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Article in *Critical Reviews in Food Science and Nutrition* · June 2012

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Wheat Aleurone: Separation, Composition, Health Aspects, and Potential Food Use

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Over the last three decades substantial attention has been given to the role of dietary fiber in health and disease, in particular diabetes, cardiovascular disease, intestinal health, and some types of cancer. As a result the food industry started to add back fiber to refined foods and develop fiber rich foods. Scientists suggested that whole grain foods are superior to foods enriched with fibers obtained/synthesized using enzyme treatment, and thermal or chemical processing because the content of bioactive components and micronutrients in whole grain is more abundant. This triggered interest in how to isolate the micronutrient rich aleurone fiber fraction from wheat. Aleurone is a single cell layer at the inner site of the bran. It contains most of the minerals, vitamins, phenolic antioxidants, and lignans of the wheat grain. Novel milling and dry-fractionation techniques have recently allowed for full-scale separation of aleurone cells from the other layers of wheat bran, yielding a fiber rich concentrate which potentially contains many of the “whole grain kernel bioactives,” which recently have been used in a variety of studies. The present review highlights available data on aleurone isolation, composition, intestinal physiology, and its metabolism and potential health benefits as well as its use in food.

Keywords wheat aleurone, dietary fiber, grain bioactives, ferulic acid, lignans, gut health

INTRODUCTION

There is growing evidence that whole grain plays an important role in the prevention of chronic diseases. In epidemiological studies increased whole grain intake has been associated with a lower incidence of cardiovascular disease, obesity, diabetes, and cancer. Although whole grain consumption is often associated with a healthy lifestyle (Jacobs et al., 2001) an ever growing number of studies have reported beneficial effects to health and reduced over-all mortality, even when the results have been adjusted with life-style factors (Kushi et al., 1999;

Chatenoud et al., 1998; 1999; Slavin et al., 1999; Slavin, 2000; 2003; 2004; Jacobs et al., 1998; 2000; 2001; Steffen et al., 2003; Koh-Banerjee and Rimm, 2003; Larsson et al., 2005; Esmaillzadeh et al., 2005; Sahyoun et al., 2006; Jensen et al., 2006; de Munter et al., 2007; Murtaugh et al., 2007; Liu, 2007; Chan et al., 2007; Mellen et al., 2008; Schatzkin et al., 2008; van de Vijver et al., 2009; Fardet et al., 2010). Whole grains are a rich source of an array of micronutrients and plant compounds which have the potential to exert beneficial effects. Thus the potential mechanisms affecting health and disease are diverse (Fardet et al., 2010). The aleurone layer is the innermost layer of the wheat bran and is where many of these minerals, vitamins, and bioactive phytochemicals, such as antioxidant compounds and lignans, are concentrated (Antoine, 2002; Buri et al., 2004; Pomeranz, 1988; Fardet et al., 2010). In the present paper we review the aleurone fraction as a key component in the wheat

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grain and a major contributor to the reported health effects associated with whole grain consumption. We describe its isolation, composition, intestinal metabolism, and modification, as well as the bioavailability of its minor constituents and potential health related benefits. Possible food applications of aleurone are also discussed and highlighted by the example of aleurone enriched whole wheat bread.

THE ALEURONE LAYER WITHIN THE WHOLE GRAIN

Wheat grain is a complex structure composed of different tissues (Fig. 1). These layers exhibit various functions during the grain development, and are therefore characterized by distinct structures and compositions. The starchy endosperm, bran, and germ layers represent 80–85%, 12–18%, and 2–3% of the grain, respectively. The endosperm is mostly composed of starch and proteins, while most of the fibers, vitamins, minerals, and phytochemicals are concentrated in the outer and germ layers (Pomeranz, 1988). Botanically, the aleurone layer (which represents 5–8% of the wheat grain) is the outer part of the starchy endosperm. However, as it stays attached to the hyaline layer during milling and is therefore removed from the endosperm with the grain outer layers, the miller considers the aleurone as a part of the bran. The bran fraction is a composite multi-layer material made up of several adhesive tissues: outer pericarp, inner pericarp, testa, nucellar epidermis (i.e., hyaline layer), and aleurone layer, with some attached starchy endosperm residues. The outer pericarp and inner pericarp are composed of empty cells, mostly made of branched heteroxylans, cellulose and lignin, with numerous cross-links between the polymer chains, due to a high content of ferulic acid (FA) dimers (Fincher and Stone, 1986; Pomeranz, 1988). The testa is a hydrophobic layer rich in lignin, and characterized by the presence of lipidic compounds

such as alkylresorcinols present in a cuticle at the surface of this tissue (Evers and Reed, 1988; Landberg et al., 2008). The hyaline layer contains more than 90% poorly cross-linked arabinoxylans (Barron et al., 2007).

The wheat aleurone layer is composed of a single layer of living cells (Fig. 2), or multilayered in barley, rice, and oats (Stone, 1985). In wheat, the diameter of aleurone cells is 20–75 μm (Stevens, 1973), and the aleurone layer represents ~50% of the wheat bran. The aleurone cell is composed of the cytoplasm or intracellular medium, surrounded by thick non-lignified cell walls, which represent ~35% of the cell volume (Fulcher et al., 1972), and more than 40% of the layer in mass (Hemery et al., 2009a). Aleurone cell walls contain 29% β -glucans, few proteins, and 65% relatively linear arabinoxylan with a low arabinose-to-xylose ratio, and high amounts of esterified FA monomer (Bacic and Stone, 1981; Rhodes et al., 2002a; 2002b; Saulnier et al., 2007). The intracellular medium of aleurone cells contain many spherical particles (2–4 μm diameter) called aleurone granules, which are either phytate inclusions (type 1: composed of phytic acid minerals), or niacin inclusions (type 2: composed of niacin and proteins), each granule being surrounded by a fine layer of lipidic droplets (Morrison et al., 1975).

The aleurone layer is particularly rich in nutrients (Table 1). Indeed, the intracellular medium of aleurone cells is characterized by high amounts of protein, minerals, phytates, B vitamins such as niacin and folates, and lipidic compounds such as plant sterols (Buri et al., 2004; Hemery et al., 2011; Pomeranz, 1988). Aleurone provides ~15% of the total wheat protein but also ~30% of the total lysine (which is the first limiting essential amino acids in wheat) (Pomeranz, 1988). At least 80% of total niacin in wheat is found in the aleurone layer and a considerable amount of other B vitamins. Overall, around 40–60% of the total wheat mineral content is found in the aleurone layer, reflecting a rich mineral source (Pomeranz, 1988).

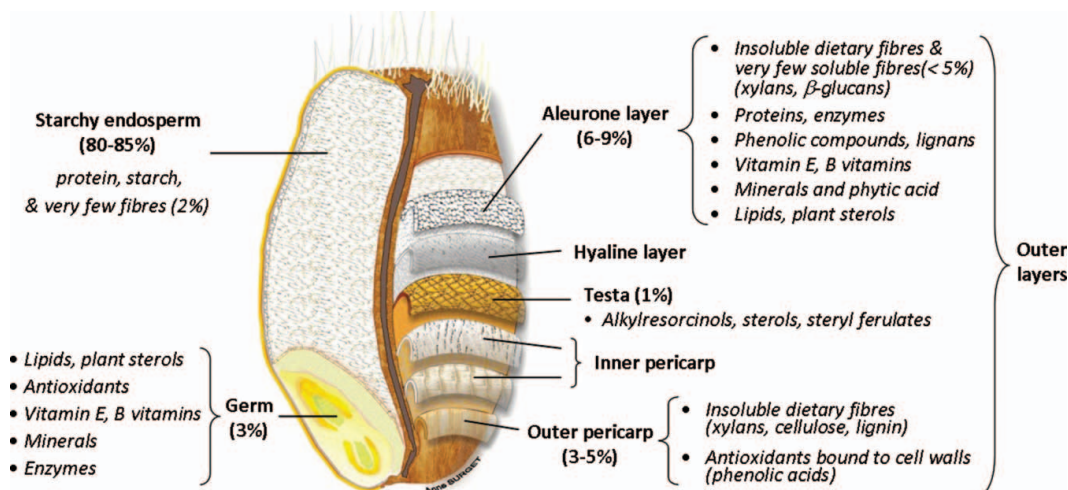


Figure 1 Histological structure of wheat grain. Adapted from Surget and Barron (2005). (color figure available online.)

