Small-Scale Extrusion of Corn Masa By-Products

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ABSTRACT

Corn masa by-product streams are high in fiber and are amenable for utilization in livestock feed rations. This approach is a potentially viable alternative to landfilling, the traditional disposal method for these processing residues. Suspended solids were separated from a masa processing waste stream, blended with soybean meal at four levels (0, 10, 20, and 30% wb), and extruded in a laboratory-scale extruder at speeds of 50 rpm (5.24 rad/sec) and 100 rpm (10.47 rad/sec) with temperature profiles of 80-90-100°C and 100-110-120°C. Processing conditions, including dough and die temperatures, drive torque, specific mechanical energy consumption, product and feed material throughput rates, dough apparent viscosity, and dough density, were monitored during extrusion. The resulting products were subjected to physical and nutritional characterization to determine the effects of processing conditions for these blends. Extrudate analysis included moisture content, water activity, crude protein, in vitro protein digestibility, crude fat, ash, product diameter, expansion ratios, unit and true density, color, water absorption and solubility, and durability. All blends were suitable for extrusion at the processing conditions used. Blend ratio had little effect on either processing parameters or extrudate properties; extrusion temperature and screw speed, on the other hand, significantly affected both processing and product properties.

Mounting economic and environmental concerns, coupled with a growing interest in alternative disposal methods, have led to a decline in landfilling of agricultural and food processing wastes. Current options include reprocessing, recycling, incinerating, composting, producing biomass energy, land applying, and feeding to livestock, which can include either direct feeding or feeding after additional processing (Ferris et al 1995; Bohlsen et al 1997; Derr and Dhillon 1997; Wang et al 1997). Many research efforts have focused on the development of livestock feed ingredients, especially for utilization of grain processing by-products. Particular attention has been given to corn gluten, distillers', and brewers' by-products (Davis et al 1980; Annexstad et al 1987; Larson et al 1993; Ham et al 1995; Lodge et al 1997). Corn masa milling, however, is one segment of the grain processing industry that generates large quantities of waste materials but to date has received little attention regarding by-product disposal alternatives.

Masa is a corn dough that is used to make corn snacks, chips, and tortillas, the latter having been a staple in the diets of Mexican and Central American peoples for centuries. Even today, masa is produced by simulating ancient Aztec cooking methods on a modern, industrial scale. Whole corn is typically cooked with 120–300% water and 0.1–2.0% lime (on a corn mass basis) for 0.5–3.0 hr at 80–100°C and is then steeped up to 24 hr. This process, called *nixtamalization*, removes much of the outer hulls of the corn kernels and can either be a batch process or a continuous process, depending on production equipment and procedures used. The cooked grain (*nixtamal*) is then separated from the steep liquor (*nejayote*), which is rich in lime and corn pericarp tissues. The nixtamal is washed to remove residual lime and extraneous pericarp and is then stone-ground to produce corn masa dough (Gomez et al 1987; Rooney and Serna-Saldivar 1987; Serna-Saldivar et al 1990).

Nejayote slurries commonly contain ≈2% total solids. Suspended solids, which constitute 50–60% of the total solids, are generally removed by screening, centrifuging, or decanting, and are disposed of in landfills. The remaining waste water and dissolved solids are typically sent to municipal facilities for treatment. All solids in the waste stream, which consist primarily of fiber-rich pericarp tissues, result from corn dry matter lost during processing. Estimates of this by-product generation have ranged from 5 to 17% of the original dry corn mass (Bressani et al 1958; Katz et al 1974; Gonzalez de Palacios 1980; Khan et al 1982; Rooney and Serna-Saldivar 1987; Pflugfelder et al 1988; Serna-Saldivar et al 1990). Corn dry matter loss during nixtamalization is affected by many processing parameters, including corn hybrid, endosperm hardness, kernel quality, lime type and concentration, cooking and steeping times, cooking and steeping temperatures, friction during washing and conveying, and processing equipment used. These processing losses can be economically significant due to lost masa yield, waste processing and disposal costs, and potential environmental pollution and subsequent legal penalties (Khan et al 1982; Rooney and Serna-Saldivar 1987; Serna-Saldivar et al 1990).

