Characterization of Extruded-Expelled Soybean Flours

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ABSTRACT: In recent years there has been widespread growth in extruding-expelling (E-E) facilities for small-scale processing of soybeans. To compete in a highly competitive market, these E-E operations are looking for ways to optimize production of their oil and meal products for values to their customers. The objective of this study was to determine the ranges of residual oil contents and protein dispersibility indices (PDI) possible with E-E processing of soybeans. We also characterized the partially defatted meal for other factors important in food and feed applications. Residual oil and PDI values ranged from 4.7 to 12.7% and 12.5 to 69.1%, respectively. E-E conditions significantly influenced residual lipase, lipoxygenase (L1–L3), and trypsin inhibitor activities. Chemical compositions were different for whole, dehulled, and reduced-moisture soybeans, with dehulled soybeans tending to produce meals having higher residual oil contents at higher PDI values. It was possible to process soybeans with different characteristics (e.g., moisture content, whole, dehulled) to produce meals and flours with wide ranges of properties, providing E-E operators with opportunities to market value-added products.

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KEY WORDS: Expelling, extrusion, oil extraction, partially defatted soy flour, PDI, screw pressing, soybean meal, soybean processing.

Extruding-expelling (E-E) is a relatively new process developed by Nelson *et al.* (1) to mechanically recover oil from soybeans. This process eliminates the need for costly steam dryers and conditioners and associated steam generation, enhances oil extraction over simple screw pressing, and eliminates the use of organic solvents. Small-scale E-E facilities, also known as mini-mills, are increasing in popularity because of the low capital investment required and ability to process identity-preserved and organic products. The low-fat, high-protein, high-energy meals are desirable products for use as animal feeds, especially dairy cattle feed (2). E-E soybean meal reportedly has higher digestible energy and amino acid availability compared with solvent-extracted meal (3,4). In addition, the nonuse of organic solvents in E-E meal production makes partially defatted soy flour particularly attractive to producers of natural foods.

To develop value-added products from E-E soybean meal, it is important to understand the ranges of protein solubilities, oil contents, enzyme activities, and protease-inhibitor activities that are possible with this new processing technology. Soy flours with high protein dispersibility indices (PDI) and low oil contents are generally considered to be required to produce food-grade soy flour and high-quality texturized proteins with fewer processing difficulties, although the activities of certain enzymes, often associated with high PDI, could contribute to off-flavor development or antinutritional effects (5). However, increasing the range of PDI values for partially defatted soy flour that can be produced by E-E soybean mills could enable using these products in a wide variety of food applications.

The objective of this study was to determine the ranges of residual oil contents and PDI values of partially defatted soy flours that are achievable by changing extruder and expeller (screw press) conditions within practical confines of a commercial E-E mini-mill operation. These partially defatted soy flours were characterized to determine their suitabilities for human food and animal feed applications.

EXPERIMENTAL PROCEDURES

Experimental design. This experiment was designed to use E-E to produce partially defatted soy flours with the widest possible ranges of residual oil contents and PDI values. The targeted PDI and residual oil values were selected to represent the widest range believed, *a priori*, to be possible and useful using different processing conditions that are easily attainable or commonly used at E-E mini-mills. Both whole and dehulled soybeans were used.

Raw materials. Whole soybeans (Latham 610) at 9.5% moisture were obtained from Iowa Soy Specialties (Vinton, IA). Some of the beans were dried to 6.7% moisture using ambient temperature (22°C) air; the remainder were used as is. The beans were dehulled using traditional methods of cracking the soybeans into 6–8 pieces with a corrugated roller mill (Ferrell-Ross, Oklahoma City, OK), and then aspirating the hulls with a Multi-Aspirator (Kice, Wichita, KS).

