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Review

Do “ancient” wheat species differ from modern bread wheat in their contents of bioactive components?

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A B S T R A C T

Ancient wheat species (einkorn, emmer, spelt and Khorasan wheat) have been suggested to have health benefits when compared with modern cultivars of bread and durum wheat. Although limited data are available on the contents and compositions of bioactive components in ancient wheat species, reported studies show that they differ little from modern wheat species in the contents of most bioactive components, and may be lower in some components (such as dietary fibre).

Although einkorn, emmer and Khorasan wheat all have higher high contents of the carotenoid lutein than bread wheat, durum wheat is also rich in lutein due to selection for yellow colour.

These reported analyses do not support the suggestion that ancient wheats are generally more “healthy” than modern wheats.

1. Introduction

The major wheat species grown throughout the world, accounting for about 95% of the 700 + million tonnes of wheat which are grown annually, is *Triticum aestivum*, a hexaploid species (genomes AABBDD) which is usually called “common” or “bread” wheat. In addition, about 35–40 mt are grown each year of *Triticum turgidum* var. *durum*, a tetraploid species which is adapted to the hot dry conditions surrounding the Mediterranean Sea and similar climates in other regions. This is used mainly for making pasta and is often referred to either as “pasta wheat” or “durum wheat”.

Other more “ancient” wheat species were cultivated historically but are today only grown on small areas. The most well-known and widely studied of these are the diploid wheat einkorn (*Triticum monococcum* var. *monococcum* genome AA), tetraploid emmer (*T. turgidum* var. *dicoccum* genomes AABB) and hexaploid spelt (*T. aestivum* var. *spelta* genomes AABBDD) which is now considered to belong to the same species as bread wheat. Spelt, emmer, and most forms of einkorn differ from bread and durum wheats in being hulled (i.e. the glumes remain tightly closed over the grain and are not removed by threshing). Hulled wheat species are therefore mechanically dehulled before milling or other forms of processing.

Small amounts of ancient wheat species may still be grown in some countries for traditional foods, but there has been renewed interest in them in recent years as they have been proposed to be rich sources of bioactive components and hence suitable for producing high value food products with enhanced health benefits (see, for example, Ruibal-Mendieta et al., 2005; Lachman et al., 2013). Bread wheat is a young species, having arisen in cultivation about 10,000 years ago, probably by spontaneous hybridization of cultivated tetraploid wheat (genomes AABB) with the wild grass *Triticum tauschii* (DD) (Dubcovsky and Dvorak, 2007). Since this recent origin it has been transported to all continents, with the exception of Antarctica, and has become the major staple crop in temperate zones, ranging from the south of Argentina to northern Scandinavia. This migration has been facilitated by the development of immense genetic diversity, allowing the selection of forms adapted to a wide range of local environments. The development of such diversity results from high genome plasticity (Dubcovsky and Dvorak, 2007) and there is no reason to doubt that further diversity will continue to accumulate at a similar rate in the future.

Although a number of studies of the contents and compositions of bioactive components in ancient wheat species, particularly spelt, have been published, definitive comparisons of these species with modern bread and durum wheat are rare. There are a number of reasons for this. Firstly, ancient wheat species are usually grown in organic, or traditional low input, farming systems, while modern

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wheat species are usually bred for high input intensive systems. In addition, it is necessary to analyse sufficient numbers of cultivars grown on multiple sites to allow for the significant effects of genotype (G), environment (E) and G × E interactions on grain composition (Ward et al., 2008; Shewry et al., 2010).

We have therefore carried out an extensive literature review in order to determine whether ancient wheat species do indeed differ from bread wheat in a range of components which have established or proposed benefits to human health. Analyses of white flours are not included as yields and degrees of purity may vary between species and milling procedures. All data reported on an "as is" basis are converted to a dry weight basis, assuming a water content of 14% unless otherwise stated.

2. Dietary fibre (DF)

The whole wheat grain contains between 11.5% and 15.5% dry weight total dietary fibre (TDF), with the major components being cell wall components: the polysaccharides arabinoxylan (5.5%–7.4% dry weight) (Andersson et al., 2013), cellulose (1.67–3.05% dry weight) and β-glucan (0.51%–0.96% dry weight) and Klason lignin (0.74%–2.03% dry weight). However, these components differ in their distribution between the different grain tissues. The outer layers (pericarp and testa) comprise 45–50% cell wall material (Barron et al., 2007), with the well-characterised outer pericarp being rich in lignin (12%), cellulose (30%) and a complex form of arabinoxylan termed glucuronoarabinoxylan (on account of its high content of glucuronic acid residues) (60%) (Du Pont and Selvendran, 1987). The aleurone cells which form the outer layer of the endosperm are also rich in fibre (35%–40% dry weight) (Barron et al., 2007), which comprises 29% β-glucan, 65% arabinoxylan and about 2% each of cellulose and glucomannan (Bacic and Stone, 1981). By contrast, the starchy endosperm cells, which give rise to white flour on milling, contain only about 2–3% cell wall polysaccharides, with the major components being arabinoxylan (70%) and β-glucan (20%) with small amounts of glucomannan (7%) and cellulose (2%) (Mares and Stone, 1973).

