Fate of Starch in Food Processing: From Raw Materials to Final Food Products

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Abstract

Starch, an essential component of an equilibrated diet, is present in cereals such as common and durum wheat, maize, rice, and rye, in roots and tubers such as potato and cassava, and in legumes such as peas. During food processing, starch mainly undergoes nonchemical transformations. Here, we focus on the occurrence of starch in food raw materials, its composition and properties, and its transformations from raw material to final products. We therefore describe a number of predominant food processes and identify research needs. Nonchemical transformations that are dealt with include physical damage to starch, gelatinization, amylose-lipid complex formation, amylose crystallization, and amylopectin retrogradation. A main focus is on wheat-based processes. (Bio)chemical modifications of starch by amylolytic enzymes are dealt with only in the context of understanding the starch component in bread making.

STARCH

Starch: reserve polysaccharide in plants mainly consisting of two glucose polymers, i.e., amylose and amylopectin

Amylose (AM): essentially linear starch polymer consisting of predominantly α-(1,4)-linked D-glucopyranosyl units

Amylopectin (AP): highly branched starch polymer consisting of chains of α-(1,4)-linked D-glucopyranosyl units joined through α-(1,6) linkages

GT: gelatinization temperature

Starch gelatinization: process occurring during heating of a starch suspension above a characteristic temperature, consisting of swelling and irreversible changes in starch granules

In nature, starch occurs as granules. It consists mainly of two glucose polymers, amylose (AM) and amylopectin (AP). AM is essentially linear and is made up of mainly α-(1,4)-linked D-glucopyranosyl units having a low degree of branching with less than 1% linkages (**Figure 1**). It has a molecular weight (MW) in the range of 10^5 to 10^6 (Lineback & Rasper 1988). To understand the properties of AM in food processing, both lipid-complexed and free amylose must be taken into account because they contribute differently to starch functionality (Vandeputte et al. 2003a, Vandeputte et al. 2003b, Vandeputte et al. 2003c).

AP is highly branched and consists of chains of α-(1,4)-linked D-glucopyranosyl units joined through α-(1,6) linkages. Its MW of 10^7 to 10^8 is one of the highest known among naturally occurring polymers (Lineback & Rasper 1988). AP chains are subdivided in A-, B-, and C-type chains (Peat et al. 1952, French 1984, Hizukuri 1986). The A chains are outer chains and do not carry other chains. They are linked with the inner B chains, which can be subdivided into B_1, B_2, B_3, and B_4 chains. AP contains a single C chain that carries the only reducing end (**Figure 1**). The cluster model for AP (Robin et al. 1974) is now widely accepted. In this model, the A and B_1 chains form double helices organized in discrete clusters, whereas the B_2, B_3, and B_4 chains traverse 2, 3, or 4 clusters, respectively (Tester et al. 2004).

Starch granule dimensions and morphologies depend on the botanical origin (Delcour & Hoseney 2010). The granules consist of alternating concentric amorphous and semicrystalline growth rings (120 nm to 400 nm). When viewed under polarized light, they are birefringent and show the typical Maltese cross. This indicates a degree of molecular order in the granule and an orientation of the macromolecules perpendicular to its surface (French 1984). The less dense amorphous shells contain AM and less-ordered AP, whereas the semicrystalline material consists of a regular repeat of alternating amorphous and crystalline lamellae of approximately 9 nm to 10 nm. The latter consist of ordered AP double helices. The former contains AP branching points and possibly some amorphous AM (Oostergetel & Vanbruggen 1989, Jenkins et al. 1993). The lamellae are part of larger, more or less spherical structures named blocklets, which range in diameter from 20 nm to 500 nm (Gallant et al. 1997).

Based on differences in packing of the AP double helices, several crystal types are distinguished (Hizukuri 1996, Buléon et al. 1998). A-type starches are found in most cereal starches, whereas the B-type occurs in some tuber and root starches, high AM cereal starches, and retrograded starch. A-type crystals are compact and less hydrated than those of the B-type. The C-type, an intermediate form between the A- and B-types, occurs in certain root, legume, and seed starches.

Starch is the main structure- and texture-determining component in many cereal-based food products. Heating starch in sufficient water results in water absorption and swelling of the starch granules. Below a characteristic temperature, i.e., the gelatinization temperature (GT), this process is reversible. At or above GT, irreversible changes lead to loss of crystallinity and disruption of the starch granule. This process is known as gelatinization (Atwell et al. 1988). The term pasting generally covers the changes after starch gelatinization. During cooling of the amorphous paste, starch polysaccharides reassociate to a more ordered, crystalline state. After several hours, very stable AM crystallites are formed. Recrystallization of AP side chains, also referred to as retrogradation, is much slower. In the absence of emulsifiers (see below), AM might also cocrystallize with AP, hence contributing to starch retrogradation (Gudmundsson & Eliasson 1990). A more detailed description of the transformations during heating and cooling of starch suspensions is given by Goesaert et al. (2005).

Table 1 Starch properties [granule size, average degree of polymerzation (DP$_n$) of amylopectin (AP) and amylose (AM), AM content, protein content, lipid content and peak gelatinization temperature (GT) determined by differential scanning calorimetry] of common and durum wheat, maize, rice, rye, and potato starches

	Granule size (μm)	DP$_n$ AP	DP$_n$ AM	AM content* (%)	Protein content (%)	Lipid content (%)	Peak GT (°C)
Common wheat starch	1–10 15–40[1]	13000–18000[2]	830–1570[3]	17–29[1,4]	0.44–0.63[4,5]	0.33–0.8[4,5]	58–62[4,6,7]
Durum wheat starch	NR	NR	NR	26–28[4]	0.44–0.57[4]	0.5[4]	55[4]
Maize starch	5–30[8]	9600–15900[9]	320–1015[10]	25–28[11]	0.04–0.45[12]	0.01–1.1[11]	62–87[13,14]
Rice starch	3–10[15]	2700–12900[9]	920–1110[16]	0–33[17]	0.25[18]	0.1–1.3[19]	62–79[20,21]
Rye starch	1–10 10–50[22]	NR	NR	22–26[23]	0.01–0.04[23]	0.3–0.4[23]	52–54[23]
Potato starch	10–100[22]	11200[9]	4920[24]	18–21[5]	NR	NR	62–66[22]

NR = Not reported.

*AM contents of normal starches.

[1]Lineback & Rasper 1988; [2]Shibanuma et al. 1996; [3]Takeda et al. 1987; [4]Vansteelandt & Delcour 1999; [5]Swinkels 1985; [6]Jane et al. 1999; [7]Yoo & Jane 2002; [8]Tester et al. 2004; [9]Takeda et al. 2003; [10]Takeda et al. 1988; [11]Morrison et al. 1984; [12]Han et al. 2002; [13]Ji et al. 2004; [14]Colonna & Mercier 1985; [15]Dang & Copeland 2004; [16]Takeda et al. 1986; [17]Juliano et al. 1981; [18]Baldwin 2001; [19]Morrison & Azudin 1987; [20]Tester & Morrison 1990; [21]Vandeputte et al. 2003b; [22]Fredriksson et al. 1998; [23]Verwimp 2007; [24]Morrison & Karkalas 1990.