Extruding and expelling. An Insta-Pro 2500 dry extruder (Triple "F"; Insta-Pro, Des Moines, IA) was used to dry-extrude whole and dehulled soybeans. Oil expression was carried out with an Insta-Pro 1500 screw press. The extruder was capable of varying barrel temperature and mechanical input by manipulating the screw design and shear lock configuration, as well as *via* die (nose cone) restriction and design. Additionally, the feed rate to the extruder could be changed. Residence time within the extruder was *ca.* 20–25 s. Processing

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TABLE 1
Extruder and Expeller Operating Conditions for Production of Extruded-Expelled Soybean Flour

Sample code[a]	Extruder configuration[b]	Nose cone (cm)	Choke setting (cm)	Feed rate (kg/h)	Current (amps)		Barrel temp. (°C)		
					Extruder	Expeller	Zone 1	Zone 2	Zone 3
13/5/1-*W*	11-6-6-6, DF	0.8	1.0	590	128	28	162	147	107
26/5/1-*W*	11-11-6-6, SF	0.8	1.0	615	119	28	138	88	56
20/5/1-*W*	11-6-6-6, DF	1.0	1.1	590	112	25	144	107	89
14/7/1	11-6-6-6, DF	1.0	1.1	590	105	22	144	102	76
43/6/1	11-11-6-6, SF	1.0	1.9	730	107	21	129	80	48
38/8/1	11*R*-11*R*-11*R*-11, SF	Tight	0.9	590	94	21	132	72	28
45/7/1	11*R*-11*R*-11*R*-11, SF	0.8	1.1	590	95	22	126	57	31
61/10/1	11*R*-11*R*-11*R*-11*R*, SF	1.0	0.9	590	81	21	117	42	27
63/13/1	11*R*-11*R*-11*R*-11*R*, SF	1.6	Tight	950	72	25	86	55	27
54/12/1	11*R*-11*R*-11*R*-11*R*, SF	1.6	0.9	590	81	21	89	34	24
69/12/1	11*R*-11*R*-11*R*-11*R*, SF	1.6	1.1	590	74	20	88	27	23
35/5/2	11*R*-11*R*-11*R*-11, SF	0.8	1.0	730	109	24	129	99	41
43/7/1-*L*	11*R*-11*R*-11*R*-11, SF	0.8	1.0	730	119	34	137	76	46
67/10/2	11*R*-11*R*-11*R*-11*R*, SF	1.6	1.1	590	72	22	85	54	27
58/8/1	11*R*-11*R*-11*R*-11*R*, SF	1.6	1.0	730	107	28	119	64	29
55/6/2	11*R*-11*R*-11*R*-11*R*, SF	1.6	1.0	730	107	28	119	64	29
54/8/1-*L*	11*R*-11*R*-11*R*-11*R*, SF	1.6	1.0	730	98	28	129	56	37

[a]Denotes protein dispersibility index (PDI)/residual oil content/times expelled; *W* indicates whole beans; *L* indicates low moisture.
[b]Numbers and *R* denote shear lock type used from feed end to die end of the extruder; DF denotes double flighting of the screw; SF denotes single flighting of the screw.

parameters used to obtain different residual oil contents and PDI values are shown in Table 1. The extruder barrel is divided into three equal sections with temperature gauges mounted in the middle of each (Zone 1 being close to the die and Zone 3 being close to the feed).

Three samples were screw-pressed twice after one pass through the extruder in attempts to produce very low residual oil contents. After the first pass through the screw press, samples were collected into large tubs and held until sufficient material was produced to be refed into the screw press.

Each E-E processing trial was carried out in duplicate. Following E-E processing, the press cake (both single- and twice-expelled) was placed into plastic-lined paper bags and allowed to cool to ambient temperature in the open bag until sealing for transport. Samples were stored at −20°C until milled.

Flour milling. The soybean meal press cake was milled (94.7% <100 mesh) by first passing it through a set of cracking rolls and then through a Fitzmill (The Fitzpatrick Company, Elmhurst, IL). The Fitzmill was operated at 7,000 rpm using the blades in a blunt hammermill configuration, fed at 30 rpm feed screw speed, and fitted with a 1536–0060 screen. Milled samples were stored at −20°C until analyzed.

Meal characterization. Moisture contents of soy flours were determined according to the 2-h oven-drying method (6). Crude fat content was determined by Goldfisch extraction (7). Nitrogen content was measured by using a Perkin-Elmer Series II Nitrogen Analyzer 2410 (PerkinElmer Corp., Norwalk, CT). Nitrogen content was multiplied by a factor of 6.25 for estimating crude protein content. Lipase activity was measured in duplicate as outlined by Moscowitz *et al.* (8) with the modifications of Guzman *et al.* (9). Lipoxygenase activity was measured in duplicate as outlined by Zhu *et al.* (10). Trypsin inhibitor (TI) activity and PDI values were analyzed according to AOCS official methods at Woodson-Tenent Laboratories (Des Moines, IA). Moisture content, crude protein, and crude fat were analyzed in triplicate.