In addition to cell wall polysaccharides, two other groups of carbohydrates contribute to the dietary fibre fraction of wheat. Fructans (fructoligosaccharides) vary from 0.84% to 1.85% dry weight of the whole grain (Andersson et al., 2013) and are concentrated in the bran (3.4 to 4% dry weight compared to 1.4% to 1.7% in flour) (Haska et al., 2008), while a small proportion of the starch present in the starchy endosperm cells may be resistant to digestion in the upper gastro-intestinal tract and be fermented in the colon.

These differences in distributions of DF components are important as they mean that smaller grains may have higher concentrations of fibre components (and other components concentrated in the bran) than larger grains, due to having a higher ratio of bran to flour. Since grain size is determined mainly by starch accumulation and is one of the two components that determine grain yield (the other being grain number), the development of high yielding modern cultivars could lead to "yield dilution" of other components.

Table 1 summarises the contents of DF components reported for einkorn, emmer, spelt (which we will call ancient wheats), durum wheat and bread wheat (called modern wheats). The data on bread and durum wheat included in Table 1 come from the same studies as the analyses of the ancient species and therefore provide good comparisons.

The different studies also determined one or more different fractions: total dietary fibre (TDF), soluble fibre (SF), insoluble fibre (IF), total arabinoxylan (TOT-AX) and β-glucan (BG). Although only small numbers of samples were analysed in most studies the values for all fractions measured for ancient wheats tend to be lower than those reported in the same studies for bread wheat, although the range is wider in some studies. This is illustrated in Fig. 1 which shows individual DF fractions from spelt and bread wheat (Fig. 1A and B) and TDF from the individual species (Fig. 1C).

The most detailed comparative study of all five species formed part of the EU HEALTHGRAIN project (Poutanen et al., 2008, 2010), which determined TDF, Klason lignin and β-glucan in wholemeals of 151 bread wheat cultivars, 10 durum wheat cultivars and five lines each of emmer, spelt and einkorn (Gebruers et al., 2008). These data are therefore also summarised in Table 2A, together with data on total and water-extractable AX (TOT-AX and WE-AX) in white flour samples from the same lines. Analyses of bran fractions carried out in the same study are not considered here as the purity of the bran may have varied between lines due to efficiency of milling. Whereas the ranges of values for AX in flour of the ancient wheats were within the range determined for bread wheat, the contents of TDF and β-glucan in wholemeal tended to be lower, particularly in emmer and einkorn. However, it should be noted that emmer and einkorn lines were limited in diversity. The five einkorn lines comprised cultivars bred in Hungary and France, genebank accessions from Italy and Albania and a Hungarian breeding line while the emmers comprised two breeding lines and one cultivar from Hungary and two accessions from the Soviet Union and Nordic Genebank (origin not known).

Fructans are not included in Table 1 as there is little information on the contents in ancient wheats. However, Verspreet et al. (2012) compared single wholemeal flours of wheat and spelt for fructan content. The mean value for bread wheat was 1.88 g/100 g and for spelt 0.67 g/100 g. However, it should be emphasised that these were single samples, and noted that the fructan content of whole wheat grain has been reported to vary from 0.84% to 1.85% (mean 1.28%) in 129 winter wheat varieties grown on a single site (Andersson et al., 2013).

3. Phytochemicals

Data on the contents of major groups of phytochemicals in milled whole grain of the modern and ancient wheat species are summarised in Tables 2B and 3. Table 2B includes data only from the HEALTHGRAIN project, in which the different species were analysed in the same laboratories using the same suite of methods. As in Table 1, only data on bread and durum wheat from the same studies as the ancient wheat species are included for comparison.

The HEALTHGRAIN study reported detailed data on individual components of five classes: phenolic acids (free, bound and soluble conjugated forms), alkylresorcinols (a group of phenolic lipids), tocols (tocopherols and tocotrienols), sterols (including stanols which are saturated sterols) and folates (vitamin B9). Only total contents of these classes are reported here with two exceptions. Firstly, individual data are reported for ferulic acid, which is the major phenolic acid in all wheat lines and the most frequently measured. Secondly, data are reported for α-tocopherol which is the major form of vitamin E.