Few studies have been conducted into alternative disposal options for these by-product streams. Pflugfelder et al (1988) studied the composition of masa production dry matter losses and included these in a mass balance of a commercial masa processing system. Rosentrater et al (1999) conducted an extensive physical and nutritional characterization of typical masa by-product solids and determined that they were well suited for incorporation into livestock feed rations. Velasco-Martinez et al (1997) investigated the suitability of implementing nejayote solids in poultry broiler diets and found no differences in performance between control diets and diets utilizing nejayote.

Because masa by-product solids appear suitable for incorporation into livestock feed rations but to date have been utilized very little, the objective of this investigation was to develop potential feed ingredients using these residual streams. This was accomplished by combining these by-products with soybean meal at various blend ratios, extrusion processing the resulting ingredient mixtures, and investigating the effects of the extrusion on subsequent product characteristics.

MATERIALS AND METHODS

Experimental Design and Analysis

Corn masa by-product (CMB) solids and soybean meal (SBM) were blended at three CMB/SBM ratios (%/%): 10/90, 20/80, and 30/70. Additionally, a control blend of 0/100 was used as a benchmark for the process. Experimental factors and the levels of each included two extruder temperature profiles (80-90-100°C and 100-110-120°C) and two extruder screw speeds (50 rpm [5.24 rad/sec] and 100 rpm [10.47 rad/sec]). These factors and their

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subsequent levels resulted in a total of 16 treatment combinations (4 × 2 × 2 factorial design) for the study. Each treatment was replicated (extruded) twice, which resulted in a total of 32 extrusion runs; these were completed in random order. Formal statistical analyses on all collected data were performed using Microsoft Excel v. 5.0a (Microsoft Corporation, Redmond, WA, USA) and SAS software (SAS Institute, Cary, NC, USA) using a Type I error rate (α) of 0.05, and included MANOVA, LSD multiple comparisons, correlation analysis, and principal components analysis.

Sample Collection

Corn masa residues obtained from a commercial masa milling facility included all solids separated by centrifugation during the dewatering stage in the production process. Ten 19-L (5-gal) samples were collected from a single production run from a continuous-cook nixtamalization processing line. The samples were then placed in frozen storage at –10°C until needed for blending, at which time the samples were thawed at room temperature (25 ± 2°C) for 24 hr.

Raw Ingredient Preparation

Soybean meal was purchased from Waterloo Mills (Waterloo, IA, USA), mixed with appropriate amounts of CMB in a pilot-scale ribbon mixer (model B2224-1, Rapids Machinery Co., Marion, IA, USA) for 10 min and conditioned to a target moisture content of 26 ± 2.2% (wb) by manually adding appropriate quantities of water during the mixing process. The blends were then placed in polyethylene bags and stored in a refrigerated cooler at 4 ± 2°C for 24 hr to allow for thorough moisture uniformity throughout the blends. Before extrusion processing, the preconditioned blends were removed from the cooler and allowed to equilibrate to room temperature. Samples from the blends were analyzed for moisture content at this time.

Raw Ingredient Properties

Before extrusion, each raw CMB/SBM blend was subjected to extensive characterization (Table I). Particle-size distribution was analyzed and the geometric mean particle diameter (mm) and geometric standard deviation (mm) was determined using standard method S319.2 (ASAE 1996) with a Ro-tap shaker and appropriate sieving screens (W.S. Tyler, Mentor, OH, USA). Moisture content (%, wb) was determined using 15-g samples dried at 103°C for 72 hr according to Approved Method 44-15A (AACC International 2000). Water activity was measured at room temperature by placing 4-g samples into a calibrated water activity meter (model CX-2, Aqualab, Decagon Devices, Pullman, WA, USA). Proximate composition analyses included the determination of crude protein, fat, and ash contents (%, db), respectively, using Approved Method 46-11A (nitrogen conversion factor N × 6.25), Approved Method 30-25, and Approved Method 08-03 (AACC International 2000). Color was determined using a colorimeter (model SN-12414, LabScan, Hunter Associates Laboratory, Reston, VA, USA), which had been calibrated with appropriate standard color tiles using a view-port and view-area size of 1.27 cm (0.5 in.) and the *L,a,b* opposable color scales. Three samples ($n = 3$) from each of the four blends were utilized for each property determination.

