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Variation in the Content of Dietary Fiber and Components Thereof in Wheats in the HEALTHGRAIN Diversity Screen

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Within the HEALTHGRAIN diversity screening program, the variation in the content of dietary fiber and components thereof in different types of wheat was studied. The wheat types were winter (131 varieties) and spring (20 varieties) wheats (both *Triticum aestivum* L., also referred to as common wheats), durum wheat (*Triticum durum* Desf., 10 varieties), spelt wheat (*Triticum spelta* L., 5 varieties), einkorn wheat (*T. monococcum* L., 5 varieties), and emmer wheat (*Triticum dicoccum* Schübler, 5 varieties). Common wheats contained, on average, the highest level of dietary fiber [11.5−18.3% of dry matter (dm)], whereas einkorn and emmer wheats contained the lowest level (7.2−12.8% of dm). Intermediate levels were measured in durum and spelt wheats (10.7−15.5% of dm). Also, on the basis of the arabinoxylan levels in bran, the different wheat types could be divided this way, with ranges of 12.7−22.1% of dm for common wheats, 6.1−14.4% of dm for einkorn and emmer wheats, and 10.9−13.9% of dm for durum and spelt wheats. On average, bran arabinoxylan made up ca. 29% of the total dietary fiber content of wheat. In contrast to what was the case for bran, the arabinoxylan levels in flour were comparable between the different types of wheat. For wheat, in general, they varied between 1.35 and 2.75% of dm. Einkorn, emmer, and durum wheats contained about half the level of mixed-linkage β-glucan (0.25−0.45% of dm) present in winter, spring, and spelt wheats (0.50−0.95% of dm). All wheat types had Klason lignin, the levels of which varied from 1.40 to 3.25% of dm. The arabinoxylan contents in bran and the dietary fiber contents in wholemeal were inversely and positively related with bran yield, respectively. Aqueous wholemeal extract viscosity, a measure for the level of soluble dietary fiber, was determined to large extent by the level of water-extractable arabinoxylan. In conclusion, the present study revealed substantial variation in the contents of dietary fiber and constituents thereof between different wheat types and varieties.

KEYWORDS: Wheat; dietary fiber; polysaccharide; arabinoxylan; β-glucan; lignin

INTRODUCTION

Dietary fiber (DF) is defined as "the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. DF includes polysaccharides, oligosaccharides, lignin and associated plant substances. It promotes beneficial physiological effects including laxation and/or blood cholesterol attenuation and/or blood glucose attenuation" (*1*). DF is one of the most important classes of compounds in cereal grains brought in relation to positive health effects, with a recommended overall DF intake of 30−35 g/day for adults (*2*). High DF intake lowers the risk of, for example, diverticular disease, hemorrhoids, and colorectal cancer (*1*). Insoluble DF in particular reduces transit time and increases fecal bulk, frequency of defecation (*1*), and binding and excretion of carcinogens (*3*). Soluble DF, which is more readily fermentable in the colon than insoluble DF, causes a shift to lower colonic pH and increases the number and changes the profile of intestinal micro-organisms. DF fermentation results in the production of short-chain fatty acids favoring bowel health

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(*3*). Soluble DF in particular lowers both cholesterol and glucose absorption in the small intestine and postprandial blood insulin levels (*3, 4*). Attenuation of blood cholesterol is related to reduced risk of developing coronary heart disease, whereas attenuation of blood glucose is related to reduced risk of type 2 diabetes.

Common wheat (*Triticum aestivum* L.) is the most important cereal crop worldwide, together with maize and rice (*5*). It is responsible for a large portion of the DF intake in the Western human diet. The most important wheat DF components are the nonstarch polysaccharides arabinoxylan (AX), mixed-linkage β-glucan (further referred to as β-glucan), and cellulose, and the nonpolysaccharide compound lignin, which are all cell wall components.

AX is quantitatively the most abundant DF polysaccharide in bread wheat. It makes up 60−70% of the starchy endosperm cell wall dry matter (dm) weight (*6, 7*). AX makes up around 2% of the starchy endosperm dm, of which it is one-fourth to one-third water extractable (*8*). It consists of a backbone of β-1,4-linked D-xylopyranosyl residues substituted at O-2 and/or O-3 with α-L-arabinofuranosyl residues (*9, 10*) with arabinose over xylose ratios (A/X) of 0.5−0.8 (*11, 12*). Arabinofuranosyl residues can be substituted at O-5 with ferulic acid moieties (*13*). The peripheral layers (aleurone and intermediate and outer pericarp layers) and germ are richer in AX than the starchy endosperm, with the highest levels occurring in the outer pericarp (ca. 40%). Whereas lower A/X values have been reported for aleurone (ca. 0.44) and intermediate layer AX (ca. 0.42) than for the starchy endosperm AX, outer pericarp AX is more heavily substituted (ca. 1.16) (*11*). AX in the peripheral layers, especially in the pericarp, also contains uronic acid residues (*14*−*16*). Apart from their nutritional relevance, AX is also important from a technological point of view as it strongly affects wheat functionality during cereal processing, for example, in breadmaking (*17, 18*) and gluten−starch separation (*19, 20*).

β-Glucan is a linear homopolymer arranged in blocks of consecutive β-(1→4)-linked D-glucose residues separated by single β-(1→3)-linkages. The chain mainly consists of cellotriosyl (58−72%) and cellotetraosyl (20−34%) units. However, there is evidence for a minor level of cellulosic blocks having more than four residues. The cellotriosyl to cellotetraosyl ratios in wheat β-glucan (4.2−4.5) are higher than those in the corresponding barley and oat β-glucans and seem to be responsible for its poor solubility and fast gelation (*21*). The level of β-glucan in the whole grain of wheat has been reported to vary between 0.5 and 1.4% of dm (*22*). The endosperm contains as little as ca. 0.3% of dm β-glucan (*23*). Most β-glucan is found in the aleurone layer [ca. 23% of cell wall polysaccharide fresh weight (fw)] (*11*).

Like β-glucan, cellulose is a homopolymer of glucose. However, all residues are linked by β-1,4-linkages only. The cellulose content in wheat endosperm is ca. 0.6% of dm, whereas the dm of wheat bran contains ca. 8.0% cellulose (*24*). Cellulose is a very abundant cell wall polysaccharide in the outer pericarp and intermediate layers, which contain ca. 25 and 12.2% of fw of this polysaccharide, respectively (*11*).

Lignin is a nonpolysaccharide cell wall substance that is mainly derived from the three monolignols: *p*-coumaryl, coniferyl, and synapyl alcohols. The monolignols are differentially targeted to discrete regions of various cell wall types, where they are polymerized into wall-reinforcing biopolymers with distinctive biophysical properties (*25*). Wheat wholemeal typically has a lignin concentration of ca. 2% of dm (*26*).