Table 3 combines the HEALTHGRAIN data with other published studies. This table includes the same range of components as in Table 2B except that alkylresorcinols and folates are omitted (there being no other comparative studies) and carotenoids added. The methods used vary between the laboratories and this is particularly problematic with analyses of phenolic acids. Data from Table 3 are also shown graphically in Fig. 2.

These comparisons show that there are limited differences between the compositions of bread wheat and the ancient species, particularly bearing in mind the differences in numbers of samples that have been analysed, and the different methods used in the

Table 1
Contents of dietary fibre components (expressed as % dry weight) in whole grains of ancient and modern wheat species.

		Wheat	spelt	emmer	einkorn	durum
TDF	Mean (n)	14.96 (168)	11.18 (54)	9.2 (8)	10.8 (21)	13.1 (13)
	Range	11.3–21.5	8.8–14.9	7.2–12.0	8.7–16.7	10.7–15.5
Insoluble fibre	Mean (n)	11.3 (11)	9.6 (21)		6.9 (1)	10.6 (2)
	Range	9.8–13.2	7.8–12.9			9.5–11.7
Soluble fibre	Mean (n)	1.7 (6)	1.6 (26)		1.7 (1)	1.6 (2)
	Range	1.4–2.2	0.8–2.5			1.6
Arabinoxylan	Mean (n)	6.9 (11)	5.74 (28)			
	Range	6.11–7.89	4.68–6.82			
β-glucan	Mean (n)	0.72 (167)	0.64 (42)	0.36 (8)	0.39 (20)	0.37 (11)
	Range	0.37–0.95	0.23–0.90	0.3–0.4	0.25–0.48	0.25–0.53

References: Grausgruber et al. (2004); Loje et al. (2003); Marconi et al. (1999); Ranhotra et al. (1996a, 1996b); Gebruers et al. (2008); Bognar and Kellermann (1994); Abdel-Aal et al. (1995); Ranhotra et al. (1995); Bonafaccia et al. (2000); Escarnot et al. (2010); Brandolini et al. (2011); Escarnot et al. (2015).

