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Review

Waxy wheats: Origin, properties, and prospects †

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Starch amylose is synthesized through the activity of the granule-bound starch synthase (GBSS). In wheat (*Triticum aestivum* L.), there are three structural genes encoding isoforms of GBSS. Naturally occurring mutations (null alleles) resulting in the loss of one or more GBSS isoforms have recently been identified. The presence of one or two GBSS null alleles results in the production of starch with reduced amylose content. Reduced amylose wheats have been termed 'partial waxy'. Wheats with three GBSS null alleles produce essentially amylose-free, or waxy, starch. Partial waxy wheats are sources of flours with optimal quality characteristics in certain Asian wet noodle products. In addition, partial waxy wheats are essential to the development of waxy wheats with acceptable agronomic performance. Biochemical features of starch from waxy wheats are similar to those of waxy maize. Waxy wheats may find application in the production of modified food starches, as blending wheats for the formulation of superior noodle flours, and as a means to manipulate amylose contents in substrates for extrusion. Flour from waxy wheats may also be used to extend the shelf-life of baked goods, without a concomitant dilution of wheat gluten. Finally, waxy wheat may increase profitability to gluten manufacturers by providing a co-product with added value. Published by Elsevier Science Ltd.

Throughout history, starch has been a worldwide dietary staple. Starch is found in all plant tissues, but is most abundant in storage organs such as seed endosperms (cereal grains), tubers (potatoes), and roots (cassava and tapioca). Starch is a carbohydrate composed of two types of glucose polymers, amylose and amylopectin. Amylose consists of D-glucosyl units joined by α (1→4) linkages to form straight chains. Amylopectin also contains α (1→4) D-glucosyl chains, but branches occur every 20–25 residues due to the presence of α (1→6) linkages. Amylose may also contain infrequent branches, and the distinction between amylose and amylopectin, at times, may be somewhat arbitrary [1]. Regardless of the presence of branches, amylose still essentially behaves as a linear polymer [1].

In plants, starch is synthesized in specialized organelles known as amyloplasts. Within the amyloplasts, amylose synthesis seems to be solely accomplished by the granule-bound starch synthase (GBSS, EC 2.4.1.21), also known as the 'waxy' protein [2]. Amylopectin synthesis is more complicated, involving concerted activity of starch synthases, branching and de-branching enzymes [3]. Both biochemical and genetic evidence implicate GBSS as the major enzyme responsible for amylose synthesis. Sivak and Preiss [2] combined partial digestion of starch with ion-exchange chromatography to demonstrate starch synthetic activity associated with GBSS. Waxy mutants of maize [4], barley [5] and other plant species lack both GBSS and amylose. Evidently, amylose and amylopectin synthesis proceed, at least in part, by distinct pathways. Waxy mutants of a variety of plant species contain amylopectin identical to that of wild-type plants, but are deficient in amylose. The term 'waxy' was first applied to amylose-free mutants of maize, and refers to the waxy appearance of the endosperm of dried kernels, as opposed to the flinty or translucent appearance of normal (wild-type) kernels [6].

Waxy genes, waxy proteins, and waxy wheat

The genetic structure of wheat precluded the identification of spontaneously occurring waxy mutants. Wheat is a member of the grass tribe Triticeae; the base chromosome number of this group is x = 7. Bread wheat (*Triticum aestivum* L.), an allohexaploid, 2n = 6x = 42, contains three nearly identical sets (A, B and D genomes) of chromosomes inherited from three ancestral diploid species. Each genome (Fig. 1) consists of seven pairs of homologous chromosomes. Each chromosome

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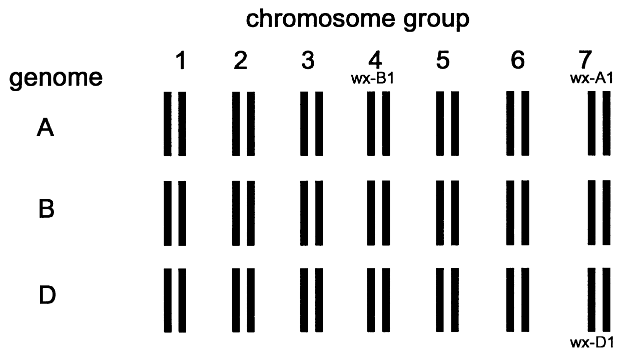


Fig. 1. Organization of bread wheat chromosomes and location of waxy loci.

