Differences in Physical Properties and Microstructure of Wheat Cultivars in Extrusion Qualities

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ABSTRACT

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Three cultivars of hard red spring wheat, grown in Glyndon, MN, and Casselton, ND, were extruded at 17, 21, and 25% moisture content with barrel temperatures of 120, 150, and 180°C and a screw speed of 350 rpm to produce expanded extrudates. Pasta-like products of the same cultivars were obtained by extruding the flour at 28, 32, and 36% moisture content with barrel temperatures of 100, 110, and 120°C and a screw speed of 140 rpm. The expanded extrudates from both locations showed significant differences ($\alpha = 0.05$) in expansion ratio, bulk density, protein particles, and air cell size. Unexpanded extrudates were significantly different among wheat cultivars and growing locations.

Extrusion is a versatile and economical cooking process. Several types of new snack foods and breakfast cereals are produced by extrusion cooking. Extruded products have unique characteristics and have rapidly gained popularity in the food market in the past decade (Faubion et al 1982). Expansion ratio and bulk density of extrudates are characteristics that influence consumer acceptance and are mainly affected by the composition of raw materials and the extrusion conditions. Faubion and Hoseney (1982a,b) studied the effects of moisture, flour type, concentration and type of protein, and lipid on extrudate properties and found that higher initial moisture content decreased the expansion ratio and weakened the texture of both starch and flour extrudates. Three properties, texture, expansion, and ultrastructure, were analyzed for hard (11% protein) and soft (9% protein) wheat flour and high-protein (15%) flour extrudates. Hard and soft wheat extrudates were different in texture only, while the high-protein flour differed in expansion and ultrastructure as well. Bhattacharya et al (1986) studied textural properties of extruded plant protein blends and concluded that higher shear rates produced more expanded extrudates with higher water-holding capacity (WHC) but low shear strength. The blend with a higher percentage of soy concentrate produced extrudates with high expansion ratio, WHC, shear strength, and cooked and uncooked viscosity. The effect of feed moisture and barrel temperature on product expansion and bulk density of cowpea meal extrudates was examined by Phillips et al (1984). Similar studies have also been done by Arora et al (1993) on potato peel, Kpodo and Plahar (1992) on yam (*Dioscorea alata*) flour, and Bhattacharya and Hanna (1987) on corn starch.

The microstructures of extrudates have been observed with scanning electron micrographs (SEM) or quantified with image analysis. Air cell structures of expanded corn extrudates have been studied by Barrett and Peleg (1992), who reported that structures are affected by the composition of feed materials and by extrusion conditions. The correlation of density, expansion, and cell size with the fat infusibility into the extrudates was studied by Barrett and Ross (1990). Data from microstructural analysis of extrudates can be used to gain an understanding of what happens inside the extrudates under different extrusion conditions.

Few studies have involved the comparison of extrusion qualities of different wheat cultivars grown in the same location with the same cultivars grown in different locations. The objective of this study was to investigate the effects of different wheat cultivars and growing locations with regard to product expansion, bulk density, and microstructures of the extrudates.

MATERIALS AND METHODS

Wheat Samples

Three hard red spring wheat cultivars (Butte 86, 2371, and Grandin) grown in North Dakota (Casselton) and Minnesota (Glyndon) during the 1992 crop year were used in this study. Wheat samples (400 kg) were collected from each cultivar at each location. The wheat was cleaned and milled at 15.5% moisture (using a standard cold-tempering procedure) on a twin Miag pilot mill at the USDA Spring Wheat Laboratory, North Dakota State University, Fargo, at a feed rate of 138 kg/hr. Straight-grade wheat flours were collected and stored in a cold room at 4°C for further use in extrusion.