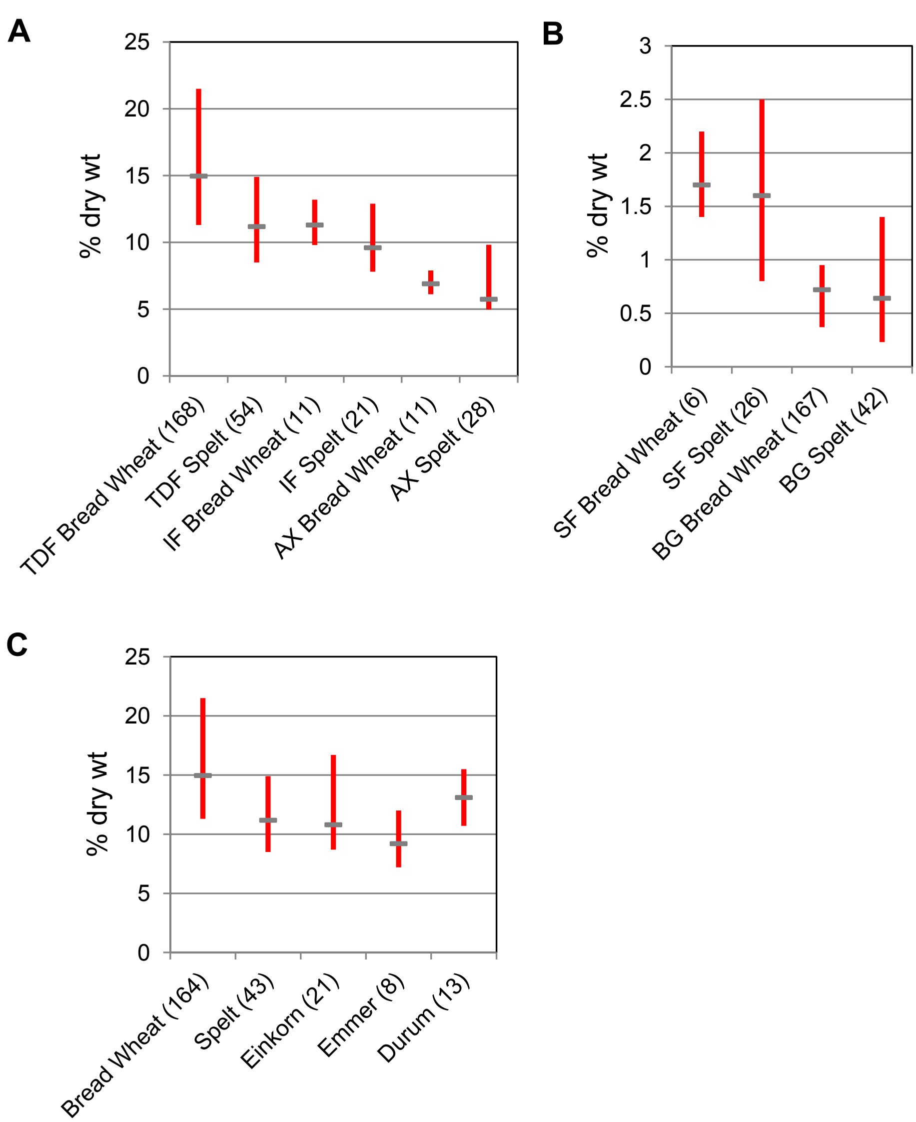

Fig. 1. A and B, reported contents of DF dietary fibre components in bread wheat and spelt. Based on data from Table 1. C, reported contents of TDF in ancient and modern wheat species. TDF, total dietary fibre; IF, insoluble fibre; SF, soluble fibre; AX, arabinoxylan; BG, β-glucan.

different reports. The limited number of samples is particularly important, as the HEALTHGRAIN study showed that the contents of phytochemicals are highly variable between samples of bread wheat, with differences ranging from x 1.39-fold (sterols) to x 3.6-fold (total phenolic acids) in the dataset summarised in Table 2B (Ward et al., 2008).

3.1. Phenolic acids

Phenolic acids are the major class of phenolics in the grain and are most frequently determined using the Folin-Ciocalteu reagent as “total phenolic acids” or as major components of “total phenolic content”, rather than by direct chemical analysis. These analyses

Table 2
Contents of bioactive components in ancient and modern wheat species analysed in the HEALTHGRAIN study (weighted means and ranges).

	No of lines	Wholemeal TDF % dry wt	Wholemeal β-glucan % dry wt	Wholemeal Klason lignin % dry wt	White flour TOT-AX % dry wt	White flour WE-AX % dry wt
A) Dietary fibre components						
Bread	151	15.1 (11.5–18.3)	0.73 (0.50–0.95)	2.19 (1.40–3.25)	1.91 (1.35–2.75)	0.50 (0.30–1.40)
durum	10	13.4 (10.7–15.5)	0.35 (0.25–0.45)	2.10 (1.85–2.55)	1.95 (1.70–2.35)	0.40 (0.25–0.55)
einkorn	5	11.0 (9.3–12.8)	0.30 (0.25–0.35)	2.60 (2.25–3.05)	1.95 (1.45–2.35)	0.60 (0.50–0.65)
emmer	5	9.8 (7.2–12.0)	0.35 (0.30–0.40)	2.30 (1.95–2.65)	1.70 (1.40–1.95)	0.25 (0.15–0.55)
spelt	5	12.0 (10.7–13.9)	0.65 (0.55–0.70)	2.25 (1.85–2.90)	1.75 (1.60–2.15)	0.35 (0.30–0.45)

	No of lines	Total phenolic acids μg/g dry wt	Total ferulic acid μg/g dry wt	Total AR[a] μg/g dry wt	Total sterols μg/g dry wt	Total tocols μg/g dry wt	α-tocopherol (vit E) μg/g dry wt	Total folates (vit B9) μg/g dry wt
B) Phytochemicals and folates (vitamin B9)								
Bread	150/151[b]	657 (326–1171)	396 (181–742)	432 (421–677)	844 (241–677)	49.8 (27.6–79.7)	13.5 (9.1–19.9)	0.56 (0.32–0.77)
durum	10	699 (536–1086)	400 (290–737)	399 (194–531)	987 (871–1106)	48.1 (40.1–62.7)	10.7 (8.3–13.1)	0.74 (0.64–0.89)
einkorn	5	615 (449–816)	298 (207–442)	595 (545–654)	1054 (976–1187)	57.0 (42.7–70.2)	9.1 (7.0–12.1)	0.58 (0.43–0.68)
emmer	5	779 (508–1161)	476 (323–711)	581 (531–714)	857 (796–937)	36.4 (29.0–57.5)	7.7 (6.4–8.6)	0.69 (0.52–0.94)
spelt	5	579 (382–726)	365 (223–502)	605 (490–741)	928 (893–963)	46.2 (40.2–50.6)	11.0 (9.9–12.5)	0.58 (0.50–0.65)

References: Gebruers et al., 2008; Andersson et al. (2008); Lampi et al. (2008); Li et al. (2008); Nurmi et al. (2008); Piironen et al. (2008).
[a] AR, alkylresorcinols.
[b] 151 lines analysed for AR.