Extrusion Processing

After mixing and conditioning, the CMB/SBM blends were randomly extruded using a 19.18 mm (0.755 in.) barrel inner diameter (i.d.), single-screw laboratory extruder (model 2003, C.W. Brabender Instruments, South Hackensack, NJ), with a single-flight tapered screw (model 05-00-035, Brabender) that had a 381 mm (15.0 in.) screw length, a 19.05 mm (0.75 in.) constant outside (top of flight) diameter (o.d.), a screw length-to-diameter ratio of 20:1, a 19.05 mm (0.75 in.) uniform pitch, a 3.81 mm (0.15 in.) initial screw feed depth, an 11.43 mm (0.45 in.) initial screw root diameter, and a screw compression ratio (feed channel depth to metering channel depth) of 3:1, in conjunction with a torque rheometer drive control system (model PL 2000, Plasti-Corder, Brabender). The extruder barrel had eight equally spaced grooves 3.175 mm (0.125 in.) wide by 0.794 mm (0.031 in.) deep, running longitudinally along the length of the barrel to improve material shearing and mixing and had a 3.175 mm (0.125 in.) diameter circular die mounted at the extruder exit.

In this study, two barrel temperature profiles and two screw speeds were utilized: a low temperature profile (LTP) of 80-90-100°C and a high temperature profile (HTP) of 100-110-120°C; a low screw speed (LSS) of 50 rpm (5.24 rad/sec) and a high screw speed (HSS) of 100 rpm (10.47 rad/sec). Temperature profile corresponded to the temperature settings at the feeding, metering, and die sections of the extruder, respectively.

Processing conditions were monitored by measuring dough temperature (°C), die temperature (°C), net torque exerted on the extruder drive (N-m) (net drive torque accounts for the amount of torque required under no-load conditions compared with the amount required during processing), specific mechanical energy (SME) consumption (J/g), feed material throughput rate (g/min), product throughput rate (g/min), dough apparent viscosity (Pa-sec), and dough density in the die (g/cm^3). Dough temperature (measured at the end of the metering zone) and die temperature (measured in the die region of the extruder) were determined using stock thermocouples (model 05-00-348, Brabender) inserted into the barrel. Torque readings were recorded by the extruder's computer control system. Product throughput rate was determined by collecting extrudate samples at 30-sec time intervals, allowing the samples to cool for 3 hr under ambient conditions, and then

TABLE I
Physical and Nutritional Characteristics of Raw By-Product Blends Before Extrusion ($n = 3$)[a]

	0% CMB[b]		10% CMB		20% CMB		30% CMB	
Property	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
GMD[c] (mm)	0.94a	0.80	0.95a	1.44	0.97ab	2.60	1.02b	5.87
GSD[d] (mm)	1.79a	1.25	1.80a	1.65	1.75a	2.57	1.64b	0.97
Moisture (%, wb)	25.84a	0.12	25.56b	0.15	25.86a	0.31	30.68c	0.11
Water activity	0.89a	0.94	0.88a	1.04	0.89a	0.96	0.92b	0.91
Protein (%, db)	48.64a	0.65	48.48a	0.84	49.26b	0.42	47.04c	0.47
Fat (%, db)	1.27a	12.59	1.12a	10.86	1.10a	10.80	1.05a	12.97
Ash (%, db)	6.68a	0.29	6.74a	0.54	7.35b	3.42	6.92a	0.48
Hunter *L* value	60.60a	0.46	59.13b	0.49	59.09b	0.16	57.86c	1.44
Hunter *a* value	3.73a	1.12	3.87a	3.98	3.93a	3.95	3.91a	2.31
Hunter *b* value	18.48a	0.93	17.94b	0.61	18.18ab	0.98	17.49c	1.11

[a] Values followed by the same letter in the same row are not significantly different ($P < 0.05$).
[b] CMB, fraction of corn masa by-product in the blend (wet basis).
[c] GMD, geometric mean diameter.
[d] GSD, geometric standard deviation.