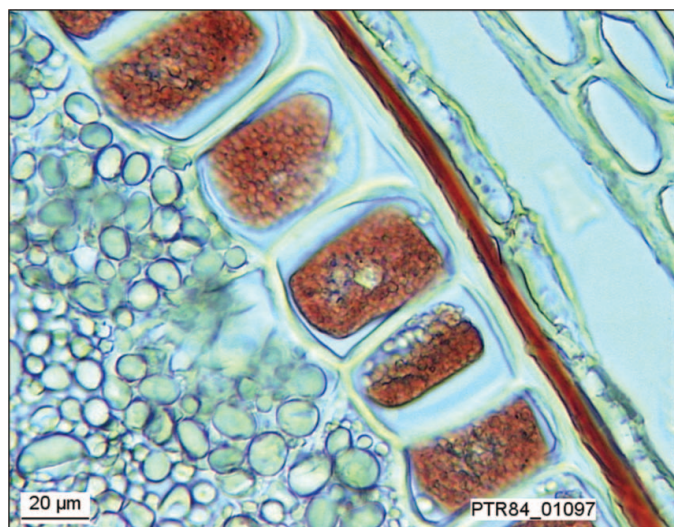


Figure 2 Microscopic View of the Aleurone Layer (Buri et al., 2004). From left to right: starchy endosperm, a single layer of aleurone cells, hyaline layer, testa (in red), inner pericarp, and outer pericarp. (color figure available online.)

ISOLATION OF THE ALEURONE FRACTION FROM WHEAT

As the aleurone layer is tightly bound to the seed coats, it is rather difficult to separate this fraction from the rest of the bran. Different fractionation methods have been developed, from laboratory small scale techniques designed for biochemical analyses, to semi-industrial processes more adapted for large-scale aleurone production. At lab-scale the manual dissection of whole grains is the method most likely to yield the purest sample. After the kernels have been soaked in water, it is possible to achieve separation of most of the grain tissues, as shown by Barron et al. (2007). However, the time and labor involved in this method limits the amount of samples produced, making it suitable for compositional analysis, but not for nutritional or bread making studies. Other methods using maceration of bran in chemical reagents or organic solvents have also been reported

(Bacic and Stone, 1981; Pomeranz, 1988). Authors were able to obtain aleurone cell walls from both wheat and barley, in sufficient purity for chemical analysis, by carrying out successive steps of milling, sieving, air classification, and centrifugation in benzene-carbon tetrachloride mixtures. Debranning of wheat grains also called pearling or decortication, has been used as a way to produce bran fractions rich in aleurone particles (Dexter and Wood, 1996; Hemery et al., 2007). Harris et al. (2005) used the PeriTec debranning process (McGee, 1995) to produce a pericarp-rich fraction and an aleurone-rich fraction, which were identified by Field-emission scanning electron microscopy. Bach Knudsen et al. (1995) produced six fractions from whole wheat kernels by carrying out five successive pearling cycles in a vertical abrasive polishing machine (Schule, Hamburg, Germany). One fraction obtained was entitled “aleurone enriched” based on the high protein (22 g/100 g), fat (4.7 g/100 g), and ash (4.2 g/100 g) content of this fraction. Liyana-Pathirana et al. (2006) also used pearling to produce various fractions, and described one of them as aleurone-rich, based on the higher FA content and antioxidant capacity of this fraction. It is relatively easy to produce aleurone rich fractions during de-branning; however, as shown by Hemery et al. (2009), these often consist of blends of various grain outer layers and do not contain more than 40–60% aleurone.

As the aleurone layer has shown to be highly interesting in regard to its nutritional profile, new wet-fractionation and dry-fractionation processes have been developed in order to isolate aleurone on a large scale. In some cases the processes are not, or only briefly described, but in other cases, the publication of patents have made it possible to understand the processes used. One wet-fractionation process, described by Kvist et al. (2010), combines several enzymatic treatments and wet milling steps, followed by sequential centrifugation and ultra-filtration. Unlike wet-fractionation methods, dry-fractionation methods do not produce effluents as they do not require the use of solvents, but only physical/mechanical processes, limiting the biochemical alterations of the aleurone structures. Dry-fractionation processes are therefore said to be “greener” processes. Such processes comprise at least two steps: during the fragmentation

Table 1 Distribution of the principal nutrients in wheat grain. Adapted from Feillet (2000) and Betschart (1988)

	Grain % G	Pericarp		Aleurone		Endosperm		Germ	
		% T	% G	% T	% G	% T	% G	% T	% G
Proteins	13.7	10	4.4	30	15.3	12.0	73.5	31	6.8
Lipids	2.7	0	0	9	23.6	2	62.9	12	13.5
Starch	68.9	0	0	0	0	82	100	0	0
Pentosans	7.4	43	35.1	46	43.8	1.6	18.3	7	2.9
Cellulose	2.8	40	87.1	3	7.6	0.1	3.1	2	2.2
Minerals	1.9	7	7–22	12	43–61	0.5	20–23	6	9–12
Niacin	–	–	4	–	82	–	12	–	2
Riboflavin	–	–	5	–	37	–	32	–	26
Piridoxin	–	–	12	–	61	–	6	–	21

% T :% of nutrients in the specified tissue

% G :% of nutrients in the whole grain kernel. For example, the protein% in the pericarp tissue (%T) amounts to 10%, which in itself contributes 4.4% to the total kernel protein content.

step, the various bran tissues are dissociated by grinding, and during the separation step, the particles are sorted out according to certain properties, such as their size, mass, density, or electrostatic properties (Hemery et al., 2007).

Separation methods are also used to insolate aleurone particles, including both well known (air-classification, sieving), and more innovative techniques (electrostatic separation). The processes developed for large-scale aleurone production often combine several fragmentation and separation steps. Some fractionation processes take advantage of properties such as particle size and density, using sieving and air-classification of ground bran to yield fractions rich in aleurone. However, these processes do not allow production of high purity fractions, due to the low differentiation in size and density of the particles generated from the different bran tissue after grinding. For example, the "Wheat Aleurone Flour," fraction used in the experiments of McIntosh et al. (2001), which was supplied by Goodman Fielder Ltd, was isolated by cleaning, steaming, stabilizing, two steps of roller-milling, sieving, and three steps of a combination of fine grinding and by air-classification (Tupper et al., 2001) and still contained 36.5% of starch.

In order to obtain purer aleurone fractions, processes based on the electrostatic properties of the different bran layers have been developed. Electrostatic separation involves first the tribo-charging of the particles (by making them impact against each other or against the walls of the charging device), followed by a second step in which the charged particles are separated in an electric field, depending on their acquired charge (Fig. 3). Hemery et al. (2009) observed that the pericarp and aleurone cell walls display different tribo-charging properties enabling separation in an electric field and that the type of cell wall polysaccharides (branched and cross-linked vs. linear and feruloylated) may be the main influencing factor (Hemery et al., 2011). This principle of electrostatic separation has been used

by Stone and Minifie (1988) to sort aleurone cells from wheat bran. Wheat bran was first hammer-milled to obtain a blend of aleurone cells, testa, and pericarp particles; then sieved to collect a fraction composed of particles with a diameter of 130 to 290 μm . This sized fraction was electrostatically charged in an elutriator column, and the charged particles were separated by passing them through an electric field. According to the authors, from the initial bran made of 34% of aleurone cells and 66% of pericarp and testa, an almost pure aleurone fraction (95% of aleurone cells) was obtained with a 10% yield.