Extrusion Cooking

A Wenger TX-52 co-rotating intermeshing twin-screw extruder with a 5.2-cm screw diameter was used in this study. For expanded products, the barrel length-to-diameter ratio was 16:1. The die (Wenger 55373-101) was 1.9 cm thick and had three 0.4 cm diameter outlets. The entrance diameter of the die was 1.2 cm. The average residence time was 15 sec. The screw configuration, similar to that used for snacks and expanded cereal-based products, is given in Table I. Extrusion conditions for flours were: moisture contents of 17, 21, and 25% (wb); product temperatures of 120, 150, and 180°C; screw speed of 350 rpm; feed rate of 38.6 kg/hr. Nonexpanded products were produced by extruding the flours at moisture contents of 28, 32, and 36%; barrel temperatures of 100, 110, and 120°C, and a screw speed of 140 rpm. The barrel length-to-diameter ratio was 25:1. The average residence time was 35 sec. The die for this part of the study (Wenger 55372-113) had two openings of 0.6 cm in diameter. The entrance diameter of the die was 2.38 cm, and the die thickness was 2.86 cm. The screw configuration is given in Table I. The length of the barrel was 130 cm. All extrudates were dried 18 hr at 50°C with dry air and stored at room temperature.

Expansion Ratio

The expansion ratio of the extrudates was derived from the diameters of the extrudates divided by the diameter of the die of the extruder. The data were obtained from three extrudates randomly selected from each extrusion condition.

Bulk Density

Bulk density of extrudates was measured relative to sand density. A 500-ml plastic beaker was weighed (w1). The beaker

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was then filled with 75-mesh flint sand, tapped 20 times, and weighed (w2). The density of sand (ds) was calculated. Five to six extrudates were weighed. The weight was recorded (w3). The extrudates were put in the beaker and the beaker filled with flint sand and tapped 20 times. The excess sand was scraped off with a ruler. The weight of five extrudates and sand was recorded (w4). The density of extrudates was obtained by the equation $de = [w3/(w2 - w4)] \times ds$. Data obtained were averages from three replicates.

Microscopic Fixing and Embedding

Fixing and embedding techniques were adapted from the method described by Feder and O'Brien (1968). Three middle sections of extrudates from each selected extrusion condition were soaked with 5% glutaraldehyde in $0.025M$ phosphate buffer, pH 6.9, at 4°C for seven days. After the seven-day hydration, the extrudate sections were embedded in 3% agar. The embedded extrudates were sectioned with a cryostat.

Staining Procedures for Air Cell Structure of Nonexpanded Products

Dry sections of nonexpanded products were stained with 0.5% iodine in 5% KI (EM Science, Gibbstown, NJ) for 30 sec. Stained sections were covered with cover slide glass and excess iodine was removed.

Protein

Extrudate specimens were stained with 0.01% (w/w) acid fuchsin (Hartman-Leddon Company, Philadelphia, PA) in 1% acetic acid for 1 min. The stained section was rinsed thoroughly with 50% ethanol for 30 sec, dipped in 95% ethanol 10 times, and then dipped in toluene. To make the permanent sections, a drop of immersion oil (Zeiss, Germany) was applied to each section before the section was covered by a cover slide.

TABLE I
Screw Configuration to Die Inlet

Expanded Extrudate	Nonexpanded Extrudate
1 D DFFSE, 25.4 mm pitch[a]	1 D DFFSE, 25.4 mm pitch
6 D DFSE, 38.6 mm pitch	0.7 D DFFSE, 38.6 mm pitch
1 D KE, 45° forward pitch[b]	1.5 D DFFSE, 51.5 mm pitch
1 D DFSE, 38.6 mm pitch	1.5 D DFFSE, 51.5 mm pitch
0.5 D KE, 45° forward pitch	0.7 D KE, 30° forward pitch
1.5 D DFFSE, 38.6 mm pitch	1.5 D DFFSE, 38.6 mm pitch
0.5 D KE, 45° forward pitch	1 D DFFSE, 38.6 mm pitch
1.5 D DFFSE, 38.6 mm pitch	0.5 D KE, 45° forward pitch
0.25 D KE, 90° forward pitch	1.5 D DFFSE, 38.6 mm pitch
1 D DFFSE, 38.6 mm pitch	1 D DFFSE, 38.6 mm pitch
0.25 D KE, 90° forward pitch	0.5 D KE, 45° forward pitch
1.5 D Cut flight, 38.6 mm pitch	1.5 D DFFSE, 38.6 mm pitch
	1.5 D DFFSE, 38.6 mm pitch
	0.5 D KE, 45° forward pitch
	1.5 D DFFSE, 38.5 mm pitch
	1.5 D DFFSE, 38.5 mm pitch
	1.5 D DFFSE, 38.6 mm pitch
	1.5 D DFFSE, 38.6 mm pitch
	1.5 D DFFSE, 38.6 mm pitch
	0.5 D KE, 45° forward pitch
	0.5 D KE, 45° reverse pitch

[a] DFFSE = Double flighted forward screw element.
[b] KE = Kneading element (shear lock).

