

Quality of Spaghetti Made from Full and Partial Waxy Durum Wheat

Nathalie Vignaux,¹ Douglas C. Doehlert,^{2,3} Elias M. Elias,¹ Michael S. McMullen,¹
Linda A. Grant,² and Shahryar F. Kianian¹

ABSTRACT

Cereal Chem. 82(1):93–100

The waxy character is achieved in durum wheat (*Triticum turgidum* L. var. *durum*) when the granule-bound starch synthase activity is eliminated. The result is a crop that produces kernels with no amylose in the starch. The presence of two *Waxy* loci in tetraploid wheat permits the production of two partial waxy wheat genotypes. Advanced full and partial waxy durum wheat genotypes were used to study the effect of waxy null alleles on pasta quality. Semolina from full and partial waxy durum wheats was processed into spaghetti with a semicommercial-scale extruder, and pasta quality was evaluated. Cooked waxy pasta was softer and exhibited more cooking loss than pasta made from traditional durum cultivars. These features were attributed to lower setback of waxy starch

as measured with the Rapid Visco Analyser. High cooking loss may be due to the lack of amylose-protein interaction, preventing the formation of a strong protein network and permitting exudates to escape. Waxy pasta cooked faster but was less resistant to overcooking than normal pasta. Partial waxy pasta properties were similar to results obtained from wild-type pasta. This indicates that the presence of a single pair of functional waxy genes in durum wheat was sufficient to generate durum grain with normal properties for pasta production. Waxy durum wheat is not suitable for pasta production because of its softening effect. However, this property may offer an advantage in other applications.

Durum wheat (*Triticum turgidum* L. var. *durum*) is the cereal of choice for pasta production due to its unique color, flavor, and cooking quality (Feillet and Dexter 1996). When pasta is cooked in boiling water, the protein network becomes loose and permits exudates to escape during starch gelatinization (Resmini and Pagani 1983). The exudates remain at the surface of the pasta and, if in excess, pasta becomes sticky (Feillet 1988), giving strands the tendency to clump. The amount of material lost is mainly determined by the strength of the protein network. Amylose seems to play dual roles in this behavior. On one hand, the helical molecular structure of amylose favors its leaching out of the granule. On the other hand, there are indications that amylose contributes to the protein network strength through its binding to a protein fraction, which may reduce leaching (D'Egidio et al 1984). Thus, at the onset of this study, it was not clear what the effect of eliminating amylose from semolina would have on pasta cooking quality.

The recent development of waxy durum wheat lacking amylose in the starch (Hegstad et al 1998) offers the opportunity to evaluate pasta cooking behavior when amylose is absent. The waxy character in durum wheat is obtained when the two *wx* loci on 4A (*Wx-B1*) and 7A (*Wx-A1*) chromosomes are homozygous for the null allele. Waxy genes code for the granule-bound starch synthase (GBSS) responsible for amylose synthesis. When only one genome carries the null alleles, durum wheat is described as partially waxy wheat.

A reduced amylose concentration in the endosperm was beneficial for making udon noodles with better eating quality (Oda et al 1980; Miura and Tanii 1994; Zhao et al 1998) and baked products with delayed staling (Schoch 1965; Krog et al 1989; Bhattacharya et al 2002). Low amylose content was detrimental to spaghetti cooking quality when starch-gluten blends with different amylose content were studied (Dexter and Matsuo 1979). However, results may be different using full and partial waxy durum wheat

wherein the starch granule population is homogeneous in amylose content. Because amylopectin is known to absorb more water than amylose, its sole presence in the waxy starch granule is expected to change the water uptake properties of semolina. Sharma et al (2002) generated a partial waxy tetraploid wheat by crossing a durum wheat with a hexaploid partial waxy bread wheat. They reported 5% less amylose in the *Wx-B1* null F2 derived F5 and F6 lines and reported lower cooking loss and higher adhesiveness from pasta produced from their partial waxy line.

In a previous report (Vignaux et al 2004), we used advanced near-isogenic waxy durum lines grown in two locations to study the effect of the null waxy alleles on grain, protein, starch, and milling characteristics. We showed that normal and partial waxy genotypes had a similar amylose concentration of 23–25%. Waxy genotypes had only 0.7% amylose, as measured with HPLC. Protein concentration was higher for the lines mutated in the *Wx-B1* locus compared with the wild-type lines, but the difference was small and was not expected to influence pasta-making quality. A protein strength test indicated that all the waxy derived lines had stronger gluten compared with the recurrent parent. It was suggested that some protein strength alleles from the hexaploid wheat parent were retained in the derived lines. Semolina starch damage was the highest for waxy lines among waxy derived lines (Vignaux et al 2004).

In this study, we used the same material described by Vignaux et al (2004) to produce 300 g of spaghetti with a semicommercial-scale extruder. The objective of this work was to investigate the effect of the waxy null allele on durum starch properties and its effects on pasta quality.

MATERIALS AND METHODS

Plant Material

Waxy and partial waxy durum lines were developed by North Dakota State University and USDA-ARS (Hegstad et al 1998). The *wx-A1* and *wx-B1* alleles were introgressed from the partial waxy hard red winter wheat cultivar Ike (Martin et al 1994) into the strong gluten durum cultivar Ben (Elias and Miller 1998). Ike is a semidwarf cultivar well adapted to western Kansas that has 13% grain protein concentration in dry land performance tests. Ben is widely grown in the northern plains of the United States. Ben is a medium height durum wheat with high test weight, large kernels, and strong gluten. After the initial cross of Ike and Ben, Ben was used as the recurrent parent to develop four generations of backcrossed (BC₄) waxy and partial waxy durum lines. Double heterozygous lines (lines heterozygous at both loci) were selected

¹ Department of Plant Sciences, North Dakota State University, Fargo, ND 58105.

² USDA-ARS, Wheat Quality Lab, Harris Hall, North Dakota State University, Fargo, ND, 58105. Mention of firm names or trade product does not imply that they are endorsed or recommended by the U.S. Department of Agriculture over other firms or similar products not mentioned.

³ Corresponding author. Phone: 701-231-8069. E-mail: Douglas.Doehlert@ndsu.nodak.edu

at each generation using the pollen iodine staining method. Anthers were collected at flowering time and isolated pollen grains were stained with a potassium iodide and iodine solution (0.2% KI, 0.04% I₂) and observed with a light microscope. The presence of a 3:1 ratio of blue to brown-red pollen was the indicator for a double heterozygous *wx-A1/Wx-A1 wx-B1/Wx-B1* plant. Heterozygous plants were used as the male parent in the next backcross. Finally, the first generation of heterozygous BC₄ plants (BC₄F₁) were selfed to produce the four possible homozygous classes for the waxy alleles, identified using restriction fragment length polymorphism (RFLP) as described by Vignaux et al (2004). These are 1) wild type (*Wx-A1Wx-A1 Wx-B1Wx-B1*), hereafter referred to as WT genotype; 2) partial waxy mutated at the *Wx-A1* locus (*wx-A1wx-A1 Wx-B1Wx-B1*), hereafter referred to as *wx-7A* genotype; 3) partial waxy mutated at the *Wx-B1* locus (*Wx-A1Wx-A1 wx-B1wx-B1*), hereafter referred to as *wx-4A* genotype; and full waxy (*wx-A1wx-A1 wx-B1wx-B1*), hereafter referred to as *wx* genotype. Together, the developed material will be referred to as waxy derived lines. The BC₄F₂ lines identified as homozygous were then selfed once in the greenhouse and once in the field for seed increase. A visual selection for the semidwarf stature (a characteristic of Ike) was also made after each backcross.

