

# Single-Kernel Characteristics of Hard Winter Wheats in Relation to Milling and Baking Quality<sup>1</sup>

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## ABSTRACT

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To investigate relationships of wheat single kernel (SK) characteristics with end-use properties, we used 12 hard winter wheat cultivars harvested at six regions in Kansas in 1993. Significant positive correlations occurred among wheat hardness parameters including near-infrared reflectance hardness score, SK hardness index (SK-HI), and SK peak force (SK-PF) obtained by the Single Kernel Characterization System (SKCS). The SKCS characteristics also were significantly correlated to conventional wheat quality parameters such as test weight, kernel density, and kernel sizing. Flour yields were significantly correlated with SK-PF, SK-HI, and SK weight (SK-WT), suggesting the usefulness of

SKCS in evaluating milling quality. The negative correlation of milling score with the standard deviation of SK-HI and SK-PF indicated that uniformity of SK hardness is desirable for good milling performance. However, bread loaf volumes had significant negative correlations with SK diameter and SK-WT, mainly due to the inverse relationship between wheat protein contents and kernel weights or sizes. Loaf volume regression values, the changes in loaf volumes per one percentage point of flour protein, also had significant negative correlations with SK-HI, SK-PF, and SK-WT.

Wheat physical quality characteristics have been tested conventionally by several methods including test weight, grain density, kernel sizing, near-infrared reflectance (NIR) hardness score (HS), etc. Test weight is one of the most common ways to evaluate wheat quality (Miller and Johnson 1956). A high linear correlation coefficient was reported between test weight and flour yield in the range from 40 to 64 lb/bu (Barmore and Bequette 1965). However, Halverson and Zeleny (1988) observed that test weight had no significant relationship with flour yield when test weight was >57 lb/bu.

Wheat density is generally measured by a pycnometer (Thomson and Isaacs 1967). Sharp (1927) reported that kernel size, moisture content, and protein quantity and quality could influence wheat kernel density. Tkachuk and Kuzina (1979) reported an inverse correlation between wheat protein content and density in hard red spring wheats. However, Pomeranz and Matern (1988) pointed out that wheat kernel density could not be a good quality parameter because of its strong environmental effect.

Wheat kernel weight and size are important quality factors for evaluation of milling characteristics. Kernel weight is generally measured as 1,000 kernel weight with the aid of an electronic seed counter (Halverson and Zeleny 1988). Wheat sizing has been performed according to the procedure developed by Shuey (1960). A linear correlation coefficient of 0.957 occurred between the predicted milling yields from wheat sizing data and actual values.

Hardness is an important index for differentiation of wheat classes and has important relationships with the end-use properties of wheat. Wheat hardness has been estimated by the NIR of ground wheat (Norris et al 1989). Wheat kernels with optimum hardness have been preferred for flour milling according to wheat class (Miller and Johnson 1956). Wheat kernel hardness is also

related to tempering of wheat before milling, distribution of flour particle size, flour density, and milling yield (Hoseney et al 1988). However, using conventional wheat hardness testing methods, differentiation of wheats that are mixed with hard and soft wheats is sometimes difficult.

Evaluation of flour for breadmaking has been performed by optimized experimental baking (Finney 1984). The evaluation parameters in experimental baking include flour protein content, mixing characteristics such as mixing time and tolerance, water absorption, and bread characteristics (such as loaf volume, color of crust, symmetry of form, uniformity of loaf, texture, crumb characteristics, aroma, and taste) (Pylar 1988). Baking parameters have close relationships with wheat characteristics. Wheat hardness influenced the baking characteristics of flour in relation to damaged starch granules, which absorb more water and are more susceptible to amylase action than intact starch granules (Pomeranz et al 1984). Slaughter et al (1992) reported significant linear relationships of wheat hardness to bread loaf volume, crumb grain score, and crumb texture, using pooled data from hard winter and spring wheats. Wheat kernel weight is known to have a negative relationship with protein content (Slaughter et al 1992, Satumbaga et al 1995).

