Extrusion Cooking of Corn Meal and Sugar Beet Fiber: Effects on Expansion Properties, Starch Gelatinization, and Dietary Fiber Content[1]

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ABSTRACT

Sugar beet fiber of different particle sizes (10-200 mesh) was mixed with corn meal and extruded with a twin-screw extruder. The variables studied were fiber particle size, fiber percentage, and extruder screw speed. Expansion properties, dietary fiber contents, and total and gelatinized starch contents of the products were determined. Increasing the percentage of sugar beet fiber resulted in less radial expansion and more elongation of the products. Decreasing the particle size of sugar beet fiber improved both radial and longitudinal expansion. Increased screw speed favored elongation but decreased radial expansion. Regardless of the dietary fiber content (0-30%), the starch in raw materials was completely gelatinized after extrusion as determined by an enzymatic method. The insoluble, soluble, and total dietary fiber (IDF, SDF, and TDF) contents were not significantly different among extruded products containing 30% sugar beet fiber. However, compared with the dietary fiber contents of the raw materials, IDF decreased by 0.6-1.7 g/100 g of dry solid after extrusion cooking. SDF increased slightly and TDF decreased slightly, but the differences were not statistically significant.

Dietary fiber has received more attention in the last few years as epidemiological studies related our inadequate intake of dietary fiber to the incidence of a wide spectrum of diseases. For example, insoluble dietary fiber (IDF), which includes cellulose, lignin, and some hemicellulose, has been linked to the shortening of transit times in the small intestine and to the softening and bulking of stool. It alleviates the risk of constipation, appendicitis, irritable bowel syndrome, and possibly colon cancer. However, soluble dietary fiber (SDF), which includes pectin and vegetable gums, is believed to increase intestinal transit times, absorb serum cholesterol, and enhance glucose tolerance (Best 1987).

Many extruded products, such as breakfast cereal and flat bread, are good sources of dietary fiber, and extrusion cooking is a suitable process for the production of fiber-enriched products. The potential change of dietary fiber content during extrusion cooking is of concern to nutritionists, food processors, and health-conscious consumers. Extrusion cooking may change the content, composition, and physiological effects of dietary fiber in various ways. First, starch could undergo modification and form enzyme-resistant fractions, which have acted in vivo as dietary fiber (Björck et al 1986). Second, degradation of dietary fiber to low molecular weight fragments would diminish its content and hence reduce its benefits. Third, macromolecular degradation of fiber may increase the solubility and change the physiological effects of the fiber. Most studies of the effects of extrusion cooking on dietary fiber content were based on wheat flour products (Varo et al 1983, Björck et al 1984a, Schweizer and Reimann 1986, Siljeström et al 1986, Theander and Westerlund 1987, Aoe et al 1989), and drew no consistent conclusion. The diverse results of these studies may be attributed to the use of different methodologies to analyze dietary fiber (Varo et al 1983).

Starch plays an important role in extrusion cooking of cereals. It is the major component that builds a matrix of extrudate and is a key element responsible for extrusion expansion. The gelatinization of starch granules by heat processing has important implications for nutrition (Holm et al 1988). Regarding coextrusion of starchy material and dietary fiber components, the possible interaction between starch and dietary fiber warrants consideration. Sugar beet fiber, which has a high water-holding capacity (Michel et al 1988), might compete for water with starch and result in a low level of gelatinized starch due to insufficient water available for gelatinization. Therefore, it is essential to evaluate the degree of starch gelatinization in the dietary fiber-starch system.

For extrusion-puffed products, one of the most important characteristics is the degree of expansion or puffing, which in turn governs the textural, functional, and sensory properties of a product. However, the attempt to incorporate high levels of fiber in extruded products often results in a compact, tough, noncrisp, undesirable texture in extrudates because of low expansions (Breen et al 1977, Andersson et al 1981, Lawton et al 1985). In baked products, particle size of dietary fiber influences bread volume (Satin et al 1978, Lai et al 1989, Sievert et al 1990). Nevertheless, no work on the effect of fiber particle size has been conducted for extruded products.

The purposes of this study were to investigate the effect of particle size of dietary fiber on extrusion puffing, to determine the IDF, SDF, and TDF (total dietary fiber) contents of extrudates, and to evaluate their total ungelatinized and gelatinized starch content and degree of gelatinization.

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MATERIALS AND METHODS

Materials

Sugar beet fiber of different particle sizes was obtained from the American Crystal Sugar Co. (Moorhead, MN). The fiber was mixed with corn meal obtained from Lauhoff Grain Co. (Danville, IL) in ratios of 0:100, 10:90, 20:80, and 30:70 (w/w). After 10 min of thorough mixing in a mixer (model A-200-F, Hobart Corp., Troy, OH), the blend was fed into the extruder through a twin-screw volumetric feeder (model T-35, K-tron Corp., Pitman, NJ). The feed rate was maintained at 45 kg/hr.

Extrusion Cooking

A corotating, intermeshing twin-screw extruder (MPF50/25, APV Baker Inc., Grand Rapids, MI) was used (Fig. 1). Water at ambient temperature (about 25°C) was injected into the extruder (as it was operating) at a rate of about 4.0 kg/hr, resulting in a moisture content of 25% (db) in the feed material. The end of the extruder was equipped with a die plate, which held two circular die openings tapered to 3.18 mm in diameter. An adjustable four-blade die face cutter was operated at 325 rpm. The cut extrudates were collected when the operation condition was at steady state. The samples were dried to a final moisture content of 7% in a fluidized bed drier at 65°C. After being cooled to room temperature, the samples were sealed in polyethylene bags and stored at 5°C for analysis.

The factors studied were screw speed (200 and 300 rpm), fiber particle size (l0-, 40-, 120-, and 200-mesh) and level of addition (10, 20, and 30%). These 24 (2 × 4 × 3) treatment combinations were duplicated in extrusion cooking.