COMMON WHEAT (*TRITICUM AESTIVUM* L.) STARCH

Common Wheat Starch: Structure and Properties

Starch is the most abundant component of wheat grain (Lineback & Rasper 1988). Its granules are packed in the starchy endosperm cells and embedded in the gluten protein matrix. Unlike the majority of starches, wheat starch granules have a bimodal size distribution (**Table 1**). The lenticular (A-type) granules are larger than the spherical (B-type) granules (approximately 15 μm to 40 μm versus 1 μm to 10 μm) (Lineback & Rasper 1988). Wheat starch AM has an average degree of polymerization (DP$_n$) of 830 to 1570. The AM content in wheat starch ranges from 17% to 29% (Lineback & Rasper 1988, Buléon et al. 1998). The hexaploid wheat genome provides buffering capacity against changes that otherwise would have led to waxy (i.e., AM-free) or high-AM cultivars (Yoo & Jane 2002). Wheat starch AP has a DP$_n$ of 13,000 to 18,000 (Shibanuma et al. 1996). AP chain length distribution shows peaks at DP 12 and 47 to 51 with a shoulder at DP 18 to 21 (Jane et al. 1999, Yoo & Jane 2002). Moreover, the presence of extra long chains (DP ~ 770) has been suggested (Yoo & Jane 2002). The lipid content is 0.37% and levels of amylose-lipid (AML) complexes range from 0.34% to 0.51% (Vansteelandt & Delcour 1999). The differential scanning calorimetry (DSC) peak GT of wheat starches varies from 58°C to 62°C (Jane et al. 1999, Yoo & Jane 2002).

DP$_n$: average degree of polymerization

AML: amylose-lipid

DSC: differential scanning calorimetry

Milling: mechanical transformation of cereals into their different fractions, i.e., starchy endosperm, bran, and germ

Common Wheat Starch: From Wheat of Varying Hardness to Wheat Flour

The main morphological parts of the wheat kernel are the endosperm (approximately 82%), the bran (approximately 15.5%), and the germ (approximately 2.5%) (Sievert et al. 2007). Milling isolates the starchy endosperm in as pure a state and as high a yield as possible, and reduces it to a suitable particle size. The isolation of the endosperm from germ and bran is achieved mainly in the break system of a flour mill, whereas the reduction of isolated endosperm particles is accomplished by the reduction system. Different types of wheat require different milling procedures (Posner 2009).

Operations prior to milling. Prior to dry milling, water is added to dry grain, which is then stored at ambient temperature to allow moisture absorption. This process, called tempering, when conducted to optimum moisture content, toughens the bran and makes it resistant to fragmentation during subsequent milling. Moreover, it softens the starchy endosperm, which is then ground more easily due to weaker protein-starch bonds in the endosperm (see below) (Delcour & Hoseney 2010). Soft wheat requires lower water levels and shorter storage times than do hard and durum wheats (approximately 15% versus 16.5% and 17%, respectively) (Eliasson & Larsson 1993, Delcour & Hoseney 2010).

Common wheat roller milling. We here briefly describe the roller milling process and refer to Delcour & Hoseney (2010) and Posner (2009) for a more detailed description. In the conversion of wheat into flour, some of the starch undergoes changes that affect its properties.

In a mill, break, purification, and reduction systems can be distinguished (Webb & Owens 2003). The break consists of multiple pairs of rolls with corrugated surfaces, which open the wheat kernel and separate the endosperm from the bran. The grains are held by the slower moving roll, whereas the other roll crushes the grain in a shearing action (Eliasson & Larsson 1993). The surface properties of the subsequent rolls influence grinding and are adapted to optimize the process based on wheat kernel size, wheat hardness, and required end products (Posner 2009). After each break step, the crushed material passes through a series of progressively finer sieves. The stock is separated into three general particle sizes: (*a*) coarser fragments, predominantly large pieces of bran containing high levels of endosperm that are sent back into the break system, (*b*) middlings that still contain bran particles that are sent through a purifier, and (*c*) the finest material, called break flour. The purifier is basically an inclined oscillating sieve through which an air current passes and segregates the particles based on size, shape, and specific weight (Delcour & Hoseney 2010). The remaining and graded endosperm particles are subsequently transported to the reduction system.

The reduction system consists of multiple pairs of smooth rolls, where the middlings are gradually reduced in size to obtain flour (Posner 2009). This grinding action reduces the friable endosperm, but leaves (remaining) bran pieces intact so that they can be separated from the endosperm particles in the purifiers. Sieving after every grinding step removes flour from the reduction system (Webb & Owens 2003).

Flour yields typically vary from 72% for white flour to 100% for wholemeal flour (Sievert et al. 2007). Different commercial flour grades can be obtained, depending on which flour streams are combined to yield the final product (Pyler 1988). A composite of all the flour produced by the mill is a so-called straight grade flour (Sievert et al. 2007).

Milling of wheats of varying hardness. Common wheats are divided into hard and soft wheats, based on the force required to crush the kernels (Delcour & Hoseney 2010). In North American terminology and practice, the *Triticum aestivum* wheats used for cake and cookie making are soft wheats, whereas those for bread making are hard wheats. The term durum wheat is reserved for wheat of the *Triticum durum* species. During milling, durum wheat is converted into coarse particles, i.e., semolina, and used for pasta production (see below).

The differences in particle size distribution after milling have been attributed to variations in wheat kernel hardness (Eliasson & Larsson 1993), which itself depends on the strength of the protein-starch interactions in the endosperm (Delcour & Hoseney 2010). Morris (2002) showed that friabilin isoform polypeptides puroindolines a and b largely determine the strength of this interaction. Wheats that either contain mutations of friabilin isoforms or lack these isoforms (Gooding 2009) have harder endosperm and usually break at the cell wall rather than through the endosperm cell content. In contrast, soft wheats generally contain both puroindolines. They have much softer endosperm and break through the cell contents along the starch granule surface (Eliasson & Larsson 1993, Delcour & Hoseney 2010). As a result, the endosperm of soft wheat is reduced to flour more readily than that of hard wheat (Pyler 1988). The resultant flour has smaller average particle size (25 μm to 35 μm versus 50 μm to 70 μm) and even contains individual starch granules (Eliasson & Larsson 1993, Delcour & Hoseney 2010).

During milling, a type of starch damage occurs, which results in granules that are no longer crystalline. They swell in cold water, have high water absorption capacity and are readily hydrolyzed by fungal α-amylase (Sievert et al. 2007, Delcour & Hoseney 2010). Starch damage increases with wheat kernel hardness and mechanical work delivered on the granules. Therefore, hard wheat generally produces more damaged starch than does soft wheat, and the level of damaged starch increases towards the end of milling.

Common Wheat Starch in Bread Making and Bread Firming

Bread making starts with mixing wheat flour, water, salt, and yeast to form a visco-elastic dough. Flour used for bread making ideally contains a limited level of damaged starch. It increases the flour water absorption capacity and, in combination with α-amylase activity, supports the fermentation process (Carson & Edwards 2009). However, too-high damaged starch levels negatively influence dough rheology and baking performance (Delcour & Hoseney 2010). At the dough stage, (non-damaged) starch is present as semicrystalline granules, which swell slightly and reversibly (Zobel & Kulp 1996). Several authors (Sandstedt et al. 1954, Bechtel et al. 1978) believe each starch granule to be surrounded by protein, whereas Eliasson & Larsson (1993) describe the microstructure of the dough as a bicontinuous network of starch and proteins.