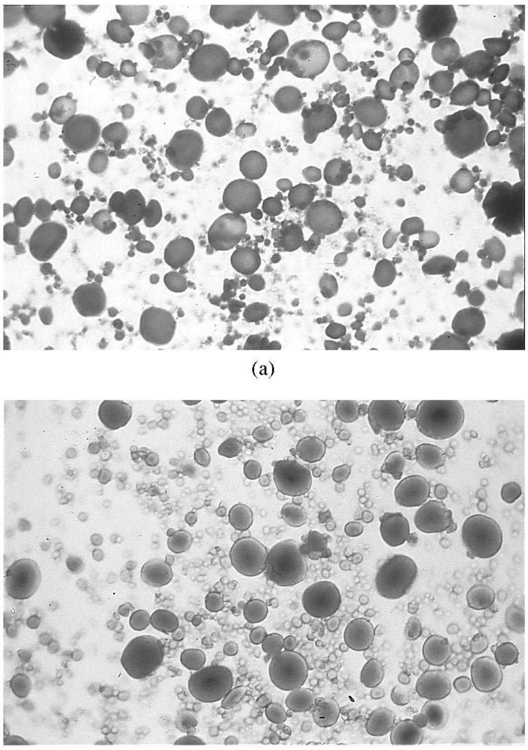
pair is genetically similar to one specific chromosome pair of each of the two remaining genomes. Hence, wheat chromosomes may be further divided into seven 'homoeologous' groups (Fig. 1); the location of genes on, and structure of, each member of these homoeologous groups is virtually identical. Durum wheats (*Triticum turgidum* L. var. *durum*) are allotetraploid, and contain only the A and B genomes.

In the haploid condition all structural genes in bread wheat occur at least in triplicate, while those of durum wheat are found in duplicate. The genetic loci (*wx*) containing the genes encoding bread wheat GBSS are found on chromosomes 7A (*wx-A1*), 4A (*wx-B1*) and 7D (*wx-D1*) [7] (Fig. 1). The 4A locus originally was located on chromosome 7B; however, during the evolution of wheat, a reciprocal translocation occurred, resulting in an exchange of genetic materials between chromosomes 7B and 4A [7]. Hence, this locus is still designated *wx-B1* despite its existence on an A chromosome. Spontaneously occurring waxy bread wheats could have arisen only through either the simultaneous mutation of all three *wx* loci to render them non-functional, or the chance combination of independent mutations through random cross-pollination. The probability of either event occurring is exceedingly low. Nevertheless, through a combination of elegant techniques, diligent detective work, and luck, researchers have now succeeded in developing waxy (amylose-free) wheats through hybridization of wheats carrying null (non-functional) alleles. In addition, the triplicate nature of the bread wheat *waxy* gene system has allowed the identification of 'partial waxy' wheats, or wheats with reduced amylose content.

The *wx-A1*, *wx-B1* and *wx-D1* loci encode GBSS isoforms with the respective molecular weights of 60.1, 59.2 and 59.0 kDa [8]. Separation of the *wx-B1* and *wx-D1* gene products by conventional electrophoretic techniques is difficult. Nakamura *et al.* [9] developed a modified sodium dodecyl sulphate polyacrylamide gel (SDS-PAGE) system that allowed simultaneous one-dimensional separation of the three GBSS isoforms. Nakamura and colleagues [10–12] then proceeded to demonstrate the existence of GBSS variation among wheats. In a number of wheat lines, the *wx-A1* and/or the *wx-B1* isoforms were lacking. The absence of these proteins was attributed to the presence of null, or non-functional alleles at either of these two loci. Null alleles at the *wx-A1* were common in wheats from Japan, Korea and Turkey, while a high frequency of *wx-B1* null alleles was detected in Australian wheats [12]. From a worldwide sample of 1,960 wheats, only one line from China ('BaiHuo') was found to carry a null allele at the *wx-D1* locus. A related wheat ('BaiHuoMai') from the same province in China has subsequently been shown to also carry a *wx-D1* null allele (Graybosch, unpublished results). Several US wheats were found to carry null alleles at either the *wx-A1* or the *wx-B1* loci [13]. One US cultivar, 'Ike', a hard red winter wheat currently grown in western Kansas and Nebraska, was found to carry null alleles at both the *wx-A1* and *wx-B1* loci; no *wx-D1* null alleles were found in US wheats. The null alleles found in US wheats all may be traced to introduction, in the late 1950s and early 1960s, of semidwarf materials from Japan and Korea, or to the western Australia wheat 'Hard Federation'. Lines with one ('single nulls') or two null alleles ('double nulls') have been termed 'partial waxy wheats' [10].