measuring the collected mass using an electronic balance (model A-250, Denver Instrument Co., Arvada, CO, USA). By considering a dry matter mass balance, which accounts for moisture loss due to evaporation when the hot product exits the die, material throughput rate (raw ingredient feed rate) could be determined (Harper 1981; Alvarez-Martinez et al 1988):

$$m_{feed} = m_{prod}\left(\frac{1\text{-}MC_f}{1\text{-}MC_i}\right) \qquad (1)$$

where m_{feed} is the raw feed material throughput rate (g/min), m_{prod} is the measured extrudate product throughput rate (g/min), MC_f is the moisture content of the collected extrudate product samples (wb), and MC_i is the initial moisture content of the raw feed ingredient material before entering the extruder (wb). Specific mechanical energy consumption, which is the energy input required to convey the material through the extruder per unit rate of flow, was calculated according to Harper (1981) and Martelli (1983):

$$SME = \frac{T \cdot \omega \cdot 60}{m_{feed}} \qquad (2)$$

where SME is the specific mechanical energy consumption (J/g), T is the net torque exerted on the extruder drive (N-m), ω is the angular velocity of the screw (rad/sec), and m_{feed} is the raw feed material throughput rate (g/min). The apparent viscosity of the dough in the extruder was calculated by approximating extruder behavior as that of a coaxial viscometer but corrected for the tapered screw geometry of the extruder barrel (Rogers 1970; Lam 1996; Lo and Moreira 1996; Konkoly 1997):

$$\eta_{app} = \left(\frac{C_{ss}}{C_{sr}}\right)\left(\frac{T}{\omega}\right) \qquad (3)$$

where η_{app} is the apparent viscosity of the dough in the extruder (Pa-sec), C_{ss} is a screw-dependent empirical correction factor (6157.57 m^{-3} for the specific screw-barrel configuration used in this study [Lam 1996]), C_{sr} is a barrel-dependent empirical geometric correction factor (7.63 for the extruder used in this study [Lam 1996]), T is net torque (N-m), and ω is the screw angular velocity (rad/sec). The density of the dough in the die was determined according to Alvarez-Martinez et al (1988) and Kokini et al (1992):

$$\rho_d = \left[\frac{1 - MC_i}{1 - MC_f}\right]\left[\rho_{ex}\left(1 - MC_i\right) + \rho_w MC_i\right] \qquad (4)$$

where ρ_d is the density of the dough in the die (g/cm^3), MC_i is the initial moisture content of the raw ingredient material (wb), MC_f is the final moisture content of the resulting extrudate product (wb), ρ_{ex} is the unit density of the resulting extrudate (g/cm^3), and ρ_w is the density of water at the die temperature (g/cm^3).

Three determinations of product and material throughput rate were conducted for each replicate run during processing; because two replicate extrusion runs were used for each treatment combination, six total measurements (*n* = 6) of these properties were actually recorded for each treatment combination. Thirty observations were taken during each extrusion run for die and dough temperatures, torque, SME, dough viscosity, and dough density; measurements were recorded every 30 sec during processing. Because two replicate extrusion runs were conducted for each treatment combination, 60 total observations (*n* = 60) for each treatment combination for each of these processing variables were actually measured.

Extruded Product Properties

After processing, resulting extrudate products were allowed to cool under ambient conditions for 3 hr, placed in polyethylene bags, and stored at room temperature. To investigate the effects of extrusion on the CMB/SBM blends, extensive physical and nutritional properties were measured, including moisture content (%, wb), water activity, proximate composition (crude protein, fat, and ash %, db), and color (Hunter *L,a,b* values); these were determined using the methods previously employed for the raw ingredient blends. In addition, in vitro protein digestibility (%), product diameter (mm), expansion ratios (cross-sectional, longitudinal, and volumetric expansion indices), unit density (g/cm^3), true density (g/cm^3), water absorption, water solubility, and durability (%) were determined. In vitro protein digestibility was conducted by the Department of Animal Science at Iowa State University following methods of Bookwalter et al (1987) and Mertz et al (1984). Extrudate samples were cut to 2-cm lengths, weighed on an electronic balance (model A-250, Denver Instrument), and measured for diameter using a digital calipers (Digimatic Series No. 293, Mitutoyo Co., Tokyo, Japan) following the methods of Alvarez-Martinez et al (1988) and Jamin and Flores (1998). The cross-sectional, longitudinal, and volumetric expansion ratios were then determined following methods prescribed by Alvarez-Martinez et al (1988):