The aim of this study was to investigate the extent of variation in the content of DF, and of components thereof, in a wide array of different wheat types and varieties. Of the different DF constituents discussed above, the focus was on AX, β-glucan, and lignin. Besides common wheats, that is, spring and winter wheats, also durum wheats (*Triticum durum* Desf.), spelt wheats (*Triticum spelta* L.), and early cultivated forms of wheat, that is, diploid einkorn (*Triticum monococcum* L.) and tetraploid emmer (*Triticum dicoccum* Schübler) wheats, were analyzed. This study is part of the HEALTHGRAIN [project supported by the European Commission in the Community sixth Framework Programme (*27*)] biodiversity screen, which explores the extent of variation in phytochemicals and other bioactive components in the gene pool available for plant breeders (*28*). The diversity screen covers not only different types of wheat but also rye (*29*), barley (*30*), and oats (*31*).

MATERIALS AND METHODS

Chemicals and Reagents. All chemicals and reagents were of at least analytical grade and obtained from a number of sources including Sigma-Aldrich (Buchs, Switzerland), VWR International (Leuven, Belgium), and Acros (Geel, Belgium). The Total Starch Assay Kit and the Mixed-Linkage β-Glucan Assay Kit were from Megazyme (Bray, Ireland).

Cereals. All cereal samples were provided by the Agricultural Research Institute of the Hungarian Academy of Sciences (Martonvásár, Hungary). The lines were sown in two replicate blocks on the field at the Agricultural Research Institute (Martonvásár, Hungary; latitude, 47° 21′ N, longitude, 18° 49′ E; altitude, 150 m) in 2004 (winter types) or 2005 (spring types). The plots were 2.5 m long, with six rows spaced at a distance of 20 cm. The soil was of the chernozem type with a loam texture and pH 6.8−7.2. The previous crop was peas, and there was a rainy period before harvest in 2005. The plots were treated with herbicide (4 L/ha U-46-M Fluid containing 500 g/L MCPA, 15 g/ha Granstar containing 75% tribenuron methyl), insecticide (0.2 L/ha Karate containing 2.5% λ-cyhalothrin), and fungicide (1 L/ha Eminent containing 125 g/L tetraconazole, 1 L/ha Tango Star containing 84 g/L epoxyconazole and 250 g/L fenpropymorph). Edge effects were negligible as the size of the plots was 2.5 m^2; the plots were surrounded by other plots (distance between the plots was 40 cm), and material from one plot was bulked to ensure homogeneity of the samples.

The present study includes 131 winter, 20 spring, 10 durum, 5 einkorn, 5 emmer, and 5 spelt wheat varieties. These lines show wide geographical diversity in origin (from Europe to East Asia, America, and Australia) and include landraces and breeding lines as well as modern and older cultivars. The description of these wheats and their cultivation conditions are discussed in detail by Ward et al. (*28*).

Sample Preparation. Winter, spring, and durum wheat samples were conditioned to 15.5% moisture content, whereas samples of the other wheat types were conditioned to 14.0% moisture content. Next, the samples were ground with a Perten Laboratory mill 3100 (Perten Instruments AB, Huddinge, Sweden) to yield wholemeal passing through a 0.5 mm sieve or milled with a Chopin CD1 Laboratory mill (Chopin Technologies, Villeneuve-la-Garenne, France) to produce white flour, shorts, and bran. The spelt wheat samples were dehulled before milling by using an impact type (centrifugal) dehuller. All samples were stored in sealed plastic bags in the dark at −20 °C until analyzed. Sample preparation is described more extensively by Ward et al. (*28*).

Determination of Dietary Fiber Content. DF content (% of dm) in the wholemeal samples was estimated using an indirect approach based on calculating the difference between total wholemeal sample dm weight and the sum of analytes (protein, ash, lipids, available starch, and free sugars, all in % of dm). Thus

$$[\text{DF}]\ (\%\ \text{of dm}) = 100 - [\text{protein}] - [\text{ash}] - [\text{lipids}] - [\text{free sugars}] - [\text{available starch}]$$

All data on these basic grain components resulted from other studies within the HEALTHGRAIN project and were made available for this

Table 1. Ranges and Average Values of 1000 Kernel Weight, Flour Yield, Shorts Yield, and Bran Yield for Different Wheat Types

	1000 kernel wt (g)		flour yield (%)		shorts yield (%)		bran yield (%)	
	range	av	range	av	range	av	range	av
winter wheat	32.4–54.3	41.45	30.6–65.8	54.5	7.4–43.7	20.7	20.0–32.9	24.9
spring wheat	28.3–46.7	38.25	39.1–60.3	50.6	9.6–40.9	24.9	19.9–30.5	24.6
durum wheat	34.8–48.5	42.15	20.6–53.8	30.4	36.0–52.5	45.2	24.2–30.9	27.1
spelt wheat	nd[a]	nd	52.2–67.4	60.7	5.5–22.3	12.5	25.5–28.1	26.7
einkorn wheat	nd	nd	60.2–66.7	64.2	10.0–13.0	11.9	21.1–26.8	23.9
emmer wheat	nd	nd	19.5–68.5	31.5	7.6–57.2	46.2	20.8–23.9	22.3

[a] nd, not determined.

study (see below). They were determined with standard methods. Moisture contents were measured according to AACC method 44-15A (*32*). Crude protein contents were analyzed with the Kjeldahl method on a Kjeltec Auto 1030 Analyzer (Foss-Tecator AB, Höganäs, Sweden) consistent with ICC method 105/2 (*33*) and AOAC method 955.04 (*34*), using N × 6.25 as conversion factor. Crude ash quantification was performed by sample incineration in a muffle furnace for 5 h at 550 °C according to method 923.03 (*34*). Total lipid contents were assessed gravimetrically by extraction with acid solvent consisting of 60:40:1 (v/v/v) chloroform, methanol, and concentrated hydrochloric acid (*35*). Enzyme digestible starch (also referred to as available starch) levels were determined with the Megazyme Total Starch Assay Kit without the use of dimethyl sulfoxide. The kit is in accordance with the methods AACC 76-13 (*32*), AOAC 996.11 (*34*), and ICC 168 (*33*). Free sugar levels were measured by gas chromatography according to the method of Knudsen and Li (*36*) as the sum of fructose, glucose, maltose, and sucrose. All measurements were performed in triplicate, except for the quantification of available starch and free sugars, which was done in duplicate.

The above-described indirect approach to assess DF content was validated by comparing the DF contents of 10 wheat samples and 3 rye samples measured in this way with results obtained with the Total Dietary Fiber Kit from Megazyme. The data obtained with both methods were very strongly correlated (R value = 0.96, P value < 0.001).