Nakamura and colleagues [14] produced the world's first completely waxy wheats. Traditional hybridizations between the *wx-D1* single null line BaiHuo and the *wx-A1*/*wx-B1* double null line 'Kanto 107' resulted in progeny that lacked all isoforms of GBSS and had no starch amylose. These results have been reproduced, using the same parental materials, in labs in both the US and Australia. Waxy durum wheat also has been developed [14]. Waxy seed can easily be identified by the traditional red–brown color seen after staining with iodine, as opposed to the dark blue–black color exhibited by wild-type wheat kernels [14]. This difference also is readily observed in starch grains (granules) (Fig. 2).

Since this initial report of waxy wheat, two additional sources have been described. Yasui *et al.* [15] recovered two waxy wheat lines after treating seed of the double null line Kanto 107 with the mutagen ethyl methane sulphonate. As Kanto 107 already carried two non-functional alleles, Yasui *et al.* [15] were able to recognize and recover a few waxy seed after nascent mutations at the *wx-D1* locus. Kiribuchi-Otobe [16] identified five waxy wheat lines from a doubled haploid breeding program designed to move rapidly a low amylose characteristic from a mutant line to adapted genetic backgrounds. Doubled haploidy is a process whereby male gametophytes from F_1 hybrids are removed and placed in tissue culture to recover haploid plants. The chromosome number of the haploids is then doubled, and one can obtain homozygous homogeneous lines in one generation, rather than the 4–6 generations typical



(a)

(b)

Fig. 2. Starch granules from a partial waxy (a) and a waxy (b) wheat, stained with a dilute solution of iodine-potasium iodide (X400).

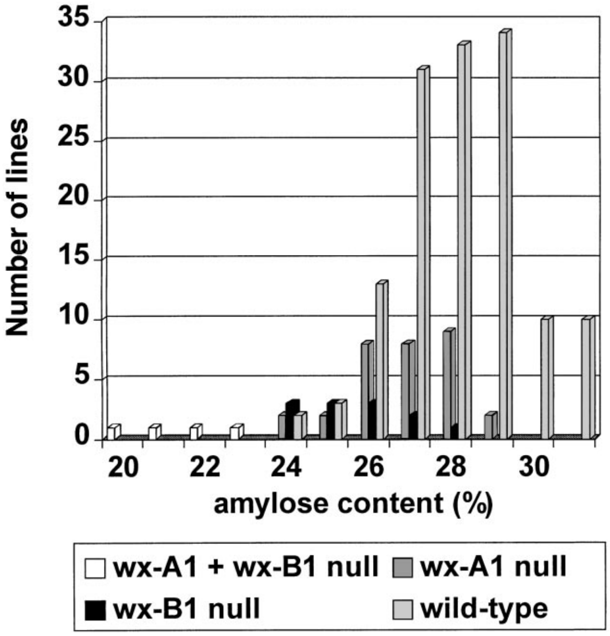


Fig. 3. Amylose contents of Japanese and US wheats–pooled data [12, 13].

of most wheat breeding programs. The origin of these particular waxy lines is puzzling, but the most likely explanation would be that the original low amylose mutant, Tanikei A6099, may have been a double null line, and subsequent somaclonal variation during the tissue culture process may have induced a mutation at the one remaining functional *wx* locus [16].

Finally, at least one GBSS gene has been cloned and sequenced [17]. This information should allow genetic engineers to develop waxy wheat through antisense RNA technology, as has been accomplished in rice [18] and potato [19]. Consumer resistance to genetically engineered foods, however, provides good cause for wheat geneticists and breeders to continue to develop adapted waxy wheats from the original Kanto 107/Bai-Huo materials.