Table 3
Contents of phytochemicals in ancient and modern wheat species (weighted means and ranges, expressed as μg/g dry weight).

Component	Bread wheat	spelt	einkorn	emmer	durum
Total tocols					
Weighted mean	46.57	37.10	69.09	46.37	48.52
Range	23.3–79.7	28.9–69.18	19.6–109.89	19.7–69.85	32.6–74.27
N	203	24	81	45	21
References	1,4,5,6,8,9,10	1,5,6,8	1,4,5,6,9,10	1,4,5,6,9,10	1,4,5,6
α-tocopherol					
Weighted mean	13.48	15.16	11.03	10.56	9.39
Range	8.69–36.94	6.26–39.56	4.89–17.35	6.4–14.5	8.19–12.55
N	205	33	81	45	14
References	1,4,5,6,7,8,9,10	1,5,6,7,8	1,4,5,6,9,10	1,4,5,6,9,10	1,4,5,6
Total sterols (including stanols)					
Weighted mean	826.4	604.4	897.4	724.7	888.5
Range	225–959	214–963	554–1187	501–937	615–929
N	158	22	9	19	15
References	2,4,11,12	2,11,12	2,4	2,4	2,4
Total phenolic acids					
Weighted mean	750.8	1081.1	836.3	961.1	857.1
Range	326–2620	331–2620.1	301.1–2590.5	508–2555.3	536–1301
N	169	32	22	44	17
References	3,4,6,14,15,17	3,6,14,16,17	3,4,6,14,15	3,4,6,14,15	3,4,6,14
Total ferulic acid					
Weighted mean	405.7	420.4	335	455.9	405.2
Range	181–742	223–579.7	207–527	323–711	290–737
n	162	11	7	6	11
References	3,6,15	3,6	3,6	3,6	3,6
Total carotenoids					
Weighted mean	2.36	2.16	2.26	8.23	3.58
Range	1.40–4.90	1.62–2.98	1.63–4.90	4.73–13.64	2.69–8.38
N	10	5	30	62	19
References	4,5,13	5,13	4,5	4,5	4,5,13

n, number of samples. References — 1. Lampi et al. (2008); 2. Nurmi et al. (2008); 3. Li et al. (2008); 4. Giambanelli et al. (2013); 5. Hidalgo et al. (2006); 6. Abdel-Aal and Rabalski (2008); 7. Ruibal-Mendieta et al. (2005); 8. Hussain et al. (2012); 9. Hejtmankova et al. (2010); 10. Lachman et al. (2013); 11. Esche et al. (2012); 12. Ruibal-Mendieta et al. (2004); 13. Panfili et al. (2004); 14. Grausgruber et al. (2004); 15. Serpen et al. (2008); 16. Calzuola et al. (2013); 17. Gawklik-Dziki et al. (2012); 18. Bognar and Kellermann (1994); 19. Abdel-Aal et al. (1995); 20. Ranhotra et al. (1995); 21. Ranhotra et al. (1996a); 22. Ranhotra et al. (1996b); 23. Marconi et al. (1999); 24. Bonafaccia et al. (2000); 25. Loje et al. (2003); 26. Gebruers et al. (2008); 27. Escarnot et al. (2010); 28. Brandolini et al. (2011).

are therefore combined in Table 3. Table 3 and Fig. 2A and B shows that "ancient wheat" species have similar contents of phenolic components to bread wheat, including total ferulic acid. However, one study was not included in this analysis. Świeca et al. (2014) compared six spelt cultivars grown in Poland, determining total phenolics using the Folin-Ciocalteu method. The contents determined ranged from 13.31 to 14.45 mg gallic acid equivalents per g dry weight. This range is substantially above other published values, which vary from 331 to 2620 μg/g dry weight (Table 3). Although Świeca et al. (2014) did not analyse bread wheat lines in the same study, they quote values of 2.71–3.16 mg/g dry weight for bread wheat cultivated in Poland (Konopka et al., 2012).