Determination of Nonstarch, Noncellulosic Polysaccharide Content. *Arabinoxylan.* Total (TOT-) and water-extractable (WE-) AX levels in flour and bran were determined by gas chromatography of alditol acetates as described by Englyst and Cumming (*37*).

Hydrolysis was performed with trifluoroacetic acid. For TOT-AX levels, flour (15 mg) or bran samples (50 mg) were hydrolyzed in 2.0 M trifluoroacetic acid (5.0 mL) for 120 min at 110 °C. For WE-AX quantification, extracts were prepared by suspending flour (2.0 g) or bran (1.0 g) in deionized water (20.0 mL), shaking for 30 min at 7 °C on a horizontal shaker, and centrifugation (10000*g*, 10 min, 4 °C). To the aqueous extracts (2.5 mL) was added 4.0 M trifluoroacetic acid (2.5 mL), and the solution was heated for 60 min at 110 °C. Reduction was performed with sodium borohydride and acetylation with acetic anhydride (*37*). The alditol acetates (1.0 μL) were separated on a Supelco SP-2380 polar column (30 m × 0.32 mm i.d.; 0.2 μm film thickness) and detected with a flame ionization detector in an Agilent chromatograph (Agilent 6890 series, Wilmington, DE) equipped with an autosampler and splitter injection port (split ratio 1:20). The carrier gas was He. Separation was at 225 °C, and injection and detection were at 270 °C. The coefficient of variation of the analytical data was typically 3% for triplicate analysis of samples. AX content was defined as 0.88 times the sum of xylose and arabinose. For flour AX, the arabinose content was corrected for the presence of arabinogalactan peptide on the basis of an arabinose to galactose ratio of 0.7 and with the assumption that all of the arabinose of arabinogalactan peptide is present in the aqueous extract (*38*). AX contents are expressed on a dm basis.

β-Glucan. β-Glucan levels were determined in whole meal with the Megazyme Mixed-Linkage β-Glucan Assay Kit according to the streamlined method, which is consistent with methods AOAC 995.16, AACC 32-23, and ICC 166 (*32*−*34, 39*). The assay is based on the enzymic degradation of the glucan with lichenase and β-glucosidase and the quantification of the released glucose using an oxidase/peroxidase reagent. All measurements were performed in duplicate. The experimental error was below 4% deviation of the mean value. β-Glucan contents are expressed on a dm basis.

Determination of Klason Lignin Content. Klason lignin contents were determined gravimetrically as described by Theander and Westerlund (*40*) according to AACC method 32-25 (*32*). Wholemeal (0.50 g) was weighed into 50 mL tubes and dispersed in 72% sulfuric acid (3.0 mL). The tubes were incubated at 30 °C for 60 min with occasional stirring. Next, deionized water (33 mL) was slowly added, and the mixture was further incubated for 180 min at 100 °C. After cooling, insoluble material was quantitatively recovered by filtration (crucible porosity no. 2), washed with deionized water, 80% ethanol, and acetone, dried (105 °C, 16 h), and ashed (550 °C, 5 h). The percentage of Klason lignin was calculated on the basis of the loss in weight by ashing of the dried insoluble material and expressed on a dm basis.

Determination of Water Extract Viscosity. The viscosities of wholemeal aqueous extracts were analyzed. To this end, wholemeal samples were 1:3 (w/w) extracted with deionized water for 60 min at 30 °C. The suspensions were then centrifuged (10000*g*, 10 min, 4 °C), and the viscosities of the supernatants were immediately determined at a shear rate of 225 s and 30 °C on Brookfield model LVDV-II+ Cone/Plate Digital Viscometer (Brookfield, Stoughton, MA) equipped with an 0.8° cone spindle (*41, 42*). Viscosity measurements were carried out in duplicate, and results are expressed in mP•s.

Statistical Analysis. Tukey tests (P value < 0.05) were performed with the Statistical Analysis System software 8.1 (SAS Institute, Cary, NC). R and P values between different parameters were determined with the same software. Box plots and histograms with normal distribution curves were drawn in Excel (Microsoft) in combination with SigmaXL 5.17 software (Sigmazone). Normal distribution was validated at a confidence level of 95%. Data were considered to be normally distributed when the Anderson−Darling test gave a P value ≥ 0.05 (*43*). However, this test is only valid when the data set size is greater than 40 (*44*) and, therefore, it was performed only on the data for winter wheat.

RESULTS AND DISCUSSION

Description of Wheat Samples. All wheat lines were treated similarly and harvested in 2005 as described in detail by Ward et al. (*28*). Traditional quality traits including yield per plot area, 1000 kernel weight, kernel hardness index, kernel diameter, Zeleny sedimentation value, Hagberg falling number, and contents of protein, gluten, ash, lipid, starch, and free sugars were measured. In addition, the flour and bran yields after milling were determined. These characteristics are described extensively by Rakszegi et al. (*45*).

Table 1 summarizes the 1000 kernel weights and the flour, shorts, and bran yields of the different types of wheat. In general, the winter, spring, and durum wheats are comparable in terms of 1000 kernel weight, and all wheat types have similar bran yields. Flour yields differ for the different wheat types. Under the conditions used, the spelt and einkorn wheat samples have, on average, the highest flour yield, whereas the durum and emmer wheat samples have the lowest flour yield. Lower flour yield goes hand in hand with higher shorts yield. For 1000 kernel

Table 2. Average Contents (Dry Matter Basis) of DF, TOT-AX, WE-AX, β-Glucan, and Klason Lignin in Different Wheat Types[a]

	DF (%)	TOT-AX in flour (%)	WE-AX in flour (%)	TOT-AX in bran (%)	WE-AX in bran (%)	β-glucan (%)	Klason lignin (%)	viscosity (mP·s)
winter wheat	15.2a	1.90a	0.50ab	18.0a	0.40a	0.75a	2.20a	1.90a
spring wheat	14.7a	2.00a	0.50ab	16.8a	0.40a	0.60b	2.15a	1.90a
durum wheat	13.4ab	1.95a	0.40abc	12.0bc	0.40a	0.35c	2.10a	1.45a
spelt wheat	12.0bc	1.75a	0.35bc	12.7b	0.30ab	0.65ab	2.25a	1.45a
einkorn wheat	11.0c	1.95a	0.60a	10.0cd	0.55c	0.30c	2.60a	4.25b
emmer wheat	9.8c	1.70a	0.25c	8.9d	0.30b	0.35c	2.30a	1.50a

[a] All analyses were performed on wholemeal, unless specified otherwise. The average viscosities of wholemeal aqueous extracts, determined as outlined under Materials and Methods, are also presented. Values with the same letter in one column are not significantly different (P value < 0.05) from each other. $[\text{WE-AX}]_{\text{Flour}} = 0.88 \times ([\text{Ara}]_{\text{Soluble}} - 0.7 \times [\text{Gal}]_{\text{Soluble}} + [\text{Xyl}]_{\text{Soluble}})$; $[\text{TOT-AX}]_{\text{Flour}} = 0.88 \times ([\text{Ara}]_{\text{Total}} - 0.7 \times [\text{Gal}]_{\text{Soluble}} + [\text{Xyl}]_{\text{Total}})$; $[\text{WE-AX}]_{\text{Bran}} = 0.88 \times ([\text{Ara}]_{\text{Soluble}} + [\text{Xyl}]_{\text{Soluble}})$; $[\text{TOT-AX}]_{\text{Bran}} = 0.88 \times ([\text{Ara}]_{\text{Total}} + [\text{Xyl}]_{\text{Total}})$.