Characteristics and potential uses of partial waxy wheats

At present, more is known of the characteristics of partial waxy wheats than of those of waxy wheats, not only because partial waxy types are more common, but many already are present in currently cultivated lines. Nakamura *et al.* [10] first applied the term 'partial waxy' to wheat lines characterized by a slight reduction in amylose content associated with the presence of null alleles at one or two of the *wx* loci. The reduction in amylose content seems to be the only difference between the starch of partial waxy and wild-type (three active *wx* alleles) [20]; hence, both partial waxy and wild-type starch are often termed 'normal' [20]. Seed and starch grains of partial waxy wheats stain purple to blue–black with iodine staining, and cannot be differentiated visually from wild-type. The extent of amylose reduction in partial waxy lines appears to be dependent both on the number of null alleles present, and the genetic background. Double null lines typically have lower amylose contents than single null lines, which, in turn, may have lower amylose contents than wild-type lines [12, 13] (Fig. 3). The reported ranges in amylose content of single null and wild-type wheats overlap. Even when two null alleles are present, amylose contents are reduced only by about 5% amylose, relative to wild-type (Fig. 3).

Estimates [12, 13] of the extent to which amylose content is reduced by *wx* null alleles are confounded when the effects are compared in different genetic backgrounds. Modifier genes may be operating that alter amylose content independent of the effects of GBSS. For example, Miura *et al.* [21] provided evidence of a possible regulator gene on chromosome 7B that influenced the expression of the *wx* genes. More accurate determinations of the true genetic effects of the various null alleles are possible only when they can be compared in common genetic backgrounds, and some such studies have been completed. Miura and Sugawara [22] measured amylose content in nullisomic–tetrasomic lines of the experimental wheat 'Chinese Spring'. In nullisomic lines, one specific homologous pair of chromosomes has been deleted, and is replaced by additional copies of a homoeologous pair from one of the two remaining genomes. Removal of chromosome 4A, the home of the *wx-B1* locus, reduced amylose content from ~25.5% to 22.5%; when chromosomes carrying either *wx-A1* or *wx-D1* were removed, amylose content declined, but the reduction was only 50% that observed when *wx-B1* was removed. Thus, there may be a differential effect of the individual GBSS isoforms. However, absence of the *wx-B1* GBSS isoform does not always result in a loss of amylose. Mean amylose content of 19 lines carrying a *wx-B1* null allele was lower than the mean of 15 wild-type sister lines derived from a cross between two Australian cultivars; however, some of the individual *wx-B1* null lines had amylose contents that exceeded those of some wild-type lines [23].

The presence of single null alleles, then, does not seem to be a consistent means of developing reduced amylose wheats. Most wheats with two null alleles [12, 13], however, have significantly lower amylose contents than single null or wild-type wheats. Further evidence of the effect of double null lines recently was obtained when amylose contents of isogenic lines derived from the cultivar 'Norin-1' were measured. Studies in the author's laboratory have determined that Norin-1 is actually a mixture of *wx-A1* single null, and *wx-A1* and *wx-B1* double null biotypes. Mean amylose content, measured using two different methods [24, 25] of the double null biotype was significantly lower than that of the single null type (Fig. 4). Thus, the development of double null wheats appears to be the most reliable method for the production of reduced-amylose wheats.

Partial waxy wheats may be of greatest value in the production of certain Asian noodles. Asian noodles are diverse, and vary with both type of raw materials and method of manufacturing [26]. Asian noodles produced from wheat include Japanese udon, also known as white salted noodles, typically produced from medium-protein soft wheats, Chinese-style ra-men or yellow alkaline noodles, formulated from hard wheats, and buckwheat noodles, produced from a mixture of wheat and buckwheat flours [26]. Consumers of udon noodles prefer a soft noodle with a firm surface [26]. Wheats suitable for udon production typically have starch or flour with high swelling volumes [27], and high peak pasting viscosities [28]. Both starch swelling power and high peak viscosities have been associated with reduced amylose contents and the presence of GBSS null alleles [23, 28, 29]. The high frequency of GBSS null alleles in wheats from Japan and Korea [12], and western Australian wheats preferred for Asian noodle applications [23] is likely no accident. Over time, wheat breeders may have unconsciously fixed these alleles in their breeding materials through selection for superior performance in udon noodle production.