Since 2002, Bühler AG has filed a series of patents, documenting dry-fractionation processes aiming at isolating the aleurone layer from wheat bran (Bohm et al., 2002; Bohm and Buri et al., 2004; Bohm and Kratzer, 2008). After an initial size reduction step designed to favor the particles separation, the aleurone tissue is separated from the other seed coats by mechanical action (grinding). Following this, the blend of aleurone particles and other outer layer particles undergo a number of separation steps. The particles are charged, either by using a disk-shaped rotor element, or a curved charging pipe; then they are separated in an electrical field using their distinct electrical polarization. The obtained aleurone fraction comprises platelet-like aleurone cells in clusters of five to 40 cells attached to the hyaline layer and to very small amounts of testa, pericarp, and endosperm. The fraction was found to contain 60–90% aleurone, quantified using the biochemical marker method (Hemery et al., 2009) which has proved to be an efficient tool for the assessment of grain tissue proportions within various milling fractions. With this method, a specific biochemical marker is associated with each part of the grain (pericarp, intermediate layers, aleurone cell walls, aleurone intracellular compounds, and endosperm), and the quantification of these five markers allows calculation of the proportion of each grain tissue in the analyzed fraction.

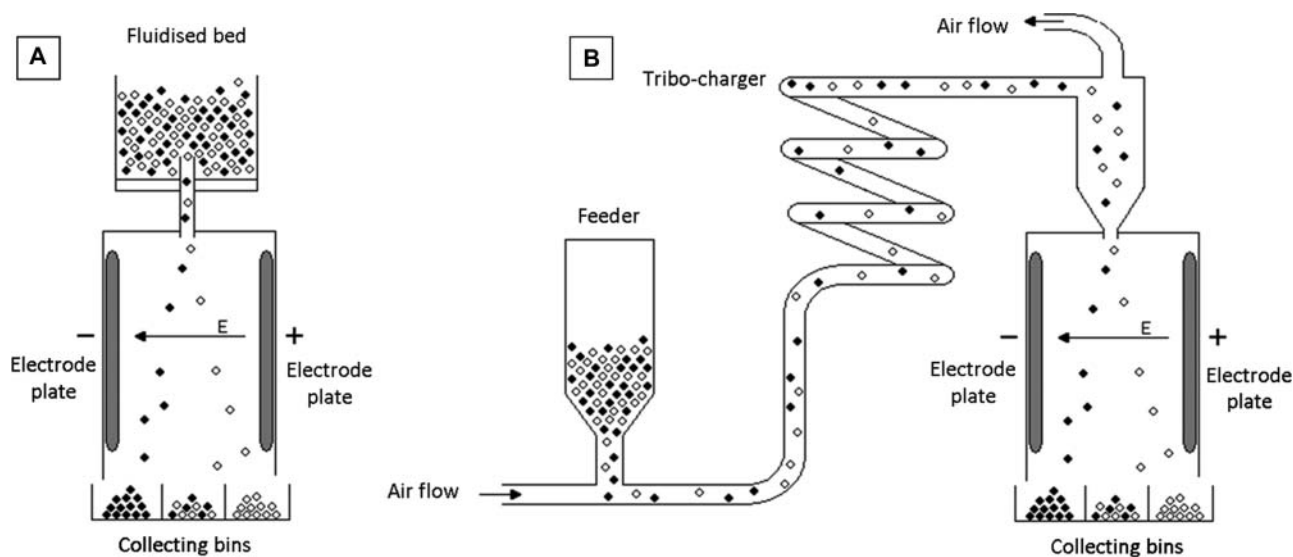


Figure 3 Examples of free-fall electrostatic separators used for selective sorting of insulator material first differently charged by tribo-electrification. (A) In the fluidised bed, the frequent collisions of particles result in contact charging, and (B) In tribo-charging pipes, charging is due to impacts between particles and the equipment walls. Adapted from Hemery et al. (2007).

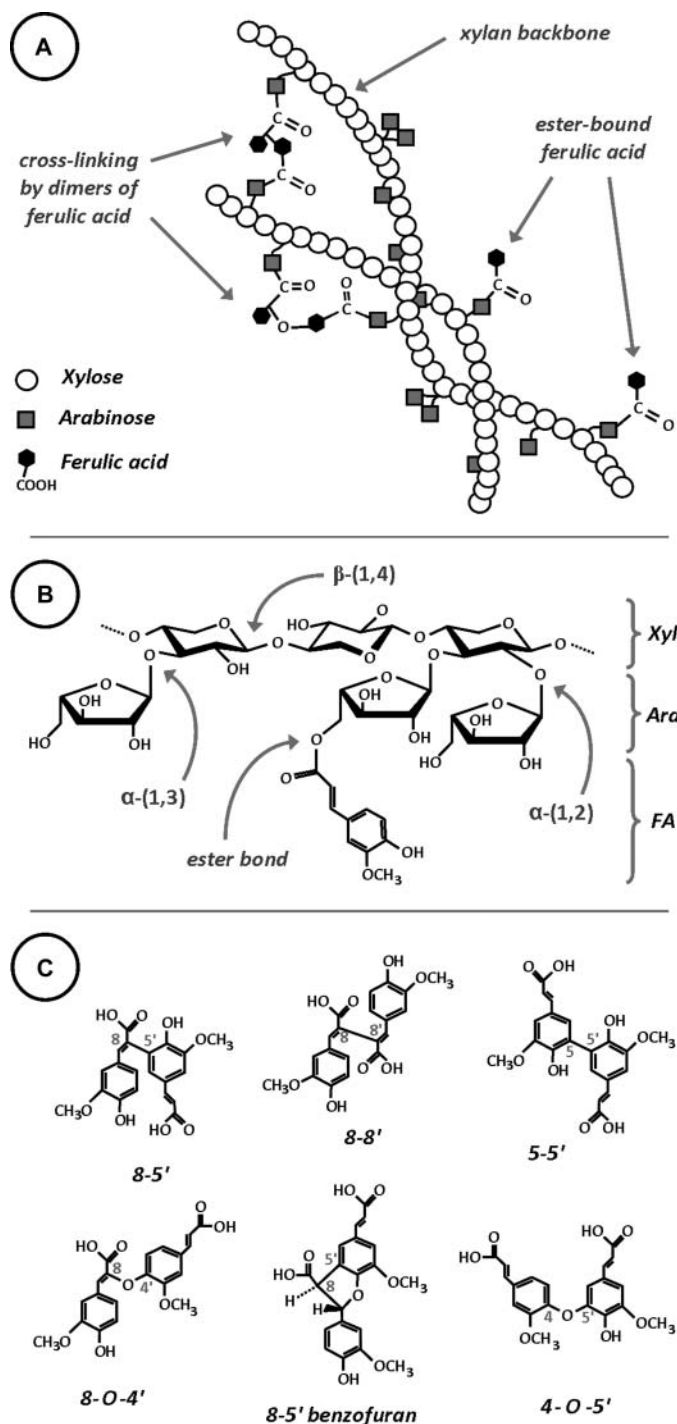


Figure 4 Cross-linking of the chains by different dehydro-diferulates. B Chemical structure of a linear β -(1,4) linked xylan backbone, substituted with arabinose side residues via α -(1,3) and α -(1,2) linkages. C Examples of dehydrodimers of ferulic acid (diferulates) found in wheat aleurone cell walls.

COMPOSITION OF THE ALEURONE FRACTION

The aleurone fraction can be of variable purity depending on the fractionation process used and the amount of aleurone cells recovered.

Fiber

The dietary fiber (DF) content of aleurone has been estimated to be 44–50 g/100 g DM (Amrein et al., 2003), depending on the wheat variety and purity of the aleurone fraction. The major polysaccharides present in the fiber fraction are arabinoxylan (65%) and β -glucans (29%), while cellulose plays a more minor role (Bacic and Stone, 1981; Saulnier et al., 2007). Arabinoxylans (AX) are made of a linear β -(1,4) linked xylan backbone to which α -L-arabinofuranose units are attached as side residues via α -(1,3) and/or α -(1,2) linkages. Ferulic acid or diferulate residues are esterified to arabinose residues at O-5 (Fig. 4). AX have very heterogeneous structures depending on their degree of branching (not- or mono- or di-substituted by arabinose), distribution of arabinose residues, and degree of polymerization. These variations in structure significantly affect the physical properties of AX. The ratio between arabinose and xylose (A:X) decreases from the pericarp to the endosperm. Thus the neutral AX from the aleurone layer as well as AX from starchy endosperm have a lesser degree of branching than acidic AX from pericarp/testa, which may theoretically improve their solubility and their digestibility. However, because AX from the aleurone layer are cross-linked via diferulates (Fig. 4); the dietary fibers present in the aleurone layer are mostly insoluble (Bach Knudsen et al., 1995; Bunzel et al., 2001; Izydorczyk and Biliaderis, 1995; Saulnier et al., 2007).

