Effects of Twin-Screw Extrusion on the Physical Properties of Dietary Fiber and Other Components of Whole Wheat and Wheat Bran and on the Baking Quality of the Wheat Bran[1]

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ABSTRACT

The effects of twin-screw extrusion processing at three different screw speeds on the physical properties of whole wheat and wheat bran were evaluated. Also, a baking study was conducted to show how different extrusion-processing conditions affected the functionality of wheat bran in whole wheat bread. Small decreases in total and insoluble dietary fiber were noted in extruded versus raw wheat and wheat bran, along with increases in soluble dietary fiber. The largest increase in soluble dietary fiber occurred in wheat bran extruded at the highest screw speed. Protein solubility decreased in the extruded products. Although total fat was somewhat lower in both whole wheat and bran after extrusion, the percentage of ether-extractable fat increased in wheat bran and decreased in whole wheat. Enzyme-digestible starch and water absorption were higher for extruded samples than they were for raw samples. Although viscosities of whole wheat and wheat bran slurries at 95°C were much lower for the extruded samples than they were for the raw samples, slurries of extruded whole wheat at 37°C were more viscous than those of the raw sample. The baking study showed that extruded wheat bran is an acceptable product for use in preparation of "whole wheat" bread.

Extrusion cooking is essentially a process in which moistened starchy or proteinaceous foods are worked into a viscous, plastic-like dough and cooked before being forced though a die. Some results of cooking during the extrusion process are the gelatinization of starch, denaturation of protein, inactivation of many native enzymes causing food deterioration during storage, destruction of naturally occurring toxic substances (such as trypsin inhibitors in soybeans), and diminishing of microbial counts in the final product (Harper 1981). Extrusion processing is unique from other heat processes in that the material is subjected to intense mechanical shear; extruder shear forces are capable of breaking covalent bonds in biopolymers. The intense structural disruption and mixing facilitate reactions otherwise limited by diffusion of reactants and products (Asp and Bjorck 1989). Extrusion is increasingly used to produce food for human consumption, as well as animal feed.

Although the elevated pressure, high temperature, and intense mechanical shear applied during the process obviously alter physical and chemical properties of the extruded products, the changes have not been well defined. The purpose of this study was to evaluate the effects of extrusion processing at three different screw speeds on the physical properties of whole grain wheat and wheat bran. Also, a baking study was conducted to show how different conditions of extrusion processing can affect the functionality of wheat bran in whole wheat bread.

MATERIALS AND METHODS

Hard red winter wheat was obtained from a local elevator in Manhattan, KS. Wheat bran (12% of the grain) from hard red winter wheat was obtained from the pilot mill in the Department of Grain Science and Industry, Kansas State University, Manhattan, KS. During milling, the flour-shorts-red dog plus germ-bran ratio was 74:12:2:12.

Grains were ground through the 1/8-in. (3.2-mm) screen of a Fitz mill (Fitzpatrick Co., Elmhurst, IL) and then extruded. The high-shear screw configuration for the Wenger TX-52 corotating twin-screw extruder (Sabetha, KS) is shown in Table I; process conditions are described in Table II. The die configuration also added to the shear placed on the products. A backup die had two holes (positioned against the extruder barrel) that converged to one in the center. The final die had three openings; the entry orifices were larger than the exit orifices (3/16 in.). Ground samples (200 lbs) of the whole wheat (8.4% moisture) or wheat bran (8.8% moisture) were added to the extruder hopper. Samples were collected after a steady state was attained. Moisture was added to the conditioning cylinder at a rate of 260 g/min. Extruder screw speeds for the experimental treatments were set at 200, 300, or 400 rpm, which are referred to as *low, medium,* or *high* conditions, respectively. The extrudate temperature increased and barrel pressure decreased with increasing extruder screw speed. Moisture content of extrudates ranged from 18.2 to 21.8%. After drying (104°C for 10 min), extrudates were ground

TABLE I
Wenger TX-52 Screw Configuration for Extrusion of Whole Wheat and Wheat Bran