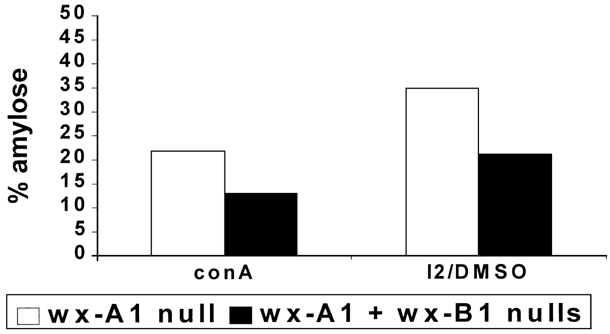


Fig. 4. Amylose contents of Norin-1 biotypes having 1 or 2 active GBSS genes. Amylose contents were measured either by the concanavalin A[24] or iodine in DMSO[25] procedures.

The role of reduced amylose content in conferring superior udon quality recently has been questioned. Batey and colleagues [30] found a non-linear relationship between amylose content and noodle quality; 22% amylose appeared to be optimal, with higher or lower amylose contents being less desirable. Their results, however, were obtained from a cultivar survey, and the experiments were not conducted in a common genetic background. Similarly, the role of starch swelling power, paste viscosities, amylose content and GBSS alleles in the determination of yellow alkaline noodle quality also is the topic of some current debate. Konik *et al.* [31] claimed positive effects could be obtained from increased starch swelling and paste viscosities. Yasui *et al.* [32] found negative relationships between flour swelling volumes, the presence of *wx-B1* null alleles, and alkaline noodle firmness and elasticity. Additional research on the role of amylose content in Asian noodle quality clearly is necessary, and the GBSS gene system provides wheat geneticists and cereal chemists an excellent tool for the conduct of such investigations.

While the development and selection of partial waxy wheats in wheat breeding programs may be of immediate importance in the development of wheats with superior udon noodle quality, their ultimate value may be only in the development of completely waxy (amylose-free) wheats. Widespread availability of waxy wheats will allow millers to blend flours to precise amylose levels, while partial waxy wheats seem to produce starches with amylose contents of no lower than 15%. Before waxy wheats enter commercial production, adapted types must be developed. Introgression of the waxy character from the current unadapted backgrounds to desirable agronomic types will be rendered a far easier task due to the presence of the *wx-A1* and *wx-B1* null alleles already available in cultivars and advanced breeding lines. In addition, partial waxy wheats will provide information on the role of amylose reduction in a variety of wheat products.

Characteristics and potential uses of waxy wheats

Initial study of the functional properties of waxy wheats has been limited by the small supplies available. The waxy wheats produced to date are either unsuitable for cultivation or, in the case of the induced mutants in Kanto 107 [15], very narrowly adapted. In addition, wheat end-use applications are highly dependent upon many features of the wheat grain and endosperm. High-protein hard wheats are favored for bread production, durums are used for pasta, low-protein soft wheats are used to produce biscuits, cookies and crackers, and medium-protein hard or soft wheats are used in Asian noodle applications. The true effects, and value, of waxy wheats may not be completely realized until the waxy character can be combined with various other endosperm specific traits in genetic backgrounds suitable for culture in a range of environments. Initial chemical and physical characterization of waxy wheats, and long histories of studies on the use of waxy starch from maize and barley, however, do provide some clues as to the potential applications of waxy wheats.

Waxy wheat starch has been shown to lack any measurable amylose [20, 32]. Amylopectin structure of waxy wheats is similar to that of wild-type and partial waxy wheats. No differences in amylopectin branching frequencies [20] or degree of polymerization of amylopectin chains [20, 32] were detected. X-ray diffractograms showed the waxy starch granules to have a slightly higher ratio of crystalline to amorphous region, but the difference was not great [20]. Waxy wheat starch had little integral starch lipid, no doubt due to the absence of amylose with a subsequent loss of the amylose-lipid inclusion complexes that contain the majority of starch lipids [32]. Similar differences in lipid content occur when starch from waxy maize or waxy barley were compared to their respective wild-type starches [33]. In two independent studies, thermal transition temperatures of waxy wheat starch, as measured by differential scanning calorimetry (DSC), were found to be similar [20, 32]. T_o (temperature at onset of melting) of both waxy wheat and normal wheat starch was approximately 59°C; T_p (peak of the melting endotherm) of waxy wheat was 65°C while that of normal wheat samples ranged from 62–64°C, and T_c (temperature at completion) of waxy wheat was 4°C higher than that of normal wheat starch [20, 32]. In both studies, measured enthalpy (ΔH) was 3 J/g higher in waxy wheat starch, but ΔH of the amylopectin fractions was identical. Relative to waxy maize starch [20], T_o, T_p and T_c were all ~9°C lower in waxy wheat starch. ΔH and ΔH (amylopectin) of waxy wheat and waxy maize starches were identical [20].