Experimental Design

Thirty-five BC₄F₄ lines of the four different genotypic classes were grown in replicated plots at two locations (Langdon and Casselton, ND) in the summer of the year 2000. In addition, seven durum cultivars (Ben, Maier, Plaza, Mountrail, Rugby, Lebsock, and Belzer) were used as checks in the experiment. The experiment included 10 lines of *wx*, 4 lines of *wx-4A*, 9 lines of *wx-7A*, 12 lines of WT, and 7 cultivars as checks for a total of 42 lines. The small number of *wx-4A* lines was due to the difficulty in their selection with the RFLP marker. The difference between those lines and WT lines was a matter of band thickness in a gel. After selecting the lines using the marker, the genetic composition was verified with a SDS-PAGE gel to detect GBSS as described by Zhao and Sharp (1996). This technique detected false *wx-4A* lines that were reallocated to the WT class. Each plot was planted in a 5.94 m² area arranged in a randomized complete block design with two replicates and two locations. Durum samples were cleaned and milled into semolina as described by Vignaux et al (2004).

Starch Isolation Procedure

Starch was separated from the semolina using the modified dough-kneading procedure described by Grant (1998). Semolina was mixed with distilled water (2:1) for the minimum time necessary to form homogeneous dough using a 500-g mixer (National Mfg. Co., Lincoln, NE). The dough mass was kneaded by hand in aliquots of distilled water, changing the water periodically until a gluten ball was formed, and the wash water was clear. The starch and tailings were separated from the water-soluble material by centrifugation (2,000 × *g* for 20 min). Tailings were removed and the starch was resuspended in distilled water and centrifuged to remove contaminants. The starch was air-dried, ground with a mortar and pestle, and passed through a US standard No. 70 sieve.

Starch Pasting Properties

Pasting properties of the starches were determined using a Rapid Visco Analyser (RVA) (Newport Scientific, Ltd., Narrabeen, Australia) according to a method described by Deffenbaugh and Walker (1989). Starch (3 g, 14% moisture basis) was added to an appropriate amount of distilled water in an RVA canister to produce a constant weight of 28 g. The temperature profile was 1 min at 50°C to equilibrate the solution, increasing the temperature to 95°C at 13°C/min, holding the temperature at 95°C for 2.5 min, and lowering the temperature to 50°C at 13°C/min. Peak viscosity (highest viscosity during heating), peak time, final viscosity (viscosity at the end of the test), breakdown (difference

between the peak and the holding viscosity), and setback (difference between final and holding viscosity) were measured from the pasting curve using ThermoLine for Windows software (Newport Scientific, Narrabeen, Australia) and recorded in Rapid Visco Analyser (RVU) units.

Differential Scanning Calorimetry (DSC)

Gelatinization properties of the durum starches were determined using a calorimeter (DSC 7, Perkin-Elmer Corp., Norwalk, CT) according to the procedure of White et al (1989). The samples were heated from 10 to 120°C at a scanning rate of 10°C/min. DSC onset (*T*_o), conclusion (*T*_c), and peak (*T*_p) transition temperatures as well as the enthalpy of gelatinization (ΔH) were computed automatically.

Retrogradation

The percentage of retrogradation of starch samples was investigated using DSC as described by Zhang and Jackson (1992). Starch samples were gelatinized using DSC as previously described, then stored for seven days at 25 and 4°C. After each storage period, the samples were equilibrated at room temperature for ≈2 hr before being scanned between 10 and 120°C at a rate of 10°C/min. The extent of retrogradation of starch was determined by expressing the ΔH of the retrograded gel (ΔH_{retro}) as a percentage of the ΔH of initial gelatinization (ΔH_{native}) as described by Paton (1987). Only one randomly selected line per waxy class was included in this test, with the same experimental design described above.

Freeze-Thaw Stability

The method of White et al (1989) was used to measure freeze-thaw stability. Ten freeze-thaw cycles were performed on gelatinized starches before they were heated by DSC. The peak was automatically analyzed, and the enthalpy was expressed as a percentage of the original starch gelatinization as previously described. This test included the same material that was used for the retrogradation test.

Spaghetti Processing

After mixing semolina with water at 32% absorption for 4 min, the dough was transferred to the mixer of a semicommercial-scale vacuum pasta extruder (DEMACO, Melbourne, FL) and processed into spaghetti according to Approved Method 66-41 (AACC 2000). The extruded spaghetti samples were case-hardened by allowing them to stand for ≈15 min at room temperature and 65% rh before being placed in a drying cabinet. Spaghetti was dried at high temperature using a laboratory pilot-scale drier (Standard Industries, Fargo, ND) with a two-stage cycle described by Debbouz (1994).

Color

A Minolta colorimeter equipped with a DP-301 data processor and CR-300 series chromameter was used to measure dry spaghetti color. Spaghetti strands were disposed in an adapted stand that allowed a flat surface to be formed. Spaghetti was measured using the Hunter Lab scale. The *L** values (brightness) range from 0 (black) to 100 (white). The *a** values (redness) range from negative (green) to positive (red). The *b** values (yellowness) range from negative (blue) to positive (yellow). Values reported are the means of triplicate determinations.

Cooking Quality

Spaghetti (10 g) was broken into pieces 5 cm long and cooked in 300 mL of boiling distilled water. Optimum cooking time (OP) was determined as the time necessary for the white core in the middle of the strand to disappear when pressed between two plexiglass slides. The cooked spaghetti was poured into a Buchner funnel, rinsed with distilled water, and allowed to drain for 2.5 min (Dick et al 1974). The drained spaghetti was weighed to determine cooked weight in grams to calculate water absorption (WA_{OP}). Cooking loss (CL_{OP}), the amount of solid substance lost

to cooking water) was determined using Approved Method 16-50 (AACC 2000). The combined cooking and wash waters were collected in a tared beaker, placed in an air oven at 110°C, and evaporated to dryness. The residue was weighed and reported as a percentage of dry spaghetti. Firmness was measured using a texture analyzer (TA-TXT2, Stable Micro System, Surrey, UK) as described by Fardel et al (1999). The texture analyzer was equipped with a custom-made plexiglass tooth and was operated in the compression mode with a probe speed of 0.2 mm/sec and compression distance of 3.9 mm. The force required to shear five cooked strands of spaghetti was measured, and the results were reported in Nm. A higher value indicates a firmer product.

To test the resistance of the spaghetti samples to overcooking, the same procedure was used except that cooking time was extended by 6 min after optimum cooking time. Firmness, water absorption, and cooking loss at overcooking were recorded and reported as F_{OV} , WA_{OV} , and CL_{OV} , respectively. This cooking time allowed calculation of firmness loss ($F_{OV}/F_{OP} \times 100$ where F_{OP} = firmness at optimum cooking), water absorbed ($WA_{OV} - WA_{OP}$), and solids lost ($CL_{OV} - CL_{OP}$) during the 6 min past optimum cooking time.