Statistical analysis. Statistical analyses were performed using the General Linear Model procedures of SAS 6.06 (11). Significance was established at $P < 0.05$.

RESULTS AND DISCUSSION

E-E equipment performance. Whole soybeans generally produced higher extruder barrel temperatures compared with dehulled soybeans (Table 1). Jin *et al.* (12) reported that fiber addition caused extruder torque, die pressure, and specific energy to increase, which they attributed to increased dough mass viscosity. Total dietary fiber content (not measured) is significantly higher for E-E meal from whole soybeans than from dehulled soybeans. Given the reported health benefits associated with dietary fiber (13), the use of whole soybeans might be attractive in food applications, if the fiber is not detrimental to the performance, taste, and texture of foods in which the flour is incorporated.

We also observed higher foots contents during oil collection when dehulled soybeans were processed. This is an important consideration for processors because more oil settling capacity will be required when dehulling soybeans prior to E-E processing.

Proximate analyses. Results from the compositional analyses of the E-E soybean meal samples are presented in Table 2. Partially defatted soy flours with a wide range of PDI values (12.5–69.1) and residual oil contents (4.73–12.65%) were produced by E-E. Highest and lowest oil recoveries were 76.0% (PDI/residual oil content/times expelled, 13/5/1) and 35.8% (63/13/1), respectively. Dehulled soybeans tended (not significant at $P = 0.05$) to have increased PDI values and higher residual oil contents compared with whole soybeans

TABLE 2
Chemical Analyses of Extruded-Expelled Soybean Flour[a]

Sample code[b]	Dry matter (%)	Crude protein (% mfb)[c]	PDI	Residual oil (% mfb)
13/5/1-W	96.1[g,h]	50.4[c,d]	12.5[a]	4.7[a]
26/5/1-W	94.5[e]	48.1[b]	25.6[b]	5.3[a,b]
20/5/1-W	95.6[f,g]	49.4[b,c]	20.0[a,b]	5.2[a,b]
14/7/1	95.9[g]	50.2[c,d]	14.3[a]	6.8[b,c]
43/6/1	94.1[d,e]	51.1[d]	42.9[c,d]	6.3[b]
38/8/1	95.2[f]	51.4[d]	37.8[c]	7.8[c]
45/7/1	94.8[e,f]	51.2[d]	45.2[c,d]	7.6[c]
61/10/1	94.2[d,e]	50.6[c,d]	61.4[e,f,g]	9.6[d]
63/13/1	93.8[d]	49.6[c]	63.0[e,f,g]	12.7[e]
54/12/1	92.8[c]	48.6[b,c]	54.0[d,e,f]	11.6[e]
69/12/1	91.8[b]	49.6[c]	69.1[g,h]	11.7[e]
35/5/2	94.3[d,e]	51.6[d]	35.4[b,c]	5.4[a,b]
43/7/1-L	96.5[h]	50.9[d]	43.0[c,d]	6.6[b,c]
67/10/2	94.2[d,e]	50.6[c,d]	66.7[f,g]	9.9[d]
58/8/1	93.7[d]	50.9[c,d]	58.1[e,f,g]	7.8[c]
55/6/2	94.0[d,e]	52.4[d]	55.4[d,e,f]	5.7[a,b]
54/8/1-L	96.0[g,h]	50.4[c,d]	53.8[d,e,f]	8.1[c]
Control	91.3[a]	39.7[a]	98.7[i]	19.7[f]

[a]Means within each column with different roman superscripts are significantly different at $P < 0.05$.
[b]Denotes PDI/residual oil content/times expelled; *W* indicates whole beans; *L* indicates low moisture. See Table 1 for other abbreviation.
[c]mfb, moisture-free basis.

processed under identical E-E conditions, as in the case for sample 14/7/1 (dehulled) vs. 20/5/1 (whole). These results are contrary to those of Nelson *et al.* (1), who reported significantly higher oil yield when using dehulled soybeans, although that difference diminished following removal of oil fines or foots.

