Flavor and Texture in Processing of New Oat Foods

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Northern countries like Finland, Canada, and Scotland have a long tradition of using oats in a variety of foods. Even in these countries, however, the consumption of oats is low in comparison with that of other cereals. Processing of oats is required to provide edible products that are stable in storage and have good sensory properties. "Grandmother's" cookbooks contain a variety of oat recipes that form the traditional foods that are the basis of current food uses, namely, porridge, bread, fermented oat custard, and flour made of boiled, lightly smoked oats. Traditionally, oats are used as whole grains. The development of new ingredients, such as various milling fractions (i.e., bran, flour, and hulls) and enriched fractions (i.e., starch, protein, and β-glucan), started in the 1980s in response to accumulating evidence of the health benefits of oat dietary fiber. New functional oat foods conferring specific health benefits are needed to make the most of these nutritionally based assets of oats.

Oats' distinguishing features, in comparison with other cereal grains, are their high lipid and β-glucan concentrations and lower starch concentration. These features give rise to special challenges: lipid oxidation during storage and processing can cause rancid flavors, and the high viscosity of water-solubilized β-glucan—i.e., mixed-linkage (1→3)(1→4)-β-D-glucan—impacts texture and sensory characteristics. Oat starch is special in comparison with other cereal starches. It contains more lipids and has a lower gelatinization temperature and slower rate of retrogradation than cereal starches in general. Oat grain also contains dietary fibers other than β-glucan, as well as vitamins, minerals, phenolic antioxidants, sterols, and proteins high in lysine (Lásztity 1998, South et al 1999). Special properties of oat lipids (Chapter 9), β-glucan (Chapter 11), and starch (Chapter 7) are reviewed in their own chapters.

Appearance, odor, texture, and flavor are key attributes in determining the overall sensory characteristics of a food. Since sensory quality is a crucial criterion in consumer food choice, control of sensory attributes is important to the attractiveness of new oat foods. Oats are considered by most people to make a tasty cereal, and they have a positive health image. However, a tendency to develop rancidity and bitter off-flavors may limit their use. Control of texture is a challenge in products with high levels of dietary fiber, especially soluble β-glucan; sliminess is an undesirable texture associated with oat-containing foods of high water content.

The flavor of native[1] oat grain is mild. The familiar oat flavor is, to a large extent, formed during traditional heat processing and arises from a combination of volatile and nonvolatile compounds, including or produced from phenolics, amino acids and peptides, sugars, and fatty acids. The flavor perceived depends upon the relative amounts of all of these components, some of which have greater influence than others. To some extent, flavor formation can be controlled by careful selection of raw material combinations and processing steps (Heiniö 2003). Knowledge of the chemistry and structure-function relationships of raw materials and products is needed to produce specific qualities that meet consumer expectations (Fig. 16.1).

The usage of oats in various food products (Ranhotra and Gelroth 1995, Welch 1995, Welch and McConnell 2001) as well as the flavor of oats (Heydanek and McGorrin 1986) have been reviewed in the past. Flavor, texture, and color are the salient sensory attributes of cereal foods, and each product has a characteristic sensory profile. For example, crispiness is a characteristic texture attribute of dry cereal products, and roasted flavor is an especially important attribute in thermally processed foods

[1] In this chapter, the term *native* is applied to oats that have been traditionally milled to provide a stabilized product for human consumption. The precursor is the groat, or dehulled "raw" oats.

such as bread and other bakery products. An understanding of the influence of different processing systems on oat components, of the role of these components in the flavor and texture of the products, and of consumer preferences and differences should allow sensory quality to be adjusted in the desired direction. There are, for example, large differences between individual perceptions of mouthfeel. Understanding the physiochemical factors involved in mouthfeel requires correlation of instrumental measurements with sensory testing data (Bourne 1994, Meullenet and Gross 1999, Lillford 2001, Autio et al 2003). This chapter reviews literature about recent developments in factors affecting the sensory quality of oat foods and discusses the challenges of combining high sensory quality with health benefits.

EFFECT OF PROCESSING ON OAT FLAVOR

Flavor of Native Oats

Flavor is composed of the simultaneous perception of taste, odor, and chemical feeling factors (i.e., astringency, spice heat, cooling, and bite) stimulating the nerve ends (Lawless and Haymann 1999). During eating, flavor perception is determined by the nature and amount of the flavor components, their availability to the senses as a function of time, and the mechanism of perception.

The flavor of oat products results from a mixture of many chemical compounds, some volatile and in the airspace of the product (such as aldehydes, ketones, and alcohols) and some nonvolatile (such as phenolic compounds, sugars, amino acids and small peptides, free fatty acids, and lipids). The second group may also indirectly influence the flavor of the product by acting as flavor precursors in reactions that form various new flavor compounds during processing. The same compounds can give very different flavors as their amounts and relative proportions vary depending on the process parameters.

Similar volatile compounds are found in different types of processed oats; the extent of processing affects mainly their amounts and relative proportions. Some volatile compounds (i.e., aldehydes, ketones, and alcohols) are dominant in both raw and processed oats, but heat treatment produces numerous pyrazine and pyridine derivatives. In general, untreated grain or flour contains small amounts of just a few flavor-active compounds (Hansen 1995). These include aliphatic aldehydes, such as pentanal and hexanal, formed as oxidation products from fatty acids, and the corresponding alcohols pentanol and hexanol. Some of the carbonyl compounds possess a "green" odor note with a pungent flavor.

Nonvolatile phenolic compounds, such as phenolic acids, lignans, and avenanthramides, often contribute considerably to the flavor of oat products (Dimberg et al 1996, Weidner et al 1999, Peterson 2001, Heiniö et al 2008). (See also Chapter 10.) The most abundant phenolic acid in cereals is ferulic acid, but others, such as sinapic, *p*-coumaric, syringic, and caffeic acids, also contribute to the flavor (Welch 1995, Weidner et al 1999). Although phenolic acids are mostly present in bound form, free phenolic acids may influence the flavor in very small (10–90 mg/kg) amounts (Dimberg et al 1996). Some phenolic compounds (*p*-coumaric acid, vanillin, *p*-hydroxybenzaldehyde, and coniferyl alcohol) may also contribute to the rancid, bitter, intense flavor of oats (Molteberg et al 1996b).

Proteases produce amino acids or peptides in the product. Free amino acids and, especially, small peptides may themselves influence flavor or may act as flavor precursors. At high temperatures, amino acids form flavor-active volatile compounds as a result of the Maillard reaction. This reaction is one of the major reactions influencing the flavor and color of processed foods (Fayle and Gerrard 2002). It consists of several complex reactions, not all of them yet known in detail. High temperatures and dry atmosphere accelerate the reaction, in which free amino acids or small peptides together with free sugars form volatile flavoring compounds, such as heterocyclic pyrazines, pyrroles, furans, and sulfur-containing compounds.

