems to replace the current pattern of high input/ low food nutritional quality.

The compelling arguments in favor of growing ancient wheat revolve around reduced agronomic practices, lower energy requirements, environmental sustainability, and higher yield potentials on marginal lands or under organic growing conditions. They can be produced more sustainably at reduced external inputs. Longin and others (2016) evaluated grain yields by early domesticated and modern wheats (einkorn, emmer, spelt, durum, and bread wheat) to find that the yields of einkorn, emmer, and spelt amounted to only 38%, 45%, and 63%, respectively, of the bread wheat yield. Interestingly, the wheat species were ranked for their yield potential based on their ploidy levels. In addition, it was found that the ancient wheats (einkorn, emmer, and spelt) recorded greater values of plant height (30 cm) than did the bread and durum wheats. This is consistent with the finding by Konvalina and others (2010) who evaluated 169 landraces of the ancient wheat in a field with an annual precipitation of 472 mm to find that most of the landraces examined showed an inclination to lodge due to their long and weak stems. This indicates that, although plant height is genetically determined, the optimum environmental conditions favorable to the growth of ancient wheat involve much less external/agronomic inputs, plant density, and water than do those for the modern wheat.

It is, therefore, conceivable that einkorn with the lowest yield and ploidy level possesses the highest health benefits (Hidalgo and Brandolini 2014; Ziegler and others 2016). Being the oldest cultivated wheat, it was domesticated some 10000 y ago in the Fertile Crescent. Nevertheless, adaptation of ancient wheats to the less favorable environmental conditions and lower agronomic input requirements, combined with their higher tillering ability, and competitiveness against weeds make them attractive for use

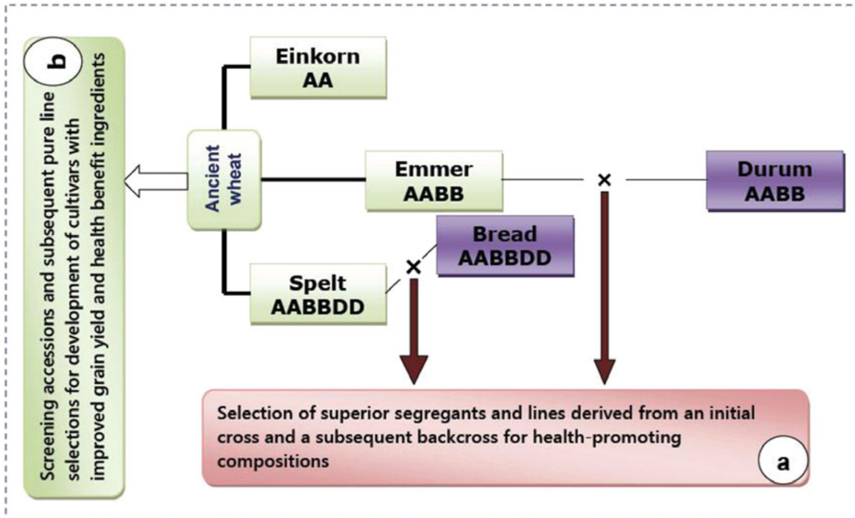

Figure 3–Suggested breeding schemes for (a) introduction of desired traits (health beneficial compounds and tolerance to biotic and abiotic stresses) from the ancient wheat (einkorn, emmer, and spelt) into modern wheat (durum and bread wheat); and (b) screening of ancient wheat accessions and subsequent selection of superior accessions (pure line selection) for sustainable grain yield and health benefit traits to develop cultivars for direct cultivation as sustainable sources of good quality nutrition.

in organic and sustainable production systems. Overpopulation and acquisition of good-quality lands for industrial development and urbanization have made it necessary to extend agricultural to marginal areas. However, the utilizing of marginal lands can only be worthwhile if adequate yields can be acquired with limited resources. The cultivation of ancient wheat is particularly important in high-altitude marginal lands where they are economically viable thanks to their cold resistance and low input requirements. The efficient growth strategies of natural grasses such as ancient wheat rely on a better partitioning of assimilates between the non-reproductive and reproductive organs, resulting from a continually shifting balance between sinks and sources throughout the growing season. This balance is influenced by abiotic and biotic (pests and diseases) stresses, particularly under limited water supply.

Diversification of staple crops is recommended not only for increasing the diversity of food sources, but also for establishing a sustainable, resilient, and food-secure agriculture (Massawe and others 2016). On the other hand, a narrow focus on only a limited number of species and cultivars within a species results in an enormous loss of genetic diversity with associated vulnerability of ecosystems, extinction of species, and a limited ability of breeders to respond to future agricultural needs. A major challenge researchers and farmers, in the face of global climate change, is to save and safeguard genetic biodiversity to allow the necessary adaptations to both biotic and abiotic stresses in species of importance.