3.2. Alkyresorcinols

Alkylresorcinols were only determined in the HEALTHGRAIN study, which showed higher mean values for einkorn, emmer and spelt than for bread and durum wheats (Table 2B). However, the

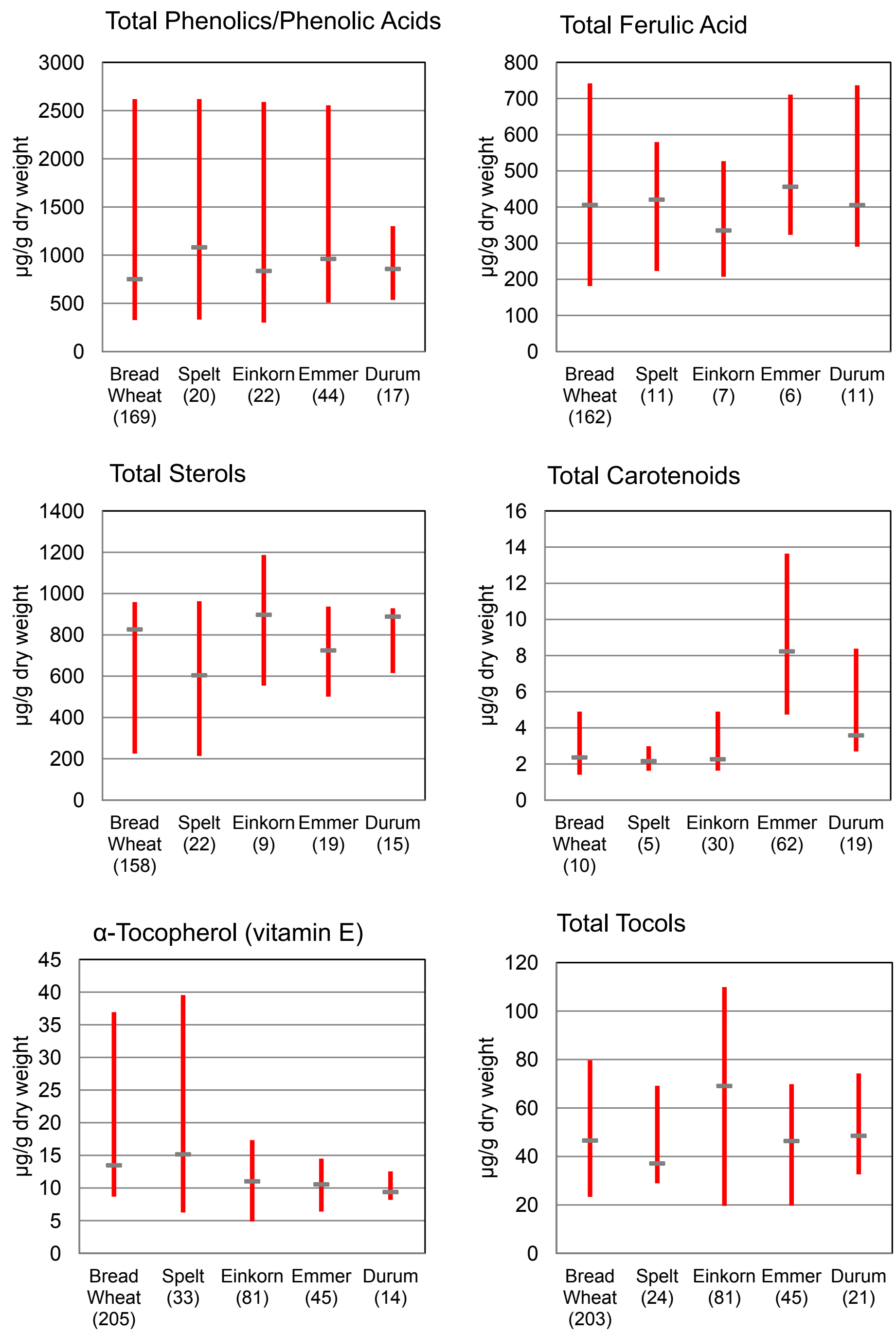

Fig. 2. Reported contents of phytochemicals in ancient and modern wheat species.

ranges for the five species overlapped and only emmer and spelt showed higher maximum values. Because alkylresorcinols are located exclusively in the outer cuticle of the grain (Tłuścik, 1978), their content in bread wheat shows a statistically significant negative correlation with 1000 grain weight (Ward et al., 2008). Hence, their content would also be expected to be higher in small seeded ancient wheats than in bread and durum wheats.

3.3. Tocols

The mean values reported for total tocols are clearly higher for einkorn than for the other wheat species, with a wider range of contents (Tables 2B and 3). However, the content of α-tocopherol is similar in all species. Einkorn also has higher contents of total sterols in the HEALTHGRAIN dataset (Table 2B), but this difference is less marked when the other published datasets are considered (Table 3).