Table 3. Ranges of DF, TOT-AX, WE-AX, β-Glucan, and Klason Lignin Contents (Dry Matter Basis) in Different Wheat Types[a]

	DF (%)	TOT-AX in flour (%)	WE-AX in flour (%)	TOT-AX in bran (%)	WE-AX in bran (%)	β-glucan (%)	Klason lignin (%)	viscosity (mP·s)
winter wheat	11.5–18.3	1.35–2.75	0.30–1.40	13.2–22.1	0.30–0.85	0.50–0.95	1.40–3.25	1.30–3.50
spring wheat	12.1–17.5	1.65–2.75	0.30–0.75	12.7–19.2	0.30–0.55	0.50–0.65	1.50–2.95	1.50–2.80
durum wheat	10.7–15.5	1.70–2.35	0.25–0.55	10.9–13.7	0.30–0.55	0.25–0.45	1.85–2.55	1.20–1.85
spelt wheat	10.7–13.9	1.60–2.15	0.30–0.45	11.1–13.9	0.30–0.35	0.55–0.70	1.85–2.90	1.35–1.55
einkorn wheat	9.3–12.8	1.45–2.35	0.50–0.65	9.5–10.4	0.45–0.65	0.25–0.35	2.25–3.05	3.20–5.65
emmer wheat	7.2–12.0	1.40–1.95	0.15–0.55	6.1–14.4	0.20–0.45	0.30–0.40	1.95–2.65	1.20–2.45

[a] All analyses were performed on wholemeal, unless specified otherwise. The viscosity ranges of wholemeal aqueous extracts, determined as outlined under Materials and Methods, are also presented. $[\text{WE-AX}]_{\text{Flour}} = 0.88 \times ([\text{Ara}]_{\text{Soluble}} - 0.7 \times [\text{Gal}]_{\text{Soluble}} + [\text{Xyl}]_{\text{Soluble}})$; $[\text{TOT-AX}]_{\text{Flour}} = 0.88 \times ([\text{Ara}]_{\text{Total}} - 0.7 \times [\text{Gal}]_{\text{Soluble}} + [\text{Xyl}]_{\text{Total}})$; $[\text{WE-AX}]_{\text{Bran}} = 0.88 \times ([\text{Ara}]_{\text{Soluble}} + [\text{Xyl}]_{\text{Soluble}})$; $[\text{TOT-AX}]_{\text{Bran}} = 0.88 \times ([\text{Ara}]_{\text{Total}} + [\text{Xyl}]_{\text{Total}})$.

weight and flour and shorts yields, considerable variation could be observed within the different wheat types.

In what follows, the variability in DF content and constituents thereof in wheat is discussed in detail. Whereas DF, glucan, and lignin contents were determined on wholemeal, TOT-AX and WE-AX were quantified in flour and bran. Next, these data, together with those on 1000 kernel weight, aqueous wholemeal extract viscosity, and bran and flour yields were analyzed to study correlations between the different parameters. Supplementary Table 1 (see the Supporting Information) is a detailed list of all the wheat varieties analyzed, their contents of DF and constituents thereof, and their wholemeal aqueous extract viscosities, whereas **Tables 2** and **3** provide a summary.

Dietary Fiber Content. As already mentioned above, wheat DF mainly consists of AX, cellulose, β-glucan, arabinogalactan peptide (*38*), resistant oligosaccharides (e.g., fructo-oligosaccharides) (*46*), lignin, and associated plant substances (*1*).

Large differences in wholemeal DF contents were observed, not only between different types of wheat but also within one wheat type. Common bread wheats, that is, winter and spring wheats, contain the highest levels of DF, that is, between 11.5% (var. Buck-Catriel) and 18.3% of dm (var. CF99075), whereas einkorn and emmer wheats have the lowest levels, that is, between 7.2% (var. 265-2004) and 12.8% of dm (var. 2004-08-01). Intermediate levels were observed in durum and spelt wheats, from 10.7% (var. Parus) to 15.5% of dm (var. Durabon) (**Tables 2** and **3**). Of the spelt lines tested, the *T. spelta* × *T. aestivum* cross-line Frankencorn has the highest DF content (13.9% of dm). The data for DF content in winter wheat are normally distributed around an average content of 15.2% of dm (**Table 2**; **Figure 1A**).

For common bread wheats, DF levels within the above-cited range have already been described earlier by Knudsen (*26*) and Charalampopoulos et al. (*47*). Wheat bran generally contains the highest level of DF, that is, as much as ca. 45% of dm (*26, 48*), whereas only ca. 3.5% occurs in flour dm (*26*). For durum, spelt, einkorn, and emmer wheats, DF levels of ca. 12.7, 10.3, 8.7, and 7.9% of dm, respectively (*49, 50*), have been reported earlier. This is in line with our results.

The DF concentrations in the barley, rye, and oat samples of the HEALTHGRAIN diversity screen are often higher than in the wheat samples analyzed, with values from 15.0 to 23.7% (*30*), from 20.4 to 25.2% (*29*), and from 10.6 to 23.4% of dm (*31*), respectively. In comparison to wheat the variation in DF content was higher in barley and oats and lower in rye.