$$CSEI = \left[\frac{D_e}{D_d}\right]^2 \qquad (5)$$

$$LEI = \left[\frac{\rho_d}{\rho_{ex}}\right]\left[\frac{1}{CSEI}\right]\left[\frac{1 - MC_i}{1 - MC_f}\right] \qquad (6)$$

$$VEI = CSEI \cdot LEI \qquad (7)$$

where CSEI is the cross-sectional expansion index, D_e is the extrudate diameter (mm), D_d is the extruder die diameter (3.175 mm), LEI is the longitudinal expansion index, ρ_d is the density of the dough in the die (g/cm^3), ρ_{ex} is the unit density of the resulting extrudates (g/cm^3), MC_i is the initial moisture content of the raw feed ingredient blend (wb), MC_f is the resulting moisture content of the extrudate (wb), and VEI is the volumetric expansion index. Unit density was calculated as the ratio of the mass of each 2-cm extrudate piece to the calculated volume of that piece (assuming cylindrical shapes for each extrudate sample) (Jamin and Flores 1998). True density was determined by placing 36-g samples into a nitrogen pycnometer (model 1330, AccuPyc, Micromeritics Instrument Corp., Norcross, GA, USA). Water absorption index (WAI) and water solubility index (WSI) were determined following the methods prescribed by Anderson et al (1969). Durability of extrudate products was determined by standard method S269.4 (ASAE 1996). Three samples from each extrusion run were analyzed for each property determination. Because two replicate extrusion runs were utilized in the experimental design, six total observations (*n* = 6) were determined for each treatment combination (except the durability analysis, which utilized only one sample for each replicate run, and thus *n* = 2 total observations).

RESULTS AND DISCUSSION

Raw Ingredient Analysis

Characterization results for the raw ingredients are shown in Table I. As the CMB fraction increased, geometric mean particle diameter (GMD) also increased, which may have been due to binding of SBM particles with CMB constituents. No clear pattern emerged between geometric standard deviation (GSD) and blend ratio, but all values were relatively low. When the raw ingredients were initially blended, CMB was mixed with SBM on an as-is (wet) basis, and additional water was added to achieve a target moisture content of ≈26% (wb), which was used because it had previously been determined to be a level acceptable for extrusion processing of SBM with other by-product materials (Wang et al 1997). Because the CMB was ≈90% water (wb), blending at the 30% level produced a mixture that had a moisture content inherently greater than the target level; all other blends did have moisture contents very close to the target. All blends had water activity (a_w) values >0.88, which was too high for safe storage, but it was anticipated that extrusion cooking would, at least partially, reduce a_w due to water evaporation at the die exit. All blends used in this study had nutrient levels (actual values reported in Table I) similar to those of unadulterated SBM, which, according to literature values, typically contain ≈44–48% (db) protein, 0.5% (db) fat, 6% (db) ash, and 40% (db) carbohydrate (Erickson 1995). No clear patterns existed between either protein or fat content and raw ingredient blend. All blends were very low in fat and, although fat levels appeared to decrease as CMB blend ratio increased, these differences were not statistically significant. All blends produced similar color results, which essentially described the raw ingredients as yellow materials with a slight degree of brownness. Hunter *L* value, a measure of lightness (100 = white)/darkness (0 = black), decreased as CMB ratio increased (i.e., became slightly darker). Hunter *a* value, a chromaticity measure of redness ± greenness, showed no significant differences between blends. Hunter *b* value, a chromaticity measure of yellowness ± blueness, was not clearly affected by blend ratio either.