3.4. Carotenoids

The greatest reported differences between species are in the contents of carotenoids. These were not analysed in the HEALTHGRAIN study, but a number of other studies have been reported. Carotenoids occur in two major forms, the oxygen-containing xanthophylls (which include lutein, β-cryptoxanthin and zeaxanthin) and the unoxygenated carotenes (which include α-carotene and β-carotene). Some carotenoids, notably β-carotene, are converted to vitamin A (retinol) in mammals, and hence are also referred to as provitamin A. Although a number of studies have been reported, the data for total carotenoids in Table 3 and Fig. 2 are based on only three studies. This is because most studies have determined one or more of the major components: lutein, zeaxanthin and carotenes (α-, β- or combined). These three fractions are therefore summarised in Table 4.

The major carotenoid in all species is lutein, and this is higher in einkorn, emmer and durum wheat than in bread wheat. The high content in durum wheat is to be expected, as carotenoids contribute to the yellow colour of durum wheat semolina and products such as pasta (Lafiandra et al., 2012). Grain colour is therefore a quality trait in durum wheat and breeders have selected for high contents of lutein. By contrast, selection for white flour colour is carried out during breeding of bread wheat. However, the highest content of lutein has been reported for einkorn, with a mean of 7.28 μg/g dry weight compared with 1.55 μg/g dry weight for bread wheat. The high content of lutein in einkorn could be significant for health in some populations: although lutein does not act as provitamin A, it may have benefits in improving eye health and visual function (Moeller et al., 2008; Carpentiera et al., 2009; Stringham et al., 2010).

3.5. B vitamins

The B vitamin complex comprises eight water-soluble components which often occur together in the same foods and were initially considered to be a single component. Wheat, and in particular wholegrain, is an important source of B vitamins: thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6) and folates (B9). Only folates have been compared in ancient and modern wheat species (Table 2B), as part of the HEALTHGRAIN project. This showed slightly higher contents in durum wheat (0.74 μg/g dry weight) and emmer (0.69 μg/g dry weight) compared to the other species (0.56–0.58 μg/g dry weight). However, the limited numbers of lines analysed of all species except bread wheat and the single growth environment should be borne in mind in drawing conclusions.

4. Other types of cultivated wheat

A number of other cultivated wheat species have been described, which are or have been grown in restricted geographical areas. Although these may differ morphologically from the major cultivated wheat species, most are now regarded as varieties or subspecies of *T. turgidum* and *T. aestivum*. An exception is *Triticum timopheevi* which is a tetraploid species with the unique genomic constitution AAGG, the G genome being related to the B genomes present in *T. turgidum* and *T. aestivum* but donated by a different wild *Aegilops* species (Feldman et al., 1995).

Giambanelli et al. (2013) analysed single accessions of several such "species" (*T. timopheevi* var. *timopheevi* (Zandari wheat), *T. turgidum* var. *paleocolchicum* (Georgian emmer) and *T. aestivum* var. *macha* (hulled Macha wheat)) for sterols, tocols, carotenoids and phenolics while Ross et al. (2003) analysed single accessions of 15 *Triticum* "species" for alkylresorcinol content. Although differences in composition were observed, the analysis of only single accessions means that it is not possible to draw conclusions as to whether these relate to differences between species.

Of more interest is Khorasan wheat (*T. turgidum* var. *turanicum*) and in particular Kamut®, a single genotype which has been trademarked and is widely marketed for organic production. Kamut® is of considerable interest as it has been reported to have health benefits compared to modern wheat species (see, for example, Saa et al., 2014; Carnevali et al., 2014; Sofi et al., 2014).

Several studies have included samples of Khorasan wheat, either Kamut® and/or other genotypes. These are summarised briefly below.

4.1. Total dietary fibre

Grausgruber et al. (2004) reported 12.72% dry weight of TDF in "Oriental wheat" (*Triticum turanicum*) compared to 14.28–15.66% dry weight in three bread wheat cultivars (with red, blue and purple grains).

4.2. Phenolic acids

Grausgruber et al. (2004) reported 955 μg ferulic acid equivalents/g dry weight in "Oriental wheat" compared to 1080–1440 μg ferulic acid equivalents/g dry weight in three bread wheat cultivars (with red, blue or purple grains).

