Effects of Frost Damage and Immaturity on the Quality of Durum Wheat[1,2]

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ABSTRACT

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Frost damage and immaturity were the predominant grading factors associated with the 1992 Canadian durum wheat crop. Canadian Grain Commission grain inspectors composited samples from the 1992 durum wheat harvest survey to yield a series of samples representative of the visual limits of frost damage and immaturity for each Canada Western Amber Durum (CWAD) wheat grade. The greater severity of frost damage and immaturity permitted in No. 4 CWAD and No. 5 CWAD compared to the higher quality milling grades was reflected by lower test weight and reduced kernel size. End-use quality assessment of the composites verified that the CWAD visual grade standards correctly classify Canadian durum wheat. There was a gradual decrease in milling performance and spaghetti quality from No. 1 CWAD to No. 3 CWAD. No. 4 CWAD, which is not intended for high quality pasta, exhibited significantly poorer quality, and No. 5 CWAD, which is a feed-wheat grade, was very poor. Severe frost damage and immaturity had a negative impact upon semolina milling performance due to the combined effects of low semolina yield, unacceptable speck counts, high semolina ash content, and dull semolina color. The poor refinement of semolina from severely frosted and immature durum wheat resulted in duller, browner spaghetti. However, frost damage and immaturity did not influence spaghetti cooking quality, even though a lower yield of wet gluten per unit protein and abnormal mixograph mixing properties indicated that gluten properties had been adversely affected. The proportion of gliadins to glutenins declined with increasing frost damage and immaturity, but no qualitative differences in gluten proteins were apparent.

The relatively short growing season in Western Canada makes the wheat crop vulnerable to frost damage and immaturity. The effects of frost damage and immaturity on the quality of common wheat have been well documented. Common wheat quality effects are related to the duration and degree of frost, and to plant maturity at the time of frost (Newton and McCalla 1934, 1935; McCalla and Newton 1935; Preston et al 1991). The major quality effects attributable to frost damage and immaturity include reduced flour yield, poorer flour refinement, weaker physical dough properties, and poorer baking quality (Geddes et al 1932, Malloch et al 1937, Tipples 1980, Dexter et al 1985a).

In contrast, the effects of frost damage and immaturity on the quality of durum wheat have received little attention. Harris et al (1943) reported increases in protein content, test weight, and improved pasta color with increasing maturity. Dexter and Matsuo (1981) showed that the main effect of immaturity and moderate frost damage was to reduce semolina refinement, which led to duller and browner pasta. To our knowledge, there have been no reports on the effects of severe frost damage and immaturity on durum wheat quality.

The predominant grading factors associated with the 1992 Canadian durum wheat crop were frost and immaturity. A large proportion of the crop was severely frost-damaged. This investigation was undertaken to: 1) establish the effects of severe frost damage and associated immaturity on durum wheat processing quality, and 2) verify that the visual guides for frost damage and immaturity used by Canadian grain inspectors can correctly classify durum wheat according to processing potential.

MATERIALS AND METHODS

Wheat Samples

Samples of durum wheat from the 1992 Grain Research Laboratory (GRL) harvest survey, obtained from producers and from grain companies operating primary elevators in Western Canada, were examined by Canadian Grain Commission grain inspectors. Samples were assigned a grade on the basis of frost damage and immaturity against visual primary standard samples. Visual primary standard samples are used as visual guides to grading grain in Canada before and upon receipt at terminal elevators (Canadian Grain Commission 1991). There are four milling grades of Canada Western Amber Durum (CWAD) wheat; No. 5 CWAD is a feed grade. For this investigation the grain inspectors were instructed to divide the Nos. 3, 4, and 5 CWAD grades into two levels, representing the top (T) and the bottom (B) of each grade. Samples that exhibited any grading factors other than frost damage and immaturity were discarded.

The protein content of each GRL harvest survey sample routinely is determined by near-infrared transmission spectroscopy (Canadian Grain Commission 1992, 1993). Samples were composited on the basis of protein content and visual assessment to give two series of eight CWAD composites each: 1, 2, 3T, 3B, 4T, 4B, 5T, and 5B; one series at 13% protein content and the other at 11% (13.5% mb). Each composite contained a minimum of 30 samples.

Test weights were determined with a Schopper chondrometer using a 1-L container (Dexter and Tipples 1987). Kernel weights were determined as described by Dexter et al (1987).

Wheats were prepared for milling as described by Dexter and Tipples (1987). All samples were tempered to 16% mc overnight (16 hr). Millings were performed in 1-kg lots with a four-stand Allis-Chalmers mill in conjunction with a laboratory purifier (Black 1966), according to the procedure of Dexter et al (1990). The yields of semolina and granulars (semolina and flour combined) were expressed as the proportion of clean wheat on a constant moisture basis. Specks in semolina and granulars were estimated as described by Dexter and Matsuo (1982).

Analytical Tests

All analytical tests are expressed on a 13.5% mb for wheat and a 14.0% mb for semolina. The moisture contents of ground wheat, semolina, and granulars were determined with a rapid moisture tester (C. W. Brabender Instruments, South Hackensack, NJ) as outlined in the instruction manual.

The sodium dodecyl sulfate (SDS) sedimentation volume of wheat was determined by the modified method of Dexter et al (1980). Particle size index (PSI) was determined according to Williams and Sobering (1986). The protein contents (N × 5.7) of wheat and semolina were determined by the Kjeldahl procedure as modified by Williams (1973). Ash content, Agtron color, yellow pigment content, and wet gluten content were determined by AACC methods 08-01, 14-30, 14-50, and 38-12, respectively (AACC 1983). Wheat falling numbers were determined on 7-g samples

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from duplicate 300-g grinds (Tipples 1971). The falling numbers of semolina were determined on duplicate 7-g samples. Mixograph curves were obtained as described in AACC method 54-40A.

Sixty kernels from each composite were randomly selected, and varietal composition was determined from electrophoregrams of gliadins by the acid polyacrylamide gel electrophoresis (acid-PAGE) procedure of Tkachuk and Mellish (1980).

Gluten Protein Characterization

The effect of frost damage on gluten protein composition was determined by both PAGE and by reversed-phase high-performance liquid chromatography (RP-HPLC). Kernels with variable degrees of frost damage were cut in half, and the gliadins of one half of each kernel were extracted into 70% ethanol for analysis by acid-PAGE (Tkachuk and Mellish 1980). Half kernels identified by PAGE as being of the cultivar Kyle were extracted into either 70% ethanol or 50% propan-1-ol (primarily gliadins) or 50% propan-1-ol containing 1% dithiothreitol (gliadins and glutenins) at 60°C (Marchylo et al 1989). Extracts then were analyzed with a Waters HPLC and Waters 860 networking computer system (Waters Associates, Inc., Milford, MA) in conjunction with a Zorbax 300 SB-C8 RP-HPLC column (Rockland Technologies Inc., Newport, DE) as described previously (Marchylo et al 1992).