The flavor of untreated oat grain is mild and bland. There is little literature available since untreated oats are not generally marketed or consumed because off-flavor develops too rapidly. The flavor of processed products is better documented (Heiniö 2003). Some examples of the sensory attributes used to describe processed oat grains and oat products are collected in Table 16.1. The flavor of native oat groats was described as *raw oats*, *weedy-hay*, and *grassy resembling*, whereas the flavor of oatmeal was described as being *mild oats*, *hay-weedy*, and *browned* (Heydanek and McGorrin 1986). Nonatrienal has been identified as the key odorant giving oat flakes the characteristic cereal-like aroma (Schuh and Schieberle 2005). The desired oatlike flavor results from heat treatment, which simultaneously inactivates the lipolytic enzymes (Molteberg et al 1996b). However, the thermal treatment of hulled oats resulted in rancid and bitter flavor notes, whereas dehulled oats were perceived as being fresh and oatlike in flavor (Molteberg et al 1996b).

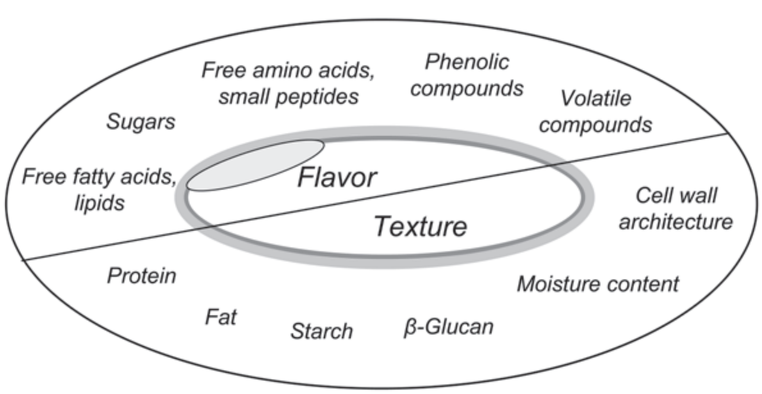

Fig. 16.1. Components of oat grain influencing perceived texture and flavor.

Effect of Toasting on Flavor

OATMEAL

Hrdlicka and Janicek (1964a,b) studied the nutlike flavor of toasted oat flakes and identified typical carbonyls and unusual amines. The authors stated that these compounds cannot be regarded as the sole source of toasted flavor. Heydanek and McGorrin (1981) reported systematic studies on various aspects of oat flavor chemistry, which form the basis of the extensive review of oat flavor chemistry by Heydanek and McGorrin (1986). In the review, they show oat flavor to be a complex, precursor-dependent, heat-induced collection of volatile flavor components. In addition to processing, variety and growing site are also important factors in determining the flavor of oatmeal (Zhou et al 2000). The sensory quality of 12 cooked-oatmeal samples was related to both variety and growing conditions, with variety being the major controlling factor. The results of volatile profile analysis indicated that most of the volatiles in oatmeals were induced during heat processing; relatively few volatiles were detected in groats, while more than 50 peaks were detected in cooked oat porridge (Zhou et al 2000).

Oat groats, the precursors of commercial oat food products, are devoid of inherent flavor contributors and have a mild flavor, defined as *raw oats*, *weedy-hay*, and *grassy*. Heydanek and McGorrin (1986) identified 111 volatile compounds from oat groats. The principal components responsible for the weak hay, grassy odor were identified as monoterpenes and hexanal. In the concentrations observed, they would be expected to make little contribution to oat flavor in cooked, hydrated, or processed systems (Heydanek and McGorrin 1986). The major components composing the green cereal-type odor and flavor were identified as 3-methyl-1-butanol, 1-pentanol, 1-hexanol, hexanal, 1-octen-3-ol, (*E,E*)- and (*Z,E*)-3,5-octadien-2-one, and nonanal. In addition, Heydanek and McGorrin (1986) found many components associated with enzymatic activity, such as alcohols and aldehydes; those most notable from a flavor standpoint included 3-methylbutanal, 2,4-decadienal, and benzaldehyde.

The well-known flavor of oatmeal and toasted oat flakes has been shown to be composed of both neutral and basic flavor compounds. Nitrogen heterocycles, formed by Maillard reactions, and lipid oxidation products are the key compositional types of flavor volatiles. Heat-induced reactions of precursors native to the oat groat are primarily responsible for the development of oat flavor during its normal processing into commercial food products. The flavor of vacuum-steam-distilled oat flavor volatiles was evaluated by a laboratory panel (Heydanek and McGorrin 1986). The sensory properties of the oat systems show progressive flavor development as additional heat treatments are applied during oatmeal manufacture and consumption (Table 16.2). When groats are rolled and flaked to make oatmeal, the steaming step, which also completes enzyme inactivation, provides the first development of true oat flavor. The 5-min cooking step required to prepare oatmeal completes the development of its flavor character.

Most of the nutty, browned flavor character was found in the basic flavor fraction of heat-processed oatmeal. The acid/neutral flavor fraction contained green-grain-type flavor notes. The two major flavor characteristics of oats were further studied in separate fractions. The basic flavor fraction exhibited an increase in oaty-nutty flavor, the result of an increase in the complexity and concentration of nitrogen heterocycles (Table 16.3). The more highly substituted pyrazine and thiazole compounds 2-ethyl-3,5-dimethylpyrazine, 2-methyl-4-ethylthiazole, and 2,4-dimethyl-5-ethylthiazole were the most abundant. As these compounds have the lowest flavor thresholds (Maga 1974), they are expected to be important to the nutty flavor developed in

TABLE 16.1
Examples of Sensory Attributes Used to Describe Processed Oats and Oat Foods