Statistical Analysis

For each quality test, an analysis of variance (ANOVA) was performed using the general linear model (GLM) procedure (v. 6.10, SAS Institute, Cary, NC). Location was considered a random effect, and waxy classes and lines were considered fixed effects. There were two replicates for each treatment and analyses were performed in duplicate. Results were analyzed separately per location and combined when variance was homogeneous across location using Bartlett's test of homogeneity. Fisher's protected least significant differences (LSD) test was used to differentiate treatment means at the 5% significance level. Because of unbalanced data, different LSD values were used to compare different means (data not shown).

Correlation coefficients (r) were calculated among quality characteristics using the PROC CORR procedure of SAS for each location independently. If homogeneous, correlation coefficients were pooled over the two locations (Steel et al 1997). Values for r and P reported in this study are pooled correlation with the associated probabilities.

RESULTS

Starch Properties

Starch isolated from wx lines had distinctly different pasting properties, as determined by the RVA, than starch isolated from other genotypes (Fig. 1). Peak viscosity and breakdown were the highest for wx lines, with few significant differences found

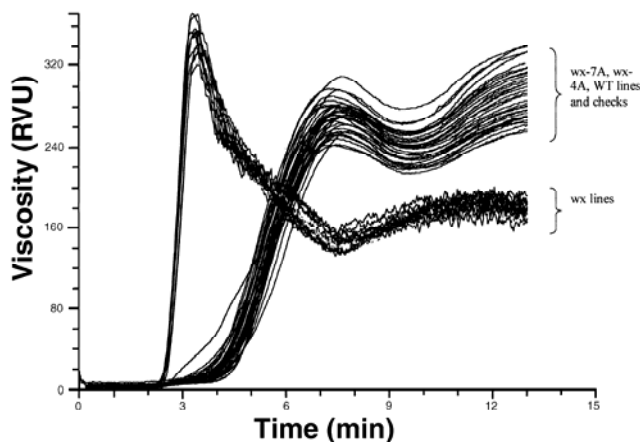


Fig. 1. Example of pasting properties of starch of waxy and partial waxy lines and cultivars using rapid viscoanalysis.

among other genotypes (Table I). The wx lines reached their peak viscosity about 4 min before any other genotype. Starch from wx durum lines was also unique in terms of its distinctly lower final viscosity and setback. Most pasting properties were similar between partial waxy starches and WT starch. An exception was that the setback of partial waxy starches was higher than in most of the normal starches. The significantly higher peak time detected for wx-4A starches compared with WT starches was not considered meaningful because the magnitude of the difference was small and it was similar to the recurrent parent peak time. Final viscosity and setback were lower for the recurrent parent Ben than for the WT lines, although the holding viscosity of these lines (data not shown) did not differ significantly.

Differential scanning calorimetry (DSC) was used to detect heat flow occurring while heating starch with excess water. A DSC thermal profile of WT starch showed two peaks at $\approx 60^\circ\text{C}$ and 100°C (Fig. 2). These corresponded to starch gelatinization and amylose-lipid melting phase transition. The second peak was absent in wx samples. Gelatinization peak temperature and gelatinization enthalpy (ΔH) of wx starches were higher than those of WT, partial waxy, and cultivar starches (Table II). Also, gelatinization peak was wider for wx starch than for any other genotype, as measured by interval temperature ($T_c - T_o$). The wx-4A lines had intermediate values in terms of peak and onset gelatinization temperatures (Table II).

A starch retrogradation experiment was conducted to determine the stability of wx, partial waxy, and WT starches during cold storage and freeze-thaw cycles. After a storage period of seven days on the bench at room temperature, none of the starch types showed retrogradation, as indicated by an absence of a peak after rescanning the samples with DSC (data not shown). Apparently, the temperature and storage time were not favorable for retrogradation. However, when the gelatinized starch samples were stored at 4°C for seven days or when they were submitted to 10 freeze-thaw cycles before DSC analysis, a retrogradation peak was observed (Table III). The size of the peak was an indicator of the extent of retrogradation that occurred in the starch after the treatment. In general, seven days of storage at 4°C induced twice as much retrogradation as 10 freeze-thaw cycles. Also, the peak for wx starches was half the size of the peak of the other genotypes, as indicated by the enthalpy value relative to the value

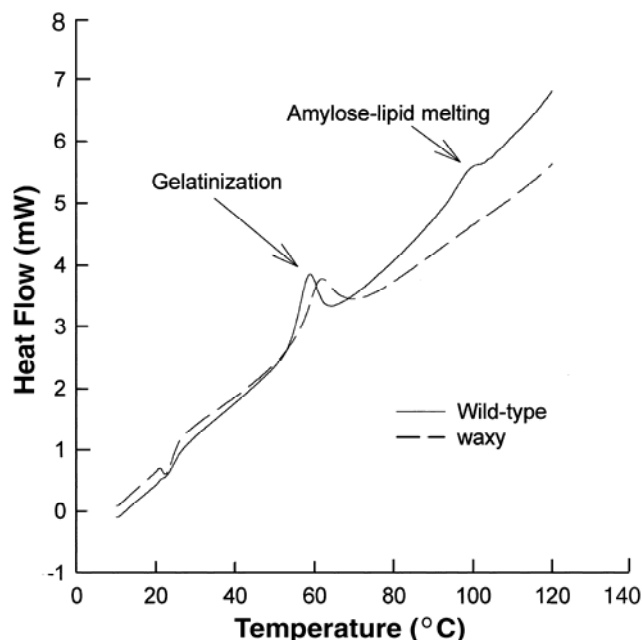


Fig. 2. Example of differential scanning calorimetry profile of waxy and wild-type durum starch.

obtained with native starch for both treatments. This result indicates that wx starch is more resistant to cold storage and freeze-thaw cycles than partial waxy and WT starches. In general, the transition temperature of wx starches was lower, and the shape of the endothermic peak was wider (data not shown), which indicates the presence of a different structure of the retrograded starch compared with the native starch.

Dry Pasta Color

Pasta color was assessed for three color attributes (brightness, redness, and yellowness) (Table IV) using a reflectance colorimeter. Pasta brightness values were slightly lower for the partial waxy lines compared with the WT and wx lines. This difference may not reflect a biologically relevant difference because of the small magnitude. Among the derived lines, wx and wx-7A pasta had the highest redness values. The third coordinate, yellowness, was also affected by the genotype. The wx pasta was significantly less yellow than pasta from partial and WT lines. Also, partial waxy pasta showed an intermediate index between wx and WT index for this characteristic. However, wx pasta yellowness index was similar to the index obtained with pasta made from most of the checks. Pasta made from WT-derived lines were more red and more yellow than pasta made from most cultivars, including pasta made from Ben.