Recently, measurement of wheat single kernel (SK) characteristics and their standard deviations has become possible using the Single Kernel Characterization System (SKCS) developed by Martin et al (1993) at the USDA, Agricultural Research Service, Grain Marketing and Production Research Center, Manhattan, KS. The SKCS, developed for wheat classification, has shown a potential for determining wheat quality parameters (Martin et al 1993, Satumbaga et al 1995, Gaines et al 1996, Osborne 1997). The SKCS can be used to measure the mean values of SK hardness index (SK-HI), SK moisture content (SK-MC), SK weight (SK-WT), and SK diameter (SK-DM) of wheat and to calculate the standard deviation (SD) of each parameter using data obtained from  $\approx$ 300 kernels. The SKCS measures hardness based on the force required for crushing single wheat kernels.

Wheat characteristics have significant relationships with flour milling and breadmaking characteristics as previously stated. The SKCS parameters are also expected to improve wheat quality evaluation for flour milling and breadmaking in addition to wheat classification. Thus, a study is necessary to evaluate and identify SK wheat characteristics as quality factors in relation to end-use properties of hard winter wheats. Kansas is a major hard winter wheat producing state in the United States. In 1997, Kansas yielded  $\approx$ 42% of total hard winter wheat produced in the United States (Anonymous 1997). Thus, investigation of the SK charac-

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teristics of wheat produced in Kansas is expected to give valuable information on quality evaluation of hard winter wheats. This research was performed to investigate the relationships between SKCS characteristics and milling and baking parameters in hard winter wheats produced in Kansas. In the present study, 12 wheat cultivars harvested at six regions in Kansas were investigated for variables including conventional wheat characteristics (physical and chemical), baking parameters, and SK wheat characteristics measured by the SKCS.

## MATERIALS AND METHODS

### Materials

Winter wheat cultivars Arlin, Cimmaron, Discovery, Karl, Karl 92, Newton, Scout 66, TAM 107, TAM 200, Tomahawk, Voyager and 2163 harvested in Ellis, Franklin, Greeley, Labette, Stafford, and Thomas Counties in Kansas in 1993 were used in this study. All wheats were cleaned with a Carter Dockage Tester before analyses. All the analyses, testing, and measurements were duplicated.

### Methods

Protein content (PC) ( $N \times 5.7$ ) was determined by a Nitrogen Determinator (Leco Corp., St. Joseph, MI). Ash content (AC) and moisture were determined by Approved Methods 08-01 and 44-15A, respectively (AACC 1995). Micro-test weight was determined using  $\approx 70$  g of wheat cleaned by a Carter Dockage Tester (Chang 1988). Micro-test weight was converted to pounds per Winchester bushel (lb/bu). Grain density was measured by an air pycnometer (model SPY2, Quantachrome Corp., Syosset, NY) to determine the volume of grain samples as described by Chang (1988). Distribution of wheat according to size was determined by sieving wheats on Tyler No. 7 (2.92-mm openings) and Tyler No. 9 (2.24-mm openings) sieves. Large, medium, and small kernels, which were the amounts of overs from the Tyler No. 7 and Tyler No. 9 sieves and remainders, respectively, were designated as percentages of the total amount of wheat. The NIR-HS was measured by the method described by Norris et al (1989) with a slight

modification. Whole wheat ( $\approx 18$  g) was ground in a cyclone sample mill (Udy Co., Fort Collins, CO) with a sample feed controller. Ground samples were analyzed (6500, NIRSystems, Inc., Silver Springs, MD) after the ground sample was stabilized for more than 3 hr. Standardization of the NIR analyzer was performed according to Approved Method 39-70A using the standardization grain sample set provided by the Federal Grain Inspection Service (AACC 1995). Hardness scores obtained by NIR were corrected for moisture content (Windham et al 1993).

Approximately 300 kernels of wheat were analyzed by an experimental SKCS (Martin et al 1993). Single kernel wheat characteristics included mean values and standard deviations of SK-HI, SK-PF, SK-MC (%), SK-WT (mg, as is), and SK diameter SK-DM (mm). The SK-PF (A/D count) indicates maximum load cell force in force-time crush profile of wheat.