Arabinoxylan Content. *TOT-AX Content.* The flours of the different types of wheat have on average comparable TOT-AX levels. The average levels vary between 1.70 and 2.00% of dm (**Table 2**). However, for each wheat type, there is considerable variation. The widest variation is observed for flour of the winter wheats, with TOT-AX contents varying between 1.35% (var. Bleu/AG) and 2.75% of dm (var. Yumai-34). The levels in the nonwinter wheat flours all fall within this range (**Table 3**). For the bran samples, which evidently are richer in AX, significant differences are noticeable between the different types of wheat, whereas the mean bran yields for the different wheats are comparable (**Table 1**). Common wheat bran dm contains on average ca. 17% TOT-AX, durum and spelt wheat bran on average ca. 12% of dm, and einkorn and emmer wheat bran contain ca. 9% of dm (**Table 2**). The largest variation in bran TOT-AX content is observed for winter wheat [from 13.2% (var. Thesee) to 22.1% of dm (var. Albatros-Odesky)], spring wheat [from 12.7% (var. Cadenza) to 19.2% of dm (var. Milan)], and emmer wheat [from 6.1% (var. 264-2004) to 14.4% of dm (var. MVGB304)] (**Table 3**). The data for TOT-AX in winter wheat flour and bran are normally distributed around the mean values of 1.90 and 18.0% of dm, respectively (**Figure 1B**,**C**). **Table 4** summarizes the degrees of substitution (A/X ratios) of TOT-AX in the flour and bran fractions of all types of wheat.

TOT-AX content ranges from 1.4 to 2.6% of dm, from 17 to 31% of dm, and from 4.0 to 9.0% of dm have already been reported previously for common wheat flour, bran, and wholemeal, respectively (*51*). Whereas the range for flour corresponds very well with the one obtained in this study, higher TOT-AX levels were described earlier for bran, probably because of differences in cultivation conditions and/or milling. According to Lempereur et al. (*52*), 4.1−6.0% of dm TOT-AX occurs in durum wheat wholemeal, whereas for durum wheat semolina

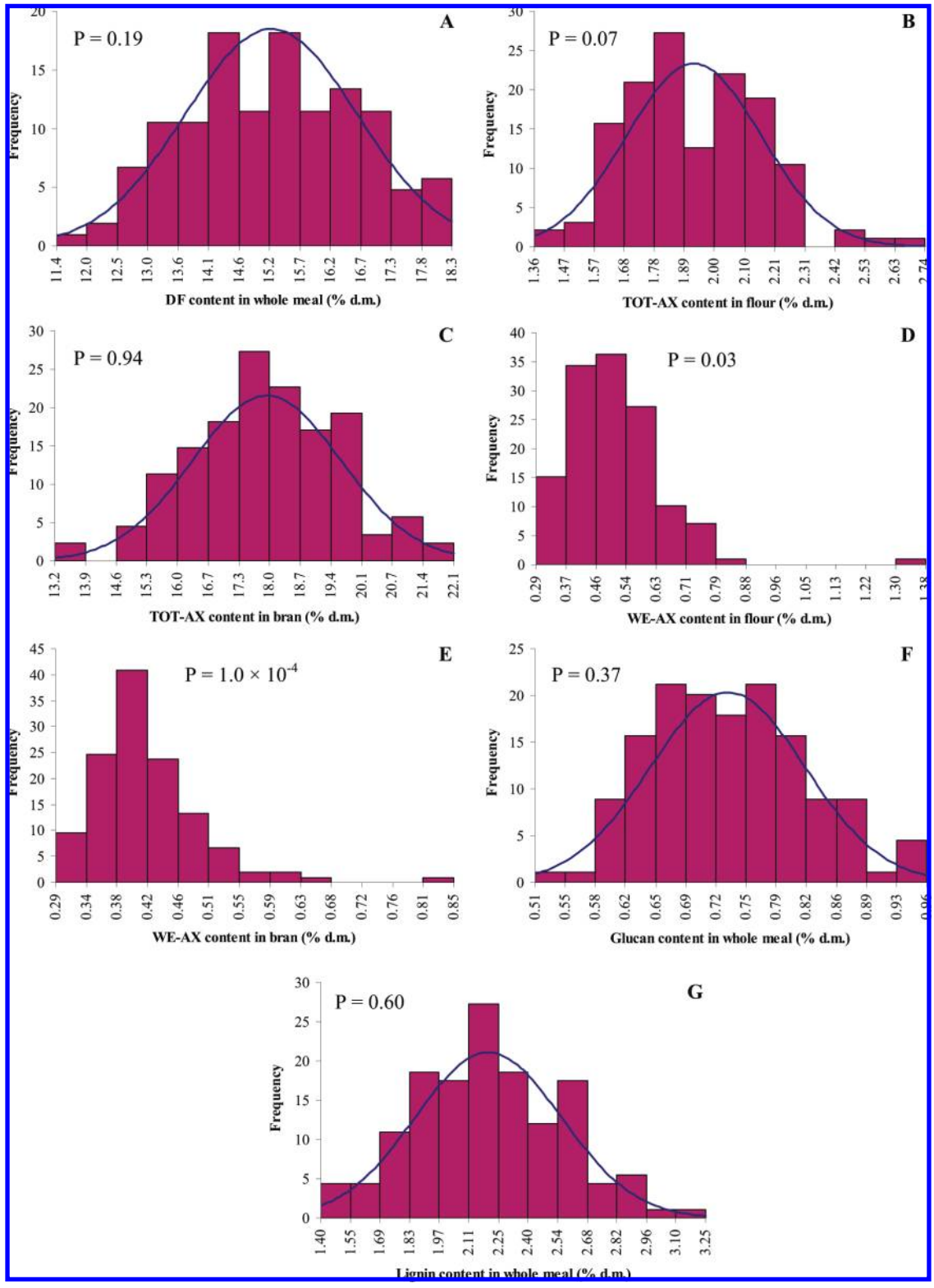

Figure 1. Frequency histograms (bars) for contents of DF in whole meal (**A**), TOT-AX in flour (**B**), and bran (**C**), WE-AX in flour (**D**) and bran (**E**), β-glucan in whole meal (**F**), and lignin in whole meal (**G**) from winter wheats. For the normally distributed data (Anderson−Darling *P* value > 0.05) also the corresponding normal distribution curves are shown.

TOT-AX levels of 0.6−3.0% of dm have been reported by others (*53*). The values described here for durum wheat flour [from 1.70% (var. Semperdur) to 2.35% of dm (var. Orjaune)] fall within the latter range.