Pasta Cooking Quality

To assess the effect of the waxy null alleles on pasta cooking quality, samples of spaghetti were cooked and optimum cooking time, firmness, cooking loss, and water absorption were recorded (Table V). Results indicated that the wx durum wheat differed dra-

matically in terms of pasta cooking quality from WT lines and conventional durum cultivars. Water absorption was the only measured parameter unaffected by the mutations. Optimum cooking time was significantly shorter for wx spaghetti, which cooked 1 min faster than other spaghetti. The starch gelatinized faster (as indicated by the disappearance of the white core) in the wx pasta than in partial waxy, WT, or cultivar pasta. Partial waxy pasta also showed a slightly shorter cooking time than the WT control, although it did not differ from Ben. At optimum cooking time, firmness was significantly lower for wx pasta than for any other pasta of the experiment. The wx-7A pasta was also slightly softer when compared with wx-4A and WT pasta, but when compared with the reference pasta made from Plaza, wx-7A pasta firmness appeared to remain satisfactory for pasta production. Finally, with 6.2% of material lost in the cooking water, wx samples ranked the highest in terms of cooking loss among all pasta. Partial waxy pasta did not differ from WT pasta for this characteristic.

To determine the resistance of the pasta to overcooking, 6 min was added to the optimum cooking time and the same quality parameters were measured (Table VI). As expected, the general consequences of a longer cooking time were lower firmness, higher water absorption, and higher cooking loss for all samples tested. However, pasta firmness decreased at a different rate for each genotype. The wx, wx-4A, wx-7A, and WT pasta lost 26, 19, 17, and 17% of their firmness, respectively, which indicated that the firmness of wx pasta decreased at a faster rate than other pasta genotypes. Cooking loss was also greater in pasta made with the wx semolina. The rate of water absorption did not follow the same trend as firmness loss. The wx pasta absorbed as much water as did wx-4A pasta and pasta made from Plaza.

TABLE I
Starch Pasting Properties of Waxy, Partial Waxy, and Nonwaxy Durum Genotypes as Determined Using a Rapid Visco Analyser^a

Genotype ^b	Peak Viscosity (RVU)	Breakdown (RVU)	Final Viscosity (RVU)	Setback (RVU)	Peak Time (min)
wx	303.9a	114.1a	148.5a	22.0a	3.4a
wx-4A	262.8b	29.4b	286.2e	106.9f	7.7e
wx-7A	259.6b	29.8b	284.3e	94.4d	7.5cd
WT	257.6bc	28.9b	279.3de	88.5e	7.5d
Ben	228.2cd	27.2b	240.0b	69.5b	7.5c-e
Belzer	252.6b-d	28.1b	274.3c-e	76.7bc	7.3b-d
Lebsock	250.8bd	28.0b	275.6c-e	74.8bc	7.3bc
Maier	238.1b-d	27.1b	254.4bc	69.1b	7.4b-d
Mountrail	247.8b-d	28.6b	262.2b-d	88.7c-e	7.6de
Plaza	253.9b-d	26.6b	282.8de	68.0b	7.2b
Rugby	218.9d	24.2b	238.4b	64.6b	7.4b-d

^a Values with the same letter in the same column do not differ significantly at $P < 0.05$ (means separation, LSD). Means separation was performed using different LSD for each comparison due to different number of observations.

^b WT = wild type (*Wx-A1/Wx-A1 Wx-B1/Wx-B1*); wx-7A = partial waxy mutated at the *Wx-A1* locus (*wx-A1/wx-A1 Wx-B1/Wx-B1*); wx-4A = partial waxy mutated at the *Wx-B1* locus (*Wx-A1/Wx-A1 wx-B1/wx-B1*); wx = full waxy (*wx-A1/wx-A1 wx-B1/wx-B1*).

TABLE II
Gelatinization Properties of Waxy, Partial Waxy, and Normal Durum Starches as Determined by Differential Scanning Calorimetry^a

Genotype ^b	ΔH^c (J/g)	Peak Temp. (°C)	Interval Temp. (°C)	Onset Temp. (°C)	Conclusion Temp. (°C)
wx	14.4a	62.1a	14.7a	55.3a	70.1a
wx-4A	12.1b	60.3b	12.1bc	54.0b	66.1b
wx-7A	11.9b	59.4c	12.0bc	53.3c	65.2cd
WT	11.8b	59.5c	12.2b	53.3c	65.5bc
Ben	11.2b	58.0d	11.6b-d	52.1d	63.7e
Belzer	11.7b	58.8cd	11.0cd	53.1cd	64.1de
Lebsock	11.1b	58.7cd	11.3b-d	53.0cd	64.4c-e
Maier	11.1b	58.8cd	11.6b-d	53.1cd	64.6c-e
Mountrail	11.6b	57.8d	11.3b-d	52.2d	63.5e
Plaza	11.6b	58.4d	10.6d	52.8cd	63.4e
Rugby	11.6b	58.4d	12.2b-d	52.2d	64.5c-e

^a Values with the same letter in the same column do not differ significantly at $P < 0.05$ (means separation, LSD). Means separation was performed using different LSD for each comparison due to different number of observations.

^b WT = wild type (*Wx-A1/Wx-A1 Wx-B1/Wx-B1*); wx-7A = partial waxy mutated at the *Wx-A1* locus (*wx-A1/wx-A1 Wx-B1/Wx-B1*); wx-4A = partial waxy mutated at the *Wx-B1* locus (*Wx-A1/Wx-A1 wx-B1/wx-B1*); wx = full waxy (*wx-A1/wx-A1 wx-B1/wx-B1*).

^c Gelatinization enthalpy.

DISCUSSION

The derived lines used in this study were the result of four backcrosses to a recurrent durum parent (Ben) and would be expected to share 96.9% of the genome of the recurrent parent if no other selection had occurred. However, an additional selection for the semidwarf stature was included at each generation. The results of this selection for height was indicated in our earlier report on the grain quality of these derived lines (Vignaux et al 2004). A number of characteristics differ between the WT line and Ben that would suggest that these lines share less than the expected amounts of genome after four backcrosses, including plant height, test weight, kernel size, and protein characteristics. Whereas these differences confound comparisons of the WT lines with Ben, the derived lines can still be considered near-isogenic among themselves, and effects of the waxy genes on pasta quality can be derived from comparisons of the different waxy lines with the WT lines. Pasta quality of cultivars, including Ben, provide an indication as to how the derived lines compare with accepted cultivars.

The main objective of our study was to determine the effect of waxy null alleles on pasta quality. Cooking quality can be separated into pasta texture after cooking and surface condition (extent of disintegration), which determine stickiness and degree of smoothness of the cooked product. These two aspects are relatively independent of each other (D'Egidio et al 1990). Our results indicate that wx durum pasta performed poorly in terms of pasta texture after cooking. Even though it cooked faster, spaghetti made with wx semolina was too soft (Table V) and did not resist overcooking (Table VI). Those characteristics do not match the consumer preference for al dente pasta. Softness was also a characteristic of waxy cooked rice (Singh et al 2000). Surface condition was not measured in this study, but wx pasta was observed to be stickier than any other pasta in the experiment. Those properties may be beneficial in the ready-to-eat market where pasta needs to cook fast and often with a dry sauce to be hydrated. In our study, the decrease in firmness during cooking was accompanied by an increase in solids lost in the water and a similar loss of firmness. This result identified cooking loss as a major factor in the rapid loss of firmness during pasta cooking. Adding 6 min of cooking time caused wx pasta to soften and lose more solids into water than pasta made from other genotypes (Table VI). Because the lost material could not be amylose, it was likely to be amylopectin that leached out from the waxy pasta. Grant et al (2001) reported higher soluble carbohydrates in wx durum wheat. Therefore, it is also possible that the material lost in the cooking water was composed of soluble carbohydrates yet to be defined. Lipids may also be present in the material lost in the cooking water. Sharma et al (2002) reported lower cooking loss for wx-4A partial waxy pasta, but they measured amylose loss

only (iodine-binding materials). In contrast, the cooking loss results of this study represent all of the solids lost.