Cereal Product	Sensory Attributes	Reference
Heat-treated oat grains	Odor: oat odor, intensity, rancidity, freshness Flavor: intensity, freshness, oat flavor, sweetness, bitterness, aftertaste Texture: hardness, crispiness, greasiness, stickiness	Molteberg et al (1996b)
Germinated, dried oat	Odor: cereal, roasted, moist, musty, earthy, intense Flavor: cereal, roasted, nutty, sweet, bitter, germ-like, musty, rancid, intense, aftertaste Texture: hard, tough, moist, crisp, brittle	Heiniö et al (2001, 2002)
Muesli oat flakes	Odor: roasted Flavor: sweet, cardboard-like, overall intensity Oral texture: fragility, adhesiveness, mushiness, mastication needed	Kälviäinen et al (2002)
Cooked oatmeal	Odor: overall intensity, toasted Manual texture: thickness, adherence to spoon Flavor: overall intensity, toasted Oral texture: average size of swollen flake particles, uniformity of mass, slipperiness, coarseness Appearance: darkness of color	Lapveteläinen and Rannikko (2000), Lapveteläinen et al (2001)
Yogurt-type fermented oat-based product	Visual: appearance Texture: consistency Flavor: sweetness, acidity, oat flavor Texture: mouthfeel	Mårtensson et al (2001)
Yogurt-type fermented oat bran product (Yosa), orange-flavored	Odor: overall intensity Manual texture: thickness, adherence to spoon Flavor: overall intensity, sweetness, orange flavor intensity Texture: “shortness” and firmness	Kälviäinen et al (2003)
Oat bread	Visual texture: volume, pore size, uniformity of pore size Mouthfeel of crumb: moistness, softness, density, crumbliness, springiness	Salmenkallio-Marttila et al (2004c)

TABLE 16.2
Sensory Assessments of Oat Flavor Isolates[a]

			Separated Vacuum-Steam Isolate	
Source	**Initial Flavor**	**Vacuum-Steam Distillate Flavor**	**Acid/Neutral Fraction**	**Basic Fraction**
Groats	Raw oat	Raw grain	Green-weedy	Weak/none
	Weedy-hay	Hay-feedy	Mashy grain	
	Grassy	Grassy		
Oatmeal	Mild oat	Mild oat	Green-weedy	Brown-nutty
	Hay-weedy	Raw-green	Mashy grain	Pleasant
	Browned	Brown-nutty		
Cooked oatmeal	Oat-nutty	Oaty, slightly burnt	Mashy grain	Nutty-pecan
	Browned-burned	Nutty-browned	Malty	Raw potato
	Weak weedy	Weedy-grain	Caramelized slightly oat	Harsh-chalky

[a] Source: Heydanek and McGorrin (1986); used by permission.

Table 16.3
Composition of the Basic Fraction of Oatmeal Flavor as a Function of Process Conditions[a]

Compound	**Groat**	**Uncooked Oatmeal**	**Cooked Oatmeal**
Sensory assessment of the flavor isolates	Weak/none	Brown-nutty, pleasant	Nutty-pecan, raw potato, harsh-chalky
Pyridines			
H-	+	+	+
2-Methyl			+
3- or 4-Methyl			+
2,6-Dimethyl		+	+
2-Ethyl		+	+
3-Ethyl		+	+
2-Propyl			+
Pyrazines			
2-Methyl	+	+	+
2,5-Dimethyl	+	+	+
2,6-Dimethyl		+	+
2,3-Dimethyl		+	+
Trimethyl		+	+
2-Ethyl, 5- or 6-methyl		+	+
2-Ethyl, 3,5-dimethyl		+	+
Tetramethyl		+	+
Thiazoles			
H-			+
2-Methyl, 4-ethyl			+
2,4-Dimethyl, 5-ethyl			+

[a] Source: Heydanek and McGorrin (1986); used by permission.

cooked oatmeal (Heydanek and McGorrin 1986). Dramatic changes were reported to occur in the neutral flavor fraction during oatmeal preparation. Several oxygenated volatiles appear in oatmeal after the rolling and flaking operation with its associated heating steps, only one of which, hexanal, was detected in dry oat groats (Table 16.4).

TOASTED OATS

For another end use, another typical flavor characteristic of oats is developed by toasting them to a nutty, browned flavor either in the flaked or groat form (Heydanek and McGorrin 1986). Toasted oat flakes and groats are commonly used in granola-type products and specialty breads. In oats, the browning reactions that form toasted, nutty flavor are not developed exclusively from a classic Maillard system utilizing amino acids and reducing sugars. The reaction of Maillard intermediates with lipid oxidation products also potentially plays a role in the formation of flavor compounds in oats under toasting conditions (Heydanek and McGorrin 1986).

Analysis of the flavor volatile components developed during toasting of oat groats revealed that a uniquely different flavor developed in the process (Heydanek and McGorrin 1986). The basic flavor fraction of the toasted groats had strong nutty, earthy, toasted, slightly harsh, and burnt notes, whereas the neutral fraction was described as *burnt grain*, *browned*, *heavy*, and *not oaty*. The basic flavor fraction of toasted groats contained relatively larger amounts and more varied types of components than the similar fraction of oatmeal. Roughly 70 compounds were identified in the fraction, the major ones being alkyl-substituted pyrazines, alkyl thiazoles, pyridines, and oxazoles (Heydanek and McGorrin 1986). More than 150 components were noted in the neutral flavor fraction of toasted oat groats. An increase in reducing sugar degradation products (i.e., furans) and 2,4-decadienals was noted in oat groats after toasting. Toasting is a severe heat treatment. During this process, the Maillard browning reaction, Amadori rearrangements, and extensive lipid oxidation take place to provide many of the volatiles of the neutral flavor fraction (Heydanek and McGorrin 1986).

Effect of Malting on Flavor

Germination and subsequent heat treatment can be used to form new flavor compounds and to improve and enhance the pleasant nutty and grainy aroma associated with oats (Heydanek and McGorrin 1986). Moisture, temperature, and time are the usual major variables. The heating and drying that complete the process of malt formation are particularly important for flavor formation. The alkaline pH of the germination medium promotes the formation of compounds yielding a caramel-like odor (Przybylski and Kaminski 1983). During germination, the hydrolysis of β-glucan and starch and the increase in the amount of reducing sugars result in increased sweetness. The amount of free fatty acids also rises, increasing the risk of rancidity (Peterson 1998, 1999). Oil, reducing sugars, and free fatty acids are important precursors of the flavor compounds.

Germinated grains are a good source of free amino acids and sugars, which act as flavor precursors (Przybylski and Kaminski 1983). Germination of oats leads to an increase in free lysine and tryptophan and a slight decrease in prolamin (Dalby and Tsai 1976). A large array of Maillard reactive compounds is formed in germinated oats. During germination, different types of volatile compounds are formed at low processing temperatures and high moisture levels than are formed at higher temperatures and lower moisture levels. After kiln drying, oat flavor components (such as terpenes, alkylbenzenes, aldehydes, alcohols, and heterocyclic compounds) develop (Dimberg et al 1996). English-style ales brewed using malted oats had a pronounced toasted, biscuity aroma and palate, combined with a creamy and relatively intense mouthfeel (Taylor et al 1998).