During baking of wheat bread, major structural changes occur. Starch granules imbibe, swell, and gelatinize and, hence, lose their molecular order. AM leaches out, resulting in AP-enriched granules (Zobel & Kulp 1996) (**Figure 2**). However, due to the limited amount of water in the dough, swelling behavior is restricted (Varriano-Marston et al. 1980, Hug-Iten 2000). According to a number of authors (Conde-Petit et al. 1998, Hug-Iten 2000), AM and AP are not distributed homogeneously inside gelatinized granule remnants. In their view, phase separation of the polymers causes AM to accumulate in the center of the granule or to leach, whereas the outer granule zone is enriched in AP. However, it is questionable whether such a suggestion, which was based on visualizing AM following staining with iodine, was not premature. Indeed, one would expect that, in a two-dimensional view of a starch granule, stained polymers would be more visible in the center because of a higher thickness of the layer of stained polymers. Also, the (potentially apparent) increase of AM levels in the center of the granule may have been confounded with a difference in degree of AM migration from the outer granule layers and its migration from the center. We hence wonder whether or not the above outlined view by Zobel & Kulp (1996) does not correspond better to reality than that outlined by Conde-Petit et al. (1998) and Hug-Iten (2000). Following gelatinization, a portion of the AM can form AML complexes with endogenous and/or added lipids (Delcour & Hoseney 2010).

Impact of starch on bread shelf life. During storage, bread crumb, which initially is soft and resilient, gradually loses both of these essential quality attributes. Bread firming and loss of

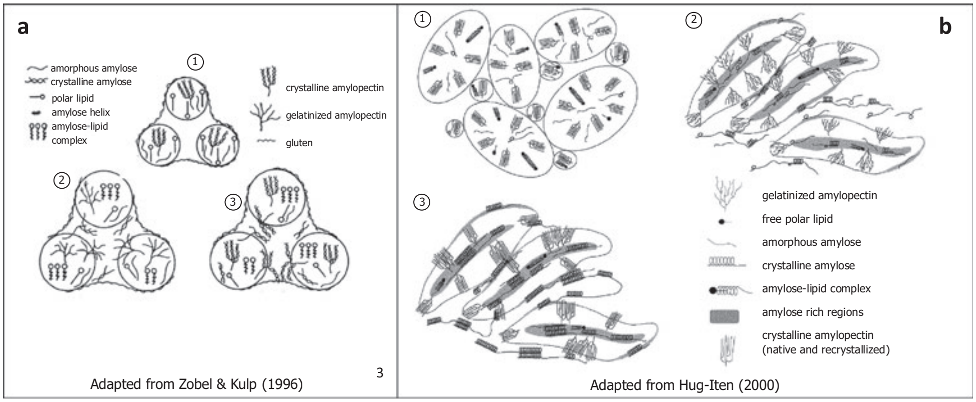

Figure 2

Schematic representation of transformations of starch components occurring during bread making and storage adapted from (*a*) Zobel & Kulp (1996) and (*b*) Hug-Iten (2000). (1) Dough stage, (2) fresh bread, and (3) stored bread.

resilience is a complex process. It involves inter alia moisture migration from crumb to crust and water redistribution between bread components (Eliasson & Larsson 1993, Chen et al. 1997).

During cooling after baking and further storage, starch molecules reassociate to a more ordered state. Initially, AM forms double helices and a continuous crystalline network develops. AM is an essential structural element already in the fresh bread crumb, and it, rather than AP, determines initial crumb firmness (Eliasson & Larsson 1993, Goesaert et al. 2005).

Amylopectin retrogradation also takes place. It is accepted to be the main contributor to bread firming (Kulp & Ponte 1981, Zobel & Kulp 1996). AP side chains form double helices, which crystallize. Although, to the best of our knowledge, there evidently is no sound experimental evidence reported in the literature to support this, we logically assume that AP crystallization is not only an intramolecular phenomenon but also an intermolecular phenomenon and that some AM can cocrystallize and/or entangle with AP. Hug-Iten et al. (2003) further suggested that AM reorganizes as well during aging and that it is also important for firming. In their view, the formation of AM double helices in the center of the starch granule increases rigidity.

Whatever be the case, after baking, the amorphous structure evolves in a semicrystalline state with appearance of a B-type X-ray diffraction pattern during aging of bread (Zobel & Kulp 1996). However, increased crystallinity and bread firming are not necessarily correlated (Dragsdorf & Varriano-Marston 1980). In this respect, molecular reorganization of each zone and increased entanglement of AP and AM crystallites, leading to a structured network, seem to be more important in bread firming than the mere increase in crystallinity (Hug-Iten et al. 2003). Also, as outlined below, we believe the incorporation of water in starch crystals to be important for crumb properties.

Amylopectin retrogradation: recrystallization of amylopectin during storage of gelatinized starch, resulting in a more ordered structure

Amylases as antifirming agents and their different effects on crumb resilience. Amylolytic enzymes cleave α-(1,4) and/or α-(1,6) linkages in starch polymers. They include α-amylases (E.C. 3.2.1.2), maltogenic (E.C. 3.2.1.133) and nonmaltogenic exo-amylases (E.C. 3.2.1.60, E.C. 3.2.1.98, E.C. 3.2.1.116), β-amylases (E.C. 3.2.1.2), glucoamylases (E.C. 3.2.1.3), and debranching enzymes (E.C. 3.2.1.41, E.C. 3.2.1.68). α-Amylases, which are mainly endo-acting enzymes, more or less randomly hydrolyze starch molecules, yielding low molecular weight dextrins. Maltogenic and maltooligosaccharide producing amylases are typical exo-amylases. In contrast to the former, debranching enzymes hydrolyze α-(1,6) linkages in starch polymers, thus removing side chains of the molecules.

Some amylases can be used as antifirming agents (Kulp & Ponte 1981, Hug-Iten et al. 2001, Goesaert et al. 2009a), with those of intermediate temperature stability being the most suitable. The ideal enzymes are indeed neither heat inactivated before the initiation of starch gelatinization nor sufficiently heat stable to survive the baking step. Prolonged activity can lead to undesirable crumb gumminess (Hebeda et al. 1991, Zobel & Kulp 1996). Differences in amylase action mechanisms determine differences in starch structure and starch hydrolysis products in bread and the moments in the breadmaking process at which they are generated. Amylases also differ in the degree to which they not only impact bread crumb firming but also its loss of resilience (Goesaert et al. 2009b). For example, an endo-α-amylase from *Bacillus subtilis* hydrolyzing inner AP chains reduces the number of connections between crystallites in the starch networks and results in softer bread. However, it hardly affects AP recrystallization, given that it leaves the outer AP chains intact. Thus, its role in reducing crumb firmness can be ascribed to reduction of the size of AP molecules. As it hardly impacts AP outer chains, it does not interfere with their crystallization and hence does not prevent water incorporation in the crystalline structures. The latter is especially important because it was rationalized earlier that the incorporation of water in the AP crystals withdraws this plasticizer from the gluten phase and therefore makes the gluten less resilient. Thus, both in control bread and in bread made with addition of the cited *Bacillus subtilis* endo-α-amylase, during bread firming water is incorporated in starch crystals and withdrawn from the gluten phase. This then is believed to result in loss of resilience (Goesaert et al. 2009a, Goesaert et al. 2009b). In contrast to this, a *Bacillus stearothermophilus* maltogenic amylase mainly degrades the outer crystallizable AP side chains, resulting in limited AP recrystallization and network formation during storage. At the same time, little if any water is immobilized in AP crystals, and softer bread crumb with good resilience is obtained (Goesaert et al. 2009a).

Emulsifiers in bread making. Some emulsifiers may positively impact bread making and/or the quality of bread. Positive effects include increased bread volume and decreased firming during storage (Kulp & Ponte 1981).

Small emulsifier molecules can enter the granule and complex with intragranular AM, as reported by Ghiasi et al. (1982), and hence delay AM leaching out of the granule. Complexation with AM leached outside the granule has also been described (Eliasson & Krog 1985). This results in formation of an insoluble film at the granule surface that prevents transport of water inside the granule and, thus, further AM leaching and granule swelling (Eliasson & Krog 1985). Formation of AML complexes thus decreases disruption of the granules and increases the GT range (Eliasson et al. 1981).