The wx pasta did not absorb more water than pasta made from either of the other pastas from the derived lines. This result suggested that pasta softness and cooking loss are due to unique intrinsic properties of wx pasta. Our results on wx pasta cooking quality agree with the recently published work of Grant et al (2004), who also found lower firmness values and shorter cooking time for wx pasta compared with the nonwaxy counterpart. It is important to note that protein strength alleles from Ike may have been retained in the derived lines (Vignaux et al 2004) and may have contributed to the texture of the spaghetti made from the waxy derived lines.

The starch pasting results indicated that wx durum starch swelled at a lower temperature and generated a higher viscosity than did the WT and cultivar starches. These results are consistent with several other reports on wx starch characteristics from tetraploid and hexaploid wheat (Hayakawa et al 1997; Kiribuchi-Otobe et al 1997; Zeng et al 1997; Sasaki et al 2000; Grant et al 2001; Park et al 2001). The reason for such a unique pasting profile was attributed to a looser packing of the granules in the endosperm due to the lack of amylose-lipid complex (Tester and Morrison 1990; Hermansson and Svegmarm 1996). Granules swell rapidly and generate higher viscosity at lower temperatures than starch restricted by the presence of amylose. The large breakdown was explained by the fragile nature of the swollen granules that rupture at a lower temperature than amylose-containing granules, which results in a dramatic drop in viscosity. Setback and final viscosity of wx starch were low because no amylose molecules were present to bind together and crystallize irreversibly during cooling, as occurs in a normal system after granule starch disruption. The unique fast swelling and low setback displayed by wx starch is likely related directly to wx pasta quality. We suggest that fast swelling resulted in faster starch gelatinization, as indicated by shorter optimum cooking time (Table V). High temperature drying promotes protein coagulation (Resmini and Pagani 1983), which results in stronger protein network and improved pasta cooking quality. However, high temperature dried wx pasta had high cooking loss. In a previous report, using the same material (Vignaux et al 2004), we found that wx lines suffered more starch damage. We suggest that higher cooking loss from the wx pasta could be the result of high starch damage and lack of amylose-protein interaction. The low final viscosity of the wx starch (Table I) compared with all other starches may provide the basis for the wx pasta softness after cooking. The significant differences reported between the recurrent parent Ben and the recovered

TABLE III
Retrogradation After Cold Storage and Freeze-Thaw Cycles of Full, Partial Waxy, and Wild Type Durum Lines^a

Genotype ^b	Retrogradation ^c (%)	
	Cold Storage	Freeze-Thaw
wx	23.8a	12.1a
wx-7A	43.6b	23.6b
wx-4A	42.1b	24.6b
WT	42.4b	24.8b
Ben	42.6b	24.3b

^a Values with the same letter in the same column do not differ significantly at $P < 0.05$ (means separation, LSD).

^b WT = wild type (*Wx-A1Wx-A1 Wx-B1Wx-B1*); wx-7A = partial waxy mutated at the *Wx-A1* locus (*wx-A1wx-A1 Wx-B1Wx-B1*); wx-4A = partial waxy mutated at the *Wx-B1* locus (*Wx-A1Wx-A1 wx-B1wx-B1*); wx = full waxy (*wx-A1wx-A1 wx-B1wx-B1*).

^c Retrogradation = $\frac{\Delta H_{\text{retro}}}{\Delta H_{\text{native}}} \times 100$, where ΔH_{retro} = ΔH of the retrograded gel and ΔH_{native} = ΔH of the initial gelatinization.

TABLE IV
Color Analysis of Waxy, Partial Waxy, and Nonwaxy Pasta^a

Genotype ^b	Pasta Color		
	Brightness	Redness	Yellowness
wx	54.4b	4.16a	25.7a
wx-4A	53.3a	3.73b	26.5b
wx-7A	53.3a	4.11a	26.4b
WT	54.3b	3.52b	27.2d
Ben	55.0bc	2.71cd	25.5a
Belzer	54.1ab	3.32bc	25.8ab
Lebsock	55.6c	2.52d	26.3ab
Maier	55.4bc	2.81cd	27.5cd
Mountrail	55.6c	2.51d	26.0ab
Plaza	54.8bc	3.16b-d	27.0bc
Rugby	55.1bc	2.49d	26.3ab

^a Values with the same letter in the same column do not differ significantly at $P < 0.05$ (means separation, LSD). Means separation was performed using different LSD for each comparison due to different number of observations.

^b WT = wild type (*Wx-A1Wx-A1 Wx-B1Wx-B1*); wx-7A = partial waxy mutated at the *Wx-A1* locus (*wx-A1wx-A1 Wx-B1Wx-B1*); wx-4A = partial waxy mutated at the *Wx-B1* locus (*Wx-A1Wx-A1 wx-B1wx-B1*); wx = full waxy (*wx-A1wx-A1 wx-B1wx-B1*).

WT lines in final viscosity and setback were unexpected after four backcrosses. It suggests that there may be alleles from Ike remaining in the derived lines that influence these characteristics.

Another approach to characterize starch gelatinization is to measure the thermal transition occurring during gelatinization with DSC. With no amylose in the starch, wx samples logically did not display the typical thermal transition peak at 100°C of the lipid-amylose complex dissociation (Fig. 2). The higher gelatinization enthalpy recorded for wx starch indicates that amylose lowered the energy required for the transition from an ordered state to a disordered state. The amount of energy necessary for starch gelatinization is directly influenced by granule crystallinity. Amylopectin is thought to be responsible for the crystallinity of the granule (Flipse et al 1996). Therefore, wx granules, lacking amylose, would be more crystalline and would require more energy to gelatinize. Results consistent with this concept have been reported for barley (Gudmundsson and Eliasson 1992; Morrison et al 1993), rice (Biliaderis et al 1986), maize (Inouchi et al 1991), hexaploid wheat (Yasui et al 1996; Hayakawa et al 1997; Fujita et al 1998; Kim et al 2003), and durum wheat (Grant et al 2001). Results from DSC and RVA might appear to be inconsistent with respect to the wx granule starch gelatinization temperature. The two methods are, in fact, measuring different physical states of the starch. In the DSC analysis, starch had a limited water content, which allowed the measurement of the gelatinization thermal transition. In the RVA canister, starch mixed in excess water allowed the measurement of the viscosity change during gelatinization.

The wx starch, even though it is more crystalline than WT starch, swelled and gelatinized rapidly in the presence of excess water. However, with a limited water content, the higher crystallinity of wx starch required higher temperature and energy for the starch to gelatinize.