As expected, twice-screw-pressed flour samples had significantly, but modestly, lower residual oil contents compared with single-screw-pressed flours processed under identical operating conditions (Tables 1 and 2). Single-screw-pressed meal was *ca.* 2 percentage points higher in residual oil content than twice-screw-pressed meal. Nelson *et al.* (1), using a different type of screw press, found PDI was ~2 percentage points lower in single-screw-pressed flours. In the present study, no significant changes in the range of PDI values were observed in twice-screw-pressed flours vs. single-screw-pressed flours. Thus, screw pressing in series can modestly decrease the residual oil content while maintaining protein functionality. This may be significant for use in lower-fat flours for food applications.

The E-E processed meals produced from reduced-moisture (6.7%) soybeans did not differ significantly from soybeans with higher moisture content (9.5%) in compositional properties (Table 2). Drying did not improve oil recovery. The relationship between drying and PDI is unclear. There was a 5 percentage point decrease in PDI associated with dried samples 58/8/1 vs. 54/8/1. In addition, increased barrel temperatures were observed during extrusion of the dried soybeans (Table 1). Zhu *et al.* (10) found that PDI significantly decreased during dry extrusion with increasing extrusion temperature and moisture content.

PDI was directly correlated with residual oil content (R = 0.824, P < 0.0001; Fig. 1). Comparison of low (10–40), medium (40–60), and high (>60) PDI samples revealed significantly higher mean residual oil content for high- compared with low-PDI flours (high PDI = 10.9%, low PDI = 5.9%, P = 0.05; Fig. 2). Temperatures in the three extruder zones were the most important factors affecting PDI and residual oil of E-E processed soy flour. As the temperature of extruder Zone 1 increased, both PDI and residual oil content decreased (R = –0.861 (PDI), R = –0.946 (residual oil), P < 0.05; Fig. 3). Similar correlations were found with respect to the temperatures of extruder Zones 2 and 3. These data indicate that altering the final PDI and residual oil content of E-E partially defatted soy flour is possible by adjusting the feed rate and screw and shear lock configurations, thereby changing the extrusion zone temperatures.

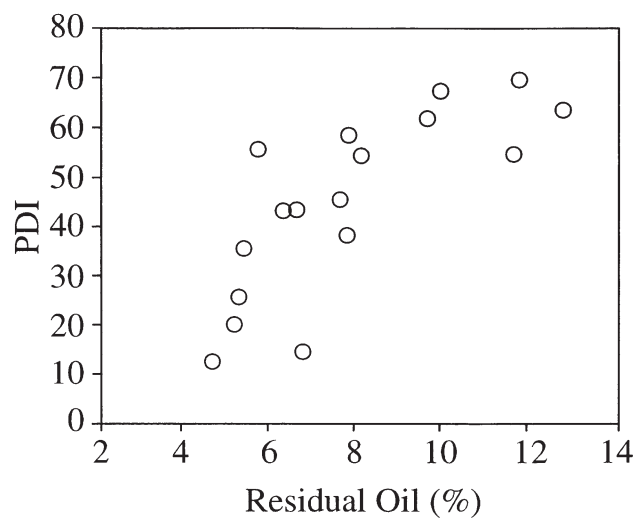

FIG. 1. Distributions of residual oil vs. protein dispersibility index (PDI) of extruded-expelled soy flours.

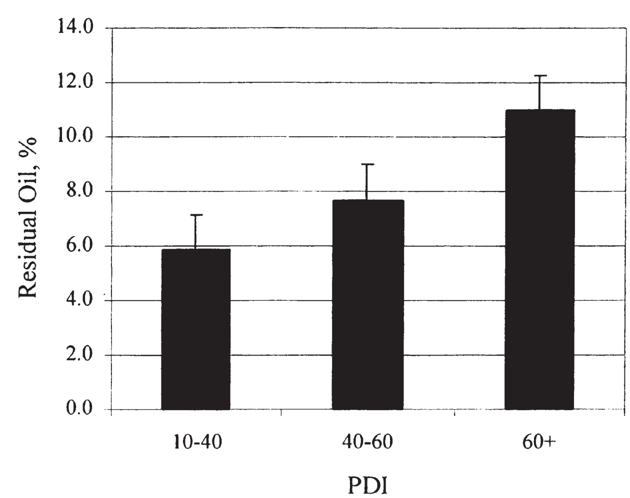

FIG. 2. Residual oil contents of extruded-expelled soy flours for low, medium, and high PDI ranges. Error bars, ± 1 SD. See Figure 1 for abbreviation.