### Flour Milling

Wheat conditioned to 15% moisture content was milled on an experimental Brabender Quadrumat Sr. mill. Temperature of the rolls was maintained at 88–90°F during milling. The feed rate of wheat to the mill was 150 g/min. A milling score that was empirically developed at the Hard Winter Wheat Quality Laboratory, Grain Marketing and Production Research Center, was calculated as:

$$\text{Milling score} = 100 - \{(\text{test weight} - 60) + (82 - \text{flour yield}) + 100 \times (\text{flour AC} - \text{wheat AC}/3.9) + 10 \times [(\text{wheat PC} - 1) - \text{flour PC}]\}$$

where the units were lb/bu for test weight and % for flour yield, and wheat/flour AC and PC. Wheat and flour PC and AC were based on a 14 % moisture basis (mb).

### Baking Procedure

The optimized, straight-dough method described by Finney (1984) and Approved Method 10-10B (AACC 1995) was used for experimental baking. The formula contained 100 g (14% mb) of flour, 6 g of sugar, 3 g of shortening (Vream, Bunge Foods), 1.5 g of NaCl, 1.0 g of dry yeast (Fleischmann), 5 mg (50 ppm) of ascorbic acid, and 0.25 g of barley malt (50–60 DU/g, 20°C).

TABLE I  
Mean ( $n = 72$ ), Standard Deviation (SD), and Range of Wheat and Milling Characteristics<sup>a</sup>

Quality Parameters	Mean	SD	Minimum	Maximum
Micro test weight (lb/bu)	57.0	2.3	51.3	61.5
Kernel density (g/cm <sup>3</sup> )	1.41	0.03	1.36	1.48
Kernel sizing (%)				
Large	60.1	16.5	15.1	81.9
Medium	38.1	15.7	17.9	79.4
Small	1.9	1.5	0	8.4
Near-infrared hardness score	61.6	11.7	38.0	85.7
Wheat protein content (%) <sup>b</sup>	11.1	1.5	8.6	15.5
Wheat ash content (%) <sup>b</sup>	1.3	0.1	1.2	1.6
Flour yield (%)	70.8	2.0	65.9	76.0
Break flour yield (%)	4.9	0.7	3.6	6.7
Milling score	78.1	7.1	54.1	89.8
Single kernel characteristics <sup>c</sup>				
Hardness index	62.0	11.6	43.9	92.0
Hardness index SD	17.7	...	14.3	29.4
Peak force	52.5	8.5	36.6	74.1
Peak force SD	17.2	...	12.7	24.1
Moisture content (%)	12.7	0.7	11.6	17.1
Moisture content SD (%)	0.3	...	0.2	0.4
Weight (mg)	30.5	2.3	24.9	34.4
Weight SD (mg)	8.5	...	6.4	10.8
Diameter (mm)	2.74	0.12	2.50	3.05
Diameter SD (mm)	0.50	...	0.40	0.64

<sup>a</sup> Mean and SD were calculated by the average of two replicates of each cultivar at a given region.

<sup>b</sup> 14% moisture content basis.

<sup>c</sup> SD of single kernel parameters estimated from  $\approx 300$  kernels.

TABLE II  
Mean ( $n = 72$ ), Standard Deviation (SD), and Range of Baking Parameters<sup>a</sup>

Quality Parameters	Mean	SD	Minimum	Maximum
Flour protein content (%) <sup>b</sup>	10.0	1.6	7.8	14.8
Bake water absorption (%) <sup>b</sup>	63.3	3.2	56.1	71.7
Bake mix time (min)	7.2	2.5	3.1	19.1
Proof height (cm)	6.8	0.4	6.3	7.7
Loaf volume (cm <sup>3</sup> )	811	83	656	1,070
Loaf volume regression (cm <sup>3</sup> % protein) <sup>b</sup>	71.8	9.2	52.5	99.0

<sup>a</sup> Mean and SD were calculated by the average of two replicates of each cultivar at a given region.

<sup>b</sup> 14% moisture content basis.