Minerals

The micronutrient content of aleurone is described in Table 2. Aleurone is a significant source of phosphorus, magnesium,

Table 2 Vitamin and mineral contents of the aleurone layer (expressed in mg/100 g of dry aleurone matter). Adapted from Antoine et al. (2002) and Buri et al. (2004)

	Lopez et al. (2001) ^a	O'Del et al. (1972) ^b	Pomeranz (1988) ^c	Buri et al. (2004) ^d
Vitamins				
Thiamin, B1	1.6		1.6	1.4
Riboflavin, B2	0.3		1.0	0.2
Niacin, B3 or PP	24.0		61.3–90.2	32.9
Pyridoxin, B6	0.3		3.6	1.3
Folates, B9	0.8			0.2
Vitamin E	2.0			1.2
Minerals				
Potassium, K	1600	1100		2250
Phosphorus, P	1140	1400	3170	2540
Magnesium, Mg	530	600		1030
Manganese, Mn	101	13	8	
Calcium, Ca	55	73		93
Iron, Fe	27	19	34	26
Zinc, Zn	8.3	12		14

^aAleurone fraction supplied by the company "Goodman Fielder."

^bSamples obtained by hand dissection.

^cSamples obtained by hand dissection (for vitamins analyses) and by bran milling followed by separation of the components in organic liquids (for minerals analyses).

^dAleurone fraction provided by Bühler AG (75–90% pure aleurone cells).

manganese, and iron. The phytates in aleurone constitute a phosphorus reserve in the wheat grain and 80% of phosphorus is in phytate form (Pomeranz, 1988). Indeed, the type 1-inclusions are composed of phytic acid (1160 mg/100 g) or myo-inositol phosphate, which forms complexes with calcium, magnesium, or trace elements (particularly zinc). Whole grains are very often blamed for decreasing mineral bioavailability due to the strong mineral chelating properties of its dietary fibers and phytic acid. Recently Schlemmer et al. (2009) reviewed that phytic acid binds strongly to minerals and trace elements under the acidic conditions of the gastric chyme and form soluble complexes, which precipitate after passage into the intestine and thereby reduce the bioavailability of bound trace elements and minerals. However, the authors also concluded that this is counteracted by fermentation of the dietary fibers in the colon leading to the production of short chain fatty acids which reduce the intestinal pH and solubilize formed complexes leading to colonic absorption of calcium, magnesium, zinc, and iron. Moreover, it is considered that any negative effects phytate may have in binding minerals would be offset by the quantity of minerals present in whole grains and its strong antioxidant potential (Levrat-Verny et al., 1999; Schlemmer et al., 2009).

Nevertheless, a daily consumption of whole grains (3 servings per day) will contribute to a good mineral status (Slavin et al., 1999). During germination, phosphatases (endogenous phytase) hydrolyze the phytates releasing its minerals. Additionally, during the baking process, diverse endogenous and exogenous phytase activities (yeast or sourdough) can be induced through a decrease in pH, an increase in temperature, and hydration of the dough. This degradation of phytates and decrease in pH during sourdough bread making has been shown to improve mineral bioavailability in rats (Lopez et al., 2001). On the other hand, dietary fibers such as resistant starch and fructans may help to improve the mineral bioavailability during their fermentation in the large bowel, compensating for any negative effects of phytates (Lopez et al., 1998).

Vitamins, Betaine, and Choline

Table 2 shows that the aleurone layer is an important source of thiamin (1.6 mg/100 g), niacin (32.9 mg/100 g), and folate (0.8 mg). It can be estimated that 100 g of aleurone may provide the recommended daily allowances of these vitamins (Lopez et al., 2001).

Thiamin and riboflavin contents are higher in the aleurone than in other bran layers (0.06 mg/100 g versus 1.6 mg/100 g and trace versus 1 mg/100 g for thiamin and riboflavin, resp.). Moreover, it has been shown that wheat aleurone flour is a significant source of bioavailable folate both within an acute (Fenech et al., 1999) and a longer-term setting (Fenech et al., 2005). Within this short-term randomized crossover intervention study with men and women, an increment of plasma folate was observed after ingestion of 100 g wheat bran (low folate control), 100 g wheat aleurone (500 μ g folic acid), or 100 g wheat bran +

500 μ g folic acid (high folate control) (Fenech et al., 1999). The increase in plasma folate during the first 7 hours after ingestion of aleurone was more than four-fold than that of wheat bran ($P < 0.0001$) and equivalent to a 500 μ g folic acid tablet with wheat bran.

Wheat grain is also a good source of other methyl donors, including choline and betaine, and the levels are higher in the aleurone than other layers of the wheat grain (1115, 867, and 23 mg/100 g betaine, and 210, 102, and 28 mg/100 g choline for the aleurone, bran, and flour layers, respectively (Graham et al., 2009)). This reflects well the findings within the in vivo situation, and Price et al. (2007) observed significant postprandial increases in plasma betaine following the consumption of wheat bran (~two-fold baseline values) but to a greater extent wheat aleurone (~three-fold baseline values) in healthy adults. In a later study authors further investigated the potential of aleurone by evaluating the habitual consumption of wheat aleurone-rich breads and ready-to-eat cereal products, 27 g of aleurone/day on plasma betaine and related measures (Price et al., 2010). The 4-week intervention showed significantly increased plasma betaine concentrations and resulted in a concomitant decrease in plasma total homocysteine in subjects consuming the aleurone products compared to the refined control products. As betaine functions not only as a methyl donor but also as an osmolyte and lipotrope (Craig, 2004), these studies indicate the potential of betaine within the aleurone fraction. Independent of betaine, the authors also noted a decrease in LDL-cholesterol in subjects consuming the aleurone products, again demonstrating the potential role of aleurone as a functional food ingredient (Price et al., 2010).

Phenolic Compounds

The main phenolic compounds in aleurone can be ordered in simple phenols; phenolic acids (ferulic acid (FA), p-coumaric acid, sinapic acid (3,5-Dimethoxy-4-hydroxycinnamic acid), syringic acid, vanillic acid), alkylresorcinols, and complex phenols; lignin and lignans.

In the wheat grain, most phenolic acids exist in three forms: soluble free acids, soluble conjugated moieties esterified to sugars, and other low molecular mass compounds, and insoluble bound moieties, esterified to the arabinoxylans and other cell wall structural components. FA and p-coumaric acid are mostly found in the bound form (~92% and ~63% respectively), whereas sinapic and vanillic acid are mostly found in the conjugated form (~69% and ~67%, respectively) (Li et al., 2008).

Other simple phenols abundant in wheat grain are the alkylresorcinols, which reach concentrations of 280–1400 μ g/g grain (Chen et al., 2004; Fardet et al., 2008; Landberg et al., 2008). The plasma alkylresorcinol C17:0 to C21:0 ratio reflects the intake of whole grain wheat and rye and as such the plasma total alkylresorcinol concentration appears to be a useful biomarker of whole grain cereal intake (Linko-Parvinen et al., 2007).