The ratio of gliadins to glutenins in each composite was estimated by HPLC analysis of fractions obtained by sequential extraction of 1 g of ground grain at 60°C in 50% propan-1-ol (mainly gliadins) and then 50% propan-1-ol containing 1% dithiothreitol (glutenins) (Marchylo and Kruger 1988, Marchylo et al 1989). Gliadin-to-glutenin ratio was computed as the ratio of total integrated peak area for corresponding chromatograms of gliadins and glutenins.

Spaghetti Processing and Evaluation

Spaghetti was prepared by the microprocedure described by Matsuo et al (1972). The 39 and 70°C drying programs described by Dexter et al (1981) were used. Spaghetti color was determined with a spectrophotometer (DU-7, Beckman Instruments, Fullerton, CA) on whole strands of spaghetti mounted on white cardboard (Daun 1978).

Optimum cooking time was defined as the time required for the white core to disappear, determined by crushing strands between transparent plates. Cooking tests were performed on 10 g of spaghetti broken into 5-cm strands and cooked in 200 ml of boiling water. The cooking water was adjusted to a predetermined hardness (Dexter et al 1985b) to eliminate the effect of variable hardness on cooking loss.

Cooking score, which combines instrumental measurements of elasticity and firmness, was obtained as described by Dexter et al (1988). Cooking loss, a measure of the loss of solids to the cooking water, was determined as described by Matsuo et al (1992).

Experimental Design and Statistics

All wheat physical and analytical tests were performed in duplicate. Wheat samples were sequentially extracted in duplicate for estimation of gliadin-to-glutenin ratio.

Milling performance, semolina properties, and spaghetti quality were evaluated in duplicate in complete block design. Each block contained each composite. For milling, sample order within each block was fixed by alternating high and low protein composites in descending order of grade. This design eliminated the possibility of contamination of highly refined semolina obtained from higher grades with less refined semolina from lower grades. For subsequent testing of semolina and spaghetti, sample order within each block was fully randomized.

All statistics were calculated using procedures of the SAS (1988) software system v6.04. Evaluation of milling, semolina, and spaghetti properties was a factorial experiment with two factors (both fixed effects): protein content (two levels) and grade (8 levels). The analysis of variance (ANOVA) sources of variation (with degrees of freedom in brackets) are: blocks (1), protein (1), grade (7), protein to grade interaction (7), error (15), for a total of 31 df. Whenever a significant ($\alpha = 0.05$) treatment effect was observed from the ANOVA of a particular test result, the mean values for each treatment were compared by Fisher's protected least significant difference test ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Varietal Composition

Frost damage and associated immaturity were general across Western Canada in 1992, but the extent of the damage was greater in some areas than others. The possibility existed that composites with a given degree of damage could arise from a localized area, and quality differences among composites could be attributable partly to differences in varietal composition, or to environmental factors other than frost damage and immaturity. Therefore, two separate series of samples were prepared with a high mean wheat protein content (mean 13.1%; range 12.6–13.7%) and a low mean wheat protein content (mean 11.0%; range 10.5%–11.3%). Consistency in the trends observed for the two protein series would suggest strongly that observed quality trends with CWAD grade are primarily due to frost damage and immaturity, exclusive of other factors.

Varietal compositions of individual CWAD grade composites determined by electrophoregrams of gliadins from individual kernels were relatively consistent. As seen in Table I, the proportion of Kyle was near 60% for all grades. Wascana and Medora were the other most prominent cultivars. These results were consistent with estimates of varietal distribution of CWAD for 1992 released by Canadian grain companies and Statistics Canada, and provide strong evidence that samples from all grades were representative of the complete CWAD growing area.

Wheat and Semolina Properties

The top three grades of CWAD wheat are high-quality grades intended for processing by discriminating end-users. The No. 4 CWAD grade is intended as a buffer between wheat of high quality and wheat suitable only for feed purposes (No. 5 CWAD). Therefore, No. 1 CWAD is reasonably well matured and essentially free of frost damage. Increasing degrees of frost damage and immaturity are allowed in No. 2 CWAD and No. 3 CWAD, but severe frost is excluded until the No. 4 CWAD grade is reached. As a result, a significant ($P < 0.05$) progressive decline in test weight was observed throughout the complete CWAD grade range for both protein content series (Fig. 1A). However, kernel weight remained relatively constant until the top (T) of the No. 4 CWAD grade (Fig. 1B), indicative of the exclusion from the top three grades of severely frosted and immature kernels that were thin, shriveled, and light.

Severe frost damage and immaturity in common wheat imparts hard kernel texture, which makes it difficult to reduce middlings into flour, and disrupts the balance of stock in flour mills (Geddes et al 1932, Dexter et al 1985a, Preston et al 1991). Durum wheat is intrinsically very hard. Therefore, it may not be surprising that, in the current study, on the basis of PSI, frost damage was not correlated ($P < 0.05$) to durum wheat hardness (data not shown). The complete range of PSI values for all composites from both protein series was very narrow: 34.9–39.4%.

TABLE I
Mean Varietal Composition (%) by Grade[a]

Grade	Kyle	Wascana	Medora	Others
No. 1 CWAD	60	19	8	13
No. 2 CWAD	66	16	12	7
No. 3 CWAD	58	18	13	11
No. 4 CWAD	69	11	7	12
No. 5 CWAD	56	8	16	14

[a] Mean of low-protein and high-protein series, and mean of top and bottom of grade of Nos. 3, 4, and 5 Canada Western Amber Durum (CWAD). Number of kernels analyzed: 120 for Nos. 1 and 2 CWAD; 240 for Nos. 3, 4, and 5 CWAD.

Test weight and kernel weight are strongly related to durum wheat milling yield potential (Watson et al 1977; Dexter et al 1987, 1991). Semolina yield and milling yield (semolina and flour combined), when expressed on a clean wheat basis, followed a pattern the same as that for kernel weight (Fig. 1C and D). Semolina yield and milling yield did not decline significantly ($P < 0.05$) until the top of the No. 4 CWAD grade; they declined rapidly thereafter. It should be noted that cleaning loss, an important commercial milling consideration, increases as grade declines. As a result, when yields are expressed on a clean wheat basis, as in Figure 1 (C and D) the drop in yield for No. 3 CWAD relative to No. 1 CWAD on a dirty wheat basis, which is commonly used commercially, is understated by about 1%; it is understated by considerably more for the lower grades.

Wheat ash content followed a pattern similar to that of kernel weight. Wheat ash content remained essentially constant from No. 1 CWAD to the top of the No. 4 CWAD grade (Fig. 2A). Thereafter, each successive lower grade composite showed a significantly ($P < 0.05$) higher ash content. This higher wheat ash content of the lower grades can be attributed to reduced endosperm content. It is well established that bran layers contain 15–20 times as much mineral material as does the endosperm (Morris et al 1946).

When marketing semolina, most millers must meet a semolina refinement specification that assures the pasta producer that pasta color will be satisfactory (Dexter and Matsuo 1978, Abecassis and Alause 1979, Matsuo and Dexter 1980, Houliarapoulos et al 1981). The most commonly used semolina refinement indices are ash content, brightness, and degree of speckiness.