TABLE III  
Simple Linear Correlation Coefficients ( $n = 72$ ) Among Single Kernel Wheat Parameters<sup>a</sup>

Single Kernel Parameters <sup>b</sup>	<i>r</i> Values
Hardness index vs. peak force	0.85**
Hardness index vs. peak force SD	0.76**
Peak force vs. peak force SD	0.80**
Peak force vs. weight (mg)	0.66**
Peak force vs. diameter (mm)	0.40**
Weight (mg) vs. diameter (mm)	0.81**
Weight SD (mg) vs. diameter SD (mm)	0.81**

<sup>a</sup> \*\* = Correlation coefficient significant at  $P < 0.01$ .

<sup>b</sup> Standard deviation (SD) estimated from  $\approx 300$  kernels.

Optimum baking water absorption and mix time were determined during mixing by the feel and appearance of the dough. After mixing, the dough was fermented at 30°C for 120 min, during which time the dough was punched twice, after 69 min of fermentation and then 34 min later. The fermented dough was proofed at 30°C until the dough of the control flour had risen to 7.6 cm. It was baked at 218.3°C (425°F) for 18 min and weighed immediately after removal from an oven. Loaf volume then was determined by rapeseed displacement. The bread was cooled for 2 hr at room temperature and put into a plastic bag. One-day-old bread was sliced by a machine (Oliver, Grand Rapids, MI), and bread crumb grain was evaluated on a seven-point scale of 0–6, in which 0 and 6 mean unsatisfactory and outstanding crumb grain, respectively. Height of the proofed dough was measured before baking. Loaf volume regression (LVR) (cm<sup>3</sup>/% of flour PC) is the loaf volume change by one percentage point of flour protein content for a pup loaf baking system. The equation obtaining the slope is approximated by the expression:

$$(LV-300)/(P-3) \text{ for flours with PC } \geq 12\% \\ \text{and} \\ (LV-300)/(0.534 P + 0.018 P^2) \text{ for flours with PC } < 12\%$$

where LV is loaf volume in cm<sup>3</sup> and P is flour PC (14% mb). The LVR is the same quality parameter as loaf volume potential or a protein quality index (Finney 1985).

### Statistical Analysis

Statistical analysis was performed using the SAS Version 6.11 (SAS Institute, Cary, NC). The mean, SD, and range were calculated. Pearson's correlation analysis was performed to investigate

the relationship among quality characteristics. Simple linear correlations were calculated from data across all combinations of 12 cultivars and six regions. Correlations among cultivars were estimated using each mean performance of 12 cultivars across six counties (Souza et al 1993).

## RESULTS AND DISCUSSION

### Mean and Range of Quality Characteristics

Wheat physical characteristics, conventionally used as quality parameters, include test weight and kernel sizing. We have added density and hardness to wheat physical parameters. The means and ranges of these physical characteristics and chemical parameters including wheat PC and AC are summarized in Table I. Microtest weight ranged from 51.3 to 61.5 lb/bu with a mean of 57.0 lb/bu and SD of 2.3 lb/bu. Wheat kernel density ranged from 1.36 to 1.48 g/cm<sup>3</sup>; there was no significant difference among cultivar means for wheat density, which was in the range of 1.40 to 1.43 g/cm<sup>3</sup>. The percentage of large kernels by the kernel sizing method ranged widely from 15.1 to 81.9% with a mean of 60.1% and SD of 16.5%. The mean and SD for NIR-HS were 61.6 and 11.7, respectively. Wheat PC and AC are important chemical characteristics for evaluating the quality of wheats. The wheat PC varied greatly from 8.6 to 15.5% (14% mb) with a mean of 11.1%. The wheat AC ranged from 1.2 to 1.6% (14% mb).

The milling quality of wheat can be judged by flour yield, break flour yield, milling score, flour AC, and other characteristics. Flour yield of wheat may be one of the most important quality factors for millers. Mean value of flour yield was 70.8% with the range from 65.9 to 76.0%. Break flour yield ranged from 3.6 to 6.7% with a mean of 4.9%. The milling score, a calculated value from test weight, flour yield, and respective PC and AC of wheat and flour, ranged from 54.1 to 89.8 with a mean of 78.1 (Table I).