In bread making, some emulsifiers decrease initial bread firmness as they interfere with AM crystallization. AM complexation by lipids also changes the distribution of water between starch and the environment (Kulp & Ponte 1981, Gudmundsson 1992). In the presence of emulsifiers, AM single helix conformation excludes its further participation in double helix formation either with other AM chains or with AP outer branches. AP has also been described to complex with emulsifiers (Gudmundsson 1992), although earlier studies concluded the opposite (Kugimiya et al. 1980, Evans 1986). AP complexation is probably masked by complexation with AM, which is more abundant and leads to better detectable complexes. Complexation of emulsifiers both with AM (with the subsequent hindrance to double helix formation) and with AP thus lower the rate of starch crystallization (Eliasson & Ljunger 1988, Gudmundsson & Eliasson 1990). An elaborate review of the significance of in situ formed AML complexes in food systems can be found elsewhere (Eliasson & Wahlgren 2000).

Common Wheat Starch in Cake Making and Cake Firming

Based on their production methods and formulations, cakes span a wide range of products. Depending upon the mechanism of air incorporation in the batter, cake-making methods can be divided into single or multistage mixing (Sievert et al. 2007). Cakes can also be classified as based on formulation in, for example, high-ratio cake (sugar to flour ratio at least 1.0) and traditional pound cake consisting of equal portions of fat, sugar, egg, and flour (Wilderjans et al. 2008).

Regardless of cake type, all cake formulas contain high levels of sugar, flour, and water. For cake making, in many instances, soft wheat flour with small particle sizes, which are obtained by pin milling, is used. Although pin milling increases the level of damaged starch, the positive effects of reduced particle size cancel the negative effects of up to five percent damaged starch (Miller et al. 1967).

Influence of sugar on starch gelatinization.

The major effect of increasing sucrose levels is a marked delay in gelatinization. This has been attributed to sucrose limiting water availability to the starch granule and lowering of water activity (Spies & Hoseney 1982, Beleia et al. 1996). According to Slade & Levine (1988), sugar exerts an antiplasticizing effect relative to water, and replacement of water by sugar raises the glass transition temperature of starch. At the same time, sucrose narrows the GT range, possibly due to the loss of water-binding ability of sucrose with increasing temperatures (Chiotelli et al. 2000). Sucrose to water ratios can be used to control the starch peak GT. Sucrose levels of approximately 60% increase the peak GT with approximately 35°C (Kim & Walker 1992). Hence, GT control by sucrose concentration allows optimization of oven rise, structure fixation, and collapse.

Role of starch during cake baking.

Due to the large variety in cake types, the complexity of the systems, and the lack of literature, it is difficult to generalize the role of starch during cake baking. The transformation of an aqueous, fluid batter into a solid, porous cake structure during baking is accompanied by water absorption of the starch granules (Howard et al. 1968, Willhoft 1973). Most authors agree that the extent of water absorption by the starch granules codetermines final cake quality. As mentioned above, cake volume depends on GT control, which itself is affected by moisture and sugar levels.

Analogous with what occurs during bread baking, starch granules imbibe, swell, and gelatinize during cake baking. Starch granule swelling produces the building bricks of the final crumb and removes excess water from the crumb (Donovan 1977). Properly baked cake contains sufficiently swollen granules that make mutual contact. Most authors further agree that it is essential for the formation of a good cake structure that most of the swollen starch granules still retain a recognizable granular shape (Howard et al. 1968, Gough et al. 1978). Compared to bread crumb, the starch granules in the cake crumb are considerably more swollen (Derby et al. 1975). This may well be due to the specific effect that sugar solutions have on granule swelling (Bean & Yamazaki 1978).

Role of starch during cake cooling and firming.

As for bread, starch molecules reassociate to a more ordered state upon cooling. According to Wilderjans et al. (2010), the starch gel forms too late during cooling to prevent collapse, but can contribute significantly to cell wall texture and hence, initial cake firmness.

During storage at ambient temperatures, cake crumb gradually firms. This has been related to the combination of an intrinsic firming process of the cell wall material and the migration of moisture from crumb to crust. The latter can continue for up to five weeks, but once equilibrium is established, no further loss of moisture from the central crumb occurs (Guy 1983). The few existing studies on cake firming regrettably do not address the importance of total water loss versus water redistribution and moisture transfer at the microscopic level between the cell wall constituents. Although the starch fraction in cake batter is more diluted than in bread dough, it does retrograde during short cake storage times (Guy & Pithawala 1981).

Common Wheat Starch in Cookie Making

Cookies (biscuits) are generally characterized by high fat and sugar levels and low water levels (2% to 5%) (Pareyt et al. 2009b). Cookies with a large diameter, uniform surface cracking, and a tender bite are considered to be superior (Pareyt & Delcour 2008, Delcour & Hoseney 2010). Cookie quality is largely influenced by flour type, composition, and properties (Miller & Hoseney 1997). Part of the differences in flour properties leading to altered cookie quality may be overcome by adjusting the physical properties and/or levels of sucrose, fat, and dough moisture (Miller et al. 1997, Pareyt et al. 2009a,b).

The importance of starch properties on cookie quality is discussed for two general cookie types: (*a*) cookies made from short dough, which has relatively high sugar and fat levels, e.g., wire-cut cookies and ginger- and sugar-snap cookies, and (*b*) cookies made from hard dough with relatively less sugar and fat, e.g., crackers and semisweet products. The former spread during baking because they lack a developed gluten network, whereas the latter do not (Wade 1988, Manley 2000).

Role of starch during cookie dough making. Due to its low level of damaged starch, flour from soft wheat is preferred for cookie production. Ideally, for cookie making, soft flour is milled without damaging any of the starch as damaged starch reduces cookie dough spreading in the oven. For short doughs, damaged starch is regarded as the main water controlling ingredient in the production of cookie dough of the required consistency (Wade 1988). More starch damage generally leads to higher water absorption and reduced final cookie diameter, which is detrimental for short dough cookie types (Donelson & Gaines 1998). Damaged starch influences both cookie dough stiffness and cohesion (Gaines et al. 1988). Hard doughs, on the other hand, do not spread during subsequent baking. Their final cookie dimensions are thus little affected by the level of damaged starch. However, damaged starch may influence the amount of water held during baking and hence the product quality during storage (see below).

For short dough, models proposed and reviewed by Pareyt & Delcour (2008) maintain that starch granules act as fillers in the structure provided by other dough ingredients. This would also be the case for hard dough, as long as it is not heated above the starch GT in the system.

Role of starch during cookie baking. As in cakes, higher sucrose levels increase the starch GT (Spies & Hoseney 1982). The GT can be raised to such an extent that, for cookies with relatively high sugar levels (e.g., sugar-snap cookies), no gelatinization occurs during baking (Abboud & Hoseney 1984, Pareyt et al. 2009a). This is not only due to the high sugar levels, but also to the low dough water levels (Delcour & Hoseney 2010). However, in some recipes, some of the starch granules still swell during baking to the point at which they lose birefringence (see above). Cookies containing ungelatinized starch are softer eating (Manley 2000). However, sugar-rich cookies may be hard because of the sugar glass formed during cooling.

Pareyt & Delcour (2008) warned against drawing generally valid conclusions, as cookie types differ in their formula. Cookies from recipes with higher water and lower sugar levels, such as those made of hard dough, may show some starch gelatinization (Delcour & Hoseney 2010). In this case, the granules that gelatinize first will take (most of) the available water (Ghiasi et al. 1983) and consequently limit the water available for other granules to gelatinize. When some of the starch is gelatinized, more water can be held in the cookie during baking.