We expected partial waxy pasta to be more similar to normal pasta because of the presence of a functional pair of waxy genes. Cooking quality differences between partial waxy pasta and WT pasta were minor (Table V). Only wx-7A pasta showed significant but slightly lower firmness compared with the WT samples. However, when compared with the cultivar samples, wx-7A pasta firmness was in the appropriate range for pasta manufacturing. This neutral single mutation effect was also detected in the corresponding starch pasting properties. Partial waxy starch had pasting properties similar to WT starch (Table I). Amylose content was similar in partial waxy and WT lines, as measured by HPLC (Vignaux et al 2004). This result is consistent with the results we reported regarding starch properties and pasta quality. However, it differs with results reported by Sharma et al (2002) and Yamamori and Quynh (2000), who found significant differences in peak viscosity and breakdown between wild-type lines and lines mutated at the 4A locus of durum and hexaploid wheat, respectively. The two studies also reported significant differences in amylose content between lines carrying the null allele at the Wx-4A locus and their normal counterparts. Thus, amylose content appears to be the determinant factor in starch properties and pasta quality. We can offer no explanation for the difference in observation

TABLE V
Pasta Cooking Quality of Waxy, Partial Waxy, and Nonwaxy Durum Pasta at Optimum Cooking Time^a

Genotype ^b	Optimum Cooking Time (min)	Water Absorption (%)	Firmness (Nm)	Cooking Loss (%)
wx	8.8a	29.1ns	0.36a	6.2a
wx-4A	9.9cd	28.9ns	0.57cd	5.6b
wx-7A	10.0df	29.1ns	0.56b	5.6b
WT	10.2e	29.2ns	0.58cd	5.5bc
Ben	9.9cd	28.8ns	0.64de	5.2cd
Belzer	9.7c	28.2ns	0.63de	5.5bc
Lebsock	10.1d-f	29.2ns	0.61b-e	5.2c
Maier	10.0c-f	28.6ns	0.62c-e	5.1d
Mountrail	10.0c-f	28.5ns	0.67e	4.7d
Plaza	9.9cd	29.0ns	0.56b-d	5.5bc
Rugby	9.1b	28.9ns	0.53bc	5.1d

^a Values with the same letter in the same column do not differ significantly at $P < 0.05$ (means separation, LSD). Means separation was performed using different LSD for each comparison due to different number of observations; ns, not significant.

^b WT = wild type (*Wx-A1Wx-A1 Wx-B1Wx-B1*); wx-7A = partial waxy mutated at the *Wx-A1* locus (*wx-A1wx-A1 Wx-B1Wx-B1*); wx-4A = partial waxy mutated at the *Wx-B1* locus (*Wx-A1Wx-A1 wx-B1wx-B1*); wx = full waxy (*wx-A1wx-A1 wx-B1wx-B1*).

TABLE VI
Pasta Cooking Quality After 6 min of Overcooking^a

Genotype ^b	Firmness (Nm)	Firmness Loss ^c (%)	Water Absorption ^c (%)	Additional Water Absorption ^c (%)	Cooking Loss ^c (%)	Additional Cooking Loss ^c (%)
wx	0.27ac	26a	34.8b	5.7ns	7.8a	1.6a
wx-4A	0.47bd	19b	34.6a-c	5.7ns	7.0bc	1.4b
wx-7A	0.46b	17b	34.5a-c	5.4ns	7.0b	1.4b
WT	0.48bd	17b	34.4ac	5.2ns	6.8b-d	1.3b
Ben	0.53ef	16b	33.6de	4.8ns	6.3d-f	1.1c
Belzer	0.53ef	15b	33.6de	5.4ns	6.4d-f	0.9c
Lebsock	0.51d-f	16b	34.4bc	5.2ns	6.2ef	1.0c
Maier	0.56f	10b	33.6de	5.0ns	6.4d-f	1.3b
Mountrail	0.57f	17b	33.4e	4.9ns	5.7f	1.0c
Plaza	0.49b-e	13b	34.8a-c	5.8ns	6.6b-e	1.1c
Rugby	0.42c	22a	34.2cd	5.3ns	6.4c-f	1.3b

^a Values with the same letter in the same column do not differ significantly at $P < 0.05$ (means separation, LSD). Means separation was performed using different LSD for each comparison due to different number of observations; ns = not significant

^b WT = wild type (*Wx-A1Wx-A1 Wx-B1Wx-B1*); wx-7A = partial waxy mutated at the *Wx-A1* locus (*wx-A1wx-A1 Wx-B1Wx-B1*); wx-4A = partial waxy mutated at the *Wx-B1* locus (*Wx-A1Wx-A1 wx-B1wx-B1*); wx = full waxy (*wx-A1wx-A1 wx-B1wx-B1*).

^c Firmness loss = $1 - (F_{ov}/F_{op} \times 100)$; additional water absorption = $WA_{ov} - WA_{op}$; cooking loss = $CL_{ov} - CL_{op}$ where F_{op} = firmness at optimum cooking and F_{ov} = firmness at overcooking; WA_{op} = water absorption at optimum cooking and WA_{ov} = water absorption at overcooking; and CL_{op} = cooking loss at optimum cooking and CL_{ov} = cooking loss at overcooking. Additional water absorption = $WA_{ov} - WA_{op}$.

between our study and the studies of Sharma et al (2002) and Yamamori and Quynh (2000), except for a possible effect of differing genetic backgrounds containing the waxy alleles among the different studies.

The RVA results indicated that wx starch did not retrograde upon cooling (Table I). This unique property was confirmed by measuring retrogradation after storage at -4°C and after freeze-thaw cycles (Table III). In both cases, wx starch was more resistant to retrogradation than partial and WT starch. The resistance of wx starch to retrogradation has also been reported in hexaploid wheat (Hayakawa et al 1997; Yoo and Jane 2002) and waxy rice (Schoch 1967), whereas the retrogradation rate was similar for waxy maize starch (Jane et al 1999) and waxy durum starch (Grant et al 2001) compared with their normal counterpart. According to Miles et al (1985), amylose retrogrades rapidly and reaches maximum crystallization after two days, whereas amylopectin recrystallizes slowly over time. Therefore, in wx starch, retrogradation is likely to be slower, and seven days of storage might not be long enough for the amylopectin to recrystallize to the degree that amylose did in a WT starch. Longer storage time is needed to investigate this hypothesis.