Table 3 Phenolic acid composition of wheat grain, wheat bran, and wheat aleurone fractions ($\mu\text{g/g}$)

	p-OH Benzoic Acid	Vanillic acid	Syringic acid	p-Coumaric acid	Sinapic acid	Ferulic acid	Ferulic acid dimers
Whole Grain	5.0	4.9–21	13–18	15–28	60–81	399–870	19–150
Wheat Bran	19.7	16.5	57.2	130–162	115–276	4610–5670	780–1550
Wheat Aleurone*	28.4	20.0	90.3	160–288	269–353	6440–7980	360–950

*Pure hand isolated aleurone or milling aleurone fraction from Bühler AG (70–90% aleurone). Data from Barron et al. (2007), Hemery et al. (2009a; 2010a; 2010b; 2011), Li et al. (2008), Noort et al. (2010), and Zhou et al. (2004).

However, they are mainly located in the bran, specifically in the testa, and not in the aleurone layer. Moreover, their quantitative presence in bran is also grain type dependent (Landberg et al., 2008). Therefore, to obtain reliable data on whole grain consumption as well as consumption of foods that have been enriched with whole grain bioactives by enrichment with aleurone, it should be noted that there is a necessity to search for other biomarkers that are (also) representative of aleurone intake and/or grain type intake.

Ferulic Acid

Ferulic acid (hydroxycinnamic acid derivative) is the most abundant phenolic compound in grain (Table 3). Concentrations of FA range from 290 to 740 $\mu\text{g/g}$ dry matter in durum wheat and from 180 to 870 $\mu\text{g/g}$ dry matter in aestivum wheat (Li et al., 2008), with the greatest concentration in the aleurone layer (~70%) (Piot et al., 2000). Ferulic acid occurs as a structural component of the aleurone cell walls and is responsible for their observed fluorescence properties. Ferulic acid and dimers of this acid (diferulates) have an important role in the structural properties of aleurone fiber, since diferulates are responsible for the cross-links between cell-wall polysaccharides (Fig. 4), and ~98% of FA is esterified to cell wall arabinoxylan (AX) at the C5 position of arabinose residues. These structural characteristics may be responsible for the relatively poor bioavailability of FA from aleurone (Adam et al., 2002; Klepacka and Fornal, 2006).

Besides its structural function in the cell wall, FA is a potent antioxidant due to its resonance-stabilized phenoxy radical structure. Ferulic acid is able to avoid oxidative damage by the electron donation and hydrogen atom transfer to free radicals (Graf, 1992). Compared to other structure-related antioxidants, its ability to inhibit lipid peroxidation by superoxide ($\text{O}_2^{\bullet-}$) scavenging is of greater magnitude than that of cinnamic acid but less than that of caffeic acid (Toda et al., 1991), whereas its ability to inhibit oxidation of low-density lipoprotein (LDL), the main cholesterol carrier in blood, is greater than that of ascorbic acid (Castelluccio et al., 1996). The ferulic acid radical (phenoxy radical) that is formed from its oxidation is very stable and does not initiate an oxidative chain reaction of its own (Palacios et al., 1990), since the presence of the methoxy group in the C3 enhances the resonance stabilization (Rietjens et al., 2007; Zhao et al., 2008). The total antioxidant capacity of different wheat fractions is strongly related to the FA content of these fractions (0.960, $p < 0.00001$). This was observed for ten different fractions: eight fractions were obtained

by using two debranning processes (peeling and pearling) before grain milling and two other fractions by aleurone enrichment (Mateo Anson et al., 2008). The flour fractions were the lowest in antioxidant capacity. Among the bran fractions the peeling fraction, which is composed of the outermost layers of the kernel (mostly pericarp) displayed the lowest antioxidant activity, while the aleurone fractions displayed the strongest activity. The aleurone content of the fractions was estimated by using biochemical markers as proposed by Hemery et al. (2009), and the antioxidant capacity increased with the purity of the aleurone fraction. This is reflected in the correlation ($r = 0.962$, $p < 0.0001$) found between the antioxidant capacity and the aleurone content of the different fractions (Fig. 5). The contribution of FA to the antioxidant capacity of the fraction can be calculated with the trolox equivalent antioxidant capacity (TEAC) assay by multiplying the TEAC value of FA by its content and relating this value to the TEAC of the fraction. FA is responsible for 60% of the antioxidant capacity of aleurone (Mateo Anson et al., 2008). Altogether, aleurone seems to be the key component in the whole grain antioxidant potential, and FA the main responsible compound.

Ferulic acid has been approved in certain countries as a food additive to prevent lipid peroxidation and as a drug for the treatment of cardiovascular and cerebrovascular diseases (Bao-Hua and Jing-Ping, 2005; Graf, 1992). In vitro, FA protects low-density lipoprotein (LDL) from oxidative damage (Castelluccio et al., 1996), and prevents the production of radical oxygen species in cell-culture based inflammatory models (Chang et al., 2003; Hirabayashi et al., 1995; Kong et al., 2007; Maggi-Capeyron et al., 2001; Meng et al., 1994;

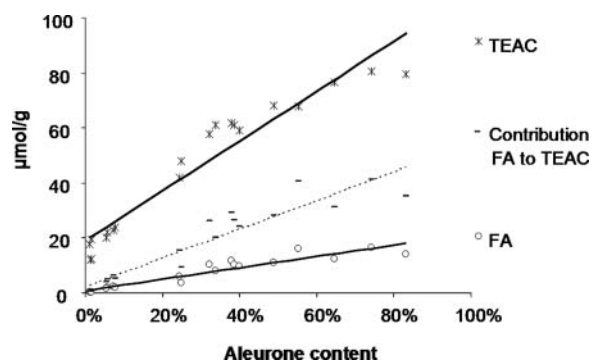


Figure 5 Correlation of the aleurone content in the wheat fraction with the content in total soluble ferulic acid (FA) and the antioxidant capacity (TEAC). The dotted line shows the contribution of ferulic acid to the TEAC of the fraction (From Mateo Anson et al., 2008).

Murakami et al., 2002; Ronchetti et al., 2006; Yao et al., 2005). In vivo, FA is able to reduce several inflammatory messengers, such as cytokines and prostaglandins, in different animal models of inflammation. (Cho et al., 2005; Jin et al., 2006; 2006; Jung et al., 2009; Liang et al., 2009; Liu et al., 2004; Sudheer et al. 2008; Yan et al., 2001; Zou et al., 2006). Additionally, a recent study in men shows that FA can reduce the pro-/anti-inflammatory cytokine ratio in an ex vivo induced inflammation (Mateo Anson et al., 2011).

With respect to the in vivo action of FA it needs to be considered that most of the phenolics present in grains are bound to indigestible polysaccharides in the cell wall, which may significantly limit their bioavailability and thus their bioactivity potential in the body. The latter was recently addressed in a paper by Mateo Anson et al. (2009) who discussed that human and rat studies generally show a low urinary FA excretion after high-bran consumption: wheat 2.5–5% and corn 0.4–0.5% as shown by Zhao et al. (2005) Mateo Anson concluded that the FA bioavailability depends on its free form and thus its release from the fiber food matrix. This was a reason to perform a study aiming at monitoring the release of FA during gastrointestinal (GI) transit, also referred to as bioaccessibility. While the bioaccessibility of FA was very low from wheat fractions, such as bran and aleurone, and breads (<1%), it was high when free FA was added to flour (60%). The bioaccessibility of FA was studied from different wheat fractions and breads with the use of a dynamic in vitro system that simulates the upper GI transit and digestion. Findings indicated that the bioaccessibility of FA appeared to be determined by the percentage of its free form present. This is a reason for the authors to propose modifications in wheat processing in favor of an increase in the contents of free FA in the cereal matrix, and accordingly increase in bioavailability. The latter was addressed in a follow-up project by Mateo Anson et al. (2009). The objective of their study was to investigate whether different bioprocessing techniques, such as fermentation and enzymatic treatments, could enhance the bioaccessibility of FA from wheat bran. The results of this study showed that bioprocessing of wheat bran by fermentation or by the combined action of hydrolytic enzymes and fermentation promoted the release of phenolic acids and increased their free fraction in the wheat breads. In vitro, a significant increase in the bioaccessibility of the phenolic acids was observed. The most effective process was the combination of fermentation and enzymatic treatment of wheat bran, which increased FA bioaccessibility by 5-fold compared to native bran. Hemery et al. (2010) have also described other techniques that when applied to the bran could increase the bioaccessibility of FA from bread using the same in vitro gastrointestinal system. Ultra-fine grinding of bran to a particle size < 50 μm (which is roughly under the diameter of an aleurone cell) can disrupt the cell wall and release the intracellular contents of the cell. This improved the bioaccessibility of sinapic acid and FA. However, as most of the FA is located within the cell walls and not intracellularly like the sinapic acid, the improvement on the bioaccessibility was less than by the bioprocessing techniques using fermentation

and hydrolytic enzymes targeting the linkages of between cell wall polysaccharides (Hemery et al. (2010).