Role of starch during storage of cookies. The increase in sugar-snap cookie rigidity during storage is due to hydrogen bonding between protein and starch (Hoseney & Rogers 1994). Also during storage, cookies sometimes develop hairline cracks, a phenomenon known as checking. Checking more commonly occurs in cookies prepared from hard dough than in those prepared from short dough (Saleem et al. 2005). After baking, the central parts of the biscuit have slightly higher moisture levels than the edge regions. Subsequent cooling and storage are accompanied by moisture diffusion from high to low moisture regions. This causes the former to contract and the latter to expand, building up stresses in the biscuit, which eventually result in cracks (Saleem et al. 2005). This phenomenon may be impacted by starch damage levels and degree of gelatinization, as these parameters determine the quantity of water held during baking.

Common Wheat Starch in Noodle Making

Noodles are generally made from flour of common wheat with ash content below 0.4%; water ($\leq$35% on flour base); common salts, e.g., sodium chloride; and/or alkaline salts, e.g., sodium carbonate (Kruger 1996, Miskelly 1996). The United States Standard of Identity for noodles states that they must be made of wheat dough containing eggs ($>$5.5% on flour base). Noodle making involves mixing of flour, water, (alkaline) salt, and (optionally) egg products into a crumbly dough (Miskelly 1996, Delcour & Hoseney 2010). Less water is used during noodle making than in bread making, resulting in minimal gluten development in the dough (Kruger 1996). After a rest, the dough is sheeted and cut. Dough containing excessive amounts of water has poor sheeting properties, whereas insufficient water absorption produces stiff and less extensive noodle sheets (Hatcher et al. 1999). Drying wet noodles reduces moisture content to approximately 10% (Delcour & Hoseney 2010). Starch characteristics, including AM to AP ratio, level of damaged starch, and swelling and pasting properties, are important for noodle quality (Kruger 1996, Delcour & Hoseney 2010). During cooking, starch gelatinizes and causes the noodle to set. If the starch on the noodle surface is overcooked before the interior is cooked, the noodle surface becomes sticky. In contrast, when the noodle is properly cooked, the starch on the surface gives a smooth mouthfeel (Delcour & Hoseney 2010). To obtain noodles with desirable eating quality, wheat flour with high amylograph peak viscosities, low GTs, and low AM content is required (Crosbie 1991, Kruger 1996).

DURUM WHEAT (*TRITICUM DURUM* DESF.) STARCH

Durum Wheat Starch: Structure and Properties

Although starch is the main constituent of durum wheat pasta, only a few investigations have characterized durum wheat starch. Overall, durum and common wheat starches only differ slightly in chemical composition. Durum wheat starches have slightly higher AM contents, ranging from 26.4% to 27.5% (**Table 1**) (Medcalf & Gilles 1965, Soulaka & Morrison 1985, Vansteelandt & Delcour 1999), and higher levels of lipids (approximately 0.5%) and AML complexes than common wheat starches (Vansteelandt & Delcour 1999).

Starch structure and properties of durum and common wheat differ. The average chain length of AP of durum wheat starches is shorter (Lii & Lineback 1977, Lintas 1988) and its double helix content is lower than that of common wheat starch (Vansteelandt & Delcour 1999). This may explain its less compact granule structure (Medcalf & Gilles 1965, Lintas 1988) and its slightly lower GT in DSC (Soulaka & Morrison 1985, Vansteelandt & Delcour 1999). Also, durum wheat starches tend to develop higher amylograph peak and end viscosities with a slightly later viscosity development. This may be caused by their higher content of lipids, which can impact on starch rheological behavior (Vansteelandt & Delcour 1999).

Durum Wheat Starch: From Durum Wheat to Semolina

The durum wheat kernel is extremely hard. Its starch granules lack puroindolines (see above), and endosperm proteins can therefore very well interact with the starch granule surface and cause kernel hardness. When durum wheat is milled into flour, starch granules—rather than the starch-protein bonds—break, inevitably resulting in too-high degrees of starch damage (Delcour & Hoseney 2010). Therefore, durum wheat is generally milled into semolina (see above). Following tempering, the kernels are ground on a series of corrugated break rolls (Dick & Matsuo 1988). In addition, durum mills have fewer reduction rolls, which are used essentially for particle sizing rather than for production of fine flour (Pyler 1988), and contain a large number of purifiers to efficiently remove the bran particles, which otherwise would result in undesirable dark specks on the pasta surface and a decreased cohesion of the pasta strand (Posner 2009).

Although coarse semolina is used in traditional and semihandcraft pasta production, pasta plants with ultrahigh-temperature drying systems use semolina with finer granulation ranging from 350 μm to 125 μm in addition to approximately 6% to 8% flour (Posner 2009).

Durum Wheat Starch in Dry Pasta Making

In the first stage of the production process following durum wheat milling, semolina and water (approximately 30% on semolina base) are transformed into dough particles that are extruded (≤45°C) or sheeted to generate continuous dough strands that are subsequently dried to approximately 12.5% product moisture content (Delcour & Hoseney 2010). As a result, starch remains granular and entrapped in a protein network.

During processing, the level of damaged starch increases (Vansteelandt & Delcour 1998, Bruneel et al. 2010) due to mechanical damage during mixing and extruding (Lintas & D'Appolonia 1973). Furthermore, when drying at high temperature, partial melting of starch crystallites or molecular rearrangements of starch polymers at the double helical level may occur (D'Egidio 2000, Zweifel et al. 2000). This increases the starch GT and narrows the GT range (Cunin et al. 1995, Vansteelandt & Delcour 1998, D'Egidio 2000).

Durum Wheat Starch in Pasta Cooking

Dried pasta requires cooking prior to consumption. The cooking conditions induce starch gelatinization. Transformations of starch in cooked pasta vary from a hydration-driven gelatinization process in the outer layer to a heat-induced crystallite melting in the center of the pasta (Cunin et al. 1995, Zweifel et al. 2003). During cooking, the starch granules absorb water and swell, and hence increase in volume and exert pressure on the protein structure. Next to starch gelatinization, (further) protein polymerization reinforces the protein structure and makes it better able to withstand the increased volume of the starch particles (Delcour & Hoseney 2010).

The final product quality depends on how the protein structure withstands the swelling of the starch (Delcour et al. 2000a, Delcour et al. 2000b). When protein polymerization during cooking does not make up for insufficient polymerization during drying, excessive cooking losses occur.

In contrast, the proteins in pasta dried at very high temperatures may well have polymerized to such an extent that they are too rigid to expand and retain the gelatinized starch during cooking, resulting in inferior quality pasta (Delcour & Hoseney 2010, Bruneel et al. 2010).

ae: amylose extender

MAIZE (*ZEA MAYS* L.) STARCH

Maize Starch: Diversity, Structure, and Properties

The maize starch granule size distribution is unimodal and is in the range of 5 μm to 30 μm (**Table 1**) (Tester et al. 2004). The granules are polygonal or round. Normal maize starch contains approximately 25% to 28% AM, whereas waxy and amylose extender (ae) mutants consist of 100% AP and 40% to 70% AM, respectively (Morrison et al. 1984, Shi et al. 1998, Campbell et al. 2002). Maize starch AM has a DP_n of 320 to 1015 (Takeda et al. 1988, Mua & Jackson 1997), whereas that of AP ranges from 9600 to 15900 (Takeda et al. 2003). Normal and waxy maize starches have higher levels of short AP chains, whereas high-AM maize starches contain more long chains ($DP > 30$) (Takeda et al. 1993, Klucinec & Thompson 1998, Shi et al. 1998). The protein and lipid levels are within the range of values for other cereal starches (Morrison et al. 1984). Maize starch has a slightly higher GT than wheat and rye starches. It ranges from 62°C to 87°C (Ji et al. 2004), with high-AM maize starch having the highest GT (70°C to 87°C) (Colonna & Mercier 1985).