X-ray diffraction analysis of starch gels [20] during retrogradation showed very little increase in crystalline areas of waxy wheat starch. DSC analysis [20] also demonstrated a marked resistance of waxy starch to retrogradation. Over a three week storage period, ΔH values of waxy wheat starch gels varied little, while those of normal wheat starch doubled. The difference in retrogradation behavior of waxy and normal wheat starches was similar to those observed with waxy and normal maize starches [20].

To date, studies of the functional properties of waxy wheat starch have been limited to Brabender Visco Analyser (BVA) and Rapid Visco Analyser (RVA) characterization of starch viscosity, and, some conflicting results have been reported. Kiribuchi-Otobe *et al.* [16], using an RVA, found waxy wheat starch reached a peak viscosity at 84°C, 10°C lower than normal wheat starch. In addition, waxy wheat starch had a higher peak viscosity, but lower setback, than normal wheat starch. Relative to waxy maize, waxy wheat starch peak paste viscosity occurred at similar temperatures, but the wheat sample displayed higher peak viscosities. Using both BVA and RVA, Hayakawa *et al.* [20], found peak viscosities of waxy wheat starch to still occur at a lower temperature than normal wheat starch, and at a temperature identical to that of waxy maize. However, the peak viscosity of the waxy wheat sample was much lower than that of both normal wheat and waxy maize. Setback of waxy wheat was still lower than that of normal wheat. The reason for the discrepancies between the two studies is unclear. However, experimental conditions, specifically rate of temperature increase, differed in the two studies, making direct comparisons tenuous. Nevertheless, waxy wheat starch viscosity differs from both that of waxy maize and normal wheat, and additional study of this phenomenon is necessary.

Commercial application of waxy wheat starch awaits the development of waxy wheat cultivars. Waxy maize was introduced to the US as early as 1908, but it was viewed as little more than a 'curiosity' until the late 1930s and early 40s [34]. Evidently, wheat scientists are a bit more curious than their maize counterparts, as numerous efforts to develop waxy wheat cultivars are underway in Europe, North America, Japan and Australia. It is unlikely that waxy wheat cultivars will be available before the year 2000. The aforementioned properties of waxy and partial waxy wheats, and extensive commercial application and study of waxy maize and waxy barley, allow some speculation as to the eventual applications of waxy wheat. Both scientific and economic factors, however, are likely to be important variables influencing commercial utilization of waxy wheat starch.

In theory, waxy wheat starch could be used in the same types of food and industrial applications currently utilizing waxy maize starch. Waxy maize starch is a preferred substrate for the development of 'modified' starches for food, papermaking and adhesive industries [35], and is a superior substrate than normal maize starch for the production of maltodextrins [36]. Due to their slow retrogradation rates, waxy starches are preferred for refrigerated and frozen food products. Fat replacement also is a common application of waxy or modified waxy maize starch [36]; this sector of the market is rapidly expanding. Waxy starches used in the food industry are typically chemically modified [35]. Modified starches are produced through the use of various chemical cross-linkers; in general, cross-linking stabilizes hydrogen bonding within starch granules, thereby maintaining granule integrity under heating [34]. Wheat starch granules exist as a bimodal population of large 'A-type' and smaller 'B-type' granules [37] while corn starch granules are of more uniform size. This observation, which may explain the differences in thermal and viscoelastic properties of waxy wheat and waxy maize starch [20, 32], might suggest waxy wheat would serve as a different substrate for starch cross-linking agents, and could result in modified starches with altered properties.

Unless waxy wheat starch offers the starch industry some unique functional properties, its use as a substitute for waxy maize starch might be limited by economic factors. In environments in which maize and wheat are co-cultivated, maize grain and starch yields per hectare typically are three times those of wheat. This, in turn, translates to a lower market price for raw materials that favors the use of maize starch. Waxy wheat cultivation might become common in those parts of the world, such as northern Eurasia and Australia, in which maize is poorly adapted. However, increasing globalization of the world's industries, including those in food processing, may still ensure the importation of waxy maize starch, even to areas in which its cultivation is not possible. The economic balance could be tipped in favor of waxy wheat starch, if its production were coupled with wheat gluten processing. Currently, wheat starch is produced essentially as a by-product of the wheat gluten industry. Coupling the waxy starch character with high-protein strong gluten wheats could allow the production of waxy wheat starch at a price that is competitive with that of waxy maize.