The impact of this bioprocessing technique was further investigated in vivo in a human bio-availability study (Mateo Anson et al., 2010). Plasma FA was measured in 8 men after the consumption of 300 g of whole wheat bread with bioprocessed bran or native bran (control bread) in a cross-over design. Figure 6 shows that the bioavailability of FA after consuming the whole wheat bread with bioprocessed bran was around 3-fold greater than after consuming the control bread. Besides FA, the bioavailability of syringic acid, vanillic acid, and 3,4-dimethoxybenzoic acid also increased. Other compounds were identified in plasma after 6 h post bread ingestion, mainly phenylpropionic acid and hydroxylated phenylpropionic acid, which are likely to be derived from the colonic metabolism of FA. This increase in FA bioavailability and its metabolites had a minor effect on the plasma total antioxidant capacity, but it was positively associated with the anti-inflammatory effects on an ex vivo induced inflammation in whole blood cultures.

The bioavailability of ferulic acid from wheat aleurone was studied by Hamill et al. (2009). The authors investigated the absorption of FA in 14 human subjects after consumption of 50 g wheat-bran fraction or 50 g wheat-aleurone fraction compared to a control meal balanced for fiber and macronutrients. Both plasma FA and urinary FA showed significant postprandial increases following consumption of the wheat-bran or wheat-aleurone fractions compared with the control. Plasma concentrations of FA were approximately 5-fold higher than at baseline following consumption of the bran fraction and 6-fold increased after aleurone fraction ingestion. The maximum postprandial plasma FA increase following consumption of the wheat-bran fraction (~ 400 nM) was approximately 2.5 times of those previously reported following consumption of 100 g wheat-bran ready-to-eat cereal.

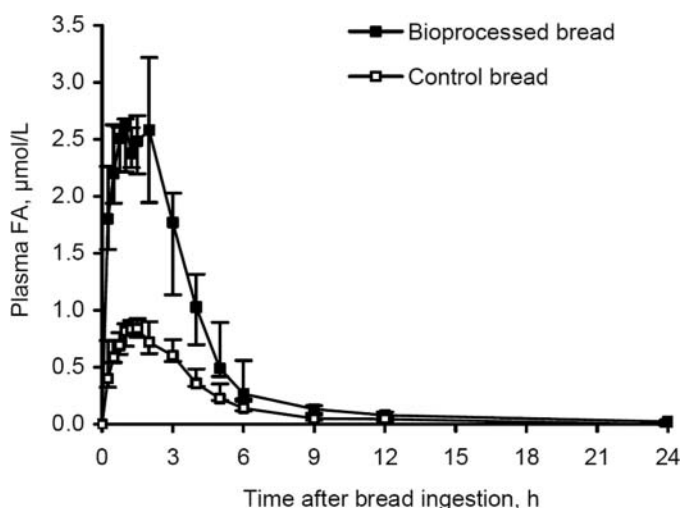


Figure 6 Plasma concentration ($\mu\text{mol/L}$) of ferulic acid (FA) over time after the ingestion of the bioprocessed bread or the control bread in men. Baseline is subtracted. Values are medians and IQR, $n = 8$ (From Mateo Anson et al., 2010).

Lignans

The term phyto-estrogen encompasses isoflavone compounds, such as genistein and daidzein, found predominantly in soya products as well as lignans such as matairesinol (MAT) and secoisolariciresinol (SECO), found in many fruits, cereals, and in flaxseed. Lignans occur as minor constituents in many plants where they function as a precursor for the formation of lignin in the plant cell walls. The total lignan content is 7 mg per 100 g for wheat aleurone and 8 mg per 100 g for wheat aleurone micro-milled (Adlercreutz, 2003) (Table 3). The higher values of wheat aleurone micro-milled can probably be attributed to a higher extraction rate after micro milling. Quantitatively, by far the most important lignan is syringaresinol. Wheat contains SECO (8.1 $\mu\text{g}/100\text{ g}$), which is concentrated in the aleurone layer (Thompson, 1994). The physiological effects of lignans are mainly based on their antioxidant activity as well as on their potential estrogenic activity after transformation and absorption. Plant lignans may be converted by the intestinal microbiota into the mammalian lignans enterodiol and enterolactone (Heinonen et al., 2001). The structural similarity of lignans to estrogens means that mammalian lignans act either as weak estrogens or as estrogen antagonists. Individuals consuming relatively large amounts of whole grain cereals may therefore have an increased protection against hormone-related cancers (Truswell, 2002; Rowland et al., 2003). Moreover, a high plasma concentration of the mammalian lignan enterolactone has been shown to be correlated with a reduced risk of breast cancer and prostate cancer (Cornwell et al., 2004, Andlauer and Fürst, 1999). These observations have led to a strong interest in the intestinal biotransformation and subsequent bioavailability in man.

IMPACT OF ALEURONE ON THE INTESTINAL TRACT

To understand how wheat aleurone and wheat bran behave in the upper digestive tract, Amrein et al. (2003) carried out an *in vitro* digestion. The overall digestibility values were found to be around 30% for aleurone, whereas only 13% of the components were digested in wheat bran. In all samples, starch was virtually completely eliminated during digestion, which was reflected in starch digestibility values of 90–95%. About two-thirds of the proteins in aleurone were digested, whereas it was only about 50% in wheat bran. Substantial amounts of ash was still present in digestion residues, indicating, as previously discussed, that minerals may be present mainly in complexes such as phytates. This fact may lead to the assumption that the *in vitro* measured mineral bioavailability when generalized to the upper digestive tract may be rather poor. Whether unabsorbed minerals become bioavailable in the colon due to fermentations processes which lead to the destruction of the cell walls in which the minerals are “packed,” remains to be elucidated. Others studies, carried out in rats and cockerels (Bach Knudsen et al., 1995) addressed the nutritive value of raw and enzyme treated whole grain wheat

and six milling fractions. They showed an increase in aleurone protein digestibility ($\approx 86\%$) compared to wheat bran ($\approx 75\%$). Generally, a strong negative relation between the digestibility of proteins, the digestible energy, and the DF level has been demonstrated. In the rat study, the highest net protein utilization (11.3–11.7%) was found with ingestion of the fractions enriched in aleurone (Bach Knudsen et al., 1995). The effect of enzyme treatment on enhanced true digestibility and biological value was significant for the pericarp/testa rich fraction.

Fermentation Profile

A batch technique using fresh human fecal material has been applied under strictly anaerobic conditions to study the fermentability of aleurone and wheat bran fibers. Fermentability, after an *in vitro* predigestion of the samples, was established by measuring a decrease of the pH, total gas, hydrogen, and short chain fatty acids (SCFA) production. Wheat bran and aleurone gave similar SCFA ratios with a relatively high molar yield of propionate and butyrate (54/21/21 for acetate/propionate/butyrate, respectively) (Amrein et al., 2003). Substrate disappearance was determined as neutral sugar decrease and microscopy was used to visualize morphological changes of cell walls during fermentation. Polysaccharides differed considerably in their susceptibility to colonic bacteria. Neutral sugars were almost totally metabolized within 24 h in aleurone, but > 50% remained non-degraded in bran. This may probably be due to the higher cellulose content of bran, which is barely fermentable in the human colon.