Conclusions and Future Direction of Research

Although consumers are conscious of the likely diet–health relationships of food, the benefits of diversified cereal grains in the human diet have not yet been fully recognized. The growing consumption of cereals calls for a profound shift in consumers' taste to use breads and products made from wheat types other than the common wheat. The increasing interest recently shown in "organic" and "natural" products has led to the "rediscovery" of ancient wheat on the following grounds:

(i) The capability of both modern and ancient wheats to yield end-products; this capability could be particularly exploited to produce many different types of dishes such as whole, pearled, or broken grains; flour to make bread, pizza, biscuits, and pastries; and semolina to make pasta;
(ii) The nutritional value, high starch-resistance, and healing properties of the ancient wheat that make it especially useful for the treatment of such diseases as high blood cholesterol, colitis, and allergies;
(iii) The ability of the ancient wheat to grow in poor soils with low input and organic crop systems as well as their higher tolerance to biotic and abiotic stresses including diseases, insects, extreme temperature (cold and heat), drought, and salinity; and
(iv) The putative ancestral and primary gene pool that can be exploited for the improvement of the health-related traits of modern wheat (durum and bread wheat).

The potentially dangerous consequences of the genetic erosion of wheat species (*Triticum* spp. L.) pose a great challenge to plant domestication and, in particular, to subsequent breeding programs. Wheat breeders should not only identify the valuable traits and properties in wheat primitive ancestors in an attempt to introduce them into modern wheat, but should also conduct genetic improvement projects aimed at their domestication. Two of the 3 ancient wheats, namely emmer and spelt, can readily be used in hybridization/breeding schemes of durum and bread wheat, while the emmer wheat genomes can also be combined with goatgrass (*Ae. tauschii*) to produce a synthetic hexaploid wheat. The study conducted by Lage and others (2006) demonstrated that the genetic variation accomplished to improve the quality of tetraploid emmer wheat could be replicated to produce synthetic hexaploid wheats.

Ancient wheats are rich in resistant-starch, fiber, minerals, and phytochemicals. They will, therefore, serve as a valuable source for improving wheat cultivars with a higher yield and better composition of health-beneficial compounds. In the primary steps of the work, assessment of the genetic diversity of the ancient wheats for their nutritional and health-beneficial properties is recommended, as has been done by workers on the German Gene Bank collection for some grain quality traits (see review by Longin and Wurschum 2016). Public–private participations that involve millers and bakers are suggested to develop ancient wheat products appealing to the urban consumer's taste either by blending grain/flour/semolina of ancient and modern wheats or by utilizing their products independently from each other. Diversification in ancient wheat food products can be improved through process models coming from European countries like Italy that have successfully produced such food products.

The prime objective of wheat breeding programs during the last century was to improve grain yield while also conserving a certain level of grain protein. However, little attention was paid to an examination of the nutritional and health-related properties of grains and their improvement (Leenhardt and others 2006; Arzani 2011). Table 1 compares the whole-grain flour compositions of einkorn and bread wheats based on the means or ranges of the genotypes tested within each group. It is necessary to determine whether both interspecific and intraspecific variations reported relate to nutritional properties of the *Triticum* spp. grains. Figure 3 presents the breeding schemes suggested for the introduction of traits of merit (health-beneficial compounds and tolerance to biotic and abiotic stresses) from the ancient wheat into the modern wheat. The proposed schemes also involve screening of ancient wheat accessions and their subsequent pure line selection to achieve sustainable grain yield, enhanced health-promoting compounds, cultivars for propagation and cultivation, and sustainable sources of good quality nutrition.

The current epidemiological and clinical evidence implies that a whole grain diet may have a protective function in the initiation and progression of type-2 diabetes (Fung and others 2002; Montonen and others 2003), coronary heart disease (Jacobs and others 2002; Behall and others 2006), age-related eye disorders, and some kinds of cancer (Chatenoud and others 1998; Kasum and others 2001). The health-enhancing values of whole wheat grain flour might be attributed to the natural antioxidants, phenolic acids, flavonoids, phytic acids, carotenoids, and tocopherols (Moore and others 2005; Mpofu and others 2006; Brandolini and Hidalgo 2011; Lachman and others 2012). Polyphenolic compounds (flavonoids, phenolic acids, and lignans) have a potentially protective function against oxidative damages such as coronary heart disease, stroke, and cancer in humans (Quinones and others 2013).

Insufficient data are currently available on the use of ancient wheat flour as a partial substitute for common wheat flour in making breads, cookies, and pasta. Although a number of studies have been carried out on the nutritional and health-related properties of ancient wheat species, thorough comparisons between these species and modern wheat will be a complicated task because of the environment-related aspects. The aspects that need to be addressed in any such comparative study will have to include: different agronomic practices and field conditions (such as plant density and water availability) favorable to each of the groups and the requirement for reliable phenotypic assessments through multiple-year and location trials (Shewry and Hey 2015).

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