TABLE 16.4
Oxygenated Neutrals of Oatmeal as a Function of Process Conditions[a]

Compound	Groat	Uncooked Oatmeal	Cooked Oatmeal
Sensory assessment of the flavor isolates	Green-weedy, mashy grain	Green-weedy, mashy grain	Mashy grain, malty, caramelized slightly oat
Pentanal		+	+
Hexanal	+	+	+
Furfural		+	+
Heptanal		+	+
Benzaldehyde		+	+
1-Octen-3-ol		+	+
2,4-Heptadien-1-al		+	+
Phenylacetaldehyde		+	+
3,5-Octadien-2-one (two isomers)		+	+
2,4-Nonadien-1-al (two isomers)		+	+
γ-Octalactone		+	+
2,4-Decadien-1-al (two isomers)		+	+
γ-Nonalactone		+	+

[a] Source: Heydanek and McGorrin (1986); used by permission.

Effect of Additional Heat Processing on Milled Oat Flavor

Flavor may be considerably modified by thermal processes, such as drying, extrusion cooking, autoclaving, puffing and roasting, or microwave heating. These methods all use high temperature. Pretreatments before the heating step may also greatly influence the flavor. Both temperature and moisture are important factors in flavor formation of extruded products (Bredie et al 1998). Two groups of flavor compounds are detected in extruded oats: compounds from the Maillard reaction, such as pyrazines, pyrroles, furans, and sulfur-containing compounds with toasted sensory descriptions, and compounds originating from lipid oxidation, such as hexanal and hexanol (Pfannhauser 1993, Sjövall et al 1997, Parker et al 2000). Maillard reaction products are especially abundant in extruded oats processed at high temperature and low moisture. These products are described as *roasted* or *toasted*, *caramelized*, and *somewhat sweet or nutty* in flavor (Heydanek and McGorrin 1986, Parker et al 2000). Extruded oat products are extremely susceptible to oxidation due to the increased surface area and high fat content.

In baking, the flavor compounds formed in the crust are mainly compounds related to the Maillard reaction, which give the crust a toasted, nutty flavor. A toasted and cereal-like flavor has also been reported in heat-treated oat flakes (Sides et al 2001). Cooked oatmeal was described with the flavor attributes *toasted*, *sweet*, *cereal*, and *chemical* (Lapveteläinen and Rannikko 2000). The roasted, sweet, and nutty characteristics can clearly be related to such volatile compounds as dimethyl sulfides and isobutanol (Heiniö et al 2001).

INFLUENCE OF STORAGE ON PRODUCT QUALITY

Changes in Flavor of Oat Products During Storage

Flavor deterioration of cereals during storage occurs through losses of desired flavor compounds by volatilization, as well as development of undesired off-flavors (Zhou et al 1999). In oat milling, heat treatment is a crucial step to prevent the development of bitter off-flavors and rancidity during storage, primarily through oxidative or hydrolytic degradation of lipids. A high fat content (4–8%) makes oats particularly susceptible to this process, although reactions of proteins and phenolic acids should not be excluded as sources of off-flavor.

During processing as well as storage, two distinct reactions may detrimentally modify oat lipids; they are hydrolysis, in which triacylglycerols or phospholipids are converted to free fatty acids, and oxidation, in which polyunsaturated fatty acids are converted to hydroperoxides and further to secondary oxidation products. Oxidative rancidity develops from both enzymatic and nonenzymatic processes. The resultant long-chain hydroxy fatty acids cause a bitter taste, whereas rancid flavor is associated with volatile aldehydes, ketones, and alcohols, hexanal being the most dominant. Note, however, that hexanal is present at low levels in samples with acceptable flavor, and so rancidity occurs when hexanal and its associated components increase dramatically above normal levels (Sides et al 2001).

Raw, unstabilized oats contain high activity of lipase (a hydrolytic catalyst), whereas the activity of lipoxygenase (an oxidative catalyst) is low (Ceumern and Hartfield 1984). Lipase, lipoxygenase, and peroxidase are activated by the physical disruption of the grain. They can be inactivated by heat treatment, although, if the grains are inappropriately stored or treated (for example, in high moisture), the level of free fatty acids may still rise (Ekstrand et al 1993, Molteberg et al 1996a, Heiniö et al 2002). In addition to high moisture content, elevated temperature (38°C) and high oxygen concentration have been shown to increase the development of rancidity in oats during storage (Molteberg et al 1996b, Larsen 2002). Thus, appropriate storage conditions of low moisture and temperature are required to prevent or minimize the development of rancidity. Stability of flavor depends both on the amount of free fatty acids and on resistance to oxidation; so phenolic compounds, such as avenanthramides and caffeic acid, by acting as antioxidants and delaying lipid oxidation, may prevent the development of rancidity (Molteberg et al 1996b).

Microbiological Quality

As with all foods, microbiological safety is important for sanitation. Additionally, the microbial flora of native and germinated oats may have an impact on the technology, nutritive value, and sensory properties of mainstream commercial oats and malted oats. The flora characteristic of oats and final oat products develop pre- and postharvest and during milling and subsequent storage and processing. Several studies have been conducted to examine the fungal flora on dried oat products such as flakes and muesli components (Weidenbörner and Kunz 1994, 1995; Nogueira and Cavalcanti 1996; Nogueira et al 1996). Various fungal genera, especially species belonging to *Aspergillus* and *Penicillium*, often cause deterioration of dry processed oat products (Weidenbörner and Kunz 1994, 1995; Nogueira and Cavalcanti 1996; Nogueira et al 1996). However, microbial or fungal deterioration normally occurs only when products are stored at high water activities.

In hydrothermal processing, spore-forming bacteria were found to be the main microbiological risk (Storgårds et al 1997). The conditions of germination required for making malted oats may promote microbiological growth. Elevated germination temperatures led to an increase in *Fusarium*, aerobic heterotrophic bacteria, *Pseudomonas* spp., lactic acid bacteria, enterobacteria, and aerobic spore-forming bacteria (Storgårds et al 1997). Therefore, the germination temperature should be kept low to avoid excessive growth of microbes. The use of lactic acid bacteria as protective cultures in malting has been shown to improve the quality of barley malt, and the application of this process to improve the microbial quality of germinated oats looks promising (Haikara and Laitila 2001).

EFFECT OF PROCESSING ON OAT TEXTURE

General Factors Affecting Texture

Processing (including milling, malting, extrusion cooking, and baking) produces changes in microstructure and in the physicochemical properties of components (i.e., starch, cell wall components, proteins, and lipids). These changes have a large effect on the texture of oat foods. The grain consists of discrete tissues (the embryo, starchy endosperm, aleurone layer, seed and fruit coats, and husks) with special structural and chemical features. Although the various cereal grains share many similar morphological features, differences exist, especially in the chemical composition and distribution of components. In oats, both the aleurone layer and the germ are rich in lipids, and, in contrast to other cereals, the starchy endosperm also contains significant amounts of lipids.