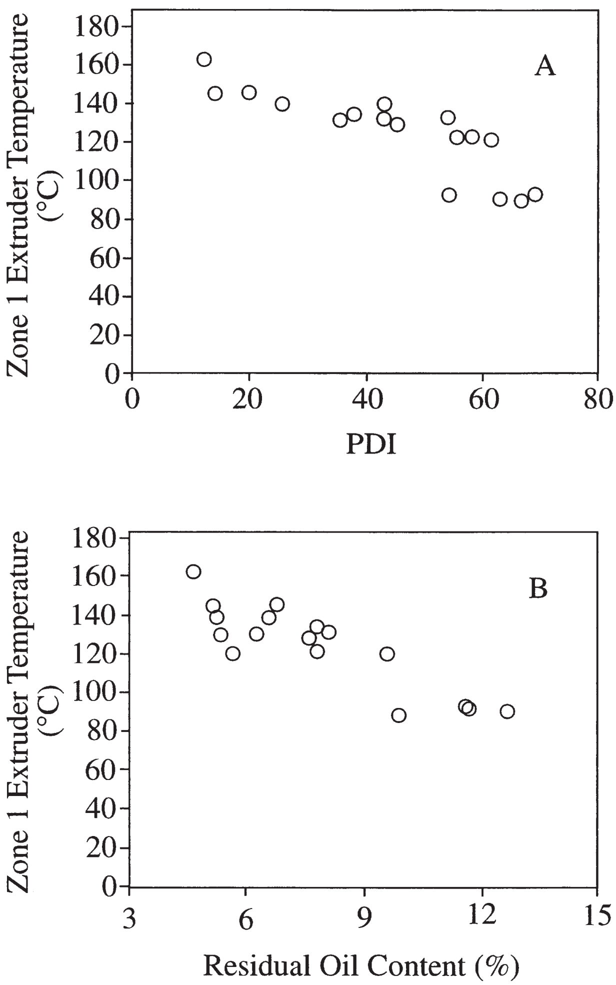

FIG. 3. Relationships between PDI (A) and residual oil content (B) of extruded-expelled soy flour, extruder barrel temperature (Zone 1, °C). See Figure 1 for abbreviation.

The low extrusion temperatures necessary to produce high PDI generally are less efficient in rupturing soybean spherosomes and therefore do not facilitate oil extraction as evidenced by the high residual oil contents. This study was designed to produce wide ranges of PDI and residual oil values (e.g., high PDI, low residual oil), and the results indicate that partially defatted soy flour with optimal properties (high PDI and low residual oil content) can be produced by altering feed materials, extruder configuration, and processing conditions from those typically used today.

TI inhibitor and enzyme activities of E-E processed soy flours. TI activities (Table 3) ranged from 4.5 to 97.5% of the activity of raw soybeans and decreased with increasing extruder barrel temperature (Zone 1) ($R = -0.816$, $P < 0.05$; Fig. 4). Guzman *et al.* (9) varied extrusion temperatures from 127 to 160°C and reported corresponding residual TI activities in nonexpelled samples between 31 and 2% of the original activity. Eweedah *et al.* (3) and Nelson *et al.* (1) used similar extrusion systems at temperatures of 150 and 135–141°C, respectively. In both studies, TI was reduced to ~6% of its original activity.

TABLE 3
Lipase and Trypsin Inhibitor Activities of Extruded-Expelled Soybean Flours

Sample code[a]	Lipase (mM H^+/min/g)	Trypsin inhibitor, trypsin inhibitor units
13/5/1-*W*	18.6	≤2,000
26/5/1-*W*	21.0	5,200
20/5/1-*W*	16.2	N/A[b]
14/7/1	15.8	5,000
43/6/1	11.8	N/A
38/8/1	28.0	N/A
45/7/1	15.4	13,500
61/10/1	18.8	N/A
63/13/1	15.1	N/A
54/12/1	17.9	26,900
69/12/1	10.7	36,500
35/5/2	20.9	10,200
43/7/1-*L*	13.8	N/A
67/10/2	10.1	43,500
58/8/1	19.2	N/A
55/6/2	17.5	27,275
54/8/1-*L*	13.2	N/A
Control	19.4	44,600

[a]Denotes PDI/residual oil content/times expelled; *W* indicates whole beans; *L* indicates low moisture.
[b]N/A denotes not applicable. See Table 1 for abbreviation.