Glucose disappearance during the fermentation process occurs mainly within the first few hours and is more pronounced in aleurone due to the presence of mixed-linked β -glucans. Slightly branched arabinoxylans (AX) in aleurone are almost completely degraded within 8 h. In bran, however, substantial amounts are still present after 24 h and a significant increase in A:X ratio after the first fermentation phase can be observed. This indicates that slightly branched AX were degraded preferentially, whereas the highly branched ones were fermented more slowly or remained completely unfermented.

Micrographs confirmed the differences in degradability by colonic bacteria (Amrein et al., 2003). After 8 h of fermentation neither cell clusters nor intact cells were observed in aleurone and only small cell wall fragments remain. In contrast, bran particles were degraded to a much smaller extent. Similar results were observed by Bach Knudsen et al. (1995) who performed studies in rats and cockerels in which they observed that the lowest degradation of cell wall non-starch polysaccharides was found in the pericarp/testa enriched fraction, resp. 24% in rats and 11% in cockerels. Aleurone degradation was 45% in rats and around 24% in cockerels, and endosperm degradation 74% and 43%, respectively. In the pericarp/testa fraction, the degradation of AX and cellulose was almost the same, while the

digestibility of AX was significantly higher than that of cellulose in the walls of aleurone and endosperm. A strong negative correlation between the degradation of xylose residue and the arabinose:xylose ratio indicates that the degradation of AX varies in response to the degree of branching. Overall it appeared that the degradation of protein and non-starch polysaccharides of the lignified pericarp/testa fraction of wheat bran is much lower than of the fractions rich in aleurone. These poorly fermentable lignified cell wall materials have a high bulking capacity whereas aleurone cells are easily degradable and stimulate microbial activity in the cecum and the colon. Findings are supported by Cheng et al. (1987) who found the highest concentrations of SCFA in cecal contents of rats fed aleurone (1088 μmol) compared to rats fed cellulose (264 μmol), pericarp/testa (302 μmol), or wheat bran (564 μmol) diets. These high values, together with the greatly elevated fecal mass of bacteria in that experimental group, are consistent with the high content of fermentable non-cellulosic polysaccharides in the aleurone fraction compared with the wheat bran and pericarp/testa diets. In a recent in vitro study the SHIME (simulator of the human intestinal microbial ecosystem) model (Possemiers et al. 2004) was applied in a continuous fermentation under anaerobic conditions at 37°C by Possemiers et al. (2009). For this study, the system was inoculated with a fecal sample from a person specifically selected for low initial starting concentrations of bifidobacteria and particularly lactobacilli. Feeding of the system consists of “3 « meals »/day.” The various sections of the colon have all a specific pH of 5.6–5.8; 6.2–6.4; 6.6–6.8 in colon ascendens, –transversum, and –descendens, respectively. Before testing started, a stable microbial community was obtained during 2 weeks of nominal “base diet” conditions, after which, for the 3 weeks lasting test period a fraction of the starch in this diet was taken out and replaced with a fraction of the test fiber, in this case aleurone (administered at a daily dose of 2.5 g). After the test period a washout period was put in place, lasting 2 weeks. During the entire experimental period SCFA are measured 3x/wk and plate count for selected bacteria 1x/wk. The results obtained showed that during continuous fermentation in SHIME a sustained production of SCFA was observed along with a significant increase in bifidus counts with a trend for clostridia to decrease. These are the first results showing a potential favorable microbiota modification by aleurone fiber. Additional in vivo human trials are warranted now to also show real life effects.

POTENTIAL HEALTH EFFECTS

Cancer Biomarkers

At present, there is substantial scientific evidence, based on epidemiological studies, case-control studies, human intervention studies, and animal studies to suggest that whole grains and wheat bran may help to reduce the risk of cancer (Slavin et al., 1999; Slavin, 2000; 2004). Isolated aleurone is nutrition-

ally the most interesting fraction of wheat bran, having both a concentrated supply of phytochemicals and antioxidants, and an excellent fiber type to support health. However, to date, only a few studies have been carried out addressing the potential health effects of isolated aleurone on biomarkers for cancer. A rat study by McIntosh et al. (2001) was designed to evaluate wheat aleurone flour (WAF), wheat bran (WB), and cellulose (control) as a source of DF (5 g/100 g diet) in a semi-purified high fat diet (20 g/100 g diet). These diets were fed to male rats in which intestinal tumors were induced using the carcinogen azoxymethane. WAF and WB fed rats showed a trend ($P = 0.06$) with 43% fewer colon tumors. WAF fiber influenced some metabolic markers of fermentation in the colon in a similar manner to WB, such as a significantly increased concentration of cecal β -glucuronidase activity and butyrate. This was independent of the bulking effect, and it was associated with a trend to reduce tumor formation. A significant inverse relationship between β -glucuronidase activity and tumor occurrence was observed ($r^2 = 0.37$, $P = 0.001$).

In a study using cell culture (Chung, 2002) quinolone alkaloid was isolated from the n-butanol soluble fraction of the aleurone layer of rice (*Oryza sativa* cv. *Mihangbyo*). The compound exhibited moderate antineoplastic activity in a human leukemia cell line (U937) with an IC_{50} value of 118.1 $\mu\text{g/mL}$, based on the MTT (3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazolium bromide) cell proliferation assay.

Recently, several studies were performed on the role of whole grain wheat flour or fractionated wheat aleurone fermentation on colon disease risk reduction. In these studies the material was digested in vitro, subsequently followed by in vitro fermentation, after which the fermentation supernatants were exposed to HT29 cells. The results showed that wheat aleurone and aleurone containing whole grain fractions contribute to decreasing colon cancer risk by the reduction of secondary bile acids production, induction of apoptosis, cell differentiation, and detoxification as a result of colon fermentation (Borowicki, 2010; 2010a; 2010b; Stein et al., 2010; 2011). A very recent work of Ross et al. (2011) points to the fact that favorable changes observed in the colonic metabolism of humans after whole grain consumption compared to the consumption of “refined” white flour products are the result of the importance of both fiber and phytochemical components.

CVD Biomarkers

Recently Sagara et al. (2007) compared the effect of a wheat aleurone based diet vs. a soy based diet on parameters of blood pressure and glycemia in spontaneously SHR/NDmcr-cp(cp/cp) rats. Although both diets led to the supply of phytoestrogens and lignans, the aleurone diet was more effective in reducing symptoms of hypertension as well as hyperglycemia. The authors suggest that wheat aleurone may contribute to the prevention of obesity and hyperlipidemia when ingested for a prolonged period of time. Neyrinck et al. (2008) studied the influence of a

Table 4 Lignan Contents of Aleurone Samples ($\mu\text{g}/100\text{ g}$ dry weight)

Sample	Secoisolarici-resinol	Matai-resinol	Isolarici-resinol	Larici-resinol	Pino-resinol	Syringa-resinol	Total
Wheat Aleurone *	348	33	882	208	308	6,267	8,046
Wheat Aleurone	231	22	841	89	241	5,182	6,607

*Micro-milled. Data from Adlercreutz et al., 2003.

high fat diet or high fat diet with 10% of wheat bran or wheat aleurone for 3 weeks on obese mice with glucose intolerance. Although no differences in the glucose and lipid homeostasis were observed, the counts of bifidobacteria and lactobacilli were increased in the cecal content, and circulating interleukin (IL)-6 and CD68 mRNA in the visceral adipose tissue were lowered by the diets containing the aleurone fraction or the bran fraction. Also, in the in vitro study by Mateo Anson et al. (2010) bioaccessible compounds from the digestion of wheat aleurone with the TIM system were able to decrease the pro-inflammatory Tumor necrosis factor alpha (TNF- α) in LPS stimulated U937 macrophages.