The SK-HI ranged from 43.9 to 92.0 with a mean of 62.0 and SD of 11.6. The mean for SD of SK-HI (SK-HI SD) was 17.7. The SK-PF indicated a range from 36.6 to 74.1 with a mean of 52.5 and sd of 8.5. The SD of SK-PF (SK-PF SD) indicated a mean of 17.2 with a range from 12.7 to 24.1. The SK-WT ranged from 24.9 to 34.4 mg and SD of SK-WT (SK-WT SD) from 6.4 to 10.8 mg. The SK-DM and SD of SK-DM (SK-DM SD) were in the range of 2.50–3.05 mm and 0.40–0.64 mm, respectively (Table I).

Flour PC ranged greatly from 7.8 to 14.8% (Table II). Optimum bake water absorption and mix time were determined subjectively and empirically by the feel of dough and knowledge of an experienced baker. The mean and SD for bake water absorption were 63.3% (14% mb) and 3.2%, respectively. Baking mix time requirement varied widely from 3.1 to 19.1 min. Bread loaf volume ranged greatly from 656 to 1,070 cm<sup>3</sup> with a mean of 811 cm<sup>3</sup> and SD of 83 cm<sup>3</sup>. Crumb grain scores ranged from 0 (unsatisfactory) to 4.0 (satisfactory) with a mean of 2.9 (questionable to satisfactory) and SD of 0.8. The LVR, loaf volume change by one percentage point of flour PC, ranged from 52.5 to 99.0 (cm<sup>3</sup>/% of flour PC) with a mean of 71.8 (cm<sup>3</sup>/% of flour PC).

### Relationships Among Wheat Characteristics and Milling Parameters

Simple linear correlation coefficients among SK parameters are summarized in Table III. The SK-HI had significant positive correlations with SK-PF and SK-PF SD. Single kernel peak force (SK-PF) was positively correlated with its SD, SK-WT, and SK-DM. There were significant positive correlations between SK-WT and SK-DM and between the SD values.

The simple linear correlation coefficients among conventional wheat characteristics and SK characteristics are shown in Table IV. Test weight had significant positive correlations with SK-PF, SK-HI, and SK-WT. The positive linear correlation of test weight with kernel weight was reported to be due to environmental effects (Ghaderi and Everson 1971). Wheat grain density had significant

TABLE IV  
Simple Linear Correlation Coefficients ( $n = 72$ ) Between Wheat Characteristics and Single Kernel Wheat Parameters<sup>a</sup>

Wheat Characteristics	Single Kernel Parameters			
	Hardness Index	Peak Force	Weight (mg)	Diameter (mm)
Test weight (lb/bu)	0.70**	0.75**	0.47**	ns <sup>b</sup>
Kernel density (g/cm <sup>3</sup> )	0.74**	0.73**	0.32**	ns
Large kernels (%)	ns	0.27**	0.75**	0.75**
Near-infrared hardness score	0.81**	0.82**	0.40**	ns
Protein content (%) <sup>c</sup>	ns	ns	-0.26*	-0.36**
Ash content (%) <sup>c</sup>	ns	-0.40**	-0.50**	-0.44**

<sup>a</sup> \*, \*\* = Correlation coefficient significant at  $P < 0.05$  and  $P < 0.01$ , respectively.

<sup>b</sup> Not significant.

<sup>c</sup> 14% moisture content basis.

TABLE V  
Simple Linear Correlation Coefficients ( $n = 72$ ) Between Wheat Characteristics and Milling Parameters<sup>a</sup>

Wheat Characteristics	Milling Parameters		
	Flour Yield (%)	Break Flour Yield (%)	Milling Score
Micro test weight (lb/bu)	0.50**	-0.48**	-0.28**
Kernel density (g/cm <sup>3</sup> )	0.36**	-0.48**	-0.32**
Large kernel (%)	ns <sup>b</sup>	-0.32**	ns
Near-infrared hardness score	0.50**	-0.66**	ns
Single kernel characteristics <sup>c</sup>			
Hardness index	0.43**	-0.56**	-0.25*
Hardness index SD	ns	ns	-0.26**
Peak force	0.52**	-0.69**	ns
Peak force SD	0.43**	-0.52**	-0.29*
Weight (mg)	0.38**	-0.54**	ns
Diameter (mm)	ns	-0.30**	ns

<sup>a</sup> \*, \*\* = Correlation coefficient significant at  $P < 0.05$  and  $P < 0.01$ , respectively.