Some considerable differences exist between the wheat samples described here and the barley, rye, and oat samples of the HEALTHGRAIN diversity screen. Wheat flour has a TOT-AX content (**Table 3**) comparable to that of barley flour (1.40−2.25% of dm). The TOT-AX level in einkorn wheat bran (9.5−10.4% of dm) (**Table 3**) is higher than that in barley bran (4.8−9.8% of dm) (*30*). The TOT-AX level in the wheat flour samples analyzed here (**Table 3**) is considerably lower than that in rye flour (3.10−4.30% of dm). The rye bran TOT-AX concentration (12.1−14.8% of dm) (*29*) is comparable to that in durum and spelt wheat bran (**Table 3**). For oat flour as well as oat bran, in most cases lower TOT-AX values (0.95−1.25

Table 4. Average A/X Values of TOT-AX and WE-AX in Flour and Bran of Different Wheat Types and Their Ranges[a]

	av A/X				range A/X			
	TOT-AX in flour	WE-AX in flour	TOT-AX in bran	WE-AX in bran	TOT-AX in flour	WE-AX in flour	TOT-AX in bran	WE-AX in bran
winter wheat	0.60a	0.50a	0.60a	1.00a	0.50–0.70	0.40–0.55	0.55–0.70	0.70–1.65
spring wheat	0.60a	0.50a	0.65a	1.00a	0.50–0.65	0.40–0.55	0.55–0.70	0.80–1.25
durum wheat	0.65b	0.55a	0.75b	1.25b	0.60–0.70	0.45–0.65	0.70–0.80	1.00–1.40
spelt wheat	0.60ac	0.50a	0.50c	1.40bc	0.55–0.60	0.45–0.55	0.45–0.55	1.20–1.60
einkorn wheat	0.65bc	0.55a	0.55c	0.95a	0.60–0.70	0.45–0.60	0.50–0.55	0.85–1.10
emmer wheat	0.60abc	0.35b	0.55c	1.50c	0.55–0.70	0.20–0.60	0.50–0.65	1.10–1.70

[a] Values with the same letter in one column are not significantly different (P value < 0.05) from each other. $A/X_{WE\text{-}AX,Flour} = ([Ara]_{Soluble} - 0.7 \times [Gal]_{Soluble})/[Xyl]_{Soluble}$; $A/X_{TOT\text{-}AX,Flour} = ([Ara]_{Total} - 0.7 \times [Gal]_{Soluble})/[Xyl]_{Total}$; $A/X_{WE\text{-}AX,Bran} = [Ara]_{Soluble}/[Xyl]_{Soluble}$; $A/X_{TOT\text{-}AX,Bran} = [Ara]_{Total}/[Xyl]_{Total}$.

and 4.0−13.0% of dm, respectively) (*31*) were measured than in the corresponding fractions of common wheat, durum wheat, and spelt (**Table 3**).

WE-AX Content. For each of the different wheat types, the average WE-AX levels in the flour and the bran fractions are comparable. However, for the winter and spring wheats, the concentration of WE-AX in flour (ca. 0.50% of dm) tends to be a bit higher than in bran (ca. 0.40% of dm) (**Table 2**). For the bran samples, einkorn wheat contains on average the highest concentration of WE-AX (ca. 0.55% of dm). In the einkorn flour samples the mean WE-AX concentration (ca. 0.60% of dm) is not significantly higher than in the winter (ca. 0.50% of dm), spring (ca. 0.50% of dm), and durum wheat flours (ca. 0.40% of dm). The emmer and spelt wheats analyzed here have, on average, the lowest WE-AX concentrations in flour and bran (**Table 2**). High levels of WE-AX in flour and bran seem to go hand in hand with high wholemeal extract viscosities (**Tables 2** and **3**).

The largest variation in WE-AX content in flour and bran is observed for the winter wheats [from 0.30% (var. Soissons) to 1.40% of dm (var. Yumai-34) and from 0.30% (var. Sumai-34) to 0.85% of dm (var. Yumai-34), respectively] and spring wheats [from 0.25% (var. Glenlea) to 0.75% of dm (var. Milan) and from 0.30% (var. Chinese-Spring) to 0.85% of dm (var. Milan), respectively] for which the highest number of samples have been analyzed (**Table 3**). **Table 4** summarizes the A/X ratios of the flour and bran WE-AX.

In contrast to the winter wheat TOT-AX levels, the WE-AX levels are not normally distributed, even when the variety with highest WE-AX level (Yumai-34) was not included in the Anderson−Darling test (*43, 44*) for normal distribution (**Figure 1D**,**E**).

Earlier studies on common wheat report WE-AX levels in flour, bran, and wholemeal ranging from 0.4 to 0.9% of dm (*51, 54*), from 0.8 to 1.6% of dm (*51*), and from 0.4 to 1.2% of dm (*51, 55, 56*), respectively. Whereas the range for flour is in agreement with the results described above (except for var. Yumai-34, which has a very high WE-AX level), the levels cited for bran tend to be somewhat higher than the ones obtained here, which is possibly caused by differences in milling procedure and performance, bran tissue composition, and climatological and/or agronomical conditions. According to Lempereur et al. (*52*), durum wheat contains 0.35−0.55% of dm WE-AX, whereas durum wheat semolina contains about 0.30−0.35% of dm WE-AX (*57, 58*), which is in the range of values obtained here for durum wheat flour [from 0.25% (var. Durabon) to 0.55% of dm (var. 1529-91)].

Within the entire HEALTHGRAIN diversity screening program, the highest WE-AX levels (1.05−1.50% of dm) are noted for rye flour and bran (*29*). Only the flour of the winter wheat var. Yumai-34 has a WE-AX content (1.40% of dm) in the range determined for rye. For barley (0.15−0.40% of dm) (*30*) and oats (0.15−0.20% of dm) (*31*) WE-AX values that are comparable to or even lower than those found for spelt and emmer wheats are measured (**Table 3**).

β-Glucan Content. On average, wholemeals of the winter and spelt wheat lines have the highest levels of β-glucan (**Table 2**), with values ranging from 0.50% (var. Tamaro) to 0.95% of dm (var. Granbel) and from 0.55% (var. Spy) to 0.70% of dm (var. Oberkulner-Rotkorn) (**Table 3**), respectively. The β-glucan levels in the spring wheat samples are at the lower end of the range for winter wheats (**Table 3**). The durum, einkorn, and emmer wheats contain, on average, half the level of β-glucan noted for the other types of wheat (**Table 2**). The β-glucan levels in winter wheat are normally distributed around 0.75% of dm (**Table 2**; **Figure 1F**).

Genç et al. (*22*) reported β-glucan levels in common wheat wholemeal of 0.5−1.4% of dm. The high upper limit of this range may be the result of differences in climatological conditions, for example, dry conditions before harvest, which are known to result in higher β-glucan levels (*59, 60*). Wheat endosperm contains lower concentrations of β-glucan than whole grain, that is, ca. 0.3% of dm (*23*). Wholemeals of durum, emmer, and einkorn wheats contain levels around 0.4% of dm, whereas spelt contains β-glucan contents of ca. 0.7% of dm (*49, 50*). This is in close agreement with the average values listed in **Table 2**.

The wheat types analyzed here contain lower β-glucan levels than the nonwheat cereals included in the HEALTHGRAIN diversity screen, that is, rye, barley, and oats, with levels ranging from 1.7 to 2.0% (*29*), from 3.7 to 6.5% (*30*), and from 4.5 to 5.6% of dm (*31*), respectively.