Abdel-Aal and Rabalski (2008) reported 1851 μg/g of total phenolics (expressed as ferulic acid equivalents) and 220 μg/g of ferulic acid in Khorasan wheat (cultivar CDC Dragon) and 1917 μg/g total phenolics and 326 μg/g ferulic acid in Kamut®. The mean values for 10 bread wheat cultivars were 1734 μg/g total phenolics and 495 μg/g ferulic acid. These analyses were on an approximately 10% moisture basis.

Table 4
Contents of major carotenoids in ancient and modern wheat species (weighted means and ranges, expressed as μg/g dry wt).

Component	Bread wheat	spelt	emmer	einkorn	durum
α-carotene + β-carotene					
Weighted mean	0.101	0.18	0.178	0.603	0.107
Range	0.00–0.54	0.03–0.51	0.05–0.129	0.00–2.39	0.00–0.21
N	15	5	17	67	27
References	1, 2, 4, 6.	1, 6.	2, 4.	2, 4, 6.	1, 4, 6.
Lutein					
Weighted mean	1.550	1.682	2.722	7.276	2.815
Range	0.22–2.88	1.03–2.71	0.451–5.21	0.673–12.64	0.567–6.22
N	33	19	51	116	13
References	1,2,4,5,6,7,8,9	1,6,7,8,9	1,2,4,5,6,7,8,9	2,4,5,6,7,8,9	4,6,7,8,9
Zeaxanthin					
Weighted mean	0.1282	0.12	0.190	0.197	0.209
Range	0.038–0.144	0.09–0.15	0.103–0.272	0.078–0.369	0.061–0.30
N	10	3	22	13	22
References	1,2,4	1	1,2,4	2,4	1,4

References: 1. Panfili et al. (2004); 2. Lachman et al. (2013); 4. Giambanelli et al. (2013); 5. Serpen et al. (2008); 6. Hidalgo et al. (2006); 7. Abdel-Aal and Rabalski (2008); 8. Abdel-Aal et al. (2002); 9. Abdel-Aal et al. (2007).

4.3. Alkylresorcinols

Ross et al. (2003) reported 200 μg/g dry weight total AR in a single accession of "*T. turanicum*" compared with 489–642 μg/g dry weight in three cultivars of bread wheat.

4.4. Tocols

Abdel-Aal and Rabalski (2008) reported 21.1 μg/g of total tocols (sum of α- and β-tocopherol and α- and β tocotrienol) in Khorasan wheat (cultivar CDC Dragon) and 20 μg/g in Kamut®. The combined means for these four components in 10 bread wheat cultivars were 31.75 μg/g. These analyses were on an approximately 10% moisture basis. Hidalgo et al. (2006) reported 40.21 μg/g dry weight of total tocols (again the total of α- and β-tocopherol and α- and β tocotrienol) in Kamut® compared with a mean of 75.30 μg/g dry weight in five bread wheat cultivars.

4.5. Carotenoids

Abdel-Aal et al. (2007) reported 6.65 μg/g total carotenoids in Kamut® compared with 1.94 μg/g in bread wheat. The major component was lutein, which was present at 5.77 μg/g compared with a mean of 2.06 μg/g in four bread wheat cultivars (approximately 10% moisture basis).

A high content of lutein in Khorasan wheat is confirmed by other studies: 4.8 μg/g in Khorasan wheat and 4.7 μg/g in Kamut® compared to a mean of 1.58 μg/g in 10 bread wheat cultivars (Abdel-Aal and Rabalski, 2008) (approximately 10% moisture basis); 5.37 μg/g dry weight in Khorasan wheat and 6.09 μg/g dry weight in Kamut® compared to a mean of 2.24 μg/g dry weight in two bread wheat cultivars (Abdel-Aal et al., 2002); and 4.42 μg/g dry weight in Kamut® compared with a mean of 1.79 μg/g dry weight in five bread wheat cultivars (Hidalgo et al., 2006).

These analyses therefore show that Khorasan wheat, including Kamut®, differs from modern in wheats in having a higher content of lutein, but not of other bioactive components which have been determined.

5. Conclusions

Limited data are available on the contents and compositions of bioactive components in ancient wheats. Nevertheless, the data that are available show that they differ little from modern wheat species in the contents of most bioactive components, and may be lower in some components (such as dietary fibre).

The only notable difference from bread wheat is high contents of the carotenoid lutein in einkorn, emmer and Khorasan. Carotenoids have been selected against in bread wheat due to their colour, but durum wheat also has high lutein due to selection for yellow colour.

These analyses do not support the suggestion that ancient wheats are generally more "healthy" than modern wheats. However, further detailed studies are required, with multiple genotypes of ancient and modern wheat species grown in replicate multi-site field trials and analysed with standard methods.

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