Fenech et al. (2005) studied the effect of aleurone flour (ALF) enriched bread on red cell folate and plasma homocysteine. A randomized, controlled intervention, of 16 weeks duration, was performed in free-living healthy men, assigned to one of three groups: ALF, 175 g bread made with ALF and placebo tablet each day; PCS, 175 g bread made with pericarp seed coat (PCS) flour and placebo tablet each day (low-folate control); or folic acid, 175 g bread made with PCS flour and tablet containing 640 mg folic acid each day (high-folate control). The daily folate intake contributed by the bread and tablet was 233 mg in the PCS group, 615 mg in the ALF group, and 819 mg in the folic acid group. The authors observed that plasma and red-cell folate increased significantly ($P < 0.0001$) and plasma homocysteine decreased significantly ($P < 0.0001$) in the ALF and folic acid groups only. Plasma folate and red-cell folate in the ALF group (mean, 95% CI) increased from baseline values of 12.9 (9.9, 15.7) nmol/l and 509 (434, 584) nmol/l to 27.1 (22.5, 31.7) nmol/l and 768 (676, 860) nmol/l, respectively. Plasma homocysteine in the ALF group decreased from 9.1 (8.2, 10.0) mmol/l at baseline to 6.8 (6.2, 7.5) mmol/l after 16 weeks. The authors concluded that a moderate dietary intake of ALF can increase red-cell folate and decrease plasma homocysteine substantially. In addition, Price et al. (2010) also observed a small, but significant, decrease in plasma homocysteine after feeding healthy subjects cereal products containing 27 g aleurone/day for 4 weeks (effect size of intervention $-0.62\ \mu\text{mol/L}$). The authors observed no effect on plasma folate status and attributed the change in homocysteine to the high betaine content of the aleurone products fed.

The observations outlined above indicate that health benefits described in individuals that regularly consume whole grain foods are strongly related to the amount of aleurone present in whole grain. It is therefore possible that non-whole grain foods may achieve similar beneficial effects by aleurone enrichment.

POTENTIAL USE IN FOOD

Substantial application work has been carried out in developing a white bread with whole grain characteristics (Atwell et al., 2007). It was shown that bread with a 20% replacement of flour with aleurone has the nutritional benefits of whole wheat bread, but looks and tastes more like white bread. Table 5 provides formulations for both aleurone and whole wheat bread and presents a nutritional comparison. According to US food legislation, using a 20% replacement level, a bread was obtained that could be marketed with the claim "Good Source of Fiber" or 2.5gTDF/50 g serving similar to that of whole wheat, but with a markedly whiter crumb and a milder flavor and taste compared to regular whole grain bread. Increasing the replacement level to 25% and using whole wheat as the base flour meets the claim 'Excellent Source of Fiber' claim, or 5 g TDF/50 g serving of bread." The taste and texture of this bread is similar to that of whole wheat. Replacing 11% of whole wheat flour with cottonseed fiber will also yield high fiber bread. However, as can be seen in Table 6, the nutritive value added to the bread fortified with aleurone versus cottonseed fiber is significant. As the addition of wheat outer layers is known to reduce some of the bread quality (e.g., bread volume, crumb appearance), the recipe needs to be adapted when aleurone is used, in order to preserve an attractive bread aspect. Noort et al. (2010) prepared breads by replacing 9% of the white flour by bran and aleurone (with both initial samples and samples ground to various particle sizes). They observed that both fractions exerted a negative effect on gluten yield and bread volume, and that aleurone breads displayed a lower volume than bran breads, with the bread

Table 5 Aleurone and whole wheat bread formulations (Atwell, 2007)

Ingredient	Aleurone Bakers%	Whole Wheat Bakers%
Bread Flour (11–13% protein)	100.0	0.0
Whole Wheat Flour	0.0	100.0
Aleurone	20.0	0.0
Vital Wheat Gluten	3.0–4.5 ^a	4.0 ^a
Sugar	10.0	10.0
Shortening	4.0	4.0
Non-fat Dry Milk	3.0	3.0
Salt	2.0	2.0
Dough Conditioner	1.5	1.5
Yeast	4.5	4.5
Water	83.5 ^b	76.0 ^b

^adependent on protein level of bread flour

^bDependent on flour moisture and gluten level

Table 6 Nutritional composition of whole wheat bread vs. aleurone enriched bread

Nutritional Comparison		Whole Wheat Bread ^a	Aleurone Bread ^b	High Fiber Aleurone ^c	High Fiber Cottonseed ^d
Serving size		50 g	50 g	50 g	50 g
Calories	Kcal	124	116,50	123,00	113,50
Total Fat	g	1,78	1,70	2,70	2,50
Cholesterol	mg	–	0,00	0,00	0,00
Sodium	mg	236	217,50	258,00	267,00
Total Carbohydrate	g	20,64	23,00	23,00	23,00
Total Dietary Fiber	g	6,8	3,10	5,00	6,00
Insoluble	g	–	2,30	3,80	5,20
Soluble	g	–	0,80	1,20	0,80
Sugars	g	2,79	3,40	3,40	3,20
Protein	g	6,48	4,70	6,00	5,30
Niacin	mg	5,05	5,05	2,80	1,19
Calcium	mg	53,50	15,00	31,75	28,05
Iron	mg	1,22	1,48	1,43	0,95
Vitamin B1 (Thiamin)	mg	0,18	0,27	0,19	0,13
Vitamin B6 (Pyridoxine)	mg	0,15	0,10	0,19	0,10
Ash	%	1,91	0,89	1,37	2,07
Moisture	%	19,29	39,60	34,80	37,00

^aUSDA Nutrient Data Base nr 18075, bread whole wheat commercially prepared.

^b20% replacement of enriched white flour w/ HWW aleurone

^c25% replacement of whole wheat flour w/ HWW aleurone

^d11% replacement of whole wheat flour w/ cottonseed fiber

containing non-ground aleurone displaying a volume 13% smaller than the bread prepared with non-ground bran (Fig. 7).

The whiteness and flavor of aleurone bread products are important factors for white bread consumers. Unacceptability of whole wheat bread among white bread consumers is thought to be due to the bran present in whole wheat, which contributes to not only color but also to flavor and taste. Aleurone enrichment of white bread appears to overcome these effects. Aleurone can be used in many other applications in addition to bread, for example, in buns, pizza crust, muffins, piecrust, cakes, and cookies. Depending on the application, incorporating aleurone can yield the nutritional benefits of using whole wheat flour but

with the taste and texture of the same product made with white flour (Brouns et al., 2010).

CONCLUSION

Wheat aleurone is an exciting new natural ingredient for product developers to have in their toolboxes. It has a high micronutrient content and antioxidant capacity. Aleurone allows product developers to bring the natural goodness of whole grains to products without some of the color and appearance factors that have inhibited the desirability of whole grain products to date, especially in children. It enables food companies to develop natural products with broad appeal to the general consumer but maybe most importantly it provides a vehicle to get important whole grain nutrients to the overall population. Additionally, it allows the creation of more nutrient dense foods for individuals that have low energy intakes such as the elderly. The current data also points to the fact that apart from fiber the bioactive components associated with the fiber are also of significant value for the observed effects of cereal consumption over that of refined foods.

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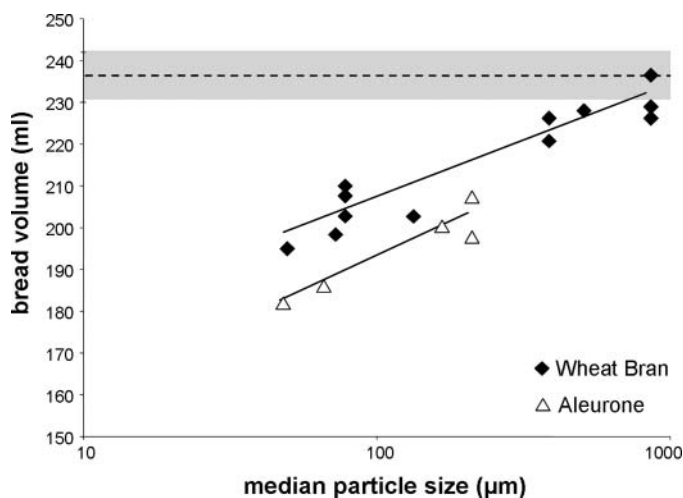


Figure 7 Effect of the particle size of wheat bran and aleurone fractions on bread volume. The average bread volume of reference bread (white bread) is indicated with the dotted line and the grey box indicates its standard deviation. Adapted from Noort et al. (2010).

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