TABLE II
Physicochemical Properties of the Hard Red Spring Wheat Flours

Cultivars	Location	Moisture	Protein[a]	Ash[a]	Milling Yield
Butte 86	MN	12.3	13.3	0.47	73.56
2371	MN	12.4	13.8	0.45	73.97
Grandin	MN	12.2	13.3	0.44	71.68
Butte 86	ND	12.1	13.9	0.44	68.07
2371	ND	13.1	12.9	0.41	72.64
Grandin	ND	12.8	13.4	0.43	70.63

[a] Means of two replicates expressed on 14% moisture basis.

Microscopic Examinations

The microstructures of sections stained with 0.5% iodine in 5% KI were visualized with a Zeiss universal research microscope under a conventional bright-field illuminating system with green filter. The images were sent through a 2.5× objective lens to the IBAS image analysis system (Kontron Elektronik, Germany), which quantified the particles. All specimens were measured at the same threshold level to reduce bias. A close-up lens was used to magnify cell structures. Eight measurements (80% coverage of total area of each specimen) were done for each sample. The average value of all replicates from each specimen were used to analyze statistical significance.

Protein particles were examined with the Zeiss microscope equipped with a III RS epi-illuminating condenser combined with an HBO 200 w/4 mercury-arc illuminator. The III RS condenser was composed of three fluorescent filter combinations, each with a dichromatic beam splitter and exiter-barrier filter set with maximum transition at 546 nm/>590 nm through a 10× DP Plan Apo 10 UV 0.40160/0.17 objective lens. Protein pieces appeared bright red. Brighter pieces were selected with different threshold levels created by the operator. Every sample was examined and measured at the same threshold level to minimize bias. Approximately 2,000 data points were obtained from each specimen.

Air Cell Measurement of Expanded Extrudates

Air cell structures of expanded extrudates were measured using the method described by Barrett and Ross (1990). Three extrudates produced at 17% moisture content were selected from all 18 samples. A segment approximately 1.5 cm long was cross-sectioned out of each of these extrudates and leveled down to 1 cm with No. 200 sand paper. The segments were pressed against a stamp pad to blacken cell structures. Images of extrudates were transferred to the IBAS image analysis system through a CCD video camera module (model xC-77, Sony Co., Japan) mounted with a C-adaptor connected to a 50-mm Olympus auto-macro lens. Lighting was controlled with four spotlights shinning upward opposite the sample to eliminate shadows. The height between the camera and the sample was initially adjusted until the extrudate image appearing on the computer monitor was large enough but did not touch the reference frame. This length was kept constant through the completion of the experiment. The reference frame image was rejected from the last image before the actual measurement occurred. The computer analyzed only bright spots in each field of measurement.

Statistical Analysis

All measurements had three replicates. Statistical analysis was conducted using the analysis of variance (ANOVA) with Microsoft MacAnova Version 3.12 (Oehlert 1993).

RESULTS AND DISCUSSION

Physiochemical properties of the hard red spring wheat flours are given in Table II. The properties of these wheat flours appeared similar, except for the percentage of flour extraction of wheats; those grown in Minnesota were slightly higher than those grown in North Dakota.