<sup>b</sup> Not significant.

<sup>c</sup> Standard deviation (SD) estimated from  $\approx 300$  kernels.

correlations with wheat hardness parameters such as NIR-HS ( $r = 0.71$ ,  $n = 72$ ,  $P < 0.01$ ), SK-HI, and SK-PF (Table IV). However, Pomeranz and Mattern (1988) pointed out that wheat kernel density should not be used as an indirect measure of wheat hardness because of the large environmental effect on PC, more genetic control on hardness, and strong influence of wheat composition (including PC) on density. Variation in wheat hardness may possibly be due to the interactions of proteins and starch granules (Hoseney and Seib 1973, Greenwell and Schofield 1986, Greenblatt et al 1995). Wheat density also had a significant positive correlation with SK-WT, suggesting that a favorable environmental condition for grain-filling also contributed to increasing wheat kernel density.

Single kernel WT and SK-DM had significant correlations with the percentage of large kernels (Table IV). Also, there was a positive correlation between SK-PF values and the percentage of large kernels. Significant correlations occurred among hardness parameters such as NIR-HS versus SK-HI, SK-PF, or SK-PF SD determined by the SKCS. The significant positive correlation of NIR-HS with SK-WT (Table IV) suggested that heavier kernels could have harder textures. Pomeranz and Afework (1984) also reported that smaller wheat kernels generally had lower NIR values. However, Peterson et al (1992) reported an insignificant phenotypic correlation and a negative genotypic correlation between kernel weight and hardness measured by the microscopic observation of crushed kernels. These inconsistent observations might have resulted from different growing conditions and wheat varieties. In a three-year crop study, Slaughter et al (1992) also found inconsistent results, as they determined positive linear correlations between kernel weights and NIR-HS for crop samples from two years but an insignificant correlation for crop samples from one year. The SK-PF had significant correlations with the percentage of large kernels, SK-WT, SK-HI, and NIR-HS.

Significant correlations also were shown among cultivars for wheat physical quality parameters. The cultivar means of SK-WT were correlated to the cultivar means of the percentage of large kernels (Fig. 1A) and SK-PF (Fig. 1B). The cultivar means of SK-PF also had a significant correlation with cultivar means of the percentage of large kernels (Fig. 1C) or NIR-HS (Fig. 1D). The significant correlations of SK parameters measured by SKCS with other quality factors suggest the potential use of SKCS in wheat quality evaluation.

Wheat PC had negative correlations with SK-DM, and SK-WT (Table IV). Wheat AC had significant negative correlations with SK-WT, SK-DM, and SK-PF. Other researchers (Slaughter et al

1992, Satumbaga et al 1995) also have reported negative correlations of PC and AC with wheat kernel size and weight. This result suggested that wheat with heavier and thicker kernels could have a higher portion of endosperm that contains lower amounts of protein and ash than the aleurone layer (Morris et al 1946). The negative relationship between wheat PC and kernel weights has been reported to be due to the grain-filling during the maturation stage of wheat. Mou et al (1994) reported that kernel weight was positively correlated with the grain-filling rate, whereas wheat PC had a significant negative correlation.

Correlation coefficients between wheat characteristics and milling parameters show that flour yield was significantly correlated to wheat hardness (NIR-HS or SK-HI), test weight and density, and to some other SKCS parameters such as SK-PF and its SK-PF SD and weight: the correlation coefficient ranged from 0.36 for density to 0.52 for SK-PF (Table V). The cultivar mean of flour yield showed significant correlations with the cultivar mean of SK-WT ( $r = 0.67$ ,  $n = 12$ ,  $P < 0.01$ ) and the percentage of large kernels ( $r = 0.65$ ,  $n = 12$ ,  $P < 0.01$ ). Therefore, SK-PF and SK-WT values determined by the SKCS may be potential parameters for estimating flour-yielding capacity of wheats.

Among cultivars, the cultivar mean of SK-PF had significant positive correlations with SK-WT, percentage of large kernels, and NIR-HS (Fig. 1B–D), suggesting that kernel weight, sizing, and texture (hardness) could have significant effects on variation in SK-PF. Because of the close relationships of SK-PF with wheat kernel texture and weight, SK-PF values showed the highest  $r$  value with flour yields ( $r = 0.52$ , Table V) among all wheat physical parameters.