The starch granules of oats are smaller than those of wheat, barley, or rye. Oat starch occurs as an aggregate composed of several individual starch granules, similar to rice starch. Both cultivar and growth conditions affect the amount and quality of starch and accordingly also the end-product quality (Lapveteläinen et al 2001, Hoover et al 2003, Rhymer et al 2005). (See also Chapter 7.) Oat starch granules are rather fragile when swollen and gelatinized, and amylose and amylopectin leach from the granules during pasting (Doublier et al 1987; Autio 1990; Virtanen et al 1993; Shamekh et al 1994, 1999). The digestibility of starches in cereal products is very dependent on the integrity of tissue structures, degree of swelling of starch granules, and amount of retrograded amylose outside the starch granules (Juntunen et al 2002). Modification of these structural features using processing options can be used to tailor products and produce desired properties (Autio et al 2004, Katina et al 2005).

β-Glucan is a linear, high molecular weight polysaccharide (Autio et al 1987, 1992; Doublier and Wood 1995). The amount and distribution of β-glucan differ in different oat varieties. In some varieties, β-glucan content is highest in the subaleurone cell walls, which can be very thick, and lowest in the inner endosperm. In high-β-glucan varieties, the β-glucan is more evenly distributed throughout the starchy endosperm. The concentration of β-glucan in cell walls allows the separation of β-glucan-rich oat bran. The content of β-glucan is not high, with ranges of 3.0–6.8% in groats of *Avena sativa* (Peterson 1991, Wood et al 1991, Autio et al 1992, Lim et al 1992, Cho and White 1993, Saastamoinen et al 2004) and 1.8–11.3% in groats of wild *Avena* species (Miller et al 1993, Welch et al 2000), but β-glucan has a significant impact upon the water-binding properties of oat bran, in which β-glucan content ranges from a minimum of 5.5 to 20% or more. Oat bran has much higher water hydration capacity than barley or wheat bran. β-Glucan is water soluble and gives highly viscous, shear-thinning solutions at low concentrations. The viscosity is strongly dependent on both molecular weight and concentration (Autio 1995, Wood et al 2000), and a doubling in concentration could lead to a 15-fold increase in viscosity (Doublier and Wood 1995). As extracted, native β-glucan in the oat grain appears to have a molecular weight of 1.5–3 million, but the molecular weight is sensitive to processing and extraction methods (Beer et al 1996, 1997a,b; Suortti et al 2000; Ajithkumar et al 2005).

Process conditions, which include temperature, moisture content, amount of mechanical energy, and levels of endogenous enzymes, have a significant impact upon the sensory attributes of the final product. Heat and water used in cooking, autoclaving, and extrusion cooking cause starch gelatinization and changes in the structure, strength, and solubility of the cell walls (Yiu et al 1987, 1991; Salmenkallio-Marttila et al 2004a). Secondary cell walls rich in cellulose (abundant in the bran part of the grain) have a stronger structure than the primary cell walls in the starchy endosperm that consist mainly of β-glucan and pentosan. Germination (a step in processing to malt) causes cell wall degradation (Salmenkallio-Marttila et al 2004a). The physical structure and chemical composition of the cell walls also influence the mobility of water and its absorption into the grain.

When the microstructure and the instrumentally measured structure of processed oats are compared, gelatinization of starch appears to contribute more to the hardness of the groats than the cell wall structure does. Hardness of processed oats perceived with the senses correlated with hardness measured as milling energy. Sensory hardness also correlated positively with sensory moistness and negatively with sensory crispness and brittleness. Autoclaving created a crisper, harder grain texture, whereas germinated samples were described as having moist sensory texture; native grains were depicted as tough (Salmenkallio-Marttila et al 2004a).

Texture of Processed Oats

OATMEAL

For human consumption, oats are traditionally flaked by flattening either groats or cut groats between rolls under heavy pressure. Flaking produces the desired change in texture for easier domestic cooking and better digestibility. Both the environment and the genotype affect the structure and chemical composition of the grains and consequently also cause differences in the quality of flakes produced (Molteberg et al 1996b, Doehlert and McMullen 2000, Lapveteläinen et al 2001, Rhymer et al 2005). Flake breakage and texture are important quality criteria for oat flakes and are influenced by process variables such as kilning and flake thickness (Ganssmann and Vorwerck 1995, Gates and Dobraszczyk 2004, Gates et al 2004, Gates 2007). The processing quality of oat groats is possibly already modified at grain drying, as changes in the mechanical properties of groats may occur even at grain drying temperatures (Gates and Talja 2004). The groats are steamed before flaking to increase their strength so that they can be easily rolled without breakage, which produces a high proportion of flour or fines (Ganssmann and Vorwerck 1995). Although it is possible to have only one steaming operation, it is more common to have two separate heat treatments: kiln drying and tempering (Ganssmann and Vorwerck 1995), the first to stabilize the oats and the second to soften them. Kiln drying had no significant effect on the mechanical properties of oat flakes, whereas tempering has been shown to decrease the amount of fine, abraded material in oat flakes (Ganssmann and Vorwerck 1995). Only minor changes in the starch are induced by kiln drying and steaming oats; i.e., a slight degree of gelatinization limited to the outer layer of the kernel has been observed (Mahnke-Plesker et al 1993).

In addition to processing, the properties of oat starch affect end-product quality (Lapveteläinen et al 2001, Rhymer et al 2005). Lapveteläinen et al (2001) studied the effects of growing year and genotype on a large number of characteristics of grain, rolled oats, and cooked oatmeal. Both cultivar and crop year significantly influenced the pasting properties of starch, measured as falling number, which trained sensory panelists found to be inversely related to the coarseness and size of swollen particles perceived in the oatmeal. Starch content was associated with the slipperiness of the oatmeal and was inversely correlated with the oatmeal's uniformity and adherence to the spoon (Lapveteläinen et al 2001). The texture of the product varies also, depending on cooking conditions (Yiu et al 1987, 1991; Lapveteläinen and Rannikko 2000). Adding flakes to cold water and cooking slowly resulted in creamy and smooth oatmeal containing extensively gelatinized starch, whereas adding the flakes to boiling water resulted in oatmeal with a grainy texture and less extensive gelatinization of starch (Yiu et al 1987, Lapveteläinen and Rannikko 2000).

MALTING

Malting is a controlled germination and drying process that changes the microstructure of cell walls, proteins, and starch granules. The traditional process consists of steeping to increase the moisture content to a level required to initiate germination, germination to modify the kernel, and kilning to dry it. The germination/malting of oats has recently been reviewed with special emphasis on changes in grain characteristics (Kaukovirta-Norja et al 2004).