Successful commercialization of waxy wheat may very well be dependent upon the identification of wheat-specific applications of waxy starch. The most likely applications would be those in which waxy wheat is used as a blending wheat to develop flours with specific amylose contents. As noted above, udon noodle quality is related to both starch swelling properties and amylose content. The optimal amylose content, however, has yet to be defined. Reduced amylose wheats (partial waxy types) are available, but no amylose contents below 16% amylose have been tested. Waxy wheat would allow a precise identification of optimal amylose content through blending to create flours with amylose contents in graduated steps from 0% to the typical normal levels of 25–30%. Regulating amylose content through blending of waxy and normal wheat flours could also enhance the quality of wheat-based extruded products such as pet foods, mixed-grain snack foods, or breakfast cereals. Both the expansion rate and final product texture of extruded foods may be manipulated through control of amylose:amylopectin ratios [38]. The rapidly expanding market for chilled and frozen dough products might create demand for waxy wheat flour, if the slow rate of starch retrogradation can be used to offset the decline in product quality during storage.

Speculation abounds as to the possibility of using waxy wheat to extend the shelf-life of baked products. Staling of baked goods results in a considerable loss of revenue for bakers and supermarket chains, and shelf-life extenders such as lecithin are among the most common additives to bakery formulations [39]. Suggestions that reduced amylose contents can retard staling derive from studies of the retrogradation behavior of amylose and amylopectin in starch gels or baked goods [40]. As reviewed by Biliaderis [40], starch retrogradation is a biphasic phenomenon, consisting of early complexing of amylose via helix–helix interactions followed by the less-rapid recrystallization of amylopectin. Reducing or eliminating amylose, then, should eliminate the rapid early component of staling. Staling, however, may not be a function solely of starch retrogradation; flour protein quality and its inherent water-holding capacity, water mobility, flour lipids, and protein–starch interactions also contribute to the phenomenon [39]. Starch retrogradation, then, might be just one of many variables governing the rate of staling. Also, any delay in the staling rate due to a reduction in amylose content through addition of waxy wheat flour might very well be offset by the absence of the integral starch lipids in waxy starch [20, 32].

At least three US patents [41–43] describing the use of waxy starch as a means of extending the shelf-life of baked goods have been granted. It is not clear, however, that the increase in shelf-life is derived from the waxy nature of the specified starches. Increased moisture-holding ability of waxy barley flour, when used as an additive to baked goods, was attributed to greater water-holding capacity of 'soluble fiber' [41], probably β-glucans known to be elevated in waxy barleys [5]. Two patents [42, 43] on the use of waxy maize starch in shelf-life extension did not specify waxy starch *per se*, but rather starches produced from maize plants that carried waxy mutations in combination with other mutations, specifically *sugary*-2 or *dull*, that affect starch structure. Zallie *et al*. [43] showed no improvement of shelf-life or bread texture following a 9% substitution of waxy maize flour for wheat flour in a bread formulation, whereas the use of either flour or starch from the *wxsu*-2 genotype dramatically improved both features. Finally, the presence of some amylose appears to be absolutely essential to the production of acceptable quality baked goods. Lorenz [44] compared the effects of waxy and normal barley starch in bread and cakes made from wheat gluten and various starches. Products baked from the normal barley and gluten differed little from the wheat starch controls; 100% waxy starch doughs led to breads and cakes with markedly reduced volume, poor appearance and reduced texture. Waxy starches did have a higher water-binding capacity than the normal starches. Any possible extension of shelf-life by greater water-binding capacity of waxy flours might be offset by the negative effect of reduced amylose on baked good quality and appearance. There may, however, be some level of amylose whereby shelf-life is extended without the loss of product quality. The availability of waxy wheats will allow the production of such flours without a concurrent dilution of wheat gluten proteins, as would occur when either waxy barley or waxy wheat starches are used.

In conclusion, waxy wheat cultivars should be available within the next five years. At present, their primary benefit may be to provide millers a means to blend defined amylose contents for wheat products in which diminished amylose is desirable. Waxy wheats will allow food scientists to manipulate wheat amylose content without dilution of wheat gluten. Such manipulations should better define the role of amylose in the diverse foodstuffs derived from wheat.

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