Maize Starch: From Maize to Maize Grits and Maize Flour

Maize dry milling differs from wheat milling. Maize kernels are large, hard, and flat and contain a larger germ (approximately 12% of the kernel) than do other cereals (Alexander 1987, Delcour & Hoseney 2010). To avoid rancidity development during storage of milled maize, the lipid-rich germ must be removed. In maize milling, the desired products are in most instances low fat grits rather than flour. Hence, bran and germ need to be removed without reducing the endosperm to small particle size. This is, in a first step, done by adjusting the moisture content to approximately 20%. Following degermination, the endosperm is reduced to grits of the desired size by a break roller milling, which is comparable to that of wheat milling. Depending on the process, large, medium, or small grits, meal, or flour is produced (Alexander 1987, Delcour & Hoseney 2010).

Maize Starch in the Production of Tortillas and Breakfast Cereals

In the production process of tortillas, maize kernels are cooked with water and alkali and steeped at ambient temperature overnight (Sahai et al. 2000). Alkali cooking improves flavor, starch gelatinization, and water uptake. Traditionally, hard white maize is used as it results in a white tortilla and lower solid losses than do soft maize types (Jackson et al. 1988). During cooking, maize starch is partially gelatinized (Gomez et al. 1992, Campus-Baypoli et al. 1999), and complexation of AM with lipids occurs (Mondragon et al. 2004, Mora-Escobedo et al. 2004). During steeping, the starch reassociates and (re)crystallizes (Campus-Baypoli et al. 1999, Mondragon et al. 2004). Following steeping, the liquid is separated from the cooked-steeped maize, i.e., nixtamal. The nixtamal is washed to remove excess alkali and bran from the endosperm. It is then stone-ground into dough, i.e., masa. Usually, water is added to avoid overheating of the stones and further gelatinization of the starch. The grinding process disrupts the gelatinized starch granules and increases water absorption (Campus-Baypoli et al. 1999). Finally, the masa is flattened into thin disks and baked. Depending on the baking conditions, the starch is partially or completely gelatinized. Cooling and storage of the tortillas results in AP retrogradation (Campus-Baypoli et al. 1999, Mora-Escobedo et al. 2004).

One of the most popular breakfast cereals is cornflakes. The flakes are made from large maize grits obtained by dry milling of maize kernels. These maize grits are pressure cooked for 1 h to 2 h with a mixture containing syrup, sugar, malt, and salt (Fast & Caldwell 2000, Delcour & Hoseney 2010). The starch gelatinizes, resulting in translucent grits at the end of the cooking process. After cooking, the moisture content is reduced from approximately 50% to 20% by hot air drying. The grits are tempered for approximately 24 h to reach a uniform moisture distribution, then flaked and toasted. Toasting dehydrates the flakes to less than 3% moisture and develops a crisp texture, brown color, and desirable flavor. Finally, the flakes can be sprayed with a solution of nutrients and tempered. Alternative flake production processes use extrusion cooking. The major advantage of extrusion is that it handles the grits at relatively low moisture content (12% to 20%), with grit expansion based on both temperature and pressure. After extrusion, the flakes (8% to 15% moisture) are dried to reduce the moisture.

RICE (*ORYZA SATIVA* L.) STARCH

Rice Starch: Diversity, Structure, and Properties

Rice starch granules are very small (Dang & Copeland 2004), ranging from 3 μm to 10 μm with a unimodal distribution (**Table 1**). Each granule has a smooth surface and is angular. In contrast to what is the case for most other cereals, one rice amyloplast contains 20 to 60 individual granules, resulting in the formation of compound granules with a diameter up to 150 μm (Bechtel & Pomeranz 1978). The AM levels of rice starches vary more widely than those of other cereal starches. Based on AM contents, Juliano et al. (1981) classified rice starches as waxy (0% to 2% AM), very low (5% to 12% AM), low (12% to 20% AM), intermediate (20% to 25% AM), or high (25% to 33% AM). *ae* mutants contain 35% to 40% AM (Juliano 1992). Rice starch AM has DP_n values of 920 to 1110 glucose units and average chain lengths of 250 to 370 (Takeda et al. 1986). DP_n of rice starch AP ranges from 2700 to 12900 (Takeda et al. 2003), and average chain lengths range from 15 to 22 (Lu et al. 1997). The main minor components in rice starch are lipids (0.1% to 1.3%) (Morrison & Azudin 1987) and proteins (0.25%) (Baldwin 2001).

Rice starches vary more widely in structural and physical properties than do other cereal starches. Rice starch peak GT may range from 62°C to 79°C (Tester & Morrison 1990, Vandeputte et al. 2003b). Waxy and normal rice starches with a low GT contain higher relative amounts of short AP chains (DP 6 to 9) and reduced levels of longer chains (DP 12 to 22) than do starches of intermediate and high GT (Vandeputte et al. 2003b). The swelling power of rice starches increases with temperature and is higher for waxy than for nonwaxy rice starches (Lii et al. 1996, Noosuk et al. 2003, Vandeputte et al. 2003a). With regard to starch gel texture, hardness and firmness increase with AM content (Tan & Corke 2002, Vandeputte et al. 2003c). The impact of AP structure on textural characteristics is not clear. Villareal et al. (1997) and Wang & Wang (2002) indicated that gel softness depends on the chain length distribution for high-AM rice starches of the same GT range and waxy rices, respectively. In contrast, Vandeputte et al. (2003c) did not find such a relation for waxy and normal rice starches.

Rice Starch in White Rice Cooking

Rice harvested from the field is called paddy or rough rice. To obtain white rice, different unit operations are required. Firstly, the hull (approximately 20% of the rough rice) is removed to obtain brown rice. This is performed mainly by passing the rough rice between two rubber-coated rolls turning at different speeds in opposite directions (Delcour & Hoseney 2010). After separation, the hull is removed by aspiration. To obtain white rice, the bran layers are removed by brown rice milling and polishing. During these processes, some rice breakage occurs. Broken and head rice (unbroken milled kernels) are separated by screening or by disk separators. As with dehulling, bran is removed by aspiration. During white rice cooking, starch absorbs water, swells and gelatinizes, leading to further starch swelling and AM leaching. High-AM rices have strong and rigid starch granules, whereas granules of low-AM rices are weak and fragile (Rani & Bhattacharya 1989). In contrast to high-AM rices, the latter are soft and sticky after cooking (Reddy et al. 1994). Apart from AM levels, the AP structure affects the rice texture as well. It has been suggested that the long B-chains of AP strengthen the starch granules through intermolecular interaction, leading to a firmer texture (Reddy et al. 1993, Ramesh et al. 1999b). Proteins also contribute to rice texture by the formation of a barrier which decreases leaching of rice components during cooking (Hamaker & Griffin 1990, Derycke et al. 2005b). Cooling and storage of cooked rice result in starch retrogradation (Perdon et al. 1999, Philpot et al. 2006), the extent of which depends on storage time and temperature. Starch retrogradation and cooked rice firmness are linearly related (Perdon et al. 1999) and affected by the AM and AP structure (Perez et al. 1993, Villareal et al. 1997).