Lignin Content. In general, all wheat types have comparable Klason lignin levels with average values varying in wheat wholemeal between 2.10 and 2.60% of dm (**Table 2**). The lignin contents in the winter wheat samples cover the complete range of the data obtained for the different types of wheat, that is, from 1.40% (var. Atay-85) to 3.25% of dm (var. Dekan), and are normally distributed around 2.20% of dm (**Table 3**; **Figure 1G**).

In line with our results, Knudsen (*26*) reported ca. 2% of dm lignin in wholegrain of common wheat. The lignin content in wheat bran ranges from 4 to 8% (*61*−*64*). Rye has a lignin content (2.0−2.9% of dm) (*29*) comparable to that of wheat (**Table 3**), whereas higher concentrations are present in the hulled cereals barley (3.3−4.7% of dm) and oats (2.6−5.9% of dm) (*30, 31*).

Statistical Analysis. **Tables 5** and **6** summarize the results of the correlation analysis of the data on the different DF constituents, aqueous wholemeal extract viscosities, total kernel weights, flour yields, and bran yields for the winter wheat samples and all wheat samples, respectively.

The WE-AX levels in flour are positively correlated to the bran WE-AX levels. The flour WE-AX contents are also related

Table 5. *R* and *P* Values (Italic) for Different Parameters and for All Winter Wheat Samples[a]

	flour WE-AX	flour TOT-AX	bran WE-AX	bran TOT-AX	wholemeal β-glucan	wholemeal lignin	wholemeal DF	water extract viscosity	flour yield	bran yield	1000 kernel wt
flour WE-AX		***0.57***	***0.59***	9.5×10^{-3}	-8.1×10^{-2}	7.1×10^{-2}	4.4×10^{-2}	**0.80**	-3.5×10^{-2}	7.3×10^{-2}	0.16
		<0.001	***<0.001***	*0.91*	*0.35*	*0.42*	*0.61*	***<0.001***	*0.69*	*0.40*	*0.066*
flour TOT-AX			***0.50***	-6.9×10^{-2}	−0.11	6.8×10^{-2}	0.14	***0.45***	***−0.39***	3.3×10^{-2}	0.15
			<0.001	*0.43*	*0.22*	*0.44*	*0.11*	***<0.001***	***<0.001***	*0.71*	*0.093*
bran WE-AX				-3.4×10^{-2}	−0.18	1.6×10^{-2}	6.9×10^{-2}	***0.52***	−0.17	-1.3×10^{-2}	-2.0×10^{-2}
				0.70	*<0.05*	*0.85*	*0.43*	***<0.001***	*<0.05*	*0.88*	*0.81*
bran TOT-AX					-6.0×10^{-2}	0.16	-4.6×10^{-2}	-7.4×10^{-2}	9.3×10^{-2}	***−0.57***	***0.29***
					0.50	*0.075*	*0.60*	*0.40*	*0.29*	***<0.001***	***<0.001***
wholemeal β-glucan						-8.8×10^{-2}	5.6 × 10^−2^	−0.13	-3.1×10^{-2}	-6.4×10^{-2}	4.6×10^{-2}
						0.32	*0.53*	*0.14*	*0.73*	*0.47*	*0.60*
wholemeal lignin							***0.23***	2.3×10^{-2}	−0.13	7.2×10^{-2}	-8.2×10^{-2}
							<0.01	*0.80*	*0.15*	0.41	*0.35*
wholemeal DF								-1.4×10^{-2}	-7.0×10^{-3}	***0.34***	−0.12
								0.87	*0.94*	***<0.001***	*0.16*
water extract viscosity									-9.2×10^{-2}	9.1×10^{-2}	-1.6×10^{-2}
									0.30	*0.30*	*0.85*
flour yield										0.12	-4.8×10^{-2}
										0.17	*0.58*
bran yield											**−0.35**
											<0.001
1000 kernel wt											

[a] The bold parameters refer to significant correlations (*P* value < 0.01).

Table 6. *R* and *P* Values (Italic) for Different Parameters and for All Wheat Samples, That Is, Including Common Wheat, Durum Wheat, Einkorn Wheat, Emmer Wheat, and Spelt Wheat Samples[a]

	flour WE-AX	flour TOT-AX	bran WE-AX	bran TOT-AX	wholemeal β-glucan	wholemeal lignin	wholemeal DF	water extract viscosity	flour yield	bran yield	1000 kernel wt
flour WE-AX		***0.49***	***0.66***	***0.27***	0.15	3.8×10^{-3}	***0.20***	***0.62***	***0.22***	6.9×10^{-2}	nd
		<0.001	***<0.001***	***<0.001***	*0.054*	*0.96*	***<0.01***	***<0.001***	***<0.01***	*0.36*	
flour TOT-AX			**0.41**	4.5×10^{-3}	-7.7×10^{-3}	2.0×10^{-2}	0.16	***0.24***	***−0.24***	7.1×10^{-2}	nd
			<0.001	*0.95*	*0.92*	*0.80*	*<0.05*	***<0.01***	***<0.01***	*0.35*	
bran WE-AX				0.11	-6.5×10^{-2}	3.9×10^{-2}	0.14	**0.56**	0.11	-1.3×10^{-2}	nd
				0.13	*0.39*	*0.60*	*0.061*	***<0.001***	*0.15*	*0.86*	
bran TOT-AX					**0.64**	-1.9×10^{-2}	**0.54**	−0.11	***0.40***	***−0.26***	nd
					<0.001	*0.80*	***<0.001***	*0.14*	***<0.001***	**<0.001**	
wholemeal β-glucan						-7.7×10^{-2}	***0.49***	−0.18	**0.41**	-2.3×10^{-2}	nd
						0.31	***<0.001***	*<0.05*	***<0.001***	*0.76*	
wholemeal lignin							0.11	0.15	6.7×10^{-3}	-1.4×10^{-2}	nd
							0.14	<0.05	*0.93*	*0.86*	
wholemeal DF								-9.5×10^{-2}	0.19	**0.24**	nd
								0.21	*<0.05*	***<0.01***	
water extract viscosity									**0.27**	-2.0×10^{-2}	nd
									<0.001	*0.79*	
flour yield										6.0×10^{-2}	nd
										0.43	
bran yield											nd
1000 kernel wt											

[a] The bold parameters refer to significant correlations (*P* value < 0.01); nd, not determined.

in a similar way to the flour TOT-AX contents. In addition, a trend toward higher bran WE-AX levels with increasing flour TOT-AX levels can be observed (**Tables 5** and **6**).