Break flour yields were correlated negatively with hardness parameters such as NIR-HS, SK-HI, SK-PF, and SK-PF SD. Gaines et al (1996) also reported similar results. Break flour yields also had significant negative correlations with test weight,

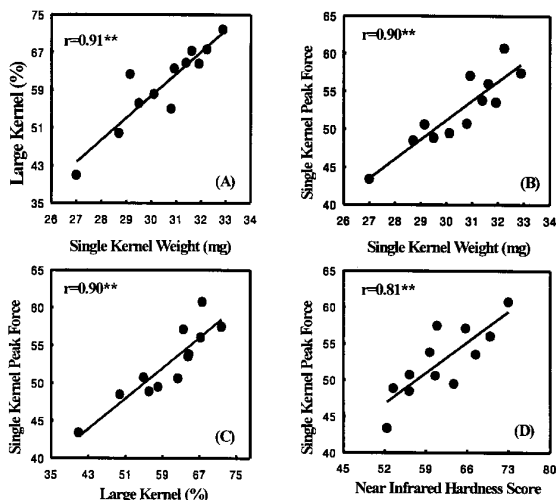


Fig. 1. Linear correlations among the cultivar mean values of single kernel characteristics and other physical quality parameters.

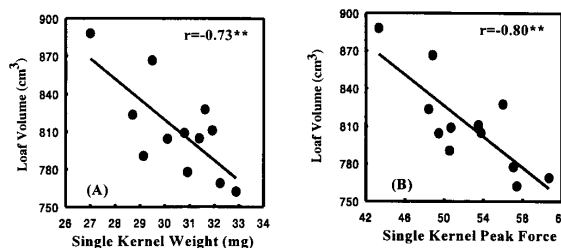


Fig. 2. Linear correlations among the cultivar mean values of single kernel characteristics and loaf volumes.

TABLE VI  
Simple Linear Correlation Coefficients ( $n = 72$ )  
Among Baking Parameters<sup>a</sup>

Baking Parameters	$r$ Values
Flour protein content (%) <sup>b</sup> vs.	
Bake parameters (%) <sup>b</sup>	0.82**
Bake mix time (min)	0.39**
Dough proof height (cm)	0.83**
Crumb grain score	0.23*
Loaf volume (cm <sup>3</sup> )	0.77**
Loaf volume regression (cm <sup>3</sup> /% protein)	-0.56**
Bake water absorption (%) <sup>b</sup> vs.	
Dough proof height (cm)	0.69**
Crumb grain score	0.32**
Loaf volume (cm <sup>3</sup> )	0.65**
Loaf volume regression (cm <sup>3</sup> /% protein)	-0.42**
Bake mix time (min) vs.	
Dough proof height (cm)	0.35**
Loaf volume (cm <sup>3</sup> )	0.38**
Dough proof height (cm) vs.	
Loaf volume (cm <sup>3</sup> )	0.84**

<sup>a</sup> \*, \*\* = Correlation coefficient significant at  $P < 0.05$  and  $P < 0.01$ , respectively.

<sup>b</sup> 14% moisture content basis.

wheat density, percentage of large kernels, SK-WT, and SK-DM. Milling scores had significant negative correlations with test weight, grain density, SK-HI, SK-HI SD, and SK-PF SD (Table V). The negative correlations of milling scores with SK-HI SD and SK-PF SD indicate that uniformity of SK hardness is desirable for good milling performance.

### Relationships Among Single Kernel Characteristics and Baking Parameters

The simple linear correlation coefficients among baking parameters are shown in Table VI. Flour PC affected bake water absorption and mix time, dough proof height, crumb grain score, and LV in a positive way. The significant negative correlation of flour PC with LVR suggests that flour with higher PC exert lower LV potential on per unit PC basis. In addition, baking water absorption showed significant positive correlations with dough proof height, LV, and crumb grain score and a negative correlation with LVR. The significant correlation of baking water absorption with LV might have resulted from the role of proteins affecting both water absorption and LV. Kamman (1970) reported that the variation in water absorption could influence the grain and texture of bread crumb. Baking mixing time had significant positive correlations with dough proof height and LV. Finney et al (1987) suggested that flour with a medium or medium-long mixing requirement would have good LV potential with good protein quality. Proof heights of dough had a significant positive correlation with LV (Table VI).