Bulk Density

Figures 1 and 2 show the effects of initial feed moisture contents and barrel temperatures on bulk density of expanded and nonexpanded extrudates. At a constant barrel temperature, the bulk density of expanded extrudates increased as moisture content increased, but decreased as temperature increased. This inverse relationship between temperature and bulk density is similar to results previously reported by Taranto et al (1975) on cottonseed meal, Cumming et al (1972) on soybean meal, Lawton et al (1985) on wheat gluten and a bran-like fraction, and Bhattacharya and Hanna (1987) on extrusion-cooked corn starch with 1 and 30% amylose. At higher temperatures, the gelatinization of starch is more complete. This means that the melt has high viscosity and, hence, a higher pressure is available, causing increased expansion and decreased density (Bhattacharya and Hanna 1987). Harper (1986) explained that extruding at a low moisture level made the denatured starch and proteins rearrange themselves along the axial direction of the barrel toward the die. When the barrel temperatures increased, the crosslinking between starch and proteins enabled the melt to form unique structures that accelerate the expansion at the die exit. Another explanation is that the water in the feed is superheated as the temperature increased and is subjected to high pressure created by the screw rotation and the restriction of the die. As the products exit to the atmospheric pressure, the superheated water vaporizes immediately and leaves a large number of air cells in extruded products. Increased temperature superheats the water, thus, creating higher pressure (Sanderude and Ziemba 1986, Harper 1981, Matson 1982, Clark 1986).

The bulk density of the extrudates at 25% moisture content increased as the temperature increased. At this moisture level, the viscous heating is probably not significant enough (due to reduced system viscosity and reduced pressure) to raise the temperature. The lower temperature rise reduced the degree of superheating (Kpodo and Plahar 1992) and allowed the starch and protein molecules to align themselves in the axial position faster and with greater ease than at lower moisture content. Plots of temperature versus bulk density at constant moisture show that wheat cultivars grown in Minnesota tend to have a lower bulk density than those grown in North Dakota. Analysis of variance (ANOVA) showed that the effect of growing locations on the bulk density of wheat extrudates was greater than the effect of the cultivar (at $\alpha = 0.05$) (Table III).