The correlation analysis including all wheat types reveals positive correlations between DF levels, on the one hand, and AX (bran TOT-AX in particular) and β-glucan levels, on the other hand (**Table 6**). No such observation can be made for the winter wheats only. Bran TOT-AX is quantatively the most important source of DF in wheat. It makes up, on average, ca. 29% of total DF in common wheat, whereas lignin, flour TOT-AX, and β-glucan account for ca. 15, 7, and 5% of total DF, respectively. The proportions of cellulose [ca. 2.4% of common wheat dm (*24, 65*)], fructan [ca. 2.2% of common wheat dm (*66*)], and arabinogalactan-peptide [ca. 0.39% of common wheat dm (*67*)], which were not analyzed in this study, can be estimated at ca. 16, 15, and 3% of total DF. AX in the shorts fraction (not analyzed here) is mainly responsible for the remaining 10% of DF in common wheat.

Both when all wheat types or when only the winter wheat samples are taken into account, wholemeal extract viscosities are most strongly positively related to flour and bran WE-AX contents (**Tables 5** and **6**).

When correlation analysis was performed on the data of all wheat samples, a positive correlation was observed between flour yield and TOT-AX level in the bran fraction, which can be explained by a better separation of the bran, resulting in less contamination by endosperm tissue (**Table 6**). The trend is much clearer when the einkorn and spelt wheat samples are not taken into account (R value = 0.61, P value < 0.001). Because this relationship between flour yield and bran TOT-AX level does not exist for the winter wheat samples alone, it can be largely explained by difference between different types of wheat rather

Table 7. Overview of Some Typical Cereal Products with Representation of Their DF Content and Typical Serving Size[a]

	DF content (g/100 g)	typical serving size (g)
breakfast cereals		
All-Bran	28.6	26
Shredded Wheat	9.5	45
cornflakes	3.0	28
puffed wheat	7.2	27
puffed rice	1.2	33
Special K	3.2	31
bread		
white wheat bread	2.5	2 slices (ca. 50 g)
brown wheat bread	4.7	2 slices (ca. 50 g)
whole meal wheat bread	8.3	2 slices (ca. 50 g)
rye bread	9.9	2 slices (ca. 80 g)
pastry		
fruit pie	2.5	125
fruit cake	3.0	50
sponge cake	1.0	50
pound cake	0.9	50
rice		
white (boiled)	0.2	180
brown (boiled)	0.8	180
pasta		
white (bioled)	1.6	230
whole wheat (boiled)	3.7	230
egg noodles (boiled)	1.7	160
pizza		
tomato and cheese	2.3	1 slice (ca. 80 g)

[a] Data based on refs *69* and *70*.

than difference between varieties. For the winter wheat samples a clear inverse relationship between flour yields and flour TOT-AX contents can be noted. The latter may, in part, result from differences in friability as harder wheat kernels typically have higher AX contents in the endosperm cell walls (*68*). Indeed, for the winter wheats the flour TOT-AX levels are positively related (R value = 0.40, P value < 0.001) to the hardness indices [data shown by Rakszegi et al. (*45*)]. Bran yields are inversely correlated to the bran TOT-AX contents and positively correlated to the DF contents (**Tables 5** and **6**).

For the winter wheat samples, 1000 kernel weights are inversely related to bran yields, whereas a positive correlation was observed for the TOT-AX levels in bran (**Table 5**). This is in line with the above-cited inverse relationship between bran yield and bran TOT-AX content.

Relevance of the Present Findings. Wheat may contribute considerably to the daily DF intake in human diets. **Table 7** provides a brief overview of some typical cereal products, their estimated DF content, and typical serving size. Depending on the type of wheat bread (white, brown, or whole grain), the consumption of six slices, for example, results in a DF intake of 7.5−24.9 g, which is ca. 21−71% of the overall recommended daily DF intake (30−35 g) (see above). Consumption of a portion of pasta or All-Bran breakfast cereal may provide an additional intake of 2.7−8.5 g of DF, that is, ca. 8−24% of the recommended DF intake. The results in **Table 3** suggest that for wheat-derived products a proper choice of wheat variety might result in an increase in DF content (up to 1.6-fold), which is relevant from a nutritional point of view. As already mentioned earlier, AX is the most abundant DF polysaccharide in wheat. Like the total DF and TOT-AX levels, the concentration of WE-AX, an important source of soluble DF, varies considerably (**Table 3**). The level of the latter can be increased in cereal foodstuffs by using xylanases, which are enzymes that degrade AX by hydrolyzing the xylan backbone internally and are nowadays already frequently applied as cereal processing aids (*17, 18, 53*). Hence, wheat varieties, rich in AX, have a strong potential for the production of healthy or even health-promoting food products that contain not only a high overall DF content but also increased levels of soluble DF and prebiotic oligosaccharides produced by in situ action of xylanases.

From a technological point of view, the variation in AX content is relevant because AX is generally considered to have a significant effect on wheat functionality and, taking into account the impact of xylanases on AX molecular weight and physicochemical properties, it is clear that AX affect the suitability of flours for certain applications. Indeed, leaving other important quality-determining characteristics such as protein content and composition aside, one might suggest that, for example, for good dough and bread characteristics, a high [high molecular weight WE-AX]/[TOT-AX] ratio is preferable (*17, 18*), whereas for gluten−starch separation, an increase in both high molecular weight WE-AX and water-unextractable AX (WU-AX) content is detrimental for gluten agglomeration (*19, 20*). In practice, xylanases are used in breadmaking and gluten−starch separation to increase this ratio by selectively solubilizing WU-AX and to extensively degrade AX to low molecular weight fragments, respectively.

General Conclusion. The present study reveals substantial variation in the contents of DF and its constituents between different types of wheat and between varieties of each wheat type. The extent of the observed variation is relevant from nutritional as well as technological points of view.

All wheat lines studied here were grown at the same cultivation site to minimize differences in climatological and agronomical conditions during growth. However, for plant breeders, it is also important to know whether the concentrations of DF and its constituents in a certain genotype remain stable from year to year regardless of growth location and agronomical or weather conditions. Thus, before breeders can exploit results from this study to select/develop stable varieties with high/enhanced levels of DF for improved human nutrition, more research is needed to assess the effects of environmental conditions and year-to-year variation on DF content in wheat. These studies are underway.

ABBREVIATIONS USED

DF, dietary fiber; AX, arabinoxylan; WE-AX, water-extractable AX; TOT-AX, total AX; A/X, arabinose over xylose ratio; av, average.

Supporting Information Available: Supplementary Table 1 is a detailed list of all the wheat varieties analyzed, their contents of total DF and constituents thereof, and their wholemeal aqueous extract viscosities. This material is available free of charge via the Internet at http://pubs.acs.org.

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