Rice Starch in Rice Parboiling and Subsequent Cooking

Approximately one-fifth of the world rice production is parboiled. The term parboiling originates from partially boiled. This three-step hydrothermal treatment consists of soaking, heating (by steaming), and drying of paddy or brown rice. Afterwards, the hull and bran of the parboiled rice are removed by dehulling and milling, respectively. The most obvious change during parboiling is starch gelatinization. Its degree is positively related to the hardness of cooked parboiled rice (Islam et al. 2002). Parboiling increases rice firmness due to lower water absorption during cooking (Priestley 1976). Besides starch gelatinization, complexation of rice lipids with AM occurs during heating and/or cooling (Biliaderis et al. 1993, Derycke et al. 2005a), hence restricting leaching of rice components and swelling of starch granules during cooking. These phenomena go hand-in-hand with increased firmness and decreased stickiness of cooked parboiled rice (Derycke et al. 2005a). Furthermore, during cooling and drying of parboiled rice, starch reassociates and forms AM crystallites (Lamberts et al. 2009), as well as retrograded AP (Mahanta et al. 1989, Ong & Blanshard 1994, Derycke et al. 2005a). It is reasonable to assume that crystalline AP formed during the process does not affect the texture of cooked rice because it has a melting temperature of approximately 50°C. By the same reasoning, as AM crystallites melt above 100°C, they may codetermine texture characteristics. However, this needs further research. There is also evidence of thermal breakdown of starch during parboiling. Mahanta & Bhattacharya (1989) and Ramesh et al. (1999a) found that the levels of starch breakdown increase with steaming temperature and suggested that degraded starch affects the firmness of cooked parboiled rice. The impact of parboiling on textural features is not only attributed to changes in starch. Derycke et al. (2005b) described that parboiling destroys protein bodies and favors disulfide cross-linking of proteins. The resulting protein barrier limits leaching of solids during cooking, is responsible for reduced water absorption, and consequently increases hardness and decreases stickiness.

RYE (*SECALE CEREALE* L.) STARCH

Rye Starch: Structure and Properties

So far, only limited data are available on the structural features of rye starch. Rye starches consist of larger lens-shaped A-type granules with a broader size distribution than wheat starch and small spherical B-type granules (**Table 1**) (Fredriksson et al. 1998). AM content of rye starch (22% to 26%) is comparable to that of wheat starch (Verwimp 2007). Silverio et al. (2000) found chain length distributions with peak maxima at DP 12, 15, and 20 and a larger proportion of material with an approximate DP 45. Rye starch AP had a higher level of chains with DP 6 to 12 and a lower level of chains with DP 13 to 24 than did common wheat starch AP (Verwimp 2007).

Rye starch gelatinization starts at somewhat lower temperatures (48°C to 49°C) than that of wheat starch (Verwimp 2007). Also, the gelatinization enthalpy of rye starch is smaller than that of wheat starch (Gudmundsson & Eliasson 1991, Radosta et al. 1992). Rye starches exhibit unique, typical swelling behavior with a stable consistency during cooking and a high viscosity increase during cooling (Schierbaum & Kettlitz 1994). They show somewhat lower amylograph pasting temperatures, lower peak and breakdown viscosities, and higher setback and end viscosities than wheat starches (Verwimp 2007). Gudmundsson & Eliasson (1991) and Fredriksson et al. (1998) showed that rye starches retrograde to a lesser extent than wheat or maize starches and ascribed this to differences in the structure of their respective APs.

Rye Starch: From Rye to Rye Flour

Rye kernels are smaller than wheat kernels. Hence, separation of rye endosperm from its bran is poorer (Nyman et al. 1984). The extraction rate of rye flour is lower and its ash content is higher than those of wheat flour (Weipert 1997). Prior to milling, rye grain is also tempered. This is generally conducted to a slightly lower final moisture level and for a shorter time than in the case of wheat. In Europe, roller and pin milling are the most important rye milling processes. In pin milling, rye is milled by the principle of impact disintegration. This results in less starch damage than in roller milling.

Rye Starch in Bread Making and Bread Firming

Rye and wheat flours have different bread making behavior. Rye proteins cannot form a gluten network, which lies at the basis of wheat bread quality. In addition, as outlined above, rye starch gelatinizes at lower temperatures and is therefore more prone to enzymic degradation during the oven phase than wheat starch. The specific volume of rye bread is normally only approximately half that of wheat (Weipert 1997).

For production of good-quality rye breads, acidification is a prerequisite. Sourdough is classically made by mixing rye flour or wholemeal with water, yeast, and a starter and allowing the mixture to ferment (Seibel & Brummer 1991, Meuser et al. 1994). Acid conditions have a positive influence on the swelling of rye flour constituents and control the enzyme activity in the dough, thereby preventing early staling. The higher the enzyme activity of the rye flour, the greater the degree of acidification required (Meuser et al. 1994).

POTATO (*SOLANUM TUBEROSUM* L.) STARCH

Potato Starch: Structure and Properties

Potato is one of the most used tubers and roots next to cassava, yam, and sweet potato starches (Hoover 2001). Potato starch granules are large, oval to spherical granules (10 μm to 110 μm) with a smooth surface, and have a broad granule size distribution (**Table 1**) (Fredriksson et al. 1998). Both the granule size and AM content depend on the size and maturity of the tubers (Karlsson & Eliasson 2003). Further, potato granules have lower protein and lipid levels than cereal starches.

These characteristics result in clear starch gels with a bland taste (Swinkels 1985). AM content is slightly lower for potato (18% to 21%) than for cereal starches (Buléon et al. 1998, Fredriksson et al. 1998). It has a DP_n of 4920 (Morrison & Karkalas 1990), which is higher than that of cereal AM. DP_n of potato starch AP is 11200, comparable to that of AP from other botanical sources (**Table 1**) (Takeda et al. 2003). Potato starch AP has relatively long chains, which is typical for starches with a B-type X-ray diffraction behavior (Vermeylen et al. 2004) and contains relatively more B_2 and B_3 chains and fewer A and B_1 chains than do cereal starches (Hoover 2001). Its chain length distribution shows a dip at DP 8 and a peak at DP 13 (McPherson & Jane 1999). Typically, phosphate groups (0.089%) are substituted on potato AP (Hoover 2001), mostly at the C-6 (61%) and the C-3 (38%) positions. Small levels occur on the C-2 position (Tabata & Hizukuri 1971). Peak GT ranges typically from 62°C to 66°C, and gelatinization enthalpies are higher than those of cereal starches (Fredriksson et al. 1998). The phosphate groups of AP lead to rapid hydration, swelling, and high viscosity during heating, as well as make the gels sensitive to the presence of electrolytes. Monovalent and divalent cations increase and decrease amylograph peak viscosity, respectively. Potato starch pastes are very sensitive to heating and agitation. Potato starch gels have a stringy and slimy texture, and rheological measurements show a low setback (Bergthaller 2004). Potato AP retrogrades to a greater extent than cereal AP (Kalichevsky et al. 1990, Fredriksson et al. 1998).

Potato Starch in Potato Processing

Potatoes and their derived products are important staple foods worldwide. They can be prepared in various ways. For fresh consumption, potatoes are boiled, baked, or fried. They are also industrially processed to obtain mashed potatoes, frozen potatoes (e.g., French fries), potato crisps, etc. During cooking, two components must be considered: a starch component and a cell wall component. Both of them contribute to the texture of the cooked potatoes. The role of starch gelatinization is not fully clear: Some authors observed a limited contribution to the texture (Verlinden et al. 1995), whereas others ascribed an important role to starch content and gelatinization (Kaur et al. 2002).