As seen in Figure 2B, semolina ash content remained relatively constant throughout the top three grades. A slight increase ($P < 0.05$) is apparent for No. 4 CWAD, and a dramatic increase is evident for No. 5 CWAD. Semolina Agtron color (Fig. 2C) and semolina speck count (Fig. 2D) revealed a moderate ($P < 0.05$) decrease in semolina refinement down to the No. 3 CWAD grade, and a more dramatic decline for the bottom two grades. The consistency in semolina ash content, color, and speck count throughout the top three CWAD grades ensures that the semolina yield achieved within a given refinement specification will relate directly to the intrinsic yield potential of the wheat. For the lower grades, when a constant degree of semolina refinement is required, semolina yield must be reduced more than the intrinsic yield potential would indicate.

There was no visible evidence of sprout damage for any of the durum wheat composites. However, as seen in Figure 3A, the falling number for both the wheat and the semolina showed a continuous decline ($P < 0.05$) as CWAD grade declined. Dexter et al (1985a) observed a similar trend for frost-damaged hard red spring wheat, which they attributed to the relatively high level of α-amylase present in immature wheat kernels (Marchylo et al 1980). Regardless, the falling numbers of even the lowest grade composites were sufficiently high that effects on processing quality attributable to α-amylase would be minimal (Dick et al 1974, Combe et al 1988, Dexter et al 1990).

Yellow pigment content, mainly the carotenoid pigment xanthophyll (Irvine 1971), is a primary attribute of durum wheat quality in some markets because of consumer preference for yellowness in pasta. As seen in Figure 3B, wheat yellow pigment content increased moderately ($P < 0.05$) from No. 1 CWAD to No. 4 CWAD, and it increased dramatically thereafter. In contrast, semolina yellow pigment (Fig. 3B) was essentially constant for all CWAD grades, indicating that endosperm yellow pigment content is not affected by immaturity and frost damage. The higher wheat yellow pigment content of the lower grades is consistent with declining endosperm content. Semolina mill stream analyses have shown that yellow pigment content in durum wheat increases from the inner to the outer part of the wheat kernel (Matsuo and Dexter 1980).

Previous studies have shown that, as the degree of frost damage and immaturity increases in common wheat, physical dough properties weaken, and bread volume, appearance, and crumb characteristics deteriorate (Tipples 1980, Dexter et al 1985a,

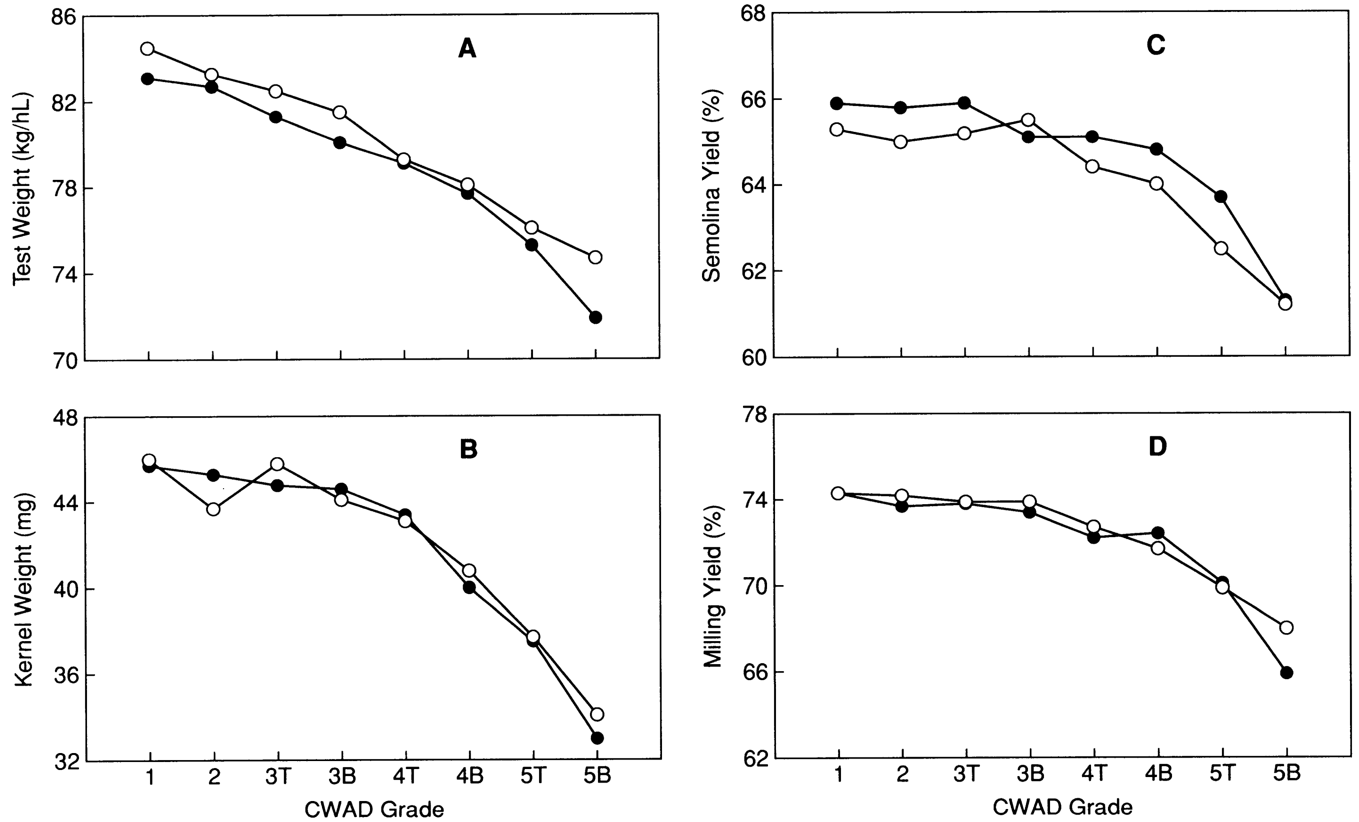

Fig. 1. Relationship of Canada Western Amber Durum (CWAD) grade (sole grading factors: degree of frost damage and immaturity) and durum wheat properties for high protein (●) and low protein (○) composites. **A,** test weight. **B,** kernel weight. **C,** semolina yield. **D,** milling yield (semolina and flour combined). For Nos. 3, 4, and 5 CWAD, composites representing the top (T) and bottom (B) of each grade were prepared.