Dry pasta color was tested in our experiment (Table IV) because of its marketing importance and possible change due to the waxy mutation. Semolina color is one of the determinants of pasta color, along with semolina lipoxygenase and processing. Pasta color results were consistent with semolina color in Vignaux et al (2004). When comparing the four waxy derived lines, red and yellow color of pasta appeared to be influenced by waxy null alleles. The wx and wx-7A pasta appeared to be more red than WT pasta, and pastas were less yellow in the nonwaxy phenotypes. However, such a conclusion needs to be reconsidered when comparing the waxy derived lines with the recurrent parent Ben. Pasta made from Ben was less red than pasta made from the wx lines. This result could be attributed to the presence of Ike alleles in the derived lines. The yellowness results are more difficult to interpret because Ben produced pasta as yellow as the wx lines. We would offer two possible explanations for this observation: first, the presence of Ike alleles contributing to higher yellow color values; or second, the presence of null waxy alleles contributing to lower yellow values. Interestingly, a QTL responsible for high yellow color in bread wheat flour has been reported on chromosome 7A on the opposite arm from the wx-A1 locus (Mares and Campbell 2001). Selection of the mutated wx-A1 gene of Ike may be responsible for a concomitant selection of the yellow color QTL in the wx and wx-7A lines, but that allele should not affect the yellow color in the wx-4A and WT lines. The origin of the high yellow values in those lines remains unclear. Because the same processing conditions were used, color difference among the derived lines was possibly due to less abundant xanthophylls in the wx durum wheat or the wx pasta might contain more free sugars undergoing Maillard reaction during drying.

Our results indicate that the waxy mutation affected pasta cooking quality. The effect was directly linked to the amylose content as it was the main characteristic separating the genotypes. However, some of the changes in pasta cooking quality in the wx lines may be attributable to the increased starch damage reported earlier in the wx derived lines (Vignaux et al 2004). A very strong correlation ($r = -0.92$; $P = 0.01$) was found between amylose content and starch damage. In noodles, increased starch damage was reported associated with firmer and more dull colored noodles (Oh et al 1985; Elbers et al 1997). In pasta, it may have contributed to the softer texture observed in the wx lines (Table V).

CONCLUSIONS

The wx semolina was not suitable for pasta production because wx pasta had higher cooking loss and lower firmness than WT or partial waxy pasta. The wx pasta was also more susceptible to

overcooking. The wx pasta color was also distinctly different from nonwaxy lines. Pasta made from partial waxy durum wheat had properties similar to those of WT durum pasta.

A model related to starch properties could be developed to explain the soft texture and high cooking loss observed for wx pasta. During cooking, wx starch gelatinized at a lower temperature than WT starch, which results in shorter cooking time. Then, because of incomplete gluten hydration at this temperature and high starch damage, starch granules are disrupted and materials leach out from the pasta. This process results in higher cooking loss. The wx starch displayed a low setback after gelatinization, which resulted in soft cooked pasta.

This study suggests that wx durum will not be useful for traditional pasta manufacturing. Because of its softening effect, waxy durum may find other unique applications in cereal products.

ACKNOWLEDGMENTS

We are greatly thankful to Frank Manthey and Monisha Chakraborty for their insights on pasta and starch quality. We also thank Brent Hinz and John Osborne for their technical help in milling and pasta manufacturing.

LITERATURE CITED

- AACC. 2000. Approved Methods of the American Association of Cereal Chemists, 10th Ed. Methods 16-50 and 66-41. The Association: St. Paul, MN.
- Bhattacharya, M., Erazo-Castrejon, S. V., Doehlert, D. C., and McMullen, M. S. 2002. Staling of bread as affected by waxy wheat flour blends. *Cereal Chem.* 79:178-182.
- Biliaderis, C. G., Page, C. M., and Maurice, T. J. 1986. On the multiple melting transitions of starch/monoglyceride systems. *Food Chem.* 22:279-295.
- Debbouz, A. 1994. What's new in pasta color? *Pasta J.* 76:31-32.
- Deffenbaugh, L. B., and Walker, C. E. 1989. Comparison of starch pasting properties in the Brabender viscoamylograph and the Rapid Visco Analyzer. *Cereal Chem.* 66:493-499.
- D'Egidio, M. G., De Stefanis, E., Fortini, S., Nardi, S., and Sgrulletta, D. 1984. Interaction between starch and a protein fraction extracted from *T. durum* semolina. *Can. J. Plant Sci.* 64:785-796.
- D'Egidio, M. G., Mariani, B. M., Nardi, S., Novaro, P., and Cubadda, R. 1990. Chemical and technological variables and their relationships: A predictive equation for pasta cooking quality. *Cereal Chem.* 67:275-281.
- Dexter, J. E., and Matsuo, R. R. 1979. Effect of starch on pasta dough rheology and spaghetti cooking quality. *Cereal Chem.* 56:190-195.
- Dick, J. W., Walsh, D. E., and Gilles, K. A. 1974. The effect of field sprouting on the quality of durum wheat. *Cereal Chem.* 51:180-182.
- Elbers, I. J., Ross, A. S., and Quail, K. J. 1997. The effect of starch damage and particle size on the processing and quality of noodles made with both alkali and salt. Pages 128-131 in: *Cereals '96: Proc. 46th Australian Cereal Chem. Conf.* C. W. Wrigley, ed. RACI: Melbourne.
- Elias, E. M., and Miller, J. D. 1998. Registration of 'Ben' durum. *Crop. Sci.* 38:895.
- Fardel, A., Abecassis, J., Hoeler, C., Baldwin, P. M., Buleon, A., Berot, S., and Barry, J.-L. 1999. Influence of technological modifications of the protein network from pasta on *in vitro* starch degradation. *J. Cereal Sci.* 30:133-145.
- Feillet, P. 1988. Protein and enzyme composition of durum wheat. Pages 93-119 in: *Durum Wheat: Chemistry and Technology*. G. Fabiani and C. Lintas, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.
- Feillet, P., and Dexter, J. E. 1996. Quality requirements of durum wheat for semolina milling and pasta production. Pages 95-131 in: *Pasta and Noodle Technology*. J. E. Kruger, R. B. Matsuo, and J. W. Dick, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.
- Flipse, E., Keetels, C. J. A. M., Jacobson, E., and Visser, R. G. F. 1996. The dosage effect of the wild type GBSS allele is linear for GBSS activity but not for amylose content. Absence of amylose has a distinct influence on the physico-chemical properties of starch. *Theor. Appl. Genet.* 92:121-127.
- Fujita, S., Yamamoto, H., Sugimota, Y., Morita, N., and Yamamori, M. 1998. Thermal and crystalline properties of waxy wheat (*Triticum aestivum* L.) starch. *J. Cereal Sci.* 27:1-5.