Extrusion Processing Analysis

Results for extrusion processing characteristics are provided in Table II. MANOVA analysis on all collected data confirmed that differences between experimental treatments did exist (the Wilks' Lambda test statistic indicated differences [$P < 0.0001$]).

Dough Temperature

The HTP produced higher resulting dough temperatures than the LTP; in fact, the differences between them were statistically significant. This was as anticipated due to the differences in barrel temperature settings. Also, the HSS generally produced slightly higher dough temperatures than the LSS, which was the result of increased frictional resistance heating at higher shear rates (Mercier et al 1989). It appeared, however, that blend ratio had no effect on dough temperatures.

Similarly, the HTP produced significantly higher resulting die temperatures than the LTP, which was also anticipated due to the differences in barrel temperature settings. In general, however, it appeared that neither screw speed nor by-product level had a consequential effect on resulting die temperatures.

Dough Throughput

Because feed material throughput rate was calculated based on measured product throughput rate, the behavior of feed material throughput was identical to that of product throughput. In general, the HSS produced higher throughput than the LSS. Higher screw speeds typically produce higher mass flow rates because of the increased ability of the extruder screw to convey material through the machine (Bouvier et al 1987; Mercier et al 1989). For a given screw speed, increasing the temperature appeared to lower throughput rate, but changing the blend ratio had little effect. However, it does appear that significantly high product and material throughputs were measured at 30% CMB-LTP-HSS; resulting data at this treatment were perhaps outliers.

Dough Viscosity

As anticipated, screw speed had a significant effect on dough viscosity, with the HSS producing apparent viscosity values much lower than the LSS. Additionally, the HTP appeared to produce viscosity results lower than those for the LTP. By-product level,

TABLE II
Effect of Temperature and Screw Speed on Extrusion Processing Characteristics of By-Product Blends (*n* = 60, unless noted otherwise)[a]

		80-90-100 (ºC)				100-110-120 (°C)			
		50 rpm		100 rpm		50 rpm		100 rpm	
Property	**CMB[b]**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
Dough temp (°C)	0	89.98b	1.15	94.40b	1.04	111.73a	4.08	113.60a	2.78
	10	92.05b	0.83	95.53b	1.76	108.10a	1.16	110.38a	0.77
	20	90.37b	1.64	94.20b	1.66	111.78a	3.49	109.67a	6.78
	30	90.80b	0.44	91.17b	2.04	111.50a	4.07	112.30a	3.65
Die temp (°C)	0	112.17d	0.96	110.12ef	0.85	133.38bc	1.31	132.23c	0.88
	10	110.88de	0.58	108.87f	1.46	134.95ab	0.96	133.75bc	0.77
	20	111.75de	1.06	109.83ef	0.97	133.25bc	1.09	136.18a	3.83
	30	111.53de	0.48	111.35ed	1.20	131.93c	0.27	131.67c	0.64
Product throughput (g/min) (*n* = 6)	0	48.00d–f	27.11	43.67ef	79.42	51.90de	21.55	59.99cd	63.57
	10	59.58cd	4.44	72.50bc	48.17	60.60cd	4.50	69.03bc	31.31
	20	59.84cd	3.90	115.32a	10.51	54.64c–e	5.33	76.07bc	29.81
	30	42.15ef	7.48	87.21b	18.61	29.52ef	21.99	37.75ef	45.00
Material throughput (g/min) (*n* = 6)	0	51.91d–f	35.01	46.83ef	95.50	56.83de	2.71	65.23cd	75.34
	10	63.55cd	1.07	78.43bc	15.62	65.62cd	5.97	75.54bc	15.08
	20	63.73cd	2.36	123.55a	6.49	60.31c–e	1.53	84.02bc	10.09
	30	45.10ef	8.46	94.13b	1.55	32.57ef	27.02	41.58ef	53.12
Dough viscosity (Pa-sec)	0	2,272.78a	32.45	423.98c	29.51	1,622.94b	49.63	402.52c	33.79
	10	2,458.30a	46.56	437.73c	25.50	2,256.85a	33.74	451.34c	32.63
	20	2,787.46a	22.15	715.11c	76.41	2,311.84a	16.42	516.48c	55.35
	30	1,445.64b	6.05	885.99c	6.86	1,005.98bc	14.49	430.02c	31.42
Net torque (N-m)	0	14.74ab	32.45	5.50d	29.51	10.53c	49.63	5.22d	33.79
	10	15.95a	46.56	5.68d	25.50	14.64ab	33.74	5.86d	32.63
	20	18.08a	22.15	9.28cd	76.41	15.00ab	16.42	6.70d	55.35
	30	9.38cd	6.05	11.49bc	6.86	6.53d	14.49	5.58d	31.42
Mechanical energy (J/g)	0	90.80b	23.93	129.37a	68.62	57.95b	49.31	72.03b	68.91
	10	78.58b	46.04	46.14b	33.14	70.32b	33.57	49.22b	35.12
	20	89.04b	21.68	48.01b	79.22	78.13b	16.64	49.51b	50.84
	30	65.42b	5.73	76.75b	7.18	64.91b	22.32	92.02b	30.77
Dough density in die (g/cm^3)	0	1.09bc	1.35	1.05c	3.89	0.97e	5.99	0.96e	4.20
	10	1.12b	1.21	1.05cd	4.60	0.98e	5.24	0.98e	4.25
	20	1.11b	3.42	1.08bc	18.55	0.96e	3.27	0.97e	7.78
	30	1.18a	6.80	1.12b	3.77	1.00de	6.95	0.96e	7.08