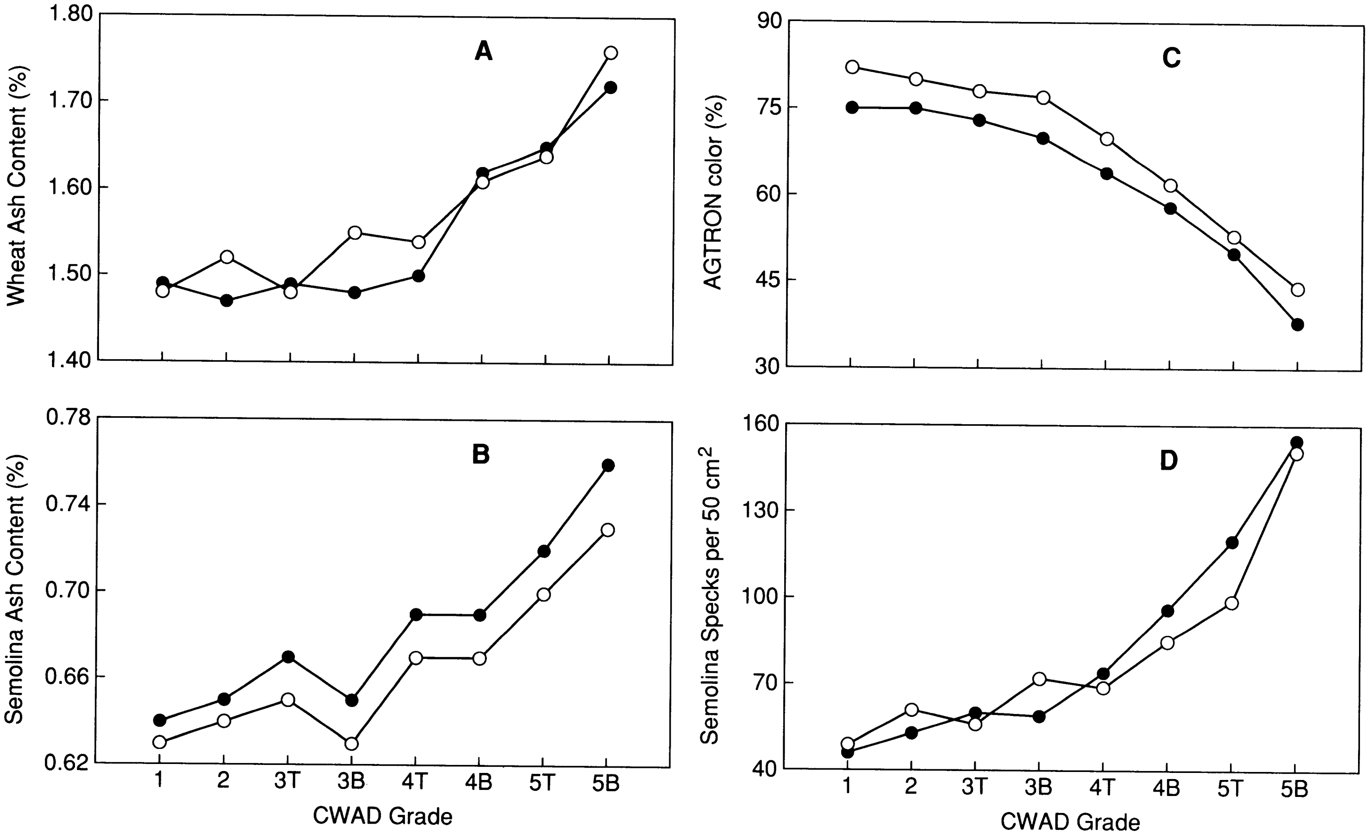

Fig. 2. Relationship of Canada Western Amber Durum (CWAD) grade (sole grading factors: degree of frost damage and immaturity) for high protein (●) and low protein (○) composites. **A,** wheat ash content. **B,** semolina ash content. **C,** semolina Agtron color. **D,** semolina speck count. For Nos. 3, 4, and 5 CWAD, composites representing the top (T) and bottom (B) of each grade were prepared.

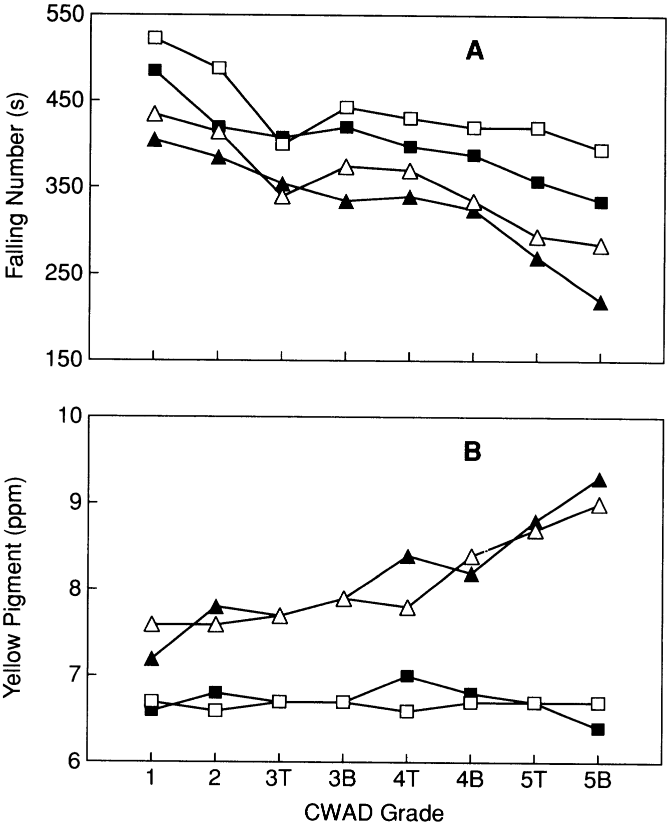

Fig. 3. Relationship of Canada Western Amber Durum (CWAD) grade (sole grading factors: degree of frost damage and immaturity) for high protein wheat (▲), high protein semolina (■), low protein wheat (△), and low protein semolina (□). **A,** falling number. **B,** yellow pigment content. For Nos. 3, 4, and 5 CWAD, composites representing the top (T) and bottom (B) of each grade were prepared.

Preston et al 1991). In the current study, the adverse effects of increasing frost damage on durum wheat physical dough properties were readily apparent from mixograph curves of lower grade composites. Figure 4 shows little evidence of a change in physical dough properties until the top of the No. 4 CWAD grade was reached. The lower grade composites gave increasingly abnormal mixing curves characterized by wild appearance, long mixing times, and low consistencies.

The SDS-sedimentation test was not significantly correlated ($P < 0.05$) to degree of frost damage and immaturity for either protein series: high (mean SDS value 32 ml, range 29–32 ml); low (mean SDS 27 ml, range 24–31 ml) (results not shown). However, as seen in Figure 5A, the yield of wet gluten per unit protein followed the pattern predicted from the mixograph curves. The apparent insensitivity of the SDS-sedimentation test to gluten damage was observed previously for heat-damaged durum wheat and common wheat (Hook 1980, Dexter et al 1989, Preston et al 1989). Therefore, although the SDS-sedimentation test has proven to be an effective durum wheat gluten strength indicator for sound samples in breeding programs (Dexter et al 1980, Quick and Donnelly 1980), it should be used with caution commercially, particularly where there is evidence of frost damage or heat damage.