Lipase activities were not significantly different among samples and were not correlated with extruder barrel temperature. These data are in agreement with those previously reported by Guzman *et al.* (9), who found no trend for lipase activity in extrusion processed soybean-corn mixtures.

The activities of all three lipoxygenase isozymes (L1, L2, and L3) decreased with higher Zone 1 temperature ($P < 0.05$) and were not detectable in the partially defatted soy flour samples when extruded at Zone 1 barrel temperatures of 117°C or higher (Table 4). This was expected following E-E processing because of the high temperatures and long hold times in both the extruder and expeller. Activity levels of L3,

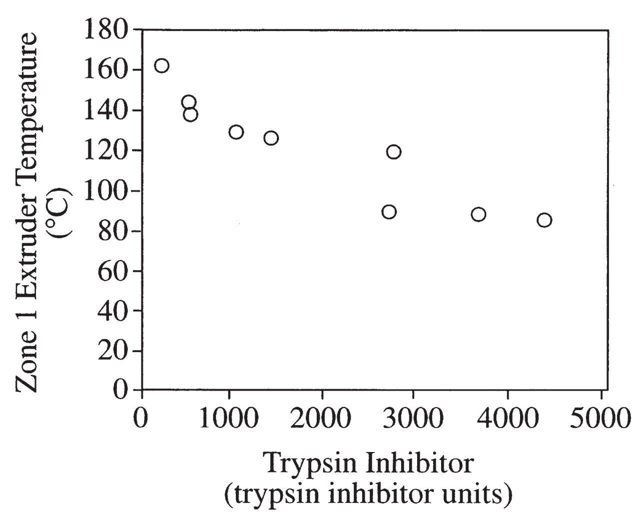

FIG. 4. Relationship between extruder barrel temperature (Zone 1, °C) and trypsin inhibitor activity of extruded-expelled soy flour.

TABLE 4
Lipoxygenase Isozyme (L1, L2, L3) Activities of Extruded-Expelled Soybean Flours[a]

	Barrel temperature (°C)		
Sample code[b]	L1	L2	L3
13/5/1-*W*	ND[c]	ND	ND
26/5/1-*W*	ND	ND	ND
20/5/1-*W*	ND	ND	ND
14/7/1	ND	ND	ND
43/6/1	ND	ND	ND
38/8/1	ND	ND	ND
45/7/1	ND	ND	ND
61/10/1	ND	ND	ND
63/13/1	16.4[b]	12.9[b]	4.4[a]
54/12/1	9.3[a,b]	8.1[a]	3.9[a]
69/12/1	10.7	14.1[b]	5.1[a]
35/5/2	ND	ND	ND
43/7/1-*L*	ND	ND	ND
67/10/2	7.8[a]	12.1[a,b]	2.1[b]
58/8/1	ND	ND	ND
55/6/2	ND	ND	ND
54/8/1-*L*	ND	ND	ND
Control	100.0[c]	100.0[c]	100.0[c]

[a]Means within each column with different nonitalic superscripts are significantly different ($P < 0.05$).
[b]Denotes PDI/residual oil content/times expelled; *W* indicates whole beans; *L* indicates low moisture.
[c]ND, not detectable. See Table 1 for other abbreviation.

the most heat-labile isozyme, were much lower than those observed for the L1 and L2 isozymes (Table 4). No lipoxygenase activity was detected in partially defatted soy flours extruded at 117°C and higher (Zone 1 barrel temperature). These results are consistent with those reported by Zhu *et al.* (10) and Guzman *et al.* (9), who detected no lipoxygenase activity at temperatures greater than 107 and 127°C, respectively. These data suggest that only those partially defatted soy flours produced using low temperatures to achieve a high PDI may contain appreciable lipoxygenase activity. This may be important in food applications of E-E processed partially defatted soy flour because these enzymes may significantly affect the colors and flavors of foods in which the flours are incorporated.

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