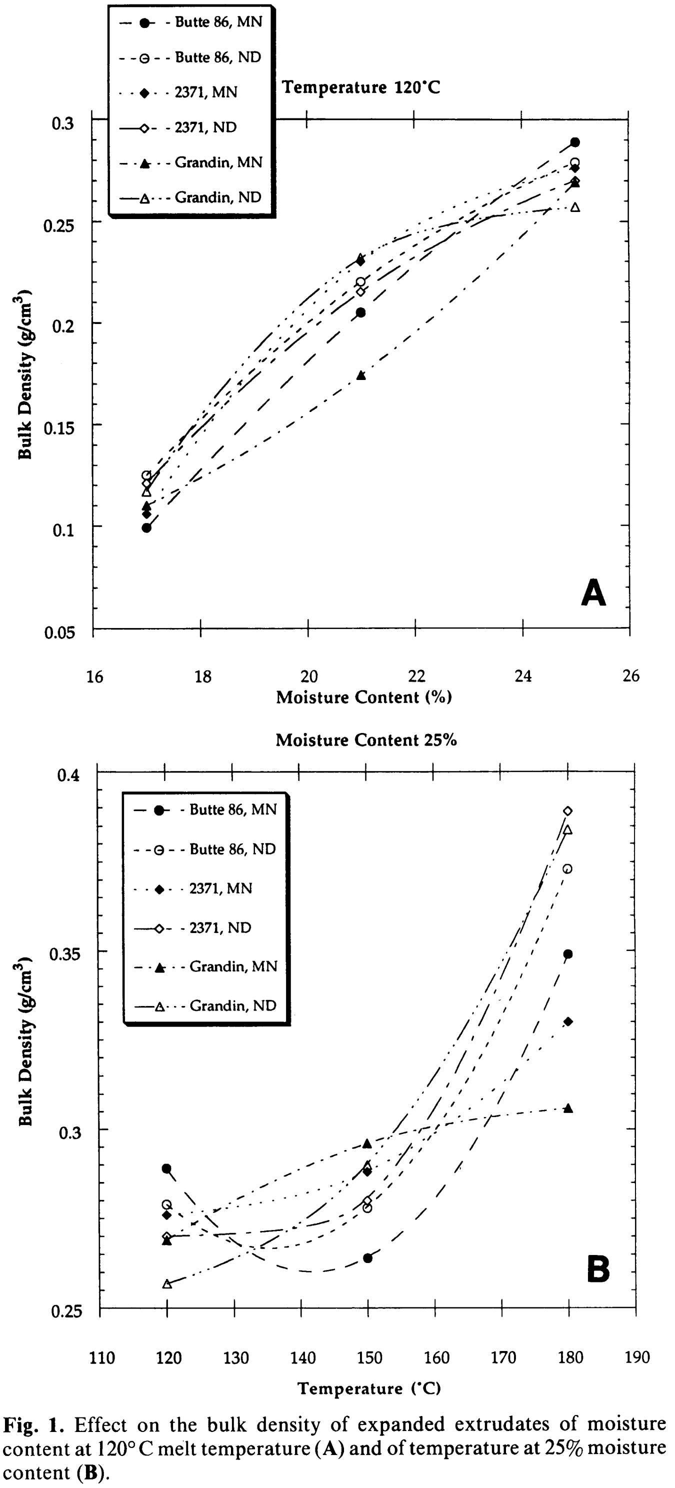

Fig. 1. Effect on the bulk density of expanded extrudates of moisture content at 120° C melt temperature (**A**) and of temperature at 25% moisture content (**B**).

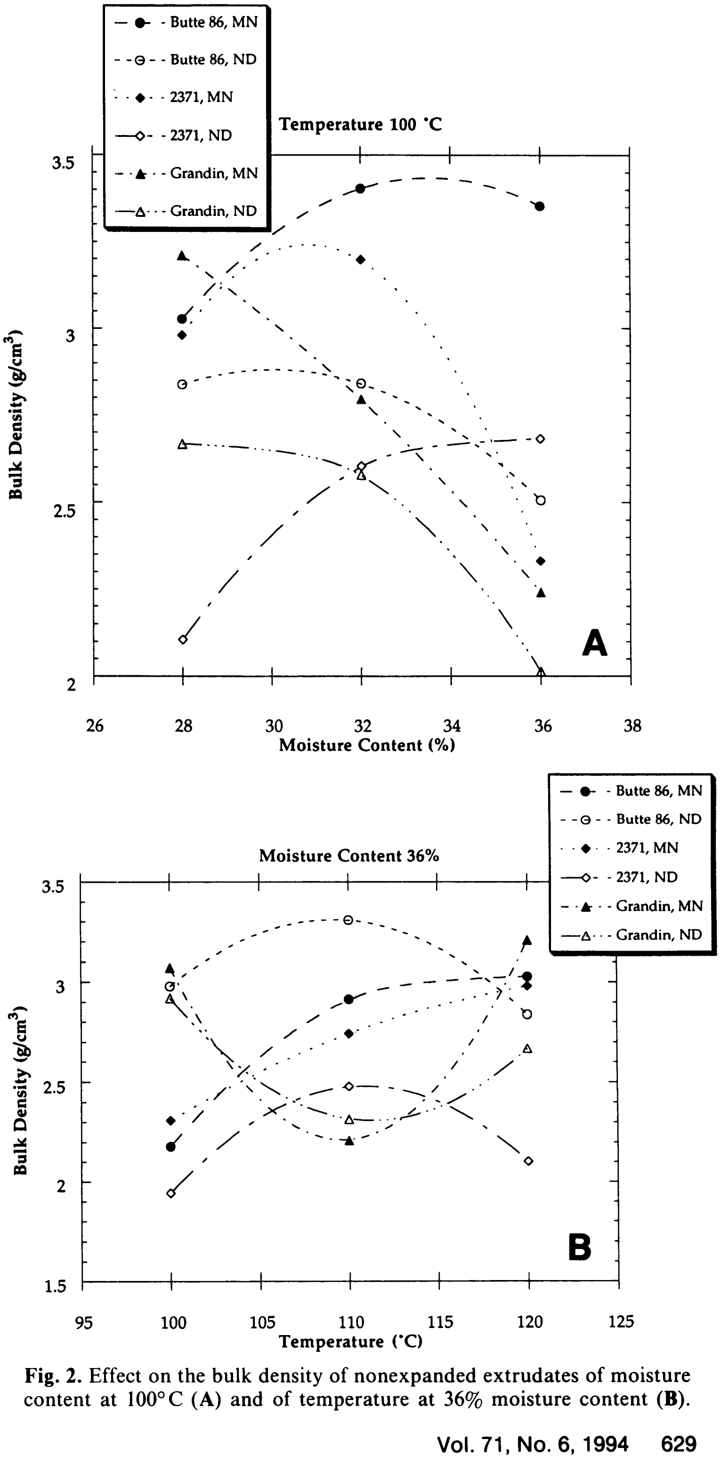

Fig. 2. Effect on the bulk density of nonexpanded extrudates of moisture content at 100° C (**A**) and of temperature at 36% moisture content (**B**).

Expansion Ratio of Expanded Extrudates

Figure 3a shows the effect of moisture content on expansion ratio. As the moisture content increased, the expansion ratio decreased. The inverse relationship between the moisture content and expansion ratio was expected because the bulk density increased as the moisture increased. Bhattacharya et al (1986) explained that foods with lower moisture content tend to be more viscous than those having higher moisture content. Therefore, the pressure differential is smaller for higher moisture foods, leading to a less puffed product. Inside the extruder, the material is still in the molten state with the water in the liquid form. Once the product is extruded from the die, the melt experiences a sudden pressure drop. The water flashes off, resulting in an expanded product (Harper 1981). Barrel temperature had an inverse relationship to puff ratio (Fig. 3b). Taranto et al (1975) stated that a more fully cooked material allowed for more expansion. Higher process temperature increased the degree of cooking and expansion. Increased mechanical energy input elevated the extruder torque and induced radial expansion (Guy and Horne 1988). Increased moisture content decreases radial expansion but increases longitudinal expansion. This condition also alters the shape of extrudate. The extrudates had increased radial expansion with decreased moisture. There were no significant differences among wheat cultivars grown in both locations, but significant differences were found for the same cultivars grown in different locations.

TABLE III
Physical Characteristics of Extrudates

Cultivars	Location	Shear Condition (rpm)	Bulk Density[a] (gm/cm^3)	Expansion Ratio[a]
Butte 86	MN	350	0.21 ± 0.08	3.40 ± 0.46
2371	MN	350	0.21 ± 0.09	3.26 ± 0.47
Grandin	MN	350	0.21 ± 0.09	3.44 ± 0.46
Butte 86	ND	350	0.19 ± 0.08	3.26 ± 0.42
2371	ND	350	0.21 ± 0.08	3.14 ± 0.46
Grandin	ND	350	0.20 ± 0.09	3.26 ± 0.40
Butte 86	MN	140	2.45 ± 0.45	NE[b]
2371	MN	140	2.42 ± 0.67	NE
Grandin	MN	140	2.97 ± 0.55	NE
Butte 86	ND	140	2.63 ± 0.42	NE
2371	ND	140	2.45 ± 0.53	NE
Grandin	ND	140	2.80 ± 0.63	NE

[a] Means of three replicates.
[b] NE = No expansion.

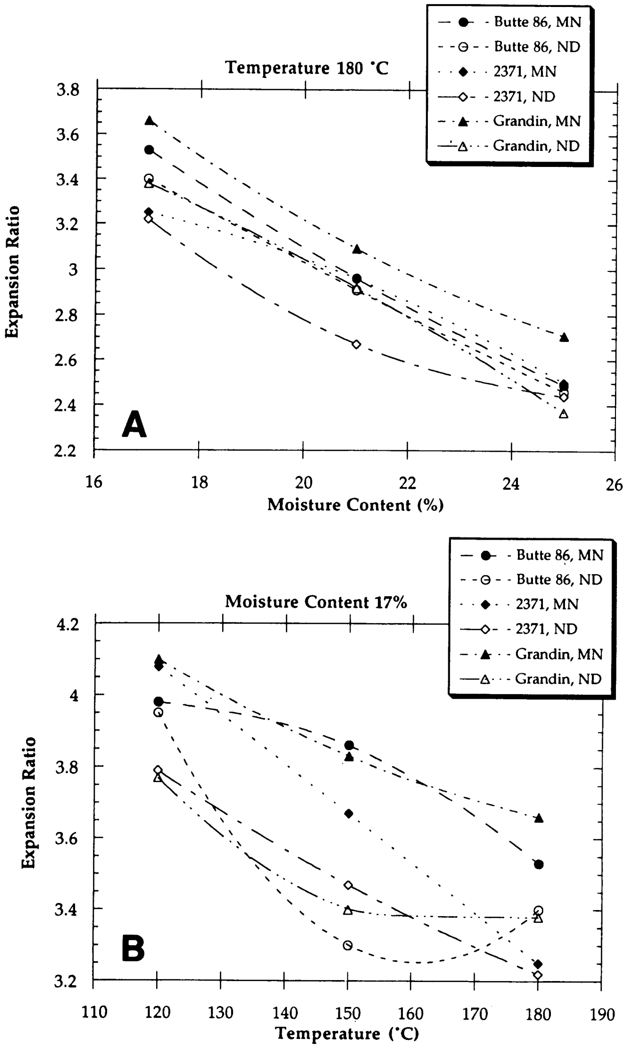

Fig. 3. Effect on the expansion ratio of extrudates of moisture content at a melt temperature of 180°C (**A**) and of temperature at 17% moisture content (**B**).

Air Cell Size and Distribution

Air cell size of wheat extrudates decreased as the temperature increased (Tables III and IV). Extrudates from wheats grown in Minnesota had average air cell sizes that were nearly twice as large as those from wheats grown in North Dakota. The differences among cultivars were not significant. In some cases, large standard deviation was observed. This is primarily because of a single large air cell in the matrix. The imaging system does not selectively delete outliers. It has been reported that cell size distribution of extrudates is affected by the moisture content. High moisture content in extrudates increased the setting time of cell wall and the coalescence of air bubbles (Barrett and Ross 1990). At low temperature (120°C), water is not as superheated when compared to water at high temperature (150 and 180°C). Because the water is not really superheated, it migrates slowly from the extrudates, causing high moisture content products after extrusion. High moisture extrudates have soft and flexible cell walls that allow small air bubbles to coalesce and form large air cells. At high temperature, the water vaporizes more quickly and the cell walls are fixed immediately. There is not much time for air cell bubbles to move together. The physical appearances of the extrudates from 120 and 180°C were very different. The extrudates at 120°C appeared glassy, hard, and sharp when broken, whereas at 180°C they were soft, puffy, and easy to break. The number of air cells also supported the coalescence phenomenon. Extrudates at 120°C had lower numbers of air cells than those at 180°C. Air cell numbers of extrudates from Minnesota were significantly lower than those from North Dakota.

Protein Size

Figure 4 shows a typical structure of wheat extrudate. Gelatinized starch forms a network surrounding air cells. Proteins are embedded inside of the gelatinized starch network and away from air cells. The structure appeared in this fashion because

TABLE IV
Air Cell and Protein Fragment Data of Extrudates

Cultivars	Location	Screw Speed (rpm)	No. of Air Cells[a] Per Area	Average Cell Size (mm^2)	Protein[b] (μm^2)
Butte 86	MN	350	32 ± 10	5.58 ± 2.74	174 ± 24
2371	MN	350	28 ± 6	4.80 ± 1.61	174 ± 22
Grandin	MN	350	27 ± 9	6.03 ± 3.87	190 ± 47
Butte 86	ND	350	41 ± 11	3.19 ± 1.50	197 ± 23
2371	ND	350	43 ± 13	2.78 ± 0.98	208 ± 31
Grandin	ND	350	38 ± 8	2.99 ± 0.91	193 ± 31
Butte 86	MN	140	823 ± 774	692 ± 803[c]	110 ± 16
2371	MN	140	639 ± 361	522 ± 246[c]	122 ± 18
Grandin	MN	140	528 ± 147	930 ± 1206[c]	109 ± 7
Butte 86	ND	140	1014 ± 388	987 ± 609[c]	103 ± 11
2371	ND	140	660 ± 468	1478 ± 1098[c]	167 ± 33
Grandin	ND	140	1072 ± 583	1538 ± 2697[c]	146 ± 39

[a] Means of three replicates.
[b] Means of three replicates of ~2,000 protein fragments.
[c] Average air cells (μm^2).

the extruded proteins are less water soluble due to their denaturation. This was reported for soy proteins (Stanley 1989). Cereal proteins such as corn meal showed significantly decreased solubility in ethanol and alkali after extrusion (Racicot et al 1981).

Decreased moisture content increased protein size (Fig. 4c and d). Under a constant moisture, the relationship between protein size and temperature is unclear. Protein size in extrudates from wheat grown in North Dakota were significantly larger than that of wheat grown in Minnesota (Table V), which correlated with their expansion ratio and bulk density. Larger protein size extrudates had lower expansion ratios and higher bulk densities. From the extrudate structure, it appeared that the network is reinforced by protein particles. One can visualize that under certain extrusion conditions protein polymers rearrange themselves along the flow. Protein molecules appeared to be surrounded by gelatinized starch and situated away from water upon exiting from the die. The air cells appeared to be surrounded by the starch, i.e., the starch matrix appeared to foam. The starch with smaller protein particles is more homogenous and flexible than starch with larger protein particles, causing increased expansion and reduced bulk density.

The growing locations affect the quality of proteins. Though the protein content of flours from two locations may not be significantly different, the shape of the protein may be different. Proteins in wheat grown in North Dakota may be oval while the proteins in wheat grown in Minnesota are long and thin. Similarly, the functionality of these proteins may be very different. Under extrusion conditions, proteins from wheat grown in different locations respond differently. The proteins from wheat grown in Minnesota may stretch more while those from North Dakota stick together.

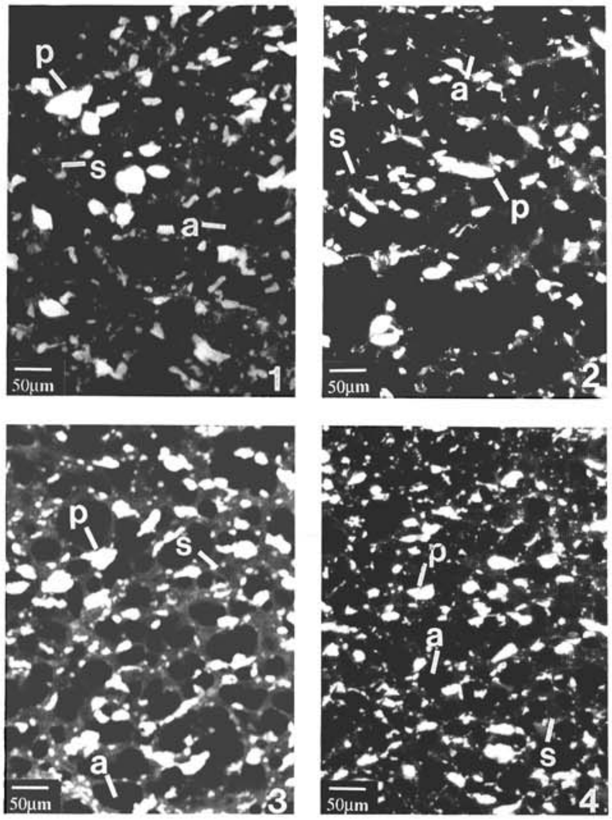

Fig. 4. Microstructure of expanded extrudates. **1,** cultivar 2371, grown in North Dakota; extruded at 150°C, 17% moisture content, and 350 rpm screw speed. **2,** cultivar 2371, grown in Minnesota; extruded at 150°C, 17% moisture content, and 350 rpm screw speed. Microstructures of nonexpanded extrudates. **3,** cultivar Butte 86, grown in Minnesota; extruded at 110°C, 28% moisture content, and 140 rpm screw speed. **4,** cultivar Butte 86, grown in Minnesota; extruded at 120°C, 36% moisture content, and 140 rpm screw speed. s = starch. p = protein. a = air cell.

CONCLUSIONS

Depending on the location in which the wheat is grown, the same wheat cultivar can show significant differences in extrusion characteristics such as bulk density, expansion ratio, air cell size and density, and protein size. Extrinsic factors such as the weather, soil type, annual rainfall, and sunshine affect the wheat flour compositions and milling yield. Though wheat flour compositions from both locations were similar, extrusion quality was very different. From the milling yield and protein size data, it is observed that the environmental factors may alter the shape and functionality of major flour components through the structure of wheat kernels.

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