During germination, hydrolytic enzymes are involved in mobilization of reserves. Starch is hydrolyzed slowly during germination; germinated oats were shown to contain approximately the same, or only a slightly lower, starch content compared to native oat grain (Hughes et al 1997, Peterson 1998). In contrast, during germination, β-glucan is largely hydrolyzed by endogenous β-glucanases, and germinated oats contained only small amounts of residual β-glucan (Hughes et al 1997, Peterson 1998). If germination is used to produce novel food ingredients with functional properties, substantial hydrolysis of β-glucan may be undesirable. A short germination terminated by oven drying was developed to produce a germinated oat that retained β-glucan content and high molecular weight (M_w >1.5×10^6) (Wilhelmson et al 2001). In the new process, the content of β-glucan in the germinated grains was 55–60% of the content in native oats, which is quite high compared to the almost total degradation of β-glucan in the regular malting process (Peterson 1998). Germination led to some breakdown of β-glucan, but the decrease in the molecular weight of β-glucan was very slow. The major changes in β-glucan during this short malting were observed in the crushed cell layer beneath the scutellum (Salmenkallio-Marttila et al 2004a).

The tough texture of native grain can be modified into a crisp, brittle texture in a carefully designed malting process (Heiniö et al 2001, Wilhelmson et al 2001). The heating and drying involved in malting are crucial to the flavor and texture formed (Heiniö et al 2001); germination alone has no significant effect on the desired texture attributes of the oat-grain. Changes in texture correspond to changes in microstructure. The starchy endosperm of the malted grains appeared more fragile than that of the native grains and was partly crumbled (Salmenkallio-Marttila et al 2004a). No microstructural changes in starch were observed, but the structure of the protein network was dense and surrounded the starch granules more tightly than in the native grains.

EXTRUSION COOKING

Extrusion is a high-temperature, high-shear process that is widely used for the manufacture of cereal products, especially for the production of fiber-rich snacks and breakfast cereals (Vainionpää 1991, Singh and Smith 1997, Liu et al 2000, Dust et al 2004, Viscidi et al 2004). It is very effective in modifying sensory characteristics, resulting in a roasted flavor and crispy texture. Extrusion causes starch gelatinization and mechanical damage to the cell walls, so the solubility of the various fiber components can be modified in the process (Dust et al 2004, Salmenkallio-Marttila et al 2004a). It is difficult to make a puffed whole-grain oat cereal using the extrusion process because of the high concentration of both lipids and water-soluble β-glucan in the oat grain (Liu et al 2000). Oat flour can be blended with corn flour to produce an extruded ready-to-eat cereal product. The extrudate expansion ratio increased with increased corn flour addition, whereas increases in oat flour percentage resulted in an increase in extrudate bulk density and harder texture (Liu et al 2000).

BAKING

In a flour milled for making conventional bread, the well-organized microstructure of the grain is disrupted, and the resultant ground flour contains starch granules, small starchy endosperm particles, and larger particles consisting of the tough bran layers. In the baking process, water, enzymes, mechanical energy, gas production, and heat transform the material into bread, which is characterized by a spongy, porous structure. The textural properties of conventional wheat bread are dependent on the size and distribution of the pores and on the properties of the gelatinized starch and protein network forming the pore walls. Wheat gluten is essential for this process, and since oats do not contain gluten, oat flour alone does not make such bread.

Both the absence of gluten and the viscous properties of β-glucan constrain the substitution of oat flour for wheat in bread baking. Partial replacement of wheat flour with oat flour affects bread quality at as low as 10% substitution, causing decreased loaf volume. However, pretreatments (steaming, roasting) of the grain improved the baking quality of the oat flours (Zhang et al 1998). Since oat flour lacks gluten, doughs prepared with oat flour have poor gas-retention characteristics. Other flour components such as starch and nonstarch polysaccharides also affect dough properties and the formation of bread structure in oat baking. Because of its high water-binding capacity, β-glucan makes the dough sticky and affects starch gelatinization. The use of wholemeal oat flour in baking additionally complicates the picture, as bran particles mechanically hinder structure formation by gluten (Gan et al 1989, 1992). In all of these baking characteristics, oats resemble rye. Rye breads are significantly harder than wheat breads. The large number of bran particles and the low porosity contribute to the hardness of rye breads (Autio et al 1997), as is probably also the case with other whole-grain breads. The addition of gluten improves the texture of whole-grain oat bread, making the breads softer and less gummy (Salmenkallio-Marttila et al 2004b).

Whole-grain oats can be used to improve the taste of bread, as they impart a pleasant, nutty flavor to the product. Most commercial oat breads contain only a small amount of oats, 5–15%. In baking, oats are usually used as rolled oats, and only a few reports have been published on oat flour in bread baking (Zhang et al 1998, Flander et al 2002, Salmenkallio-Marttila et al 2004b). Oats, as well as other whole grains rich in fiber, generally have a detrimental effect on bread quality. Dilution of wheat gluten and the mechanical disruption of the gluten network by bran particles decrease loaf volume (Pomeranz et al 1977, Gan et al 1992). At least some of the negative effects of whole-grain flour on gluten development can be compensated for by the use of added gluten or baking enzymes. The addition of gluten has been shown to improve the structure of mixed oat bread (Flander et al 2002), and transglutaminase has been shown to strengthen the protein network in oat baking (Salmenkallio-Marttila et al 2004b). The flavor and stability of the texture may be improved by using sourdough containing yeast or lactic acids. Oats retard bread staling (Zhang et al 1998). This probably is due to the slower retrogradation of oat starch and higher water-binding capacity of oat flours in comparison to wheat flours. By optimizing the process and recipe,