Acid-PAGE analysis of the gliadins extracted from half kernels exhibiting various degrees of frost damage revealed quantitative differences in some gliadin bands, particularly for the predominant cultivar, Kyle. The γ-gliadin 45 band, a marker for gluten strength in durum wheat (Damidaux et al 1978, Kosmolak et al 1980), was noticeably less intense for severely frosted kernels than it was for kernels free from frost damage. RP-HPLC analysis of gliadin proteins from severely frosted half kernels of Kyle that exhibited quantitative differences in some gliadin bands by PAGE, also showed quantitative differences in relative peak areas when compared to sound unfrosted Kyle kernels (results not shown). Similarly, RP-HPLC chromatograms of gluten proteins (gliadins and glutenins) from the most severely frosted composites, when compared to the top grade composites, also revealed some quantitative differences in relative peak areas (Figs. 6A and B, examples noted by arrows). Therefore, it appears that the effects of severe frost and immaturity on gluten protein composition are attributable mainly to quantitative rather than qualitative differences.

RP-HPLC of sequentially extracted gluten proteins also provided evidence of quantitative differences in composition attributable to frost damage and immaturity (Fig. 5B). In agreement with the mixograph and wet gluten per unit protein results, the ratio of gliadins to glutenins was relatively constant down to the bottom of the No. 3 CWAD grade. The lower grades exhibited significantly ($P < 0.05$) lower proportions of gliadins. The lower proportion of gliadins in the lower grades is consistent with pronounced immaturity. Gliadin synthesis is very rapid up to about one week before physiological maturity (Dexter and Dronzek 1975). Also, gliadins and glutenins are synthesized at different rates (Huebner et al 1990). The severe damage associated with the lower grades is caused by a severe or killing frost before the final stages of development, resulting in either a significant reduction, or more probably, premature termination of gliadin and glutenin synthesis. Thus, depending upon the stage of development of the seed, the ratio of gliadins to glutenins could be influenced significantly.

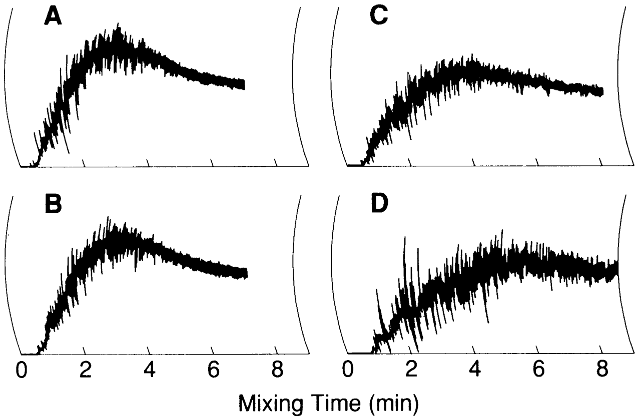

Fig. 4. Semolina mixograph curves of high-protein durum wheat composites. **A,** No. 1 Canada Western Amber Durum (CWAD). **B,** No. 3 CWAD (top of grade). **C,** No. 4 CWAD (top of grade). **D,** No. 5 CWAD (top of grade).

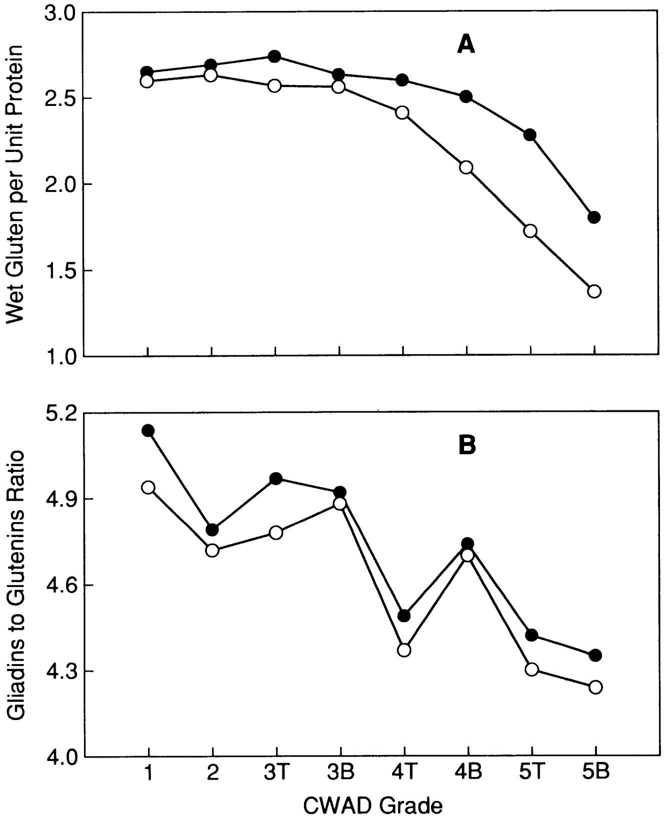

Fig. 5. Relationship of Canada Western Amber Durum (CWAD) grade (sole grading factors: degree of frost damage and immaturity) for high protein (●) and low protein (○) composites. **A,** yield of wet gluten per unit protein. **B,** ratio of gliadins (soluble in 50% propan-1-ol soluble) to glutenins (soluble in 50% propan-1-ol containing 1% dithiothreitol) from reversed-phase high-performance liquid chromatography of sequentially extracted CWAD composites. For Nos. 3, 4, and 5 CWAD, composites representing the top (T) and bottom (B) of each grade were prepared.

Spaghetti Properties

Spaghetti color and appearance were strongly influenced by frost damage and immaturity. Spaghetti drying cycle had no effect ($P < 0.05$) on brightness or purity. Results for spaghetti dried at low temperature (39° C) for both parameters are shown in Figure 7 (A and B).

The pattern for brightness of the spaghetti (Fig. 7A) was the same as the patterns for semolina ash content (Fig. 2B) and Agtron color (Fig. 2C). Spaghetti brightness exhibited a moderate drop ($P < 0.05$) from No. 1 CWAD to the bottom of the No. 3 CWAD grade, then it decreased rapidly. In addition, the increased speckiness of the lower grades (Fig. 2D) detracted from spaghetti appearance.

Spaghetti purity exhibited a pattern with CWAD grade similar to that of brightness (Fig. 7B). Commencing with the bottom of the No. 4 CWAD grade, a significant ($P < 0.05$) decline in purity became apparent. The lower purity of the spaghetti prepared from the lower CWAD grades is a direct result of dimin-