Wheat characteristics also have significant correlations with baking parameters (Table VII). Flour PC had a significant negative correlation with SK-DM ( $r = -0.29$ ,  $n = 72$ ,  $P < 0.01$ ). Hardness parameters such as SK-HI and SK-PF had significant positive correlations with bake water absorption, probably due to damaged starch, which is influenced greatly by wheat hardness (Pomeranz 1988). Because damaged starch granules absorb more water than intact starch granules, a flour from harder wheat generally requires more water for baking (Pomeranz et al 1984). Osborne et al (1997) reported that starch damage could be estimated from the SKCS data. Generally, there is a positive correlation between bake water absorption and mix time requirement. We cannot explain the negative correlation of SK-PF with baking mix time.

Single kernel weight and size had significant, negative correlations with dough proof height and LV, at least in part, due to the inverse relationship of SK-WT and SK-DM with wheat PC (Table IV). Single kernel peak force had a significant negative correlation with LV for all 72 samples (Table VII). The 12 cultivar mean values of LV were also negatively correlated with the 12 cultivar mean values of SK-WT (Fig. 2A) and SK-PF (Fig. 2B). The negative relationships between kernel weight and loaf volume is again due to the negative effect of wheat kernel size and weight on wheat PC (Table IV). However, there was no significant correlation between flour PC and SK-WT. Thus, other unknown fac-

tors, in addition to PC, associated with kernel weights, could influence LV. The LVR values of 72 samples were affected negatively by SK-PF, SK-HI, and SK-WT, suggesting that flours produced from wheats with heavier and harder kernels could result in producing smaller loaves at a given PC.

## CONCLUSIONS

Single kernel wheat characteristics were significantly correlated to conventional wheat quality factors including test weight, kernel density, kernel sizing, and NIR-HS, and milling parameters. Among SK characteristics, SK-PF values were the most highly correlated with flour yields, probably due to its significant correlation with kernel weight and hardness. The SD values of SK parameters represent the uniformity of wheat kernel distribution. The negative correlation of SK-HI SD and SK-PF SD with milling scores suggested that uniformity in wheat hardness of SK could be desirable for optimum milling performance. However, flours from wheats with desirable kernel physical characteristics could show poor breadmaking performances. Physical parameters such as SK-PF and SK-WT that had significant positive correlations with flour yields were correlated negatively with LV and LVR. This result suggests that flours produced from wheats with harder and heavier kernels could result in smaller LV due to their lower flour quality in hard winter wheats. Wheat hardness parameters had significant positive correlations with bake water absorption requirements, probably due to the influence of damaged starch on both parameters. Based on the significant correlations of SK wheat characteristics with conventional quality parameters, the SKCS could be applied usefully in hard winter wheat quality evaluation.

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TABLE VII  
Simple Linear Correlation Coefficients ( $n = 72$ ) Between Single Kernel and Baking Parameters<sup>a</sup>

Single Kernel Parameters	Baking Parameters				
	WA <sup>b</sup>	MT	DPH	LV	LVR
Hardness index	0.39***	ns <sup>d</sup>	ns	ns	-0.35**
Peak force	0.29**	-0.23*	ns	-0.27*	-0.44**
Weight (mg)	ns	ns	-0.42**	-0.44**	-0.32**
Diameter (mm)	-0.28*	ns	-0.44**	-0.49**	ns

<sup>a</sup> WA = water absorption (%); MT = mix time (min); DPH = dough proof height (cm); LV = loaf volume (cm<sup>3</sup>); LVR = loaf volume regression (cm<sup>3</sup>/% protein)

<sup>b</sup> 14% moisture content basis.

<sup>c</sup> \*, \*\* = Correlation coefficient significant at  $P < 0.05$  and  $P < 0.01$ , respectively.

<sup>d</sup> Not significant.

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