CONCLUSIONS

Starches of different sources largely differ in size, structure, and properties. Cereal starch granules are smaller than those of potato. Their size distribution is bimodal for wheat, rye, and barley and unimodal for maize, rice, oat, and potato.

Milling of cereals produces some starch damage. Flour from hard wheat with a limited level of damaged starch is used in bread making, whereas flour from soft wheat with lower damaged starch levels and smaller particle size is preferred in cake and cookie making. Water uptake, and the incorporation of starch in a gluten network, occurs during the dough stage of different food processes. The extent of transformations depends mainly on the moisture level. Baking or cooking gelatinizes the starch and may result in the formation of AML complexes. When using substantial levels of sucrose in recipes, starch gelatinization is delayed or even does not occur. Cooling and storage of food systems containing gelatinized starch result in the crystallization of AM, the retrogradation of AP, and the formation of a structured network. Moisture availability and migration also impact starch behavior. Apart from starch, other components play a role in the final food texture. For example, during pasta making and cooking and rice parboiling and cooking, protein cross-linking occurs, which limits the leaching of components and decreases the stickiness of the processed food product.

SUMMARY POINTS

1. Starch: Starch essentially consists of the polysaccharides amylose and amylopectin. The starch granule dimensions and morphologies depend on botanical origin. Starch is the main structure- and texture-determining component in many cereal-based food products. Hydrothermal treatment of starch can involve different transitions, e.g. starch swelling, gelatinization, pasting, recrystallization, and retrogradation.
2. Common wheat (*Triticum aestivum* L.) starch: Wheat starch granules have a bimodal size distribution: lenticular A-type granules and smaller spherical B-type granules. Milling isolates the starchy endosperm from bran and germ and reduces it to a suitable particle size. The milling procedure depends on the wheat type and its hardness. Flour from common wheats is used for applications including bread making, cake making, cookie making, and noodle making. Depending on the application, damaged starch levels and/or wheat flour particle size are the important quality-determining factors. Amylase and emulsifiers may positively impact starch properties and final bread quality. In cake and cookie making, starch gelatinization is delayed or prevented due to increased sucrose levels.
3. Durum (*Triticum durum* Desf.) wheat: Compared to common wheat, durum wheat is extremely hard and contains slightly higher amylose levels. During pasta making, semolina and water are mixed. The resulting dough is extruded or sheeted and subsequently dried. These unit operations increase starch damage levels. Pasta cooking induces starch gelatinization and protein polymerization.
4. Maize (*Zea mays* L.) starch: Maize starch granules are polygonal or round and have a unimodal size distribution. Their gelatinization temperature is slightly higher than that of wheat and rye starches. Tortilla production involves alkali cooking, steeping, washing, stone grinding, flattening, and baking. Depending on the conditions, the starch is partially or completely gelatinized. The production of cornflakes starts with pressure cooking of a mixture of maize grits, syrup, sugar, malt, and salt. As a result of cooking, starch gelatinizes. The grits are dried, tempered, flaked, and toasted.
5. Rice (*Oryza sativa* L.) starch: Rice starch granules are very small and angular and have a smooth surface and a unimodal size distribution. Prior to rice kernel cooking, the outer fractions are generally removed from the rough rice kernel by dehulling and milling. During rice kernel cooking, starch gelatinizes. Amylose levels and amylopectin structure are important for cooked rice texture. Rice parboiling consists of rough or brown rice soaking, steaming, and drying. Afterwards, the hull (if not done before) is removed, and the parboiled kernels are abrasively milled to remove the bran, respectively. Besides starch gelatinization, amylose-lipid complexation and a protein matrix formed or reinforced during parboiling contribute to the eating quality of the final product.
6. Rye (*Secale cereale* L.) starch: Rye starches consist of larger lens-shaped A-type granules with a broader size distribution than those of wheat starch and small spherical B-type granules. Rye starch gelatinization starts at somewhat lower temperatures than those of wheat starch. Rye flour differs from wheat flour in bread making because rye proteins are not able to form a gluten network.

7. Potato (*Solanum tuberosum* L.) starch: Potato starch granules are large and oval to spherical with a smooth surface and have a broad granule size distribution. Amylose content is slightly lower for potato than for cereal starches. In contrast to cereals, phosphate groups are substituted on potato amylopectin, leading to rapid hydration, swelling, and high viscosity during heating. For fresh consumption, potatoes are usually boiled, baked, or fried.

FUTURE ISSUES

1. How pronounced is amylose leaching when starch is gelatinized in limited water systems such as those in bread or cake making?
2. How does water migration in cereal-based and, hence, starch-based products such as bread relate to the change in their texture in time?
3. What is the starch structure-function relationship in cake and bread firming?
4. What is the relative impact of protein denaturation and starch gelatinization in cake structure setting?
5. How does the interplay of protein and starch during pasta and noodle making relate to the sensory profile of the final product?
6. How do rice parboiling conditions impact the starch-protein matrix, what is the role of rice lipids in the process, and how does all of this relate to rice cooking time and the sensory profile of the final product?
7. How do emulsifiers impact the action of amylases and the residual starch structures in food systems?

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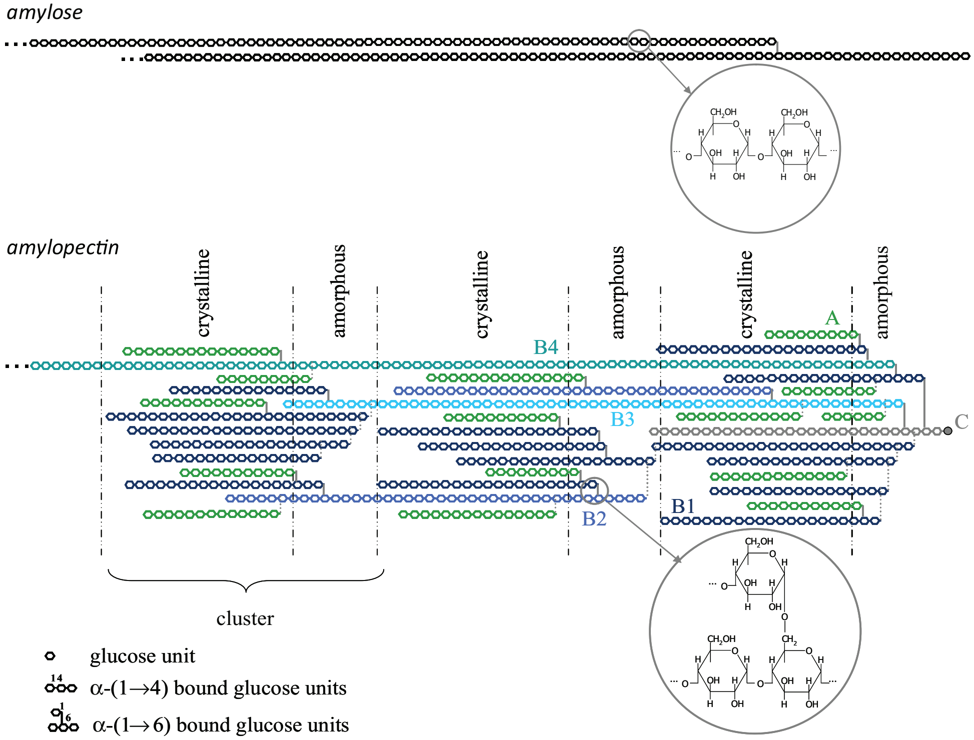

Figure 1

Structure of the main starch constituents: the quasi-linear amylose and the highly branched amylopectin. Amylopectin is presented in line with the cluster model proposed by Hizukuri (1986).

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Contents

Errata

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