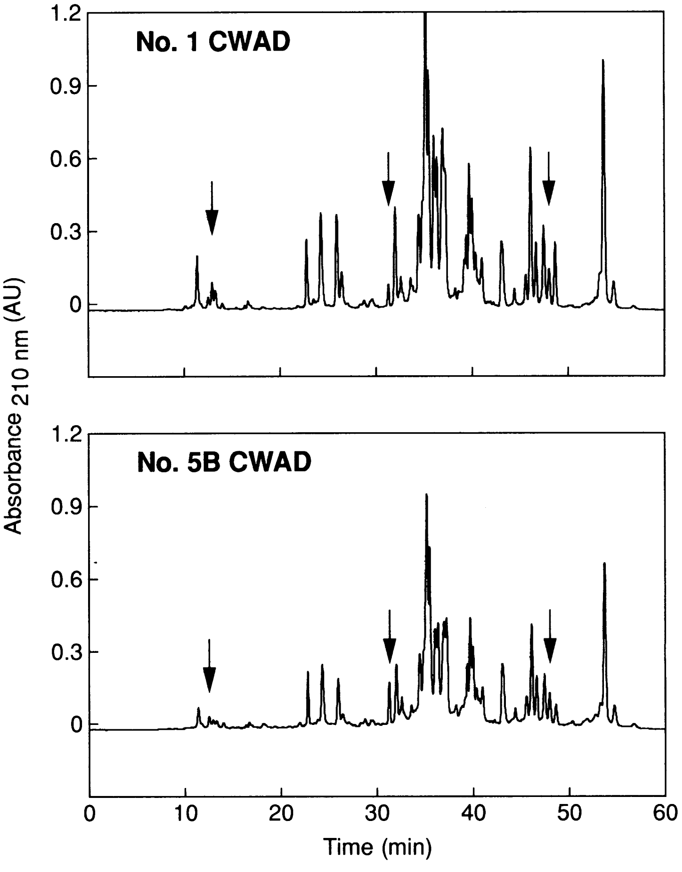

Fig. 6. Reversed-phase high-performance liquid chromatograms of durum wheat gluten proteins extracted in 50% propan-1-ol containing 1% dithiothreitol (gliadins and glutenins). **Top,** high-protein No. 1 CWAD composite. **Bottom,** low-protein No. 5 CWAD (bottom of grade) composite.

ishing semolina refinement. Pigment loss during spaghetti processing increases as semolina refinement declines (Matsuo and Dexter 1980). As shown earlier (Fig. 3A), semolina yellow pigment content was consistent for all CWAD grades.

Spaghetti dominant wavelength, an index of spaghetti brownness, also followed the patterns observed for semolina ash content and Agtron color. As seen in Fig. 7C, for a given grade, the spaghetti dried at high temperature (70°C) was browner (longer dominant wavelength) than was spaghetti dried at low temperature. However, regardless of protein content or drying cycle, spaghetti became increasingly browner (longer dominant wavelength) commencing with the bottom of the No. 4 CWAD grade.

The well-established trends of better cooking score (resilience and firmness) and lower loss of solids during cooking attributable to high-temperature drying (Manser 1980, Dexter et al 1981, Abecassis et al 1984) and to higher protein content (Autran et al 1986, Matsuo et al 1982, D'Egidio et al 1990) were readily apparent (Fig. 8A and B). However, despite the deleterious effects upon gluten properties and physical dough properties of frost damage and immaturity that were discussed above (Figs. 4 and 5), there was no evidence that spaghetti cooking quality was affected.

Although cooking quality of the most severely frost-damaged durum wheats did not appear to be affected, it is important to note that several factors of commercial importance could not evaluated by the small-scale spaghetti processing technique used in this study. The inferior gluten properties of severely frost-damaged durum wheat may adversely affect pasta extrusion properties. It is also possible that the inferior gluten properties of frost-damaged durum wheat could have a deleterious effect on the mechanical strength of the pasta.

CONCLUSIONS

The visual primary standards for frost damage and immaturity accurately reflected the quality expectations for a given CWAD grade. Quality effects from No. 1 CWAD to the bottom of No. 3 CWAD were moderate. The No. 4 CWAD fulfilled its purpose as a buffer between wheat of feed quality (No. 5 CWAD) and the higher milling grades. The No. 5 CWAD grade exhibited quality below that expected for milling grade wheat.

The severe frost and immaturity tolerated in the lower grades of CWAD resulted in lower intrinsic semolina extraction and poorer semolina refinement. The poorer semolina refinement of severely frosted and immature durum wheat caused spaghetti to become duller and browner.

Wet gluten yields and mixograph mixing properties provided evidence that severe frost damage and immaturity were associated with inferior gluten characteristics. The gluten protein compo-

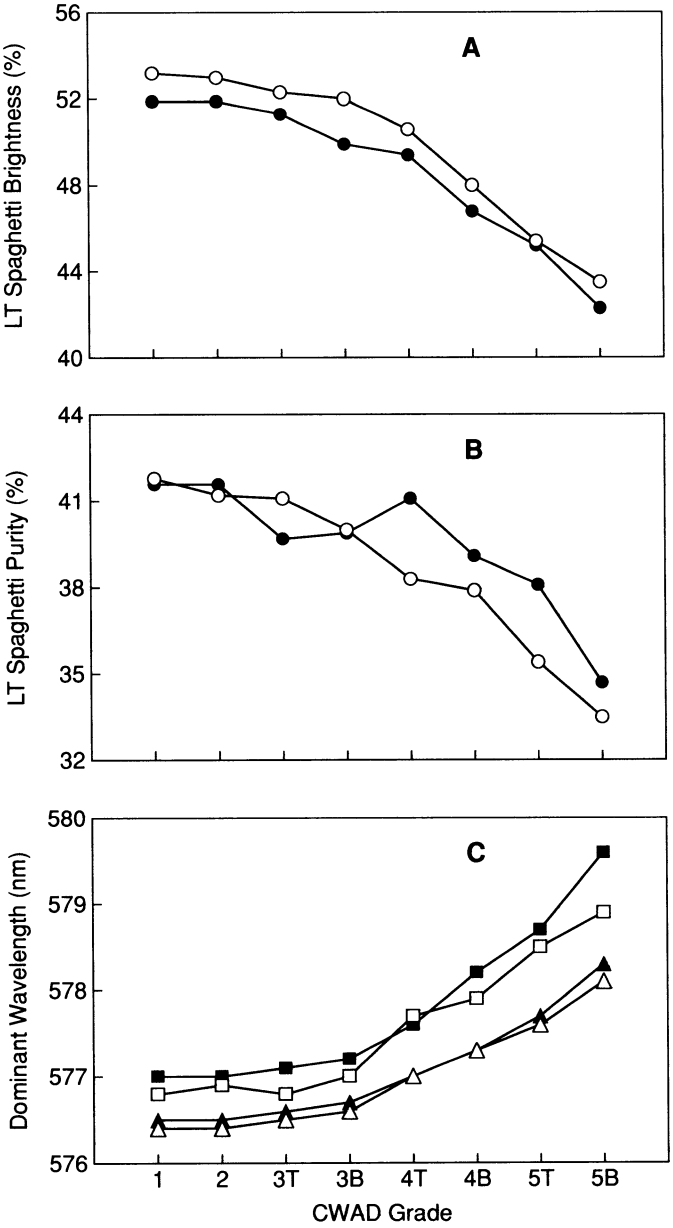

Fig. 7. Relationship of Canada Western Amber Durum (CWAD) grade (sole grading factors: degree of frost damage and immaturity) for high protein (closed symbols) and low protein (open symbols) composites. **A,** spaghetti brightness (dried at 39°C). **B,** spaghetti purity (dried at 39°C). **C,** spaghetti dominant wavelength for spaghetti dried at 39°C (▲ and △) and dried at 70°C (■ and □). For Nos. 3, 4, and 5 CWAD, composites representing the top (T) and bottom (B) of each grade were prepared.