Product Analysis

The diameters and lengths of 50 pieces of extrudate taken at random from each run were measured (in centimeters) and averages calculated. Measurement of product specific volume followed essentially the sand displacement procedure (Park 1976). About 10 g of the product was weighed and put into a container of known weight and volume. White sand of predetermined density was used to fill the remaining space in the container in four increments, with six tappings on the container each time to pack down the sand. The weight of sand in the container was the difference between total weight (container + sand + product) and that of the container and product, which was used to determine the volume of sand inside the container. The product volume was the difference between the container volume and the sand volume. Specific volume was calculated as the extrudate volume divided by the sample weight. The result for each run was the average of three determinations.

In preparing the extrudate samples for scanning electron microscopy, a razor blade was used to obtain a cross-section approximately 0.5–1.0 cm in length (Lue et al 1990). At least two specimens were included in each sample to avoid a chance erroneous result. Each sample was prepared for both transverse and external examination. For transverse observation, the specimen was mounted on aluminum stubs with the cross-section exposed. For external observation, the extrudate rod was cut in half along the longitudinal axis and placed on stubs with the curvature surface outward. The specimens were fixed with copper tape and coated with gold-palladium by a scanning electron microscopy sputter coater (model E5100, Polaron Instruments Inc., Cambridge, MA). The coating was achieved by applying 2.5 kV and a 20-mA current for 2 min to deposit a conductive layer 300 Å thick. The specimens were examined with a scanning electron microscope (JEOL, model JSM-35, Tokyo, Japan) at 20 kV. Photographs were taken with 55 P/N film (Polaroid Corp., Cambridge, MA).

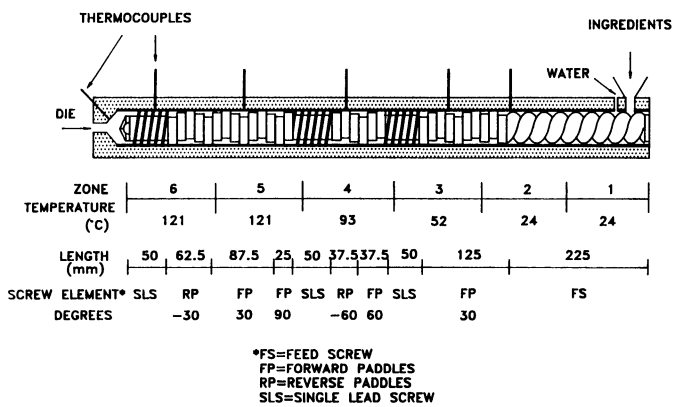

Fig. 1. Screw configuration and barrel-temperature profile used in extrusion cooking.

The percentages of SDF, IDF, and TDF contents in samples were determined by an enzymatic-gravimetric method (Prosky et al 1985, 1988). Total and gelatinized starch contents were determined with a modified method of Chiang and Johnson (1977a). The samples were ground to pass through a 40-mesh screen and were mixed thoroughly. Portions of the samples were dried in a vacuum oven to determine moisture content (AOAC, 1984), and portions were analyzed for total and gelatinized starch contents. To determine total starch, 0.2 g of ground sample was measured precisely and transferred to a 50-ml volumetric flask; 3 ml of distilled water and then 2 ml of 1*N* NaOH were added. The flask was placed in a 60°C water bath and shaken continuously. After 30 min, the flask was removed from the water bath and 2 ml of 1*N* HCl was added to neutralize the alkali. A 25-ml glucoamylase solution (8 g/250 ml of acetate buffer) was added to the flask and incubated in a 40°C water bath for 30 min, with shaking. After enzymatic digestion, 8 ml of 25% trichloroacetic acid was added to inactivate the glucoamylase. The hydrolysate was diluted to 50 ml with distilled water and filtered through filter paper (PS, Fisher Scientific). A 0.2-ml aliquot of filtrate was pipetted to a test tube containing 4.8 ml of o-toluidine reagent. The tube was then boiled for 10 min in

TABLE I
Mean Diameter (D), Length (L) and Specific Volume (V) of Extrudate Samples of 10, 20, and 30% Sugar Beet Fiber

Sugar Beet Fiber (%)	Screw Speed (rpm)	Fiber Particle Size (mesh)	L[a] (cm)	D (cm)	V (cm^3/g)
10	200	10	2.09	1.15	5.04
		40	2.47	1.20	6.82
		120	2.50	1.23	6.83
		200	2.60	1.26	7.95
	300	10	2.64	1.03	6.37
		40	3.19	1.05	8.30
		120	3.48	1.10	9.06
		200	3.33	1.10	8.70
20	200	10	1.89	0.94	3.10
		40	2.55	1.03	5.36
		120	2.86	1.04	6.37
		200	2.86	1.12	6.94
	300	10	2.82	0.83	4.47
		40	4.00	0.80	6.49
		120	4.44	0.82	7.02
		200	4.10	0.95	7.43
30	200	10	1.94	0.76	2.11
		40	2.79	0.84	4.34
		120	2.61	0.97	5.01
		200	3.10	0.96	5.73
	300	10	2.65	0.68	2.86
		40	4.20	0.63	5.50
		120	4.06	0.76	5.28
		200	4.10	0.83	5.50

[a] Least significant differences: L, 0.69 at the 0.05 level; D, 0.12 cm; V, 0.78 cm^3/g.

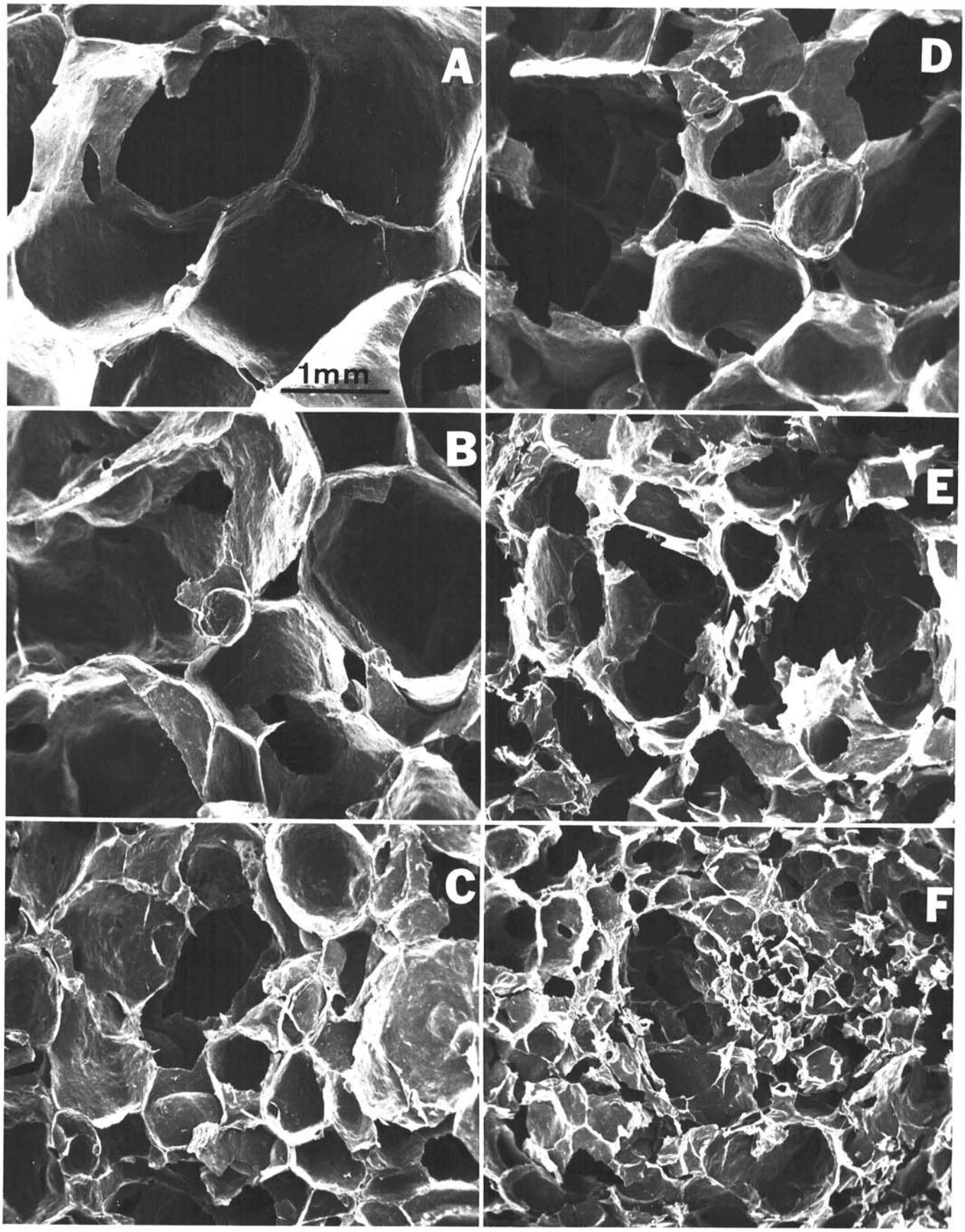

Fig. 2. Scanning electron micrographs of the internal structure of extrudates of corn meal containing sugar beet fiber (200 mesh). **A,** 10%; **B,** 20%; C, 30% (extruded at 200 rpm screw speed); **D,** 10%; **E,** 20%; **F,** 30% (extruded at 300 rpm screw speed).

100°C water for the chromophore to develop color. After the sample was cooled to room temperature, the green solution was diluted with 10 ml of glacial acetic acid. Absorbance was measured at 630 nm against a reagent blank (model Spectronic 20D, Milton Roy Co., Riviera Beach, FL).

The procedure for determining the quantity of gelatinized starch was similar to that for determining total starch, except that the samples were not treated with alkali. The samples were mixed with 7 ml of distilled water and 25 ml of enzyme solution and then were incubated. A glucose standard was run with the samples to calculate their glucose concentration. Starch content was quantified as glucose × 0.9 and expressed on a dry basis. The degree of gelatinization was calculated by the following equation:

$$Y = [(X - k) \times 100] / T - k, \quad (1)$$

where Y is the degree of gelatinization, X is the gelatinized starch content (%, db), T is the total starch content (%, db), and k is the percentage of native starch attacked by enzyme (Shetty et al 1974, Chiang and Johnson 1977a). The k value was determined by incubating various amounts of raw corn meal with glucoamylase and establishing a regression line of released glucose with starch weight.

Statistical Analysis

All statistics were performed by the SAS statistical analysis system (SAS 1985). Data were analyzed using the general linear model. Independent variables included the main effect of replication; main effects and interactions of fiber particle size (mesh), fiber percentage (fiber), and screw speed (rpm); and the nested effects of replication within mesh, fiber, and rpm. Appropriate mean comparisons were performed by least significant difference, using nested effects as error terms.

RESULTS AND DISCUSSION

Expansion Properties

Effect of dietary fiber content. Since the product was cut at a fixed speed, the length and diameter of extrudate indicated the extent of its longitudinal and radial expansions. Increasing dietary fiber content in feed resulted in decreased diameter but enlarged length of the extrudate (Table I), which is in agreement with the findings of a previous study (Lue et al 1990). In earlier studies, radial expansion decreased with increasing dietary fiber content (Andersson et al 1981, Breen et al 1977, Lawton et al 1985). Park (1976) proposed that puffing phenomena of extrudates result from the vaporization of superheated water as the extrudate exits the die. The simultaneous flash-off of vapor expands the starchy material, resulting in the porous, spongelike structure within the extrudate. The degree of expansion of extrudate is closely related to the size, number, and distribution of the air cells surrounded by the cooked matrix (Lue et al 1990). Scanning electron micrographs reveal the internal structure of the products (Fig. 2). The size of the air cells in the extrudate seemed to be correlated with the radial expansion of the product; as the radial expansion decreased, the size of the air cells decreased.

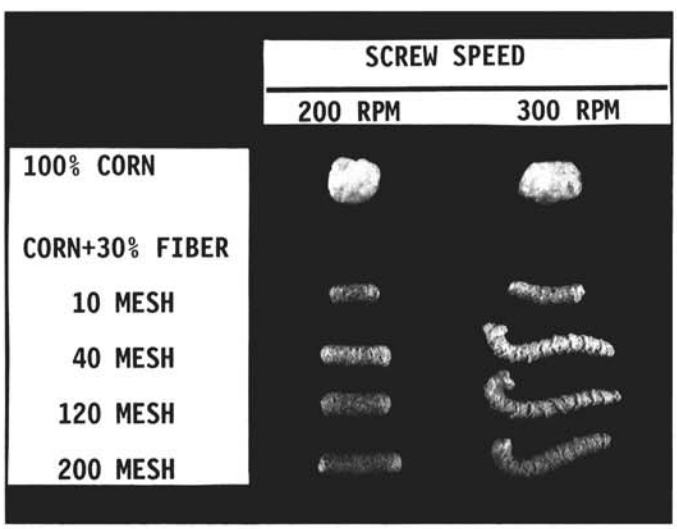

Fig. 3. Extrudate containing 0 or 30% fiber of various particle sizes. Notice the ridges ("sharkskin") in the 40- and 120-mesh samples at screw speed.

Effect of screw speed. Increasing screw speed from 200 to 300 rpm favored longitudinal expansion at the expense of radial puffing; it also increased volumetric expansion (Table I). Figure 2 shows that the air cells were smaller in the product that was processed at higher screw speed. Fletcher et al (1985) found that both radial and axial expansions of maize grit extrudate changed in the same manner as screw speed changed in the range of 150–430 rpm. They attributed this effect to decreased melt viscosity, more even moisture distribution, and increased elasticity of cooked dough when screw speed was increased. Owusu-Ansah et al (1984) and Taranto et al (1975) also found that the radial expansion of extrudate improved with increased screw speed. In extruding corn starch with a single-screw extruder, Chinnaswamy and Hanna (1988) demonstrated that increasing screw speed from 80 to 150 rpm resulted in a greater radial expansion ratio, but further increases in screw speed reduced radial expansion. They suggested that higher screw speed resulted in a shorter residence time and hence decreased the degree of starch gelatinization because of incomplete cooking. Thus, no consistent conclusion has been drawn regarding the effect of screw speed on expansion. The different screw configurations and feed ingredients used in various investigations probably make the comparisons more difficult.

In the present study, we noted that the 30% fiber products extruded at a screw speed of 300 rpm exhibited a regular, ridged surface distortion ("sharkskin") (Figs. 3, 4A) but did not do so at 200 rpm (Figs. 3, 4B). This phenomenon has not been reported for extruded food but is being studied in polymer extrusion. According to Rauwendaal (1986), it is dependent primarily on the linear extrusion speed or temperature. The mechanism of sharkskin is postulated to be caused by the rapid acceleration of the surface layers of the extrudate when polymer leaves the die. If the stretching rate is too high, the surface layer of the polymer can actually fail and form the characteristic ridges of the sharkskin surface. To reveal the surface structure of extrudate, the products were examined with a scanning electron microscope. The micrographs showed ridges on the surface structure that were predominant with openings (Fig. 4C), which had similar dimensions to the air cells in the inner cross-section of the product. Fiber appeared to disrupt the surface layer because of the inability of the extrudate to maintain a sound bubble film when expanding; this resulted in breakage of weaker sections in the air cell walls. Decreasing the screw speed to 200 rpm could eliminate the occurrence of sharkskin (Fig. 4B and D). This could be explained by the decrease in stretching rate due to a lower screw speed so that the surface layer could be maintained without disruption.

Effect of fiber particle size. As fiber particle size decreased, puffing in both directions increased (Table I). Thus, decreased fiber size favored product expansion. There are two explanations for this: 1) The coarser fiber retarded the development of air bubbles, and the gas pockets broke down before they optimally expanded; 2) the finer fiber, because of its greater water-binding capacity, had more nucleation sites for water vapor to develop as the material exited the die. Thus, even though the sizes of the air pocket, expanded by vaporization force, developed to a similar extent for extrudates containing either coarse or fine fiber (Fig. 5), the latter resulted in more radial and longitudinal expansions than the former. This is because the extrudates containing finer fiber have more air cells than those containing coarser fiber.

Starch Gelatinization

Glucoamylase extensively attacked intact starch of corn meal, as indicated by the considerable amount of glucose released after

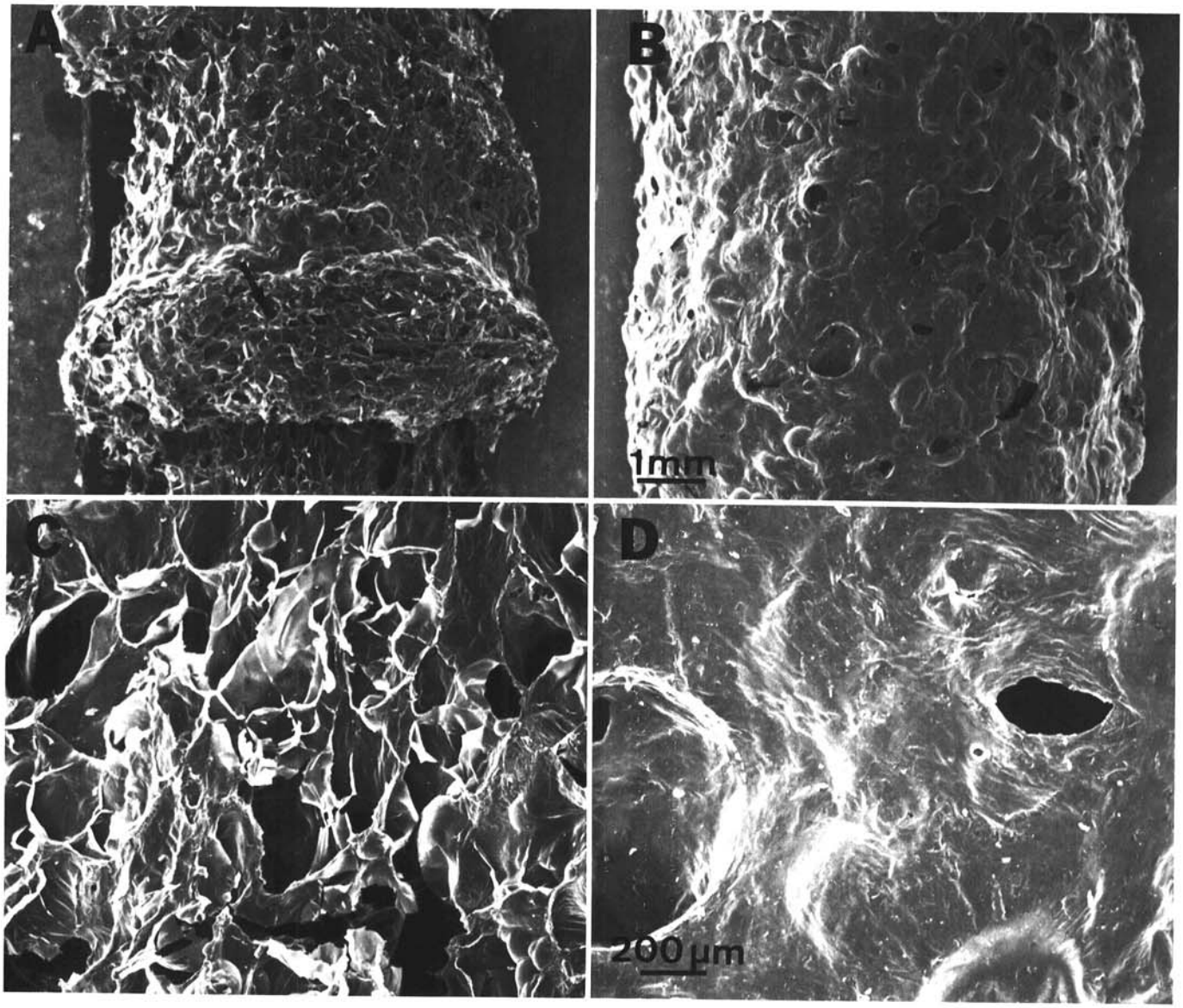

Fig. 4. Scanning electron micrographs of the surface structure of extrudate containing 30% of 40-mesh fiber. **A,** 300 rpm screw speed; **B,** 200 rpm screw speed. **C** and **D,** views at higher magnification of **A** (ridged area marked with an arrow) and **B,** respectively.

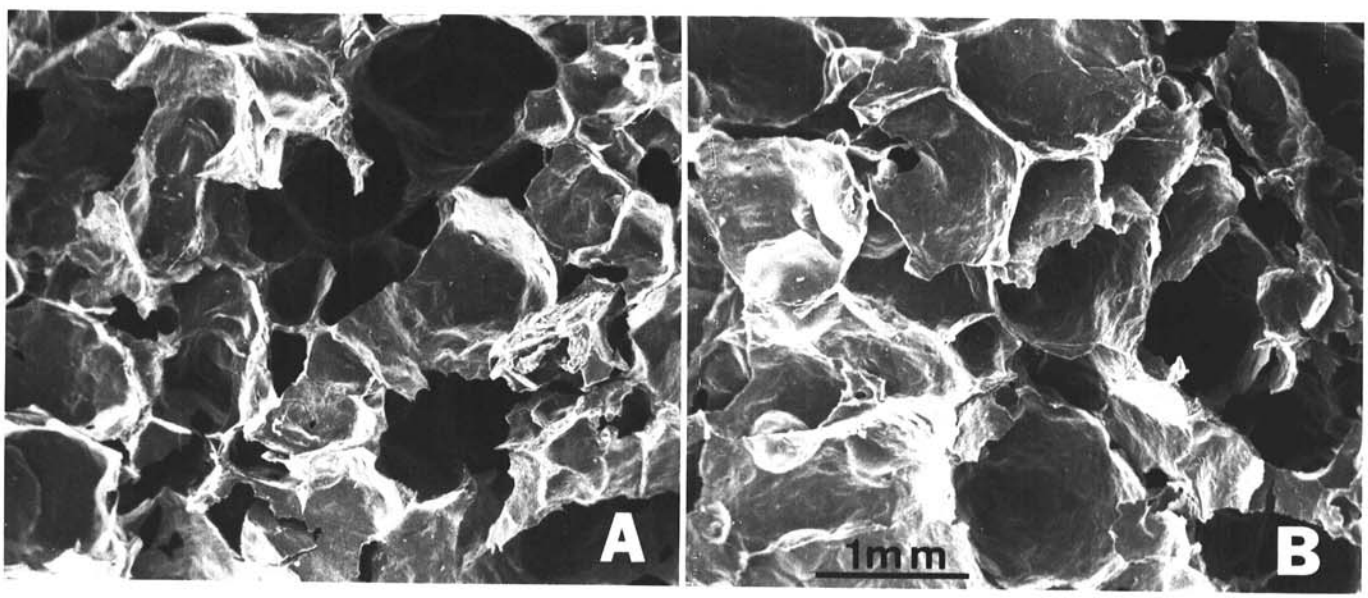

Fig. 5. Scanning electron micrographs of the internal structure of products containing 30% fiber. **A,** 10-mesh product; **B,** 120-mesh product (screw speed, 200 rpm).

the corn meal was incubated with the enzyme. The extent of enzyme digestibility of intact starch depends on the botanic source of starch (Shetty et al 1974), enzyme concentration for digestion, and incubation condition (Holm et al 1988). Fig. 6 shows a plot of weight converted to glucose (digested weight) from various amounts of corn meal. The data were used to fit a straight line through the origin. The slope of the line corresponding to digested starch (without alkali treatment) was 0.196, indicating that about 0.196 g of corn starch was digested from 1 g of dry corn meal at this incubation condition. For the line corresponding to alkali pretreatment, the slope was 0.859, which means that the total starch content of corn meal was 85.9% (db). Therefore, k in equation 1 (the percentage of intact native starch attacked by glucoamylase) would be equal to $0.196/0.859 \times 100$, or 22.8%. Standard deviations in the corn meal assay were 1.52 and 1.97% for total and gelatinized starch contents, respectively.

The corn meal extrudate, which was highly expanded, contained 82.8–88.4% total starch (db); the degree of starch gelatinization was 97.6–100.3%. The results of fiber-enriched products are shown in Tables II–IV. Total starch content was 75–79% (db) in the 10%-fiber product, 66–72% in the 20%-fiber product, and 58–64% in the 30%-fiber product. The average total starch contents were 77.1, 68.3, and 60.6% (db) for 10%-, 20%-, and 30%-fiber products, respectively. These quantities were not significantly different ($P > 0.05$) from the feed starch contents, which were calculated by adding the total starch contents of corn meal and sugar beet fiber after weight correction. The expected values were 78, 69, and 61%, for the corresponding products. Total starch content is unaffected by extrusion cooking (Varo et al 1983, Björck et al 1984b, Sandberg et al 1986, Schweizer and Reimann 1986, Siljeström et al 1986).

The gelatinized starch content was not significantly different from the total starch content for each sample (Tables II–IV). The starch was completely gelatinized during extrusion cooking, as indicated by the high degrees of gelatinization (97–106%). Chiang and Johnson (1977b) showed that as the temperature exceeded 110°C, extrusion cooking produced virtually complete starch gelatinization. A combination of heating and mechanical shear effects would result in the disappearance of starch granular structure in extruded materials even at a moisture content less than what is theoretically required for thorough gelatinization. In addition, it seemed that resistant starch, which was found during the heating process in baked products, did not form during extrusion cooking. In contrast to long heating time for baking products, the high temperature-short time processing during extrusion cooking did not change starch digestibility of products.

TABLE II
Total Starch, Gelatinized Starch, and Degree of Starch Gelatinization in 10%-Fiber Products Extruded at Two Screw Speeds[a]

Fiber Particle Size (mesh)	Total Starch (%, db)	Gelatinized Starch (%, db)	Degree of Starch Gelatinization (%)
200 rpm			
10	79.2 ± 2.3	79.8 ± 0.9	101.1 ± 2.4
40	77.7 ± 3.4	76.2 ± 0.5	97.6 ± 5.1
120	76.1 ± 4.0	79.2 ± 0.03	106.2 ± 8.0
200	77.6 ± 2.7	76.7 ± 2.4	98.2 ± 0.6
300 rpm			
10	79.0 ± 0.3	79.3 ± 0.2	100.5 ± 0.9
40	75.3 ± 2.0	75.3 ± 0.8	100.2 ± 5.4
120	75.9 ± 2.8	75.6 ± 4.8	99.3 ± 3.7
200	76.0 ± 1.9	77.8 ± 2.7	103.3 ± 1.5

[a] n = 2.

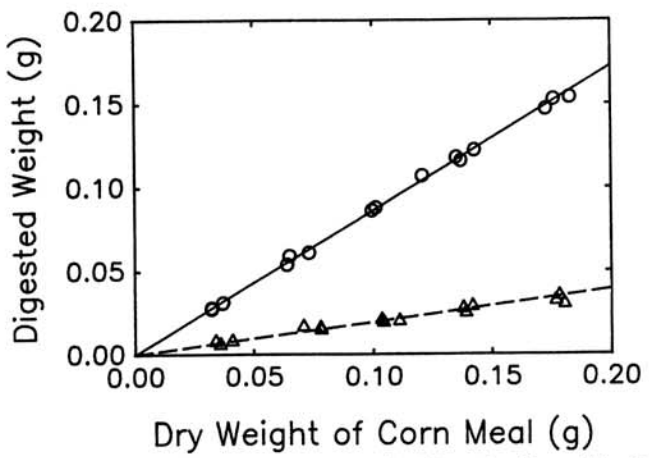

Fig. 6. Digestibility of raw corn meal with (○) and without (△) alkali pretreatment.

Dietary Fiber Contents

TDF accounted for 3% (db) in corn meal, with a negligible amount of SDF (Table V). The sugar beet fiber contained 65–70%

TABLE III
Total Starch, Gelatinized Starch, and Degree of Starch Gelatinization in 20%-Fiber Products Extruded at Two Screw Speeds[a]

Fiber Particle Size (mesh)	Total Starch (%, db)	Gelatinized Starch (%, db)	Degree of Starch Gelatinization (%)
200 rpm			
10	72.1 ± 0.6	72.2 ± 0.3	100.2 ± 0.5
40	68.6 ± 0.3	67.8 ± 0.8	98.4 ± 2.5
120	69.5 ± 1.5	68.7 ± 2.5	98.3 ± 2.4
200	68.6 ± 3.6	67.9 ± 1.1	98.7 ± 5.4
300 rpm			
10	69.4 ± 4.1	68.8 ± 1.6	99.0 ± 5.4
40	66.3 ± 1.7	65.7 ± 2.3	98.7 ± 1.4
120	65.9 ± 1.1	68.4 ± 0.8	106.0 ± 4.6
200	66.2 ± 1.0	69.1 ± 1.5	106.6 ± 5.9

[a] n = 2.

TABLE IV
Total Starch, Gelatinized Starch, and Degree of Starch Gelatinization in 30%-Fiber Products Extruded at Two Screw Speeds[a]

Fiber Particle Size (mesh)	Total Starch (%, db)	Gelatinized Starch (%, db)	Degree of Starch Gelatinization (%)
200 rpm			
10	64.5 ± 0.4	64.9 ± 0.4	99.1 ± 0.6
40	59.6 ± 0.2	60.5 ± 2.6	102.5 ± 7.6
120	60.4 ± 0.3	61.0 ± 1.7	101.7 ± 5.3
200	59.6 ± 1.3	61.7 ± 0.6	105.8 ± 5.4
300 rpm			
10	62.5 ± 0.01	63.2 ± 0.7	101.7 ± 1.7
40	58.4 ± 1.2	59.0 ± 1.1	101.8 ± 6.4
120	59.3 ± 1.4	58.2 ± 1.5	96.8 ± 0.3
200	60.6 ± 0.3	59.8 ± 0.9	97.9 ± 1.8

[a] n = 2.

TABLE V
Dietary Fiber Content in Raw Materials (%, db; n = 2)

Component	IDF[a]	SDF	TDF
Sugar beet fiber			
Mesh size			
10	69.84 d[b]	8.97 d	78.81 d
40	66.84 e	12.04 e	78.87 d
120	65.78 e	12.40 e	78.17 d
200	65.47 e	12.00 e	77.47 d
Corn meal	2.86	<0.01	2.86

[a] IDF = insoluble dietary fiber, SDF = soluble dietary fiber, TDF = total dietary fiber = (IDF + SDF).
[b] Mean values with the same letter in a column were not significantly different at the 0.05 level.

IDF, 9–12% SDF, and 77–79% TDF. The TDF content of the sugar beet fiber agreed with previously published data (Michel et al 1988, Wen et al 1988). The coarse (10-mesh) fiber had more IDF and less SDF, but TDF content was not significantly different from that of finer fibers.

IDF, SDF, and TDF contents for products from each run were determined in duplicate. Standard deviations for determining IDF, SDF, and TDF contents on the same samples were 0.361, 0.757, and 0.906% (db), respectively. Neither the screw speed nor the fiber particle size had significant effects on product fiber contents (Table VI). IDF, SDF, and TDF contents were 18–20%, 2–4% and 22–23% (db), respectively. Compared with the fiber contents of raw materials, IDF decreased significantly. SDF increased and TDF decreased, but the deviations were not significant at the 0.05 level.

For extruded wheat flour, TDF content did not change after extrusion (Varo et al 1983, Schweizer and Reimann 1986); however, a shift from insoluble to soluble fiber was observed (Björck et al 1984a, Siljeström et al 1986). Fornal et al (1987) found significant decreases in hemicellulose, cellulose, and lignin in extruded starch mixtures, indicating that thermal decomposition of dietary fiber took place. Studying the extrusion cooking of high-fiber cereal, Sandberg et al (1986) reported that mild extrusion conditions did not change the content of nonstarch polysaccharides but decreased the amount of Klason lignin. In contrast, Theander and Westerlund (1987) found increased enzyme-resistant glucans in both SDF and IDF components of extruded wheat flour and concluded that the increase resulted from external transglycosidation of starch and starch-fragmentation products. Lignin increased because of the Maillard reaction in extrusion cooking. Unlike white flour, whole-grain wheat flour showed higher TDF, IDF, and SDF contents after extrusion (Björck et al 1984a). In extruded wheat bran, Aoe et al (1989) found that TDF and IDF contents decreased but SDF increased.

It seems that differences in dietary fiber content depend on extrusion conditions as well as on the processing materials. More fiber might be modified under low moisture and high shear operating conditions. Our results showed that the formation of enzyme-resistant starch, if any, was limited. The decrease of IDF might result from thermal and/or mechanical decomposition. Thus, some IDF became soluble or degraded to low molecular weight fragments. Aoe et al (1989) proposed that the increase in SDF indicates solubilization of dietary fiber and/or the release of soluble hemicellulose fraction from the dietary fiber. This solubilization may alter the physiologically related properties of extruded dietary fiber. This nutritional concern needs further study.

CONCLUSION

Decreasing fiber particle size could counterbalance the adverse effect of adding sugar beet fiber on product expansion. This may be because the finer fiber supplied more nucleation sites for water vaporization and favored expansion by increasing the number of air cells. Dietary fiber content and degree of starch gelatinization of extrudates were not affected by fiber particle size.

Screw speed had a great influence on product expansion: Increasing screw speed caused more elongation but decreased cross-sectional expansion. High screw speed (300 rpm) resulted in surface instability (sharkskin). Extrusion cooking increased SDF but decreased IDF and TDF content. A more severe extrusion condition, with a screw speed of 300 rpm, caused more fiber modification during extrusion.

Total starch contents before and after extrusion cooking, as determined by released glucose after enzymatic digestion, were not significantly different. Furthermore, the starch was completely gelatinized during extrusion cooking. Neither fiber percentage nor screw speed influenced the degree of starch gelatinization.

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TABLE VI
Dietary Fiber Contents of Feed and Sugar Beet Fiber and Corn Meal (30:70, w/w) Extrudates[a]

Fiber Particle Size	Fiber	Feed	Extruded Products (%, db) 200 rpm	300 rpm
10 mesh	IDF[b]	21.22	19.75[c]	19.74[c]
	SDF	2.50	2.10	3.40
	TDF	23.72	21.85	23.14
40 mesh	IDF	20.37	19.77	19.15
	SDF	3.35	3.46	4.27
	TDF	23.72	23.23	23.42
120 mesh	IDF	20.10	18.64[c]	18.39[c]
	SDF	3.47	3.74	4.00
	TDF	23.57	22.38	22.39
200 mesh	IDF	20.01	19.18	18.62[c]
	SDF	3.35	3.36	3.68
	TDF	23.36	22.54	22.30

[a] n = 4.
[b] IDF = insoluble dietary fiber, SDF = soluble dietary fiber, TDF = total dietary fiber (IDF + SDF).
[c] Significantly different from feed material at the 0.05 level.

LITERATURE CITED

ANDERSSON, Y. HEDLUND, B., JONSSON, L., and SVENSSON, S. 1981. Extrusion cooking of a high-fiber cereal product with crispbread character. Cereal Chem. 58:370.

AOE, S., NAKAOKA, M., IDO, K., TAMAI, Y., OHTA, F., and AYANO, Y. 1989. Availability of dietary fiber in extruded wheat bran and apparent digestibility in rats of coexisting nutrients. Cereal Chem. 66:252.

ASSOCIATION OF OFFICIAL ANALYTICAL CHEMISTS. 1984. Official Methods of Analysis, 14th ed. The Association: Washington, DC.

BEST, D. 1987. Building fiber into foods. Prep. Foods 156(7):112.

BJÖRCK, I., NYMAN, M., and ASP, N.-G. 1984a. Extrusion cooking and dietary fiber: Effects on dietary fiber content and on degradation in the rat intestinal tract. Cereal Chem. 61:174.

BJÖRCK, I., ASP, N.-G., BIRKHED, D., and LUNDQUIST, I. 1984b. Effects of processing on availability of starch for digestion in vitro and in vivo: I. Extrusion cooking of wheat flours and starch. J. Cereal Sci. 2:91.

BJÖRCK, I., NYMAN, M., PEDERSEN, B., SILJESTRÖM, M., ASP, N.-G., and EGGUM, B. O. 1986. On the digestibility of starch in wheat bread: Studies in vitro and in vivo. J. Cereal Sci. 4:1.

BREEN, M. D., SEYAM, A. A., and BANASIK, O. J. 1977. The effect of mill by-products and soy protein on the physical characteristics of expanded snack foods. Cereal Chem. 54:728.

CHIANG, B.-Y., and JOHNSON, J. A. 1977a. Measurement of total and gelatinized starch by glucoamylase and o-toluidine reagent. Cereal Chem. 54:429.

CHIANG, B.-Y., and JOHNSON, J. A. 1977b. Gelatinization of starch in extruded products. Cereal Chem. 54:436.

CHINNASWAMY, R., and HANNA, M. A. 1988. Optimum extrusion-cooking conditions for maximum expansion of corn starch. J. Food Sci. 53:834.

FLETCHER, S. I., RICHMOND, P., and SMITH, A. C. 1985. An experimental study of twin-screw extrusion-cooking of maize grits. J. Food Eng. 4:291.

FORNAL, L., SORAL-ŚMIETANA, M., ŚMIETANA, Z., and SZPENDOWSKI, J. 1987. Chemical characteristics and physicochemical properties of the extruded mixtures of cereal starches. Starch/Staerke 39(3):75.

HOLM, J., LUNDQUIST, I., BJÖRCK, I., ELIASSON, A.-C., and ASP, N.-G. 1988. Degree of starch gelatinization, digestion rate of starch in vitro, and metabolic response in rats. Am. J. Clin. Nutr. 47:1010.

LAI, C. S., HOSENEY, R. C., and DAVIS, A. B. 1989. Effects of wheat bran in breadmaking. Cereal Chem. 66:217.

LAWTON, J. W., DAVIS, A. B., and BEHNKE, K. C. 1985. High-temperature, short-time extrusion of wheat gluten and a branlike fraction. Cereal Chem. 62:267.

LUE, S., HSIEH, F., PENG, I. C., and HUFF, H. E. 1990. Expansion of corn extrudates containing dietary fiber: A microstructure study.

Lebensm. Wiss. Technol. 23:165.
MICHEL, F., THIBAULT, J.-F., and BARRY, J.-L. 1988. Preparation and characterisation of dietary fiber from sugar beet pulp. J. Sci. Food Agric. 42:77.
OWUSU-ANSAH, J., VAN DE VOORT, F. R., and STANLEY, D. 1984. Textural and microstructural changes in corn starch as a function of extrusion variables. Can. Inst. Food Sci. Technol. J. 17(2):65.
PARK, K. H. 1976. Elucidation of the extrusion puffing process. Ph.D. thesis, University of Illinois, Urbana, IL.
PROSKY, L., ASP, N.-G., FURDA, I., DeVRIES, J. W., SCHWEIZER, T. F., and HARLAND, B. F. 1985. Determination of total dietary fiber in foods and food products: Collaborative study. J. Assoc. Off. Anal. Chem. 68:677.
PROSKY. L., ASP, N.-G., SCHWEIZER, T. F., DeVRIES, J. W., and FURDA, I. 1988. Determination of insoluble, soluble, and total dietary fiber in foods and food products: Interlaboratory study. J. Assoc. Off. Anal. Chem. 71:1017.
RAUWENDAAL, C. 1986. Polymer Extrusion. Hanser Publishers: New York.
SANDBERG, A.-S., ANDERSSON, H., KIVISTÖ, B., and SANDSTRÖM, B. 1986. Extrusion cooking of a high-fibre cereal product. I. Effects on digestibility and absorption of protein, fat, starch, dietary fibre, and phytate in the small intestine. Brit. J. Nutr. 55:245.
SAS INSTITUTE. 1985. SAS/STAT User's Guide: Statistics, Version 5 edition. The Institute: Cary, NC.
SATIN, M., McKEOWN, B., and FINDLAY, C. 1978. Design of a commercial natural fiber white bread. Cereal Foods World 23:676.
SCHWEIZER, T. F., and REIMANN, S. 1986. Influence of drum-drying and twin-screw extrusion cooking on wheat carbohydrates. I. A comparison between wheat starch and flours of different extraction. J. Cereal Sci. 4:193.
SHETTY, R. M., LINEBACK, D. R., and SEIB, P. A. 1974. Determining the degree of starch gelatinization. Cereal Chem. 51:364.
SIEVERT, D., POMERANZ, Y., and ABDELRAHMAN A. 1990. Functional properties of soy polysaccharides and wheat bran in soft wheat products. Cereal Chem. 67:10.
SILJESTRÖM, M., WESTERLUND, E., BJÖRCK, I., HOLM, J., ASP, N.-G., and THEANDER, O. 1986. The effects of various thermal processes on dietary fibre and starch content of whole grain wheat and white flour. J. Cereal Sci. 4:315.
TARANTO, M. V., MEINKE, W. W., CATER, C. M., and MATTIL, K. F. 1975. Parameters affecting production and character of extrusion-texturized defatted glandless cottonseed meal. J. Food Sci. 40:1264.
THEANDER, O., and WESTERLUND, E. 1987. Studies on chemical modifications in heat-processed starch and wheat flour. Starch/Staerke 39(3):88.
VARO, P., LAINE, R., and KOIVISTOINEN, P. 1983. Effect of heat treatment on dietary fiber: Interlaboratory study. J. Assoc. Off. Anal. Chem. 66:933.
WEN, L. F., CHANG, K. C., BROWN, C., and GALLAHER, D. D. 1988. Isolation and characterization of hemicellulose and cellulose from sugar beet pulp. J. Food Sci. 53:826.

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