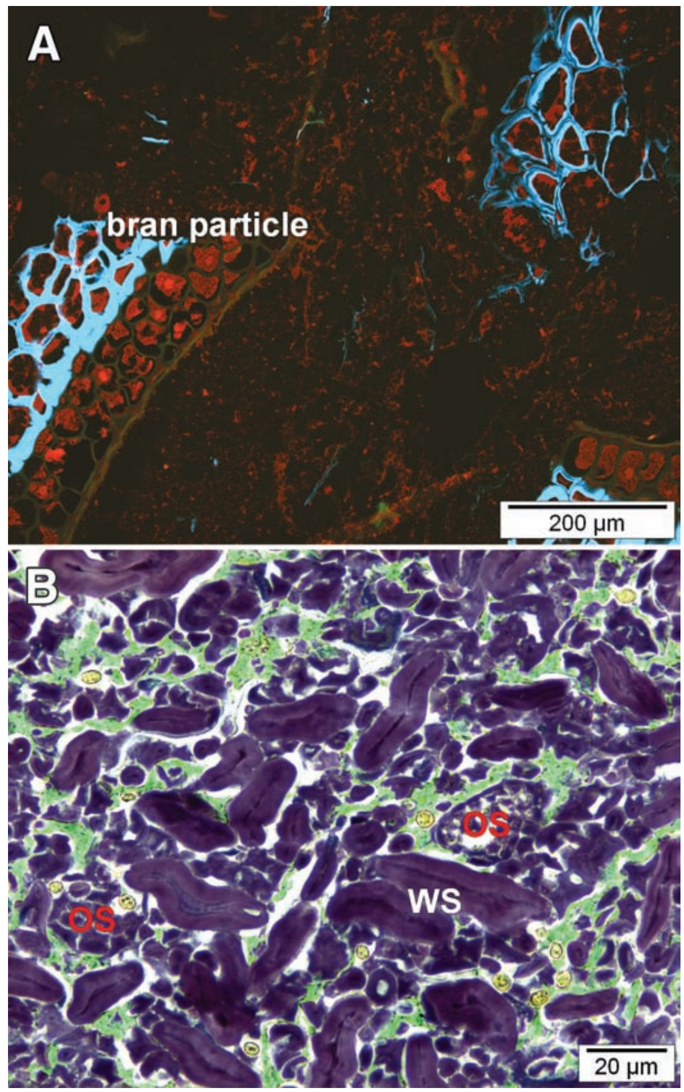

Fig. 16.2. Microstructure of oat bread baked with 51% whole-grain oat flour. **A,** β-glucan (blue) is mainly located in the bran particles; protein has been stained red; and starch granules appear black. **B,** in the section stained with iodine and light green, protein appears green, starch granules brown-violet, and yeast cells yellow; the compound oat starch granules (OS) can be distinguished from the large wheat starch granules (WS).

oat bread containing 51% whole-grain oats with good crumb and crust flavor and texture can be baked (Flander et al 2007).

The molecular weight of oat β-glucan decreases during oat bread baking (Flander et al 2002, Åman et al 2004). This has been attributed to the action of endogenous β-glucanases in wheat flour. Without counteracting increases in solubility, this would lead to lower viscosity. As high viscosity is considered a key factor in lowering blood cholesterol, optimization of the formula and baking process is needed for the preservation of the health benefits of oats in bread. *In vitro* methods to predict the potential gastric viscosity following consumption of oat foods have been developed (Anttila et al 2004). A bread enriched with oat bran has been launched in the Netherlands with the cholesterol-lowering claim.

The most visible microstructural change that occurs during baking is starch gelatinization, although the aggregate structure of oat starch sometimes remains visible in the bread, as shown in Figure 16.2 (Salmenkallio-Marttila et al 2004b). The extent of starch swelling (and leaching of amylose) depend greatly on the water content of the dough (Autio et al 1997, Autio and Salmenkallio-Marttila 2003). At higher water content, the starch granules are more swollen, and amylose leaches out. This has also been shown to be the case with whole-grain oat bread (Salmenkallio-Marttila et al 2004b).

Sensory characteristics of bread texture correlated with instrumentally measured texture and microstructure of oat bread (Salmenkallio-Marttila et al 2004c). Sensory softness decreased with increasing instrumentally measured hardness of bread. Samples with a large area of starch in the micrographs had low sensory softness, low specific loaf volume, and high instrumental chewiness. Large areas of protein in the micrographs corresponded to low sensory density and low sensory moistness values in the bread samples.

THE POTENTIAL AND THE CHALLENGES OF OATS IN FOODS

In Table 16.5, various oat products have been categorized to highlight the uses and constraints to use of oats in the food industry. Whole-grain oats in different forms are a quite different starting point for food formulations than are specific oat fractions. Similarly, the quality attributes expected of traditional oat foods differ from the quality requirements of new functional oat foods.

End Uses and Consumer Perception of Oats

Oats are mainly used as flakes (rolled oats) in traditional products like porridge, muesli, and cookies (biscuits). Additionally, several extruded oat breakfast cereals are on the market. Oats are also used as a (minor) ingredient in various forms (Table 16.5) in bread, pasta, biscuits, snack bars, and beverages. Snacks are an increasingly important sector in the food market. Convenience and health aspects favor the development of new snack foods based on whole-grain oats. Germination and processing technologies have been developed to produce new oat snacks (Heiniö et al 2001, 2002; Wilhelmson et al 2001). As for breakfast cereals, extrusion cooking is generally used for production of snacks (Onwulata et al 2000).

Several new products are reported to have promise but must still be fully developed if they are to achieve a significant market. Research has particularly focused on new liquid or high-moisture foods: oat milk (Lindahl et al 1997, Önning et al 1998, Chronakis et al 2004), oat ice cream, oat pancake mix, and meal-replacement drinks (Mikola 2004). An interesting variation of the traditional oat porridge is a yogurt-like oat bran porridge fermented with lactic acid bacteria (Salovaara and Kurka 1993, Salovaara 1997, Mårtensson et al 2001). Fermentation affects the flavor, texture, and health effects of the product, as some lactic acid bacteria produce β-glucanases while others produce exopolysaccharides that increase viscosity and ropiness (Mårtensson et al 2001, 2003, 2005).

Oats are perceived as a tasty cereal and traditionally carry a positive health image. More recently established health benefits may not, however, guarantee repeated consumer selection if the sensory quality is inadequate. Taste and texture, or overall sensory appeal, drive both the choice of new foods (Arvola et al 1999, Urala and Lähteenmäki 2003, Urala 2005) and overall food choices (Steptoe et al 1995, Martins and Pliner 1998). Functional products are first considered to be members of a specific product category and only subsequently thought of as functional food (Urala and Lähteenmäki 2003). Factors affecting the consumer's willingness to use beverages and ready-to-eat frozen soups containing oat β-glucan have been studied in Finland, France, and Sweden (Lyly et al 2007). The presence of a health claim (either cholesterol-lowering or reduced glycemic response) gave a significant but small added value to soups and beverages with β-glucan. When consumer expectations (before tasting) were

TABLE 16.5
Oat Ingredients and Food Products

Consumer Product Category	Ingredient Category	Ingredient Description
Whole grains		
Porridge, muesli, biscuits	Oat flakes	Flaked (kilned/steamed) oat grains
Bread, beer, breakfast cereals	Malted grains	Malted oats
Bread, breakfast cereals	Oat flour	Milled oat grains
Oat fractions		
Bread, breakfast cereals, fermented oat pudding	Oat bran	Outer layers of the kernel, including the aleurone layer
Bread, breakfast cereals	Endosperm flour	Ground starchy endosperm
Bread, breakfast cereals	Oat fibers	Enriched oat fiber, 10–20% β-glucan; Cellulose fiber from hulls
Oat milk	Soluble oat fibers	Hydrolyzed oat flour containing β-glucan and maltodextrin
Bread, breakfast cereals	Oat extracts	Oat malt extract, syrup or dried

surveyed, beverages with health claims were rated as having higher additional value than soups with health claims. This was explained by the fact that, as soups often are considered to be healthy, a health claim cannot easily make the product more attractive. The taste of the samples strongly affected the willingness of a consumer to use them. Also, earlier studies have demonstrated that consumers are not willing to compensate for bad taste with health effects (Tuorila and Cardello 2002).