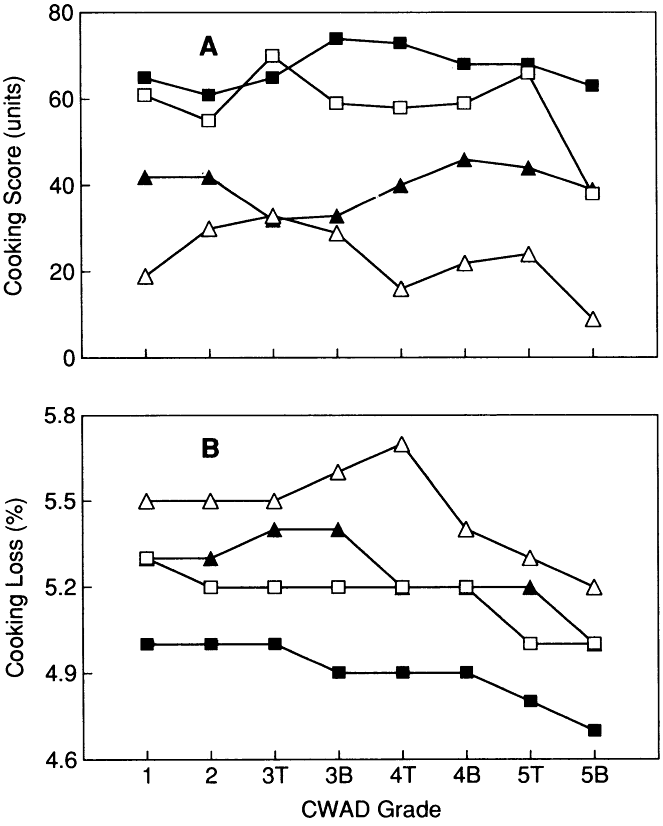

Fig. 8. Relationship of Canada Western Amber Durum (CWAD) grade (sole grading factors: degree of frost damage and immaturity) for high protein (closed symbols) and low protein (open symbols) composites. **A,** spaghetti cooking score. **B,** solids lost to cooking water for spaghetti dried at 39°C (▲ and △) and dried at 70°C (■ and □). For Nos. 3, 4, and 5 CWAD, composites representing the top (T) and bottom (B) of each grade were prepared.

sition of severely frost-damaged wheat was influenced quantitatively but not qualitatively. Cooked spaghetti texture and solids lost to the cooking water were not affected by frost damage and immaturity.

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LITERATURE CITED

ABECASSIS, J., and ALAUSE, J. 1979. Farbton-Indices und Kochqualität von Mahlerzeugnissen aus Durumweizensorten. Getreide Mehl Brot 33:71.

ABECASSIS, J., ALARY, R., and FEILLET, P. 1984. Influence des températures de séchage sur l'aspect et la qualité culinaire des pâtes alimentaires. Ind. Céréales 31:13.

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC, 8th ed. Method 08-01, approved April 1961, revised October 1981;

Method 14-30, approved October 1974, revised October 1982;

Method 14-50, approved April 1961, revised October 1982 and October 1984;

Method 38-12, approved October 1991; Method 54-40A, approved April 1961, revised October 1988. The Association: St. Paul, MN.

AUTRAN, J.-C., ABECASSIS, J., and FEILLET, P. 1986. Statistical evaluation of different technological and biochemical tests for quality assessment in durum wheats. Cereal Chem. 63:390.

BLACK, H. C. 1966. Laboratory purifier for durum wheat semolina. Cereal Sci. Today 11:553.

CANADIAN GRAIN COMMISSION. 1991. Official Grain Grading Guide. (Revised August 1, 1992). Office of the Chief Grain Inspector, Canadian Grain Commission: Winnipeg, Canada.

CANADIAN GRAIN COMMISSION. 1992. Quality of Western Canadian Wheat. Grain Research Laboratory, Canadian Grain Commission: Winnipeg, Canada.

CANADIAN GRAIN COMMISSION. 1993. Grain Research Laboratory Activity Highlights 1992-93. Canadian Grain Commission: Winnipeg, Canada.

COMBE, D., GARCON-MARCHAND, O., SELLER, M.-P., and FEILLET, P. 1988. Influence de la germination sur la qualité des blés durs. Ind. Céréales 53(3):29.

DAMIDAUX, R., AUTRAN, J.-C., GRIGNAC, P., and FEILLET, P. 1978. Mise en évidence de relations applicables en sélection entre l' électrophorégramme des gliadines et les propriétés viscoélastiques du gluten de Triticum durum Desf. C. R. Acad. Sci. Ser. D. 287:701.

DAUN, J. K. 1978. Mathematical model for estimating color of spaghetti and mustard flour. Cereal Chem. 55:692.

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. 67:225.

DEXTER, J. E., and DRONZEK, B. L. 1975. Protein synthesis in triticale and its durum wheat and rye parents. Cereal Chem. 52:577.

DEXTER, J. E., and MATSUO, R. R. 1978. Effect of semolina extraction rate on semolina characteristics and spaghetti quality. Cereal Chem. 55:841.

DEXTER, J. E., and MATSUO, R. R. 1981. Effect of starchy kernels, immaturity, and shrunken kernels on durum wheat quality. Cereal Chem. 58:395.

DEXTER, J. E., and MATSUO, R. R. 1982. Effect of smudge, blackpoint, mildewed kernels, and ergot on durum wheat quality. Cereal Chem. 59:93.

DEXTER, J. E., and TIPPLES, K. H. 1987. Wheat milling at the Grain Research Laboratory. Part 2. Equipment and procedures. Milling 180(7):16.

DEXTER, J. E., MATSUO, R. R., KOSMOLAK, F. G., LEISLE, D., and MARCHYLO, B. A. 1980. The suitability of the SDS-sedimentation test for assessing gluten strength in durum wheat. Can. J. Plant Sci. 60:25.

DEXTER, J. E., MATSUO, R. R., and MORGAN, B. C. 1981. High temperature drying: Effect on spaghetti properties. J. Food Sci. 46:1741.

DEXTER, J. E., MARTIN, D. G., PRESTON, K. R., TIPPLES, K. H., and MacGREGOR, A. W. 1985a. The effect of frost damage on the milling and baking quality of red spring wheat. Cereal Chem. 62:75.

DEXTER, J. E., MATSUO, R. R., LACHANCE, J. J., MORGAN, B. C., and DANIEL, R. W. 1985b. Veränderungen am Programm zur Beurteilung der Durum Weizenqualität der kanadischen Getreideforshungsanstalt. Getreide Mehl Brot 39:131.

DEXTER, J. E., MATSUO, R. R., and MARTIN, D. G. 1987. The relationship of durum wheat test weight to milling performance and spaghetti quality. Cereal Foods World 32:772.