[a] Values followed by the same letter within the same property are not significantly different ($P < 0.05$).

[b] Fraction of corn masa by-product in the blend (%, wb).

however, did not appear to affect the resulting viscosity values. Many food doughs, including soy doughs, are pseudoplastic and exhibit a decrease in apparent viscosity when subjected to an increase in applied shear rate (Mercier et al 1989). Furthermore, viscosity typically decreases as processing temperature increases (Chen et al 1979; Kokini et al 1992). These behaviors occur due to structural changes in the food dough (i.e., unfolding of molecules and material structures) during processing.

Because the blends behaved pseudoplastically and apparent viscosity decreased as screw speed increased, the resultant net torque required by the screw to convey the dough through the extruder decreased significantly. Furthermore, it appears that the HTP generally produced lower torque values than the LTP, which was also the result of decreased dough viscosity as temperature increased (Mercier et al 1989). Blend ratio did not appear to affect the resulting net torque values. At 30% CMB-LTP-LSS as well as 30% CMB-HTP-LSS, however, it does appear that the high CMB content did result in decreased viscosity and torque.

Specific Mechanical Energy

No clear effects on specific mechanical energy (SME) consumption due to temperature profile, screw speed, or by-product level emerged from analysis, except for the results at the 0% CMB-LTP-HSS treatment combination, which was significantly higher than all other SME values. It also exhibited high variability, so the results from this treatment combination might actually have been an outlier and thus will be revisited during a later discussion. Between all other treatment combinations, increased speed and temperature appeared to produce somewhat lower SME values. Typically, SME is an indication of the viscous dissipation of mechanical energy, which is provided by the screw drive shaft, into the dough due to frictional resistance (Marsman et al 1995). The SME, in fact, quantifies the competing effects of viscosity changes due to changes in screw speed (pseudoplastic behavior) and the resulting change in the torque that is required to convey the dough through the extruder. It has been noted that as screw speed increases, SME generally increases because the changes in energy input to the screw are typically of a greater order of magnitude than the decrease in torque associated with the decrease in apparent viscosity due to the shear thinning behavior of the non-Newtonian material (Mercier et al 1989).

Dough Density

Dough density in the die was affected by processing temperature. The HTP produced density values significantly lower than those for the LTP, primarily because the higher temperature produced a greater dough expansion. Alvarez-Martinez et al (1988) studied extrudate expansion and determined that the value for dough density in the die could be approximated as a constant value of 1.2 g/cm^3. The results from the current study are similar but are slightly lower at 0.96–1.18 g/cm^3, which is likely due to raw ingredient differences. The HSS appeared to produce density values slightly lower than those for the LSS, which could be due to the increased temperature resulting from the higher screw speed. Blend ratio did not appear to affect the density values.