Element	Left Screw Elements[a,b]	Length, mm
1	SHAFT COLLAR	26.000
2	CNVY, ¾P	78.000
3	CNVY, ¾P	78.000
4	CNVY, ¾P	78.000
5	CNVY, ¾P	78.000
6	CNVY, ¾P	52.000
7	KB, 135°	8.667
8	KB, 180°	8.667
9	KB, 225°	8.667
10	KB, 270°	8.667
11	KB, 315°	8.667
12	KB, 360°	8.667
13	CNVY, ¾P	52.000
14	KB, 135°	8.667
15	KB, 180°	8.667
16	KB, 225°	8.667
17	CNVY, ¾P	78.000
18	KB, 0°	8.667
19	KB, 45°	8.667
20	KB, 90°	8.667
21	CNVY, ¾P	78.000
22	SL, 42 mm diameter	6.500
23	SL, 47 mm diameter	6.500
24	CNVY, ¾P	52.000
25	KB, 0°	6.500
26	KB, 90°	6.500
27	TL/CF CONE	73.000
Total		853.004

[a] The left shaft (when facing extruder) was the index shaft. Matching screw elements were placed on the right shaft in the same order but were set perpendicular to those on the left shaft.
[b] CNVY = conveying screw, P = pitch, KB = kneading block (shear lock), SL = round steam lock, TL = triple-lead flighted element, CF = cut flight. A backup die and final die were used as described in the text.

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through the 1/8-in. (3.2-mm) screen of the Fitz mill to produce products with a particle size similar to that of the raw (unextruded) materials that would aid in further analyses. At that point, moisture content for the wheat samples extruded at low, medium, and high conditions was 8.5, 8.7, and 9.0%. For the wheat bran, the corresponding moisture contents were 7.2, 7.6, and 8.0%. Both the raw and the extruded products were placed in plastic bags and stored in a cold room (2°C) until analysis.

Measurement of Physical Properties

The dietary fiber contents of the raw and extruded materials were analyzed in duplicate using the AACC enzymatic-gravimetric method 32-07 (AACC 1983). Protein solubility was determined in triplicate using the AACC nitrogen solubility index method 46-23. The nitrogen-to-protein conversion factor was 6.25. An acid hydrolysis (AACC method 30-10) was used to determine total fat in the grain samples. Extractability of fat (petroleum-ether extract) was determined by AACC method 30-25. All assays were performed in duplicate. Total starch in raw and extruded samples was assayed in triplicate by a modification of AACC method 76-11 using a dual-enzyme system. Starch was gelatinized in alkali instead of autoclaving; it was then digested with glucoamylase to form glucose. The amount of glucose released was determined by the glucose oxidase technique (Whistler 1972). Enzyme-susceptible (gelatinized and damaged) starch in the grain samples was analyzed using the same procedure as for total starch, except no pregelatinization step was used. Percent starch damage and gelatinization was then calculated as the amount of enzyme-susceptible starch in the sample expressed as a percentage of the total starch. Water absorption was determined in triplicate by the procedure of Anderson et al (1969).

A Rapid Visco Analyzer (RVA-3C, Newport Scientific Pty. Ltd., NSW, Australia) was used to measure the viscosities of aqueous suspensions of the raw and processed grains. Viscosities were measured at both 95 and 37°C. Samples were measured at least in duplicate. In the 95°C viscosity test, samples containing 14% solids were held at 50°C for 2 min to allow the temperature to stabilize and to ensure uniform dispersion and wetting of the samples. They were then heated to 95°C for 8 min to gelatinize and paste the starch and cooled to 50°C for 8 min (setback). Total test time was 18 min. Stirring numbers at the peak of the 95°C test were converted to centipoise units (cP) using the manufacturer's equivalence (1 stirring number = 10 cP). To determine the viscosity at physiological temperature, samples (14% solids) were heated to 37°C, and viscosity was recorded at the end of 12 min of stirring at that temperature. The viscosity curve profiles during the test cycles were recorded on a strip chart recorder.

The average particle size of duplicate samples of reground grains was determined using the Ro-Tap sifter (Tyler Industrial Company, Mentor, OH). Particle size was calculated using software for the American Society of Agricultural Engineers sieving method (ASAE 1987). Bulk densities of the samples were determined in triplicate by weighing the reground (Fitz mill, 1/8-in. screen) material in a 1-L calibrated container. Results were expressed as grams per liter.

Design of the Baking Study

A randomized response-surface-design software program (Solo, version 4.0, BMDP Statistical Software, Los Angles, CA) was used to determine the optimum wheat bran bread formulation. Three independent variables were used at three levels, requiring 15 formula combinations. The variables and levels tested were: absorption at 65, 68, and 71%; mixing times of 9, 11.5, and 14 min; and bromate at 5, 17.5, and 30 ppm. The wheat bran level was set constant at 10% on a flour-weight basis. A formulation with intermediate levels of the three variables (68% absorption, 11.5 min of mixing time, and 17.5 ppm of bromate) was replicated three times and included in the 15 combinations to test for inherent variance in the technique. Seven dependent variables (volume, crust color, break and shred, symmetry, grain, crumb color, and texture) were scored for each trial. The optimum level of the independent variables was determined using the Solo software program. The formula for whole wheat bread (Table III) was developed using the straight-dough procedure (method 10-10B,

TABLE II
Processing Conditions During Extrusion of Whole Wheat and Bran

Treatment	Whole Wheat			Wheat Bran		
	Low	Med.	High	Low	Med.	High
Screw speed, rpm	200	300	400	200	300	400
Feed rate, kg/min	1.3	1.3	1.3	1.3	1.3	1.3
Mass temperature (°C)[a]	103	117	119	109	137	141
Mass pressure, psig[a]	1,450	1,200	1,100	1,600	1,000	750
Mass moisture, % as is[b]	21.0	19.9	20.8	20.5	18.2	21.8
Extrudate rate, kg/min	1.6	1.6	1.6	1.5	1.5	1.5

[a] Measured in the barrel immediately preceding the die.
[b] Measured using IR 100 moisture analyzer (Denver Instrument) as soon as possible after passage through the die.

TABLE III
Formulas for Breads Containing Raw or Extruded Wheat Bran[a]

Ingredients	WB-Raw		WB-Low		WB-Med		WB-High	
	Bakers %	g	Bakers %	g	Bakers %	g	Bakers %	g
Flour[b]	100	700	100	700	100	700	100	700
Wheat bran	10	10	10	70	10	70	10	70
Yeast[c]	1	7	1	7	1	7	1	7
Salt	2.25	15.8	2.25	15.8	2.25	15.8	2.25	15.8
Sugar	8	56	8	56	8	56	8	56
NFDM[d]	2	14	2	14	2	14	2	14
Shortening	3	21	3	21	3	21	3	21
Water	67.6	459.9	68.5	460.7	69.9	456.8	70.9	474.7
Bromate, ppm	13.3	13.3	18.7	18.7	30.0	30.0	21.6	21.6
Mix time, min	10.4	9.8	9.8	9.8	9.0	9.0	10.9	10.9

[a] WB-Raw = raw wheat bran, WB-Low = wheat bran extruded at low screw speed, WB-Med = wheat bran extruded at medium screw speed, WB-High = wheat bran extruded at high screw speed.
[b] Commercial bread flour with 13.08% moisture, 11.8% protein, and 0.49% ash (Cargill, Wichita, KS).
[c] Fermipan instant yeast (Gist-Brocades, Food Ingredients).
[d] Nonfat dry milk.

AACC 1983). Bread scoring was done on a 10-point scale for each dependent variable, with higher values indicating better quality. Volume was measured by a rapeseed-displacement volume meter (National Manufacturing Co., Lincoln, NE).

The data were statistically evaluated using the one-way analysis of variance procedure with the least significant difference test and the statistical analysis system at Kansas State University, Manhattan (SAS 1985).

RESULTS AND DISCUSSION

Changes in Dietary Fiber

Raw wheat bran contained more than 55% total dietary fiber (TDF), compared to 14% TDF in the raw whole wheat (Table IV); most of the fiber in both was insoluble. The soluble dietary fiber content of the raw whole wheat and wheat bran were not significantly different. After extrusion, TDF was significantly decreased only in the wheat bran low-condition sample, but insoluble dietary fiber was lower in both extruded wheat and wheat bran than in the raw samples. Soluble dietary fiber tended to increase in the extruded samples; the greatest increase was from raw wheat bran to the wheat bran high-condition sample (1.72–4.25%).

Bjorck et al (1984) reported a slight increase in TDF after extruding white and whole meal wheat flour. The same result was found in extruded whole meal barley by Ostergard et al (1989). In contrast, Siljestrom et al (1986) and Schweizer and Reimann (1986) found no changes in TDF content when extruding wheat flour. Fornal et al (1987) reported decreased contents of cellulose and lignin in extruded mixtures of buckwheat and barley. Decreased TDF, decreased insoluble dietary fiber, and increased soluble dietary fiber in extruded products could be the result of disruption of covalent or noncovalent bonds in the carbohydrate and protein moieties, leading to smaller, more soluble molecular fragments.

Effect on Fat Extractability

Both total fat and ether-extractable fat were higher in wheat bran than in whole wheat (Table V). After extrusion, total fat tended to be lower in the raw samples. This was also true for ether-extractable fat in whole wheat. However, in wheat bran, the percent of ether-extractable fat was significantly increased by extrusion. Percent of free fat decreased in all extruded whole wheat samples and increased in the extruded bran samples.

Monoglycerides and free fatty acids can form complexes with amylose during extrusion cooking (Mercier 1980). Thus, extraction with organic solvents may become more difficult. Amylose-lipid complex formation is a possible reason for lower extractability of fat in extruded materials, especially when triglycerides are hydrolyzed during the process. In the present experiment, fat may have become bound to starch during extrusion of the starch-rich whole wheat samples.

TABLE IV
Mean Dietary Fiber Content (%, db) of Raw and Extruded Samples[a]

Processing Conditions	Dietary Fiber: Total	Insoluble	Soluble[b]
Whole wheat			
Raw	14.0 c	12.8 d	1.25 d
Low	13.3 c	11.3 e	1.97 cd
Medium	13.1 c	11.2 e	1.94 cd
High	13.4 c	11.2 e	2.19 bc
Wheat bran			
Raw	55.4 a	53.7 a	1.72 cd
Low	54.0 b	51.0 bc	2.96 b
Medium	54.7 ab	51.8 b	2.89 b
High	54.4 ab	50.2 c	4.25 a
LSD[c]	1.36	0.96	0.81

[a] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.
[b] Soluble dietary fiber = total dietary fiber − insoluble dietary fiber.
[c] Least significant difference.

Changes in Total Starch Content and Enzyme-Susceptible Starch

Percent of starch was much higher in whole wheat than in wheat bran (Table VI). With the exception of high-condition extruded wheat, starch contents decreased in wheat and wheat bran after extrusion processing. When Chiang and Johnson (1977) extruded wheat in a single-screw extruder, they found significant increases in glucose, maltose, maltotriose, and maltotetraose. Those results indicate breakdown of α-(1→4) glucosidic bonds of malto-oligosaccharides and starch during extrusion.

Extrusion significantly increased the percent of enzyme-susceptible starch in both the whole wheat and wheat bran versus the raw samples. The ratio of enzyme-susceptible starch to total starch was greatly increased in extruded versus raw samples (Table VI). Full gelatinization of starch did not occur because of limiting moisture content of grains. Chiang and Johnson (1977) reported that the interaction of temperature and moisture significantly affected starch gelatinization. In that experiment, increasing extrusion temperatures sharply increased starch gelatinization when moisture contents were between 24 and 27%, but starch gelatinization increased more gradually when moisture contents were 18 or 21%.

Percent Protein Solubility

Protein solubility was higher in the raw bran than in the whole wheat (Table VII), but both had a sharp drop in protein solubility after extrusion processing. In general, different extrusion conditions had little effect on protein solubilities. Decreased percent

TABLE V
Mean Total Fat (Acid Hydrolysis) and Extractable Fat (Petroleum-Ether Extract) of Raw and Extruded Grains (db)[a]

Processing Conditions	Total (%)	Ether Extract (%)	Free Fat[b] (%)
Whole wheat			
Raw	3.14 bc	1.49 d	47.5
Low	2.52 bc	0.84 e	33.3
Medium	2.38 c	0.78 e	32.8
High	2.57 b	0.70 e	27.2
Wheat bran			
Raw	4.04 a	2.21 c	54.7
Low	3.11 bc	2.77 b	89.1
Medium	3.15 bc	2.77 b	87.9
High	3.37 ab	3.01 a	89.3
LSD[c]	0.86	0.21	

[a] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.
[b] Percent of free fat = 100 × (ether-extractable fat/total fat).
[c] Least significant difference.

TABLE VI
Total and Enzyme-Susceptible Starch (db) in Raw and Extruded Samples[a]

Processing Conditions	Starch: Total (%)	Enzyme-Susceptible (%)	Enzyme-Susceptible/Total Starch Ratio
Whole wheat			
Raw	64.0 b	11.1 c	17.7 e
Low	62.7 c	48.6 b	77.6 bc
Medium	63.9 b	51.0 a	79.5 b
High	66.4 a	49.1 b	73.9 c
Wheat bran			
Raw	11.4 d	3.6 e	31.2 d
Low	10.1 e	7.8 d	79.2 b
Medium	9.4 e	7.9 d	77.8 bc
High	9.6 e	8.2 d	86.0 a
LSD[b]	1.1	1.4	4.1

[a] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.
[b] Least significant difference.

of protein solubility in extruded products has been reported by several authors (Maga and Lorenz 1978, Aguilera and Lusas 1986, Pham and Del Rosario 1984) and could arise from noncovalent interactions between polypeptide chains or formation of new disulfide bonds (Pham and Del Rosario 1984).

Effect of Extrusion on Water Absorption

Initially, water absorption was higher in wheat bran than in whole wheat. However, since extrusion resulted in greater increases in water absorption for the whole wheat, values for extruded whole wheat products were higher than those for the extruded brans (Table VII). Water absorption tended to increase with increasing screw speeds for both grain samples. A higher percentage of enzyme-susceptible (gelatinized) starch in extruded samples probably contributed to higher water absorption in those samples. Ungelatinized starch, in its granular form, will absorb only a small amount of water and is ordinarily found in discrete particles. Ralet et al (1990) reported that extrusion cooking did not affect water-absorption capacity of wheat bran significantly, perhaps because of its relatively low starch content.

Effect of Extrusion on Grain Slurry Viscosities

The raw wheat suspension had much higher viscosity than did the raw wheat bran in the 95° C test (Table VIII), probably because the whole wheat contained a higher amount of starch. Decreases in 95° C viscosity after extrusion processing were found in both whole wheat and wheat bran. When suspensions were tested at physiological temperature (37° C), viscosities of extruded whole wheat slurries were significantly higher than those of raw grain; that was not the case for wheat bran, where viscosities of the extruded product were lower than those of the raw bran. The lower viscosities for slurries of extruded wheat bran could be the result of decreased protein and carbohydrate molecular size caused by large molecules breaking into smaller strands during the extrusion process.

Effect of Extrusion Processing on Particle Size

Although grains were ground through a hammermill screen (1/8 in.) before measurement, particle sizes of the raw samples were somewhat different. In general, the particle sizes of raw and extruded wheat bran samples was larger than those of whole wheat (Table IX). Extrusion processing and regrinding reduced the grain particle size in wheat bran, but not in whole wheat.

Effect of Extrusion Processing on Bulk Density

Bulk density was considerably higher in whole wheat than in wheat bran (Table IX). Extrusion processing increased the bulk density of the wheat bran but decreased it in whole wheat.

Functionality of Extruded Bran in Bread

Quality characteristics of bread containing raw or extruded wheat bran are shown in Table X. The total scores were slightly lower for the extruded-bran breads than for raw-bran breads, because of somewhat lower volume and break and shred scores in those breads. Raw-bran and medium-condition extruded-bran breads had a little break and shred on one side; low- and high-condition extruded-bran bread did not.

The loaves of all extruded-bran breads were comparable in appearance to the raw-bran bread (Fig. 1). All breads had uniform crumb grain with fine gas cell walls. When removed from the

TABLE VII
Protein Solubility and Water Absorption of Raw and Extruded Samples[a]

Processing Conditions	Protein Solubility, %	Water Absorption, g/g
Whole wheat		
Raw	21.7 b	2.20 g
Low	11.1 ef	5.04 c
Medium	10.0 ef	5.29 b
High	10.4 ef	6.10 a
Wheat bran		
Raw	29.5 a	4.20 f
Low	11.6 e	4.36 e
Medium	12.9 d	4.43 e
High	12.9 d	4.76 d
LSD[b]	1.15	0.14

[a] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.
[b] Least significant difference.

TABLE VIII
Viscosities (cP)[a] of Raw and Extruded Samples[b]

Processing Conditions	Viscosities, cP[c] 95° C	37° C
Whole wheat		
Raw	2,575 a	70 e
Low	1,210 b	300 b
Medium	1,080 c	355 a
High	1,005 c	330 ab
Wheat bran		
Raw	180 d	250 c
Low	65 e	165 d
Medium	75 e	175 d
High	70 e	170 d
LSD[d]	75	33

[a] Stirring numbers at the peak of 95° C test were converted to centipoise units (cP) using 1 stirring number (manufacturer's equivalence) = 10 cP.
[b] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.
[c] 95° C test temperature (14% solids); 37° C physiological temperature (14% solids).
[d] Least significant difference.

TABLE IX
Particle Size and Bulk Density of Raw and Reground Extruded Samples[a]

Processing Conditions	Particle Size, μm	Bulk Density, g/l
Whole wheat		
Raw	320 f	642 a
Low	327 e	630 b
Medium	333 e	619 c
High	324 ef	629 b
Wheat bran		
Raw	489 a	279 f
Low	401 c	428 d
Medium	373 d	400 e
High	451 b	398 e
LSD	6	6

[a] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.

TABLE X
Effect of Extruded Wheat Bran on Bread Quality[a,b]

Characteristic	Treatment[c] WB-Raw	WB-Low	WB-Med	WB-High	LSD
Volume[d]	3,505 a	3,258 b	3,391 ab	3,280 ab	227
Crust color	7.8 a	7.3 a	7.3 a	7.5 a	0.9
Break and shred	6.8 a	6.2 b	6.3 ab	6.2 b	0.5
Symmetry	8.0 a	8.0 a	8.0 a	8.0 a	...
Grain	7.8 a	7.7 a	7.7 a	7.7 a	0.5
Crumb color	7.8 a	7.3 a	7.3 a	7.3 a	0.5
Texture	8.0 a	7.8 a	7.8 a	7.8 a	0.7
Total score	46.3 a	44.3 b	44.5 b	44.5 b	

[a] Scoring based on a 10-point scale for each dependent variable; higher values indicating better quality.
[b] WB-Raw = unextruded wheat bran, WB-Low = extruded at 200 rpm screw speed, WB-Med = extruded at 300 rpm screw speed, WB-High = extruded at 400 rpm screw speed.
[c] Row means followed by the same letter are not significantly different $P < 0.05$.
[d] Measured by rapeseed displacement.

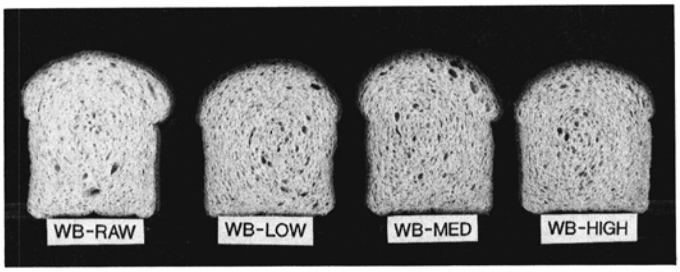

Fig. 1. Comparison of cross sections of breads containing raw (unextruded) wheat bran (WB) and WB extruded at low, medium, or high screw speed conditions.

oven, loaves with both raw and extruded bran collapsed slightly upon cooling. Extruded bran resulted in a slightly darker crust color, but the color was still acceptable when compared with raw-bran bread. The extruded bran had a slight, but uniform, darkening effect on the crumb (Fig. 1). No differences among differently extruded bran breads were found. Although they were darker than the raw-bran breads, breads made with extruded brans were judged to have an appealing tan color. Texture was determined by the sense of touch and therefore was difficult to quantitate. However, extruded-bran breads were judged to be nearly as soft as raw-bran bread.

To conclude: the use of extruded wheat bran in "whole wheat" bread is feasible. Although the overall quality of the bread was affected by the differently extruded brans, all products were judged acceptable.

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