DEXTER, J. E., MARTIN, D. G., and MATSUO, R. R. 1988. The effect of roll flute orientation on durum wheat experimental milling performance and semolina quality. Can. Inst. Food Sci. Tech. J. 21:187.

DEXTER, J. E., MATSUO, R. R., and DANIEL, R. W. 1989. The influence of heat damage on durum wheat spaghetti quality. Can. Inst. Food Sci. Tech. J. 22:227.

DEXTER, J. E., MATSUO, R. R., and KRUGER, J. E. 1990. The spaghetti-making quality of commercial durum wheat samples with variable α-amylase activity. Cereal Chem. 67:405.

DEXTER, J. E., TKACHUK, R., and TIPPLES, K. H. 1991. Physical properties and processing quality of durum wheat fractions recovered from a specific gravity table. Cereal Chem. 68:401.

DICK, J. W., WALSH, D. E., and GILLES, K. A. 1974. The effect of sprouting on the quality of durum wheat. Cereal Chem. 51:180.

GEDDES, W. F., MALLOCH, J. R., and LARMOUR, R. K. 1932. The milling and baking quality of frosted wheat from the 1928 crop. Can. J. Res. 6:119.

HARRIS, R. H., HEGESON, E. A., and SIBBIT, L. D. 1943. The effect of immaturity upon the quality of hard red spring and durum wheats. Cereal Chem. 20:447.

HUEBNER, F. R., KACZKOWSKI, J., and BIETZ, J. A. 1990. Quantitative variation of wheat proteins from grain at different stages of maturity and from different spike locations. Cereal Chem. 67:464.

HOOK, S. W. C. 1980. Dye-binding capacity as a sensitive index for the thermal denaturation of wheat protein: A test for heat-damaged wheat. J. Sci. Food Agric. 31:67.

HOULIAROPOULOS, E., ABECASSIS, J., and AUTRAN, J.-C. 1981. Produits de mouture du blé dur: Coloration et caractéristiques culinaires. Ind. Céréales 12:3.

IRVINE, G. N. 1971. Durum wheat and paste products. Pages 777-800 in: Wheat Chemistry and Technology, 2nd Ed. Y. Pomeranz, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

KOSMOLAK, F. G., DEXTER, J. E., MATSUO, R. R., LEISLE, D., and MARCHYLO, B. A. 1980. A relationship between durum wheat quality and gliadin electrophoregrams. Can. J. Plant Sci. 60:427.

MALLOCH, J. G., GEDDES, W. F., LARMOUR, R. K., and McCALLA, A. G. 1937. The quality and grading of frosted wheat. Annual surveys of the 1930 to 1935 western Canadian crops. Can. J. Res. Sec. C. 15:567.

MANSER, J. 1980. Optimal Parameter für die Teigwarenherstellung am Beispiel von Langwaren. Bericht über die Durum-und Teigwaren-Tagung, Detmold 178:97.

MARCHYLO, B. A., and KRUGER, J. E. 1988. The effect of injection volume on the quantitative analysis of wheat storage proteins by reversed-phase high-performance liquid chromatography. Cereal Chem. 65:192.

MARCHYLO, B. A., LaCROIX, L. J., and KRUGER, J. E. 1980. α-Amylase isoenzymes in Canadian wheat cultivars during kernel growth and maturation. Can. J. Plant Sci. 60:433.

MARCHYLO, B. A., KRUGER, J. E., and HATCHER, D. W. 1989. Quantitative reversed-phase high-performance liquid chromatographic analysis of wheat storage protein as a potential quality prediction tool. J. Cereal Sci. 9:113.

MARCHYLO, B. A., HATCHER, D. W., KRUGER, J. E., and KIRKLAND, J. J. 1992. Reversed-phase high-performance liquid chromatographic analysis of wheat proteins using a new, highly stable column. Cereal Chem. 69:371.

MATSUO, R. R., and DEXTER, J. E. 1980. Comparison of experimentally milled durum wheat semolina to semolina produced by some Canadian commercial mills. Cereal Chem. 57:117.

MATSUO, R. R., BRADLEY, J. W., and IRVINE, G. N. 1972. Effect of protein content on the cooking quality of spaghetti. Cereal Chem. 49:707.

MATSUO, R. R., DEXTER, J. E., KOSMOLAK, F. G., and LEISLE, D. 1982. Statistical evaluation for assessing spaghetti-making quality of durum wheat. Cereal Chem. 59:222.

MATSUO, R. R., MALCOLMSON, L. A., EDWARDS, N. M., and DEXTER, J. E. 1992. A colorimetric method for estimating spaghetti cooking losses. Cereal Chem. 69:27.

McCALLA, A. G., and NEWTON, R. 1935. Effect of frost on wheat at progressive stages of maturity. II. Composition and biochemical properties of grain and flour. Can. J. Res. Sec. C 13:1.

MORRIS, V. H., ALEXANDER, T. L., and PASCOE, E. D. 1946. Studies of the composition of the wheat kernel. III. Distribution of ash and protein in central and peripheral zones of wheat kernels. Cereal

Chem. 23:540.
NEWTON, R., and McCALLA, A. G. 1934. Effect of frost on wheat at progressive stages of maturity. I. Physical characteristics of the kernels. Can. J. Res. 10:414.
NEWTON, R., and McCALLA, A. G. 1935. Effect of frost on wheat at progressive stages of maturity. III. Milling and baking quality. Can. J. Res. 10:414.
PRESTON, K. R., MORGAN, B. C., KILBORN, R. H., and TIPPLES, K. H. 1989. Assessment of heat damage in Canadian red spring wheats. Can. Inst. Food Tech. J. 22:63.
PRESTON, K. R., KILBORN, R. H., MORGAN, B. C., and BABB, J. C. 1991. Effects of frost and immaturity on the quality of a Canadian hard red spring wheat. Cereal Chem. 68:133.
QUICK, J. S., and DONNELLY, B. J. 1980. A rapid test for estimating durum wheat gluten strength. Crop Sci. 20:816.
SAS. 1988. SAS User's Guide: Statistics, Version 6.04. SAS Institute Inc.: Cary, NC.
TIPPLES, K. H. 1971. A note on sample size error in the Falling Number test. Cereal Chem. 48:85.
TIPPLES, K. H. 1980. Effect of immaturity on the milling and baking quality of red spring wheat. Can. J. Plant Sci. 60:357.
TKACHUK, R., and MELLISH, V. J. 1980. Wheat cultivar identification by high voltage electrophoresis. Ann. Technol. Agric. 29:207.
WATSON, C. A., BANASIK, O. J., and SIBBITT, L. D. 1977. Relation of grading and wheat quality characteristics to end-use quality characteristics for durum wheat. Macaroni J. 58(11):10.
WILLIAMS, P. C. 1973. The use of titanium dioxide as catalyst for large-scale Kjeldahl determination of the total nitrogen contents of cereal grains. J. Sci. Food Agric. 24:343.
WILLIAMS, P. C., and SOBERING, D. C. 1986. Attempts at standardization of hardness testing of wheat. II. The near-infrared reflectance method. Cereal Foods World 31:417.

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