- Grant, L. A. 1998. Effects of starch isolation, drying, and grinding techniques on its gelatinization and retrogradation properties. *Cereal Chem.* 75:590-594.
- Grant, L. A., Vignaux, N., Doehlert, D. C., McMullen, M. S., Elias, E. M., and Kianian, S. 2001. Starch characteristics of waxy and nonwaxy tetraploid (*Triticum turgidum* L. var. *durum*) wheats. *Cereal Chem.* 78:590-595.
- Grant, L. A., Doehlert, D. C., McMullen, M. S., and Vignaux, N. 2004. Spaghetti cooking quality of waxy and non-waxy durum wheats and blends. *J. Sci. Food Agric.* 84:190-196.
- Gudmundsson, M., and Eliasson, A. C. 1992. Some physical properties of barley starches from cultivars differing in amylose content. *J. Cereal Sci.* 20:95-105.
- Hayakawa, K., Tanaka, K., Nakamura, T., Endo, S., and Hoshino, T. 1997. Quality characteristics of waxy hexaploid wheat (*Triticum aestivum* L.): Properties of starch gelatinization and retrogradation. *Cereal Chem.* 74:576-580.
- Hegstad, J. B., Kianian, S. F., McMullen, M. S., and Doehlert, D. C. 1998. Development of waxy (low amylose) durum cultivars. In: Proc. 9th Int. Wheat Genet. Symp. A. E. Slinkard, ed. University of Saskatchewan: Saskatoon, Canada.
- Hermansson, A. M., and Svegmak, K. 1996. Developments in the understanding of starch functionality. *Trends Food Sci. Technol.* 7:345-353.
- Inouchi, N., Glover, D., Sugimoto, Y., and Fuwa, H. 1991. DSC characteristics of gelatinization of starches of single-, double-, and triple-mutants and their normal counterpart in the inbred Oh43 maize (*Zea mays* L.) background. *Starch* 43:468-472.
- Jane, J., Chen, Y. Y., McPherson, A. E., Wong, K. S., Radosavljevic, M., and Kasemsuwan, T. 1999. Effects of amylopectin branch chain length and amylose content on the gelatinization and pasting properties of starch. *Cereal Chem.* 76:629-637.
- Kim, W., Johnson, J. W., Graybosch, R. A., and Gaines, C. S. 2003. Physicochemical properties and end-use quality of wheat starch as a function of waxy protein alleles. *J. Cereal Sci.* 37:195-204.
- Kiribuchi-Otobe, C., Nagamine, T., Yanagisawa, T., Ohnishi, M., and Yamaguchi, J. 1997. Production of hexaploid wheats with waxy endosperm character. *Cereal Chem.* 74:72-74.
- Krog, N., Olesen, S. K., Toernaes, H., and Joensson, T. 1989. Retrogradation of the starch fraction in wheat bread. *Cereal Foods World* 34:281-285.
- Mares, D. J., and Campbell, A. W. 2001. Mapping components of flour and noodle colour in Australian wheat. *Aust. J. Agric. Res.* 52:1297-1309.
- Martin, T. J., Harvey, T. L., Seifers, D. F., Cox, T. S., Sears, R. G., Bequette, R. K., Currar, S. P., Hatchett, J. H., Chung, O. K., and Witt, M. D. 1994. Registration of 'Ike' wheat. *Crop Sci.* 34:285.
- Miles, M. J., Morris, V. J., Orford, P. P., and Ring, S. G. 1985. The roles of amylose and amylopectin in the gelatinization and retrogradation of starch. *Carbohydr. Res.* 135:271-281.
- Miura, H., and Tanii, S. 1994. Endosperm starch properties in several wheat cultivars preferred for Japanese noodles. *Euphytica* 72:171-175.
- Morrison, W. R., Tester, R. F., Snape, C. E., Law, R., and Gidley, M. J. 1993. Swelling and gelatinization of cereal starches. IV. Some effects of lipid-complexed amylose and free amylose in waxy and normal barley starches. *Cereal Chem.* 70:385-391.
- Oda, M., Yasuda, Y., Okasaki, S., Yamauchi, Y., and Yokoyama, Y. 1980. A method of flour quality assessment for Japanese noodles. *Cereal Chem.* 57:253-254.
- Oh, N. H., Seib, P. A., Ward, A. B., and Deyoe, C. W. 1985. Noodles. VI. Functional properties of wheat flour components in oriental dry noodles. *Cereal Foods World* 30:176-178.
- Park, C. S., Baik, B.-K., Ha, Y. W., and Hong, B. H. 2001. End-use properties of Korean waxy wheat lines. *Korean J. Crop Sci.* 46:367-374.
- Paton, D. 1987. Differential scanning calorimetry of oat starch pastes. *Cereal Chem.* 64:394-399.
- Resmini, P., and Pagani, M. A. 1983. Ultrastructure studies of pasta: A review. *Food Microstruct.* 2:1-12.
- Sasaki, T., Yasui, T., and Matsuki, J. 2000. Effect of amylose content on gelatinization, retrogradation, and pasting properties of starches from waxy and nonwaxy wheat and their F1 seeds. *Cereal Chem.* 77:58-63.
- Schoch, T. J. 1965. Starch in bakery products. *Baker's Dig.* 39:48-57.
- Schoch, T. J. 1967. Starch: Chemistry and Technology. Page 65 in: R. L. Whistler and E. F. Paschall, eds. Academic Press: New York.
- Sharma, R., Sissons, M. J., Rathjen, A. J., and Jenner, C. F. 2002. The null-4A allele at the waxy locus in durum wheat affects pasta cooking quality. *J. Cereal Sci.* 35:287-297.
- Singh, V., Okadome, H., Toyoshima, H., Isobe, S., and Ohtsubo, K. 2000. Thermal and physicochemical properties of rice grain, flour and starch. *J. Agric. Food Chem.* 48:2639-2647.
- Steel, R. G. D., Torrie, J. H., and Dickey, D. A. 1997. Principles and Procedures of Statistics. A Biometrical Approach. 3rd Ed. McGraw-Hill: New York.
- Tester, R. F., and Morrison, W. R. 1990. Swelling and gelatinization of cereal starches. I. Effect of amylopectin, amylose and lipids. *Cereal Chem.* 67:551-557.
- Vignaux, N., Doehlert, D. C., Hegstad, J., Elias, E. M., McMullen, M. S., Grant, L., and Kianian, S. F. 2004. Grain quality characteristics and milling performance of full and partial waxy durum lines. *Cereal Chem.* 81:377-383.
- White, P. J., Abbas, I. R., and Johnson, L. A. 1989. Freeze-thaw and refrigerated-storage retrogradation of starches. *Starch* 41:176-180.
- Yamamori, M., and Quynh, N. T. 2000. Differential effects of Wx-A1, -B1, and -D1 protein deficiencies on apparent amylose content and starch pasting properties in common wheat. *Theor. Appl. Genet.* 100:32-38.
- Yasui, T., Matsuki, J., Sasaki, T., and Yamamori, M. 1996. Amylose and lipid contents, amylopectin structure, and gelatinization properties of waxy wheat (*Triticum aestivum*) starch. *J. Cereal. Sci.* 24:131-137.
- Yoo, S.-H. and Jane, J.-L. 2002. Structural and physical characteristics of waxy and other wheat starches. *Carbohydr. Polym.* 49:297-305.
- Zeng, M., Morris, C. F., Batey, I. L., and Wrigley, C. W. 1997. Sources of variation for starch gelatinization, pasting, and gelation properties in wheat. *Cereal Chem.* 74:63-71.
- Zhang, W., and Jackson, D. S. 1992. Retrogradation behavior of wheat starch gels with differing molecular profiles. *J. Food. Sci.* 57:1428-1432.
- Zhao, X. C., and Sharp, P. J. 1996. An improved 1-D SDS-PAGE method for the identification of three bread wheat 'waxy' proteins. *J. Cereal Sci.* 23:191-193.
- Zhao, X. C., Batey, I. L., Sharp, P. J., Crosbie, G., Barclay, I., Wilson, R., Morell, M. K., and Appels, R. 1998. A single genetic locus associated with starch granule properties and noodle quality in wheat. *J. Cereal Sci.* 27:7-13.

[Received March 31, 2004. Accepted September 16, 2004.]