Incorporation of Oat Fractions into Foods and Health Claims

Evidence about the health-protecting effects of whole-grain foods is accumulating and has led to a whole-grain health claim in the United States, United Kingdom, and Sweden (Marquardt et al 2004). In these countries, products containing more than 51% whole-grain oats can be marketed with a health claim. However, developing new products with high levels of whole-grain oats poses challenges with regard to controlling texture and flavor stability.

The specific oat health claim, based on soluble β-glucan fiber content (U.S. FDA 1996), has stimulated the food industry to manufacture oat-based ingredients containing higher levels of β-glucan than in the original groat. These ingredients make it possible to further expand the number of foods containing the levels of β-glucan required to meet the U.S. Food and Drug Administration's (FDA's) daily consumption guidelines (four portions with 0.75 g of β-glucan). Both oat bran fractions prepared by dry milling techniques and soluble oat β-glucan ingredients are available). The FDA's ruling refers to very specific mill fractions of oats, and soluble extracts generally do not meet the requirements. The reasoning, in part at least, is that they are likely to contain β-glucan with lower molecular weight than in the original groat. Assuming that the ingredients would meet the FDA's (or other jurisdiction's) requirements, Table 16.6 shows theoretical calculations of the amounts of the ingredient, at two different levels of β-glucan content, needed to deliver 0.75 g of β-glucan in a food portion. The substantial amount of groat components required to achieve the β-glucan levels poses challenges for processing to products that combine the expected health benefits with good sensory quality, especially acceptable texture.

High molecular weight oat β-glucan is suitable for a wide range of food applications as a hydrocolloid texture modifier and thickening agent (e.g., in ice creams, sauces, and salad dressings [Wood 1986]), and, because it is a neutral and nonionic polymer, its viscosity is not affected by pH (Dawkins and Nnanna 1995). Sodium chloride, at concentrations used in food (1–3%), decreased the viscosity of oat (Dawkins and Nnanna 1995) and barley β-glucan (Gómez et al 1997). Compared to other thickening agents, the oat gum prepared by Dawkins and Nnanna (1995) was less viscous than xanthan and guar gums at 0.5% but slightly more viscous than locust bean gum at the same concentration. The viscosity of a food modifies the taste (Paulus and Haas 1980, Godshall 1988), although the composition of the thickener has been suggested to have a greater effect on the perception of flavors than the viscosity (Pangborn et al 1973, Mälkki et al 1993). A negative correlation was found between the intensities of flavor attributes and the viscosity of oat β-glucan-enriched soups (Lyly et al 2004). Due to variable molecular weight, different β-glucan preparations showed different viscosity and sensory thickness in soups at the same concentration of β-glucan (Lyly et al 2003, 2004). The correlation between sensory thickness and molecular weight of β-glucan was strong and positive, as would be expected if the concentration remained the same. Good correlations were also obtained between sensory texture attributes and instrumentally measured viscosity of β-glucan-enriched soups. A high positive correlation between sensory oral viscosity and instrumental viscosity of β-glucan-enriched beverages has also been shown (Lyly et al 2003).

The consumption of frozen, ready-to-eat foods is growing in general (Dwyer 1999), and products such as soups, where β-glucan could be used as a thickening agent, are one possible new oat market (Lyly et al 2004). In some food products, freezing and frozen storage may reduce the solubility of β-glucan and thereby reduce its physiological effectiveness. Freezing did not reduce the molecular weight of isolated β-glucan (Suortti et al 2000) or β-glucan extracted from oat bran muffins (Beer et al 1997b), but solubility decreased by 50% (Beer et al 1997b). Heat treatment or baking may increase the solubility of β-glucan (Bhatty 1992; Jaskari et al 1995; Beer et al 1997a,b) and thus may increase its physiological effectiveness if it is not accompanied by a corresponding decrease in molecular weight. Viscosity increases with both molecular weight and concentration in solution, but it decreases reversibly with increase in temperature (Autio et al 1987, Dawkins and Nnanna 1995), so a greater enrichment with β-glucan is possible in warm foods because the decreased thickness would give greater sensory acceptability (Lyly et al 2004).

TABLE 16.6
Theoretical Calculations of Whole-Grain Oats or Oat Bran Preparation Needed in Foods (as-is basis) to Deliver 0.75 g of β-Glucan in a Portion

Food	For 0.75 g of β-Glucan: Portion Size (g)	For 0.75 g of β-Glucan: β-Glucan in Product (%)	Whole-Grain Oats (5% β-glucan) Needed (%)	Oat Bran Preparation (15% β-glucan) Needed (%)
Drink	250	0.3	6	2
Porridge	250	0.3	6	2
Soup	250	0.3	6	2
Yoghurt	200	0.375	7.5	2.5
Breakfast cereal	30	2.5	50	16.7
Bread	30	2.5	50	16.7
Bun	50	1.5	30	10
Muffin	50	1.5	30	10
Cookie	20	3.75	75	25

Future of Oat Products

The well-established nutritional and long-term health benefits of oat consumption cannot be realized unless the oats are processed to functional and palatable foods and ingredients acceptable to the consumer (Lyly 2006). Since the present level of consumption is small, it might be said that oats has hidden potential. Current end uses include porridge, bread, breakfast cereals, biscuits/cookies, snack bars, and some forms of pasta and beverages, but products that will lead to consistently increased consumption of oats are yet to be developed. Tailoring the taste and texture of novel products is a prerequisite for achieving the necessary consumer acceptance.

Despite the recognition of oats' value as a functional food, little attention has been paid to the formation of taste in oat baking or to development of baking technology to improve the baking quality of oats. If even a small portion of the efforts put toward understanding the baking quality and processability of wheat flour were devoted to oat baking, completely new types of oat bread, with specific health claims, could surely be manufactured. Another little-studied area is the structure engineering of thermally processed oat foods and beverage-type foods. Our understanding of the physical and chemical properties of the major and minor oat components remains incomplete. Specifications are needed to set criteria for the health benefits of oat foods. However, in addition to health benefits, the new oat foods must have acceptable mouthfeel, flavor, and stability. The "hidden" potential of oats is just waiting to be revealed to the consumer when convenience, good taste, and health attributes can be combined.

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