Extruded Product Analysis

Results for extruded product characteristics are provided in Tables III and IV. MANOVA analysis on all collected data confirmed that differences between experimental treatments did exist (Wilks' Lambda test statistic indicated differences [$P < 0.0001$]).

Moisture Relationships

Because of the high temperatures and pressures involved, extrusion processing has a drying effect on materials and ≤8 percentage points of a raw ingredient's moisture can evaporate due to the sudden change to ambient conditions upon exiting the die (Faubion et al 1982). Moisture content loss for the CMB/SBM blends were ≈5–8 percentage points (wb), with the higher processing temperature producing greater moisture loss than the lower temperature. Thus, in general, the HTP produced extrudates with lower resulting moisture levels than the LTP. Screw speed appeared to produce a slight decrease in moisture also. However, at 18–26% (wb), the final moisture contents of the extrudates were still too high for safe storage (Faubion et al 1982; Miller 1985; Wang et al 1997). A maximum moisture content of ≈12% (wb) is recommended for feed products because this level minimizes transportation costs and is microbiologically stable (Beauchat 1981). Furthermore, a_w quantifies the amount of "free" (unbound) water available for use by microorganisms and chemical agents, and is therefore a measure of a material's susceptibility to spoilage and deterioration. Products with no free water ($a_W = 0.0$) are not at risk for spoilage, while materials with 100% free water ($a_W = 1.0$) are at high risk for rapid spoilage. Materials have a reduced chance of bacterial growth below $a_W \approx 0.9$, mold growth below ≈0.7–0.8, and yeast growth below ≈0.7 (Barbosa-Canovas and Vega-Mercado 1996). Not only did extrusion processing reduce the moisture content of the CMB/SBM blends, but it also reduced the associated free water levels, with extrudate $a_W = 0.60–0.85$. The HTP produced extrudates with higher a_W values than the LTP. But within each temperature level, the HSS generally produced extrudates with somewhat lower a_W values than the LSS. By-product level, however, did not appear to have an effect. Therefore, to effectively utilize these extrudates as livestock feed ingredients, dehydration subsequent to extrusion will likely be necessary to reduce a_W levels and thus prevent microbial spoilage during storage.

Proximate Analysis

From the proximate nutritional analysis, it was determined that for all processing conditions, the 0% blend was significantly higher in protein than all other blends, and protein content decreased as CMB fraction increased. Protein content levels exhibited little change due to either screw speed or processing temperature however. Not only is the amount of protein important to a feed material but the digestibility of that protein is also essential. It appears that at LTP, as speed increased, digestibility decreased; at HTP, as speed increased, digestibility increased; within each of these profiles, no significant changes in digestibility were observed due to blend ratio. High-temperature processing during extrusion typically unfolds and redistributes protein molecules within the plasticized mass in the extruder barrel and can subject them to thermal denaturation in which amino acids can be altered or destroyed and can lead to a final product with decreased protein quality (Cumming et al 1973; Nielsen 1976; Dahl and Villota 1991). However, within certain limits, heat treatment can improve the digestibility of proteins. Marsman et al (1995) determined that raw, unprocessed SBM had in vitro protein digestibility of ≈61% and that extrusion processing the SBM could produce digestibility values of 73–85%, which is a substantial increase in the protein quality. They further stated that a digestibility range of ≈67–85% is ideal for livestock nutritional requirements. Protein digestibility values for the extruded by-product blends were ≈80–84% and thus fell within this optimal region. Generally, except for the 30% CMB blend at the HTP, the extrudates had lower fat contents at the HTP than at the LTP. Furthermore, within each temperature, the HSS seemed to produce lower fat contents than the LSS. Overall fat content levels in soybean products are typically affected little during extrusion processing but they are generally more shelf-stable than the raw ingredients due to deactivation of fat-splitting enzymes during cooking (Nielsen 1976). HTP seemed to produce extrudates that had slightly higher ash contents than the LTP, but neither screw speed nor blend ratio appeared to have an effect.

Extrudate Expansion

High temperatures, shear stresses, and shear strