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The Contribution of Wheat to Human Nutrition and Health

Abstract

Wheat provides 20% of calories globally but up to 50% in some regions. In addition to energy, it provides protein, dietary fibre, mineral micronutrients (iron, zinc and selenium), B vitamins and beneficial phytochemicals. However, grain composition varies between genotypes with strong effects of environment. In addition, beneficial components are concentrated in the embryo and outer layers which form the bran on milling. Hence their concentrations are depleted in white flour.

Introduction

Wheat has been consumed by humans but for at least 40,000 years, with breadmaking dating back at least 14,000 years. It currently accounts for over a quarter of all cereal production and is produced on a larger area, grown over a wider geographic range, and traded more internationally than any other arable crop. It provides 20% of the calories and protein in the global human diet, a greater contribution than any other crop (Shiferaw et al. 2013). However, the dependency on wheat varies widely between geographical areas, accounting for up to 50% of total calories in some regions. In addition to energy, wheat is an important source of other essential nutrients, notably dietary fibre, mineral micronutrients, vitamins and phytochemicals.

There is wide variation in the compositions of food products made from wheat. This is determined partly by variation in grain composition, due to effects of genotype, environment and the interactions between these. However, greater differences result from the processing systems, in particular milling to produce flour and fermentation systems (yeast or sourdough) used for breadmaking. These factors will therefore be briefly considered before discussing the contribution of wheat to dietary intakes. The article will focus on bread wheat, which accounts for about 95% of global production, but much of the discussion is also relevant to other types of wheat, notably durum (pasta) wheat which accounts for most of the remaining 5%.

Grain composition

The mature wheat grain contains about 60-70% starch, 10-15% protein and 11-15% dietary fibre, with smaller amounts of lipids, minerals, vitamins and phytochemicals. This variation results in part from genetic differences between cultivars, particularly between cultivars bred for different end uses. Much of the wheat grown globally is used for human foods, particularly breadmaking which requires a high protein content. However, in some countries substantial quantities of wheat are used for feeding livestock and for alcohol production (in beverages and for biofuel) which require low grain protein. Consequently, there may be a difference of 2% dry wt. in the protein contents of breadmaking and feed wheats when grown under the same conditions. The protein content of commercially grown wheat has also declined over the past century (Shewry et al. 2016) and the content of starch increased: this is a consequence of breeding for increased yield (which is essentially determined by starch the accumulation of starch). The protein content of the grain is also strongly affected by the environment, particularly the application of nitrogen fertiliser (Figure 1). This is important because it allows the farmer to adjust the protein content of the crop for the market requirements (which are about 13% protein for breadmaking in the UK).

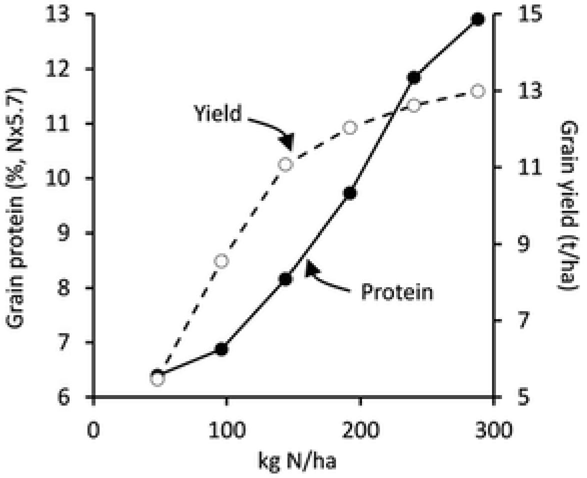


Figure 1. Relationship between application of nitrogen fertiliser, grain yield and grain protein content for the bread making cultivar cv. Crusoe grown as first wheat in the Broadbalk experiment at Rothamsted Research in 2014. Yield is expressed on an 85% dry wt. basis and protein content on a dry wt. basis. We thank the Lawes Agricultural Trust and Rothamsted Research for data from the e-RA database. The Rothamsted Long-term Experiments National Capability (LTE-NCG) is supported by the UK Biotechnology and Biological Sciences Research Council and the Lawes Agricultural Trust. Figure kindly provided by Prof Mike Gooding.

The contents of many other grain components, notably phytochemicals and vitamins, are affected to a greater extent by the environment than the crop genotype and the proportion of the variation due to genetic differences (termed heritability) may be below half of the total variation (Shewry et al. 2010, 2011).

Variation in composition in grain tissues and foods

The wheat grain is a single seeded fruit, called a caryopsis, and comprises several types of tissue which differ in their compositions (Figure 2).

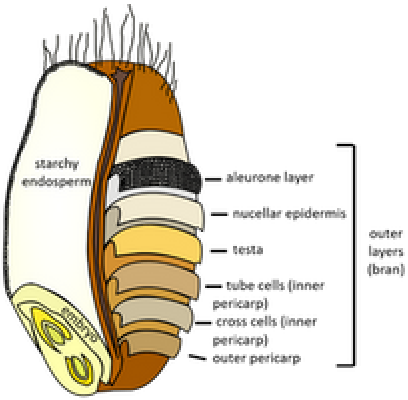


Figure 2. Schematic structure of the mature wheat grain showing the different tissues. Taken from Hazard et al (2020) and kindly provided by Dr. Brittany Hazard.

About 90% of the grain is formed by the endosperm. This is the major storage tissue of the seed and comprises two individual tissues: the outer layer of aleurone cells and the inner starchy endosperm cells. Adjacent to this is the embryo, which accounts about 3% of the grain dry wt. and consists of a single storage cotyledon and the embryonic axis which will develop to form the seedling during germination. The endosperm and embryo are seed tissues, formed by fertilisation. They are surrounded several outer layers of maternal tissues (the testa (seed coat), nucellar epidermis and several layers of pericarp (fruit coat)) which together account for 7-8% of the seed weight.

These tissue differ in their compositions (Table 1) with the starchy endosperm containing about 70-80% starch, 7-12% protein, 4-5% fibre and 1-2% lipids low but very low contents of other components while the aleurone, embryo and outer layers contain little or no starch but high fibre, phytochemicals, minerals and vitamins, with the embryo also being very rich in oil and protein.

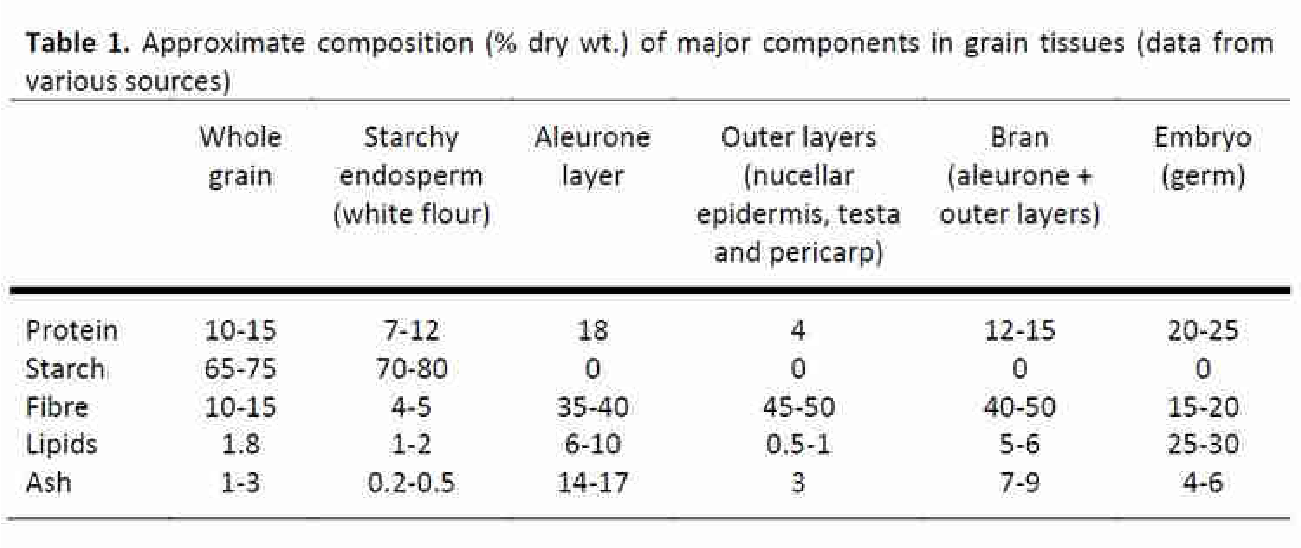


Table 1. Approximate composition (% dry wt.) of major components in grain tissues (data from various sources)

	Whole grain	Starchy endosperm (white flour)	Aleurone layer	Outer layers (nucellar epidermis, testa and pericarp)	Bran (aleurone + outer layers)	Embryo (germ)
Protein	10-15	7-12	18	4	12-15	20-25
Starch	65-75	70-80	0	0	0	0
Fibre	10-15	4-5	35-40	45-50	40-50	15-20
Lipids	1.8	1-2	6-10	0.5-1	5-6	25-30
Ash	1-3	0.2-0.5	14-17	3	7-9	4-6

Most of the wheat consumed by humans is in the form of white bread which corresponds to the starchy endosperm tissue of the grain. It is clear from Table 1 that white flour is enriched in starch but depleted in components that contribute to a healthy diet (fibre, minerals, vitamins, phytochemicals) compared to whole grain, although this can ameliorated to an extent by increasing the proportion of the grain recovered in flour from about 80% to 85% to include the aleurone tissue. Further changes in composition occur during fermentation, with some similarities and but also differences between yeast and sourdough systems.

Consequences, the compositions of the wheat products consumed globally vary with the types of wheat used, the environment, the agronomy (notably fertiliser application), the milling and processing system.

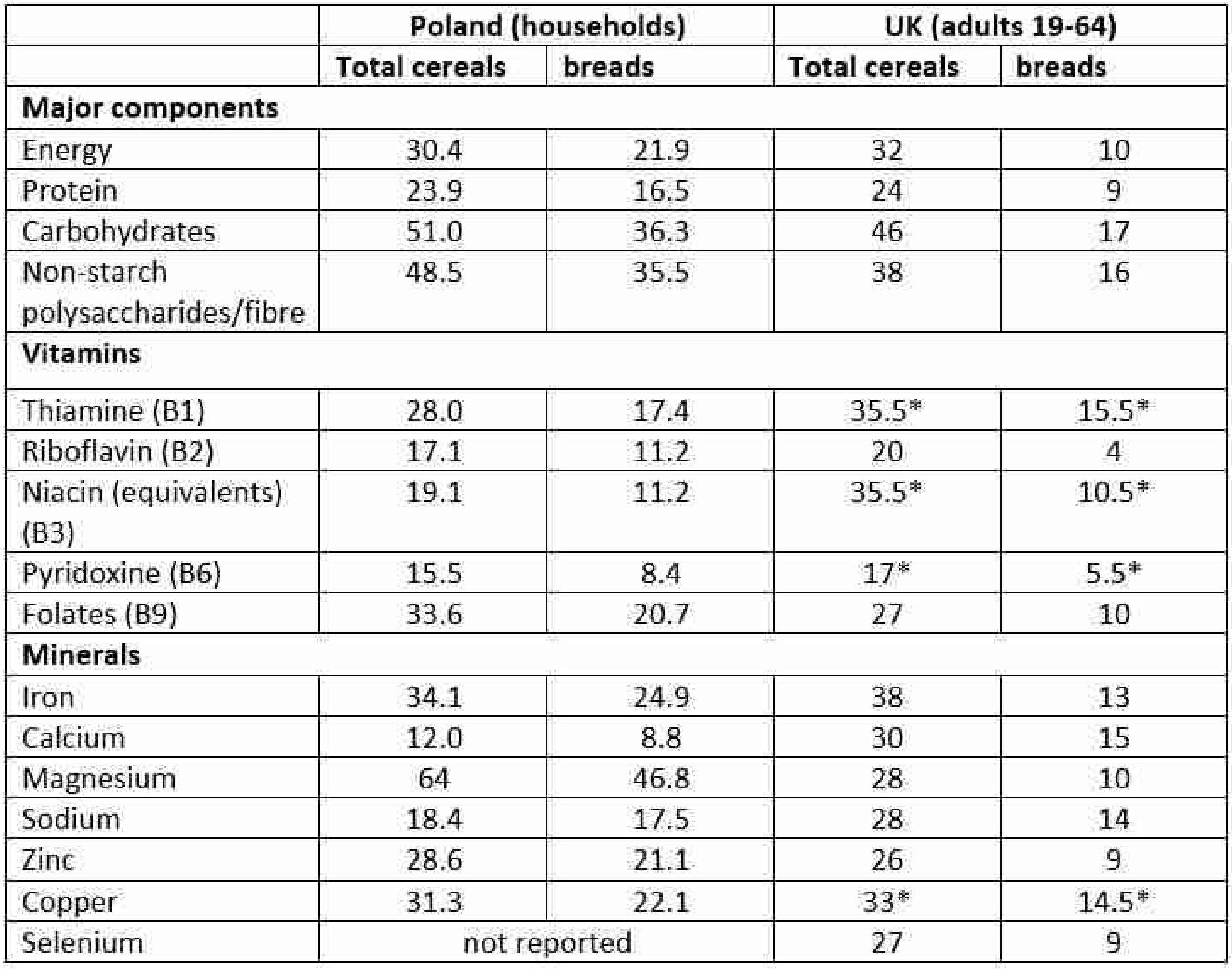
Contribution of wheat to dietary intakes of nutrients

Systematic studies of the contributions on wheat to nutrient intakes in several countries have been reported, but the data may not be strictly comparable as the product categories vary.

The data will also be affected by differences in the types of cereals and breads consumed in the two countries. This is illustrated by the datasets for total cereals and for breads and related products reported for Poland and the UK (Table 2). In this comparison the higher contributions of cereals and bread to fibre to total fibre intake in Poland could result from greater consumption of rye and wholemeal breads compared to the wheat and white flour products which are most widely consumed in the UK. Furthermore, because the data are for %age total daily intake they will be affected by the intake of other food groups. For example, a high contribution of calcium from milk would reduce the %age intake from wheat.

The consumption values for Poland and the UK are probably typical of European countries, where wheat is the staple food crop but consumed as part of a mixed diet, with cereals and bread providing about 30% and 10-20% of the total energy intake, respectively.The contribution of wheat to intakes of nutrients will therefore be much greater in areas where the consumption of wheat is higher. For example, in parts of North Africa, the Middle East, and Central Asia wheat may contribute more than 50% of daily calorific intake.

Table 2. Contributions of total cereals and breads (including rolls) to the total dietary intakes of nutrients in Poland (data for households) (taken from Laskowski et al. 2019) and the UK (data for adults aged 19-64) (taken from *Bates et al. (2014a,b) and Bates et al. (2020)).



	Poland (households)		**UK (adults 19-64)**	
	Total cereals	**breads**	**Total cereals**	**breads**
Major components				
Energy	30.4	21.9	32	10
Protein	23.9	16.5	24	9
Carbohydrates	51.0	36.3	46	17
Non-starch polysaccharides/fibre	48.5	35.5	38	16
Vitamins				
Thiamine (B1)	28.0	17.4	35.5*	15.5*
Riboflavin (B2)	17.1	11.2	20	4
Niacin (equivalents) (B3)	19.1	11.2	35.5*	10.5*
Pyridoxine (B6)	15.5	8.4	17*	5.5*
Folates (B9)	33.6	20.7	27	10
Minerals				
Iron	34.1	24.9	38	13
Calcium	12.0	8.8	30	15
Magnesium	64	46.8	28	10
Sodium	18.4	17.5	28	14
Zinc	28.6	21.1	26	9
Copper	31.3	22.1	33*	14.5*
Selenium	not reported		27	9

Dietary fibre

The importance of dietary fibre for human health has become increasingly recognised over the past half century, with high fibre intake being associated with reduced risk of a range of chronic diseases, including cardio-vascular disease, type 2 diabetes and several types of cancer. These benefits are summarised in excellent reviews and meta-analyses (Veronese et al. 2018; Gill et al. 2020).

Dietary fibre can be defined as “carbohydrate oligomers and polymers that are not digested and absorbed in the small intestine and are partially or completely fermented in the colon. It also includes associated plants substances such as lignin” (https://www.cerealsgrains.org/initiatives/definitions/Pages/DietaryFiber.aspx). Consequently, there is wide variation in the content and composition of fibre in different plant tissues. Fibre components also differ widely in their properties, from small soluble oligosaccharides to large insoluble polymers. A widely used sub-division of fibre is into soluble and insoluble forms. However, solubility depends on conditions in the GI tract and Gill et al (2021) suggest that it is important to consider the balance of three “physicochemical” properties: solubility, viscosity and fermentability. Insoluble, non-viscous fibres (such as cellulose and lignin) are either slowly fermented or not fermented in the colon and have benefits in increasing intestinal transit time and stool bulking, soluble non-viscous components such as fructans are rapidly fermented to short chain fatty acids (SCFA) and have prebiotic effects in the colon, while soluble viscous fibres (such as soluble forms of AX and β-glucan) may affect the uptake of nutrients in the small intestine as well as having prebiotic effects due to fermentation to SCFA in the colon. The beneficial effects of fibre in the small intestine include reducing the rate of starch breakdown, and hence the glycaemic response, and lowering serum cholesterol.

The major dietary fibre components in whole wheat grain are cell wall components: polysaccharides (cellulose, arabinoxylan and β-glucan ((1,3)(1,4)-β-D-glucan)) and associated lignin (Table 3). Whereas lignin and cellulose are insoluble, arabinoxylan and β-glucan occur in soluble and insoluble forms. In addition, wheat grains contain two other types of fibre which are wholly soluble. Fructo-oligosaccharides, usually called fructans, comprise three or more fructose units, with some forms also having a single glucose unit, and appear to be present, but at different concentrations, in all grain fractions. Arabinogalactan peptide (AGP) consists of a short (15 residue amino acid) peptide with three hydroxyproline residues which are *o*-glycosylated with branched arabinogalactan chains. It is present in the starchy endosperm where it may be located in the cytoplasm or vacuole.

Total dietary fibre (TDF), determined as the combined amounts of cell wall polysaccharides, AGP, lignin and fructans, accounts for between 11.5 and 15.5 of the dry weight of the mature wheat grain (Andersson et al., 2013) (Table 3). In addition to arabinoxylan, cellulose and β-glucan, small amounts of other cell wall polysaccharides have been reported, notably glucomannan, pectins, callose ((1,3)-β-D-glucan) and xyloglucan.

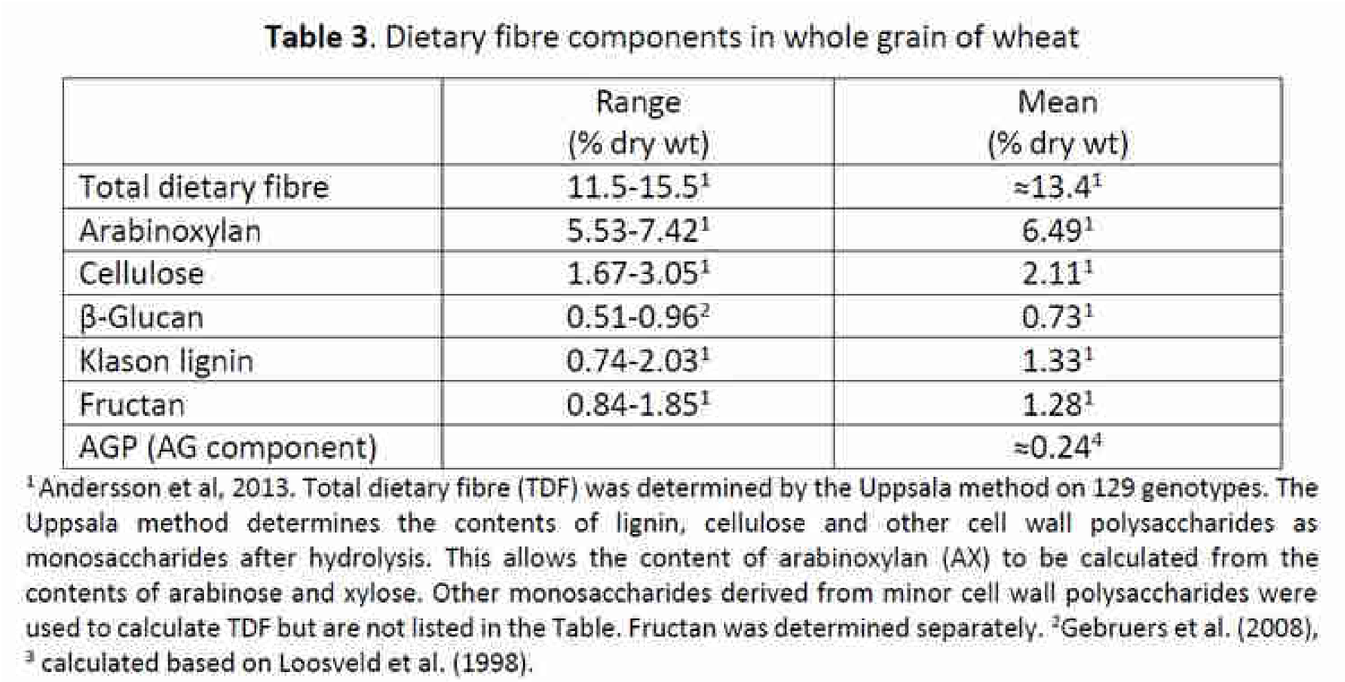


Table 3. Dietary fibre components in whole grain of wheat

	Range (% dry wt)	Mean (% dry wt)
Total dietary fibre	11.5-15.5[1]	≈13.4[1]
Arabinoxylan	5.53-7.42[1]	6.49[1]
Cellulose	1.67-3.05[1]	2.11[1]
β-Glucan	0.51-0.96[2]	0.73[1]
Klason lignin	0.74-2.03[1]	1.33[1]
Fructan	0.84-1.85[1]	1.28[1]
AGP (AG component)		≈0.24[4]

[1] Andersson et al, 2013. Total dietary fibre (TDF) was determined by the Uppsala method on 129 genotypes. The Uppsala method determines the contents of lignin, cellulose and other cell wall polysaccharides as monosaccharides after hydrolysis. This allows the content of arabinoxylan (AX) to be calculated from the contents of arabinose and xylose. Other monosaccharides derived from minor cell wall polysaccharides were used to calculate TDF but are not listed in the Table. Fructan was determined separately. [2]Gebruers et al. (2008), [3] calculated based on Loosveld et al. (1998).

White flour (derived from the starchy endosperm) contains less total dietary fibre than wholegrain (Table 4) and the major component is arabinoxylan, which accounts for between 1.35 and 2.75% of the flour dry wt.. Arabinoxylan represents over half of the total cell wall polysaccharides and about half of the total DF. The second major component, β-glucan, has been reported to account for 0.25 to 0.63% of the grain dry wt. (about 20% of the total cell wall polysaccharides). Klason lignin is absent and the contents of cellulose and other cell wall polysaccharides are generally regarded as low and hence not included in the Table 4. Whereas between a quarter and half of the arabinoxylan in white flour is water-soluble this fraction is lower for whole grain, generally about 5%.

The differences in fibre content, composition and properties of wholegrain and white flour have consequences for the impact on health, as discussed above.

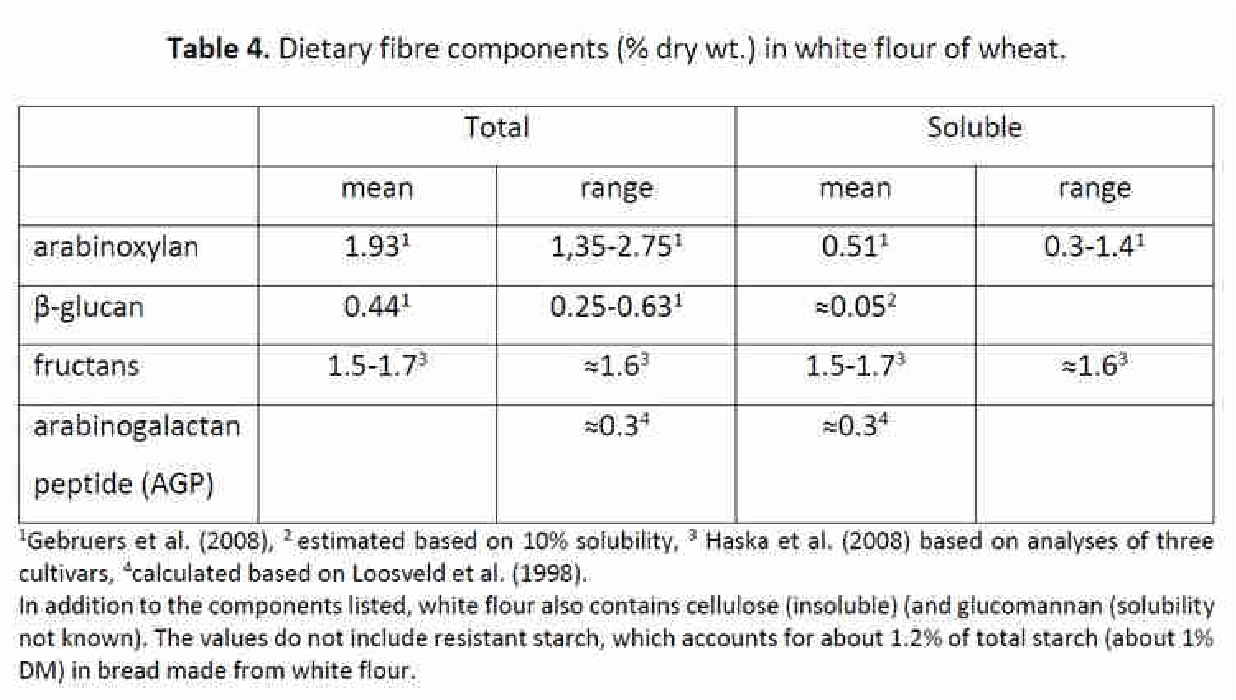


Table 4. Dietary fibre components (% dry wt.) in white flour of wheat.

	Total		Soluble	
	mean	range	mean	range
arabinoxylan	1.93[1]	1,35-2.75[1]	0.51[1]	0.3-1.4[1]
β-glucan	0.44[1]	0.25-0.63[1]	≈0.05[2]	
fructans	1.5-1.7[3]	≈1.6[3]	1.5-1.7[3]	≈1.6[3]
arabinogalactan peptide (AGP)		≈0.3[4]	≈0.3[4]	

[1]Gebruers et al. (2008), [2] estimated based on 10% solubility, [3] Haska et al. (2008) based on analyses of three cultivars, [4]calculated based on Loosveld et al. (1998).

In addition to the components listed, white flour also contains cellulose (insoluble) (and glucomannan (solubility not known). The values do not include resistant starch, which accounts for about 1.2% of total starch (about 1% DM) in bread made from white flour.

Mineral micronutrients

The amounts of iron (Fe) and zinc (Zn) in wheat grain are strongly affected by the amounts of available minerals in soils, but in broad terms both range from about 20 to 50 mg/kg dry wt. Both minerals are concentrated in the embryo and aleurone layer of the grain, but their relative distributions between these two tissues differ with Fe being more concentrated in the aleurone layer and Zn in the embryo (particularly in the embryonic axis). In common with other minerals (including calcium and magnesium), most of the Fe and Zn in the aleurone cells and in the scutellum of the embryo is present as phytates in discrete bodies known as phytin globoids. Phytates are complexes with phytic acid (inositol hexakisphosphate) which has a cyclic structure with six phosphate groups which can bind metal ions. The form of the zinc in the wheat embryonic axis has not been determined, but it is presumed to include zinc cofactors in enzymes.

The presence of Fe and Zn as phytates in the aleurone and embryo has two consequences for human health. Firstly, these tissues form the bran fraction on milling and hence the concentrations of the minerals are depleted in white flour compared to wholemeal, by about four-fold. Secondly, because phytates have low solubility the bioavailability of Fe and Zn in whole grain wheat is low, although probably higher for Zn (about 25%) than for Fe (about 10%) (Bouis and Welch 2010). The higher bioavailability of Zn could result from the presence of zinc which is not bound to phytin in the embryonic axis.

Comparisons of grain samples from older and modern types of wheat have shown significant decreases in the concentrations of Fe, Zn, and most other minerals in the grain of modern semi-dwarf types compared to traditional tall wheats. Although these decreases may result in part from “yield dilution” (due to greater accumulation of starch), they also occur under conditions of low nitrogen fertilisation where the yields of traditional and semi-dwarf cultivars do not differ (Fan et al. 2008). The older tall and modern semi-dwarf wheats may therefore also differ in their ability to source nitrogen from the soil and translocate it to the developing grain.

The strong effects of mineral availability mean that increases in the concentrations of Fe and Zn in the grain can be achieved by their application in fertilisers, a strategy known as “agronomic biofortification” (Velu et al. 2014). Increases in the content of Zn in whole grain have also been achieved by marker-assisted selection for genetic variation in total grain Zn (Velu et al. 2018) and “genetically biofortified” lines have been developed and are currently being grown and assessed in large scale dietary interventions studies (Lowe et al. 2020).

Selenium (Se) is essential for human health, being required for the activities of a number of enzymes. Wheat is an important source of Se in the diet, but the concentration in the grain is largely determined by selenium availability in soil. Consequently, the geographical source of wheat has a major effect on the Se status of consumers. For example, wheat used for breadmaking in the UK before the 1970s was largely sourced from North America where the soils have relative high soil contents of selenium. This resulted in high selenium content of the grain which contributed to adequate selenium status of the UK population. The situation changed after the UK joined the European Union, with imported breadmaking wheat being largely replaced by home grown wheat. Because UK soils are generally lower in selenium the contents in wheat and bread also decreased, contributing to a reduced intake of selenium in the UK diet, from about 60 µg/day to 30-40 µg/day.

Unlike other minerals, the concentration of selenium in grain of modern wheats does not appear to have declined when compared to older types, and there is little genetic variation in the content of Se in wheat grain grown under low Se conditions. However, agronomic biofortification using Se-containing fertilisers is effective and widely used in some countries.

Unlike most minerals, Se is not taken up using dedicated transporters, but by sulphur transporters, competing with the uptake of sulphur. Sulphur is itself deficient for the production of breadmaking wheat in some countries (such as the UK) and is therefore routinely applied as a fertiliser. The competing requirements for Se and sulphur must therefore be considered when designing strategies for biofortification.

B vitamins

The term B vitamins is applied to a group of eight water-soluble components which were initially thought to comprise a single component. Cereals are significant dietary source of five B vitamins, providing between 15% and 35% of the daily intakes of thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6) and folates (B9) in the UK and Polish diets (Table 2). The values for breads are lower, ranging from about 4% to 20% of total daily intakes.

B vitamins are concentrated in the embryo and outer layers of the grain and therefore depleted in white flour compared to whole grain. There has therefore been considerable debate on whether to fortify white flour with folates (B9) to reduce the incidence of neural tube defects during foetal development. The benefits in this respect are clear and mandatory fortification is now carried out in over 60 countries including North America and the UK.

The individual B vitamins are unrelated in their structures and synthesised by separate complex pathways. There are also strong effects of environment but little apparent genetic variation in amount (Shewry et al., 2011). Consequently. the only currently available strategies for improvement are by exploiting transgenesis, either to increase the level of expression of individual rate-limiting enzymes or the activities of whole biosynthetic pathways (Martin and Li, 2017).

Phenolic acids

Phenolic compounds are the most abundant and diverse group of phytochemicals in plants. They contain at least one aromatic ring bearing at least one hydroxyl group and the major group in wheat is phenolic acids (PAs) which have an organic carboxylic function. Phenolic acids are classified into two groups derived from cinnamic acid or benzoic acid and occur in three forms: either as free compounds, as soluble conjugates bound to low molecular weight compounds (such as sugars and sterols) and as bound forms, which are linked to cell wall polysaccharides by ester bonds.

The total contents of phenolic acids in the whole wheat grain range from about 300 to over 1000 µg/g dry wt. but the concentration is much lower in white flour, below 200 µg/g dry wt. (Shewry and Hey 2015). There is wide variation in the proportions of individual phenolic acids between different wheat genotypes and strong effects of environment on amount and composition (Shewry et al 2010). However, the bound phenolic acids generally account for over 75% of the total fraction, with one component, ferulic acid, accounting for about 75% of the bound phenolic acids. Hence, ferulic acid is generally the most abundant phytochemical in the wheat grain. Phenolics are of interest in relation to their potential health benefits. They are strong antioxidant, with strong correlations between total antioxidant activity and total phenolic acids in wheat. Antioxidant activity has been widely suggested to contribute to the health benefits of “superfoods”, including whole grain cereal products (Shahidi and Ambigaipalan 2015). Alternative mechanisms for the benefits of phenolics have also been proposed, including direct effects of ferulic acid on cardio-vascular function following the consumption of bread treated with feruloyl esterase enzyme to release the bound ferulic acid (Turner et al. 2021).

It is therefore likely that the impacts of phenolic acids and other phytochemicals on human health are complex, involving multiple mechanisms and additive and synergistic effects of individual components.

Conclusions

Wheat, and wheat-based foods such as bread and noodles, has immense importance as staple foods in many regions, including Europe, North Africa, East, Central and South Asia, China and North and South America. In addition to providing between 10% and 50% of the energy requirements in these regions they also provide substantial proportions of the dietary intakes or protein, dietary fibre, minerals, B vitamins and beneficial phytochemicals. Furthermore, wheat is increasingly consumed in countries in which it cannot be readily grown, such as Sub-Saharan Africa where it is associated with urbanisation and industrialisation. Increasing the health benefits by plant breeding and innovative processing should therefore be a priority for national and internal programmes to improve the health and quality of life of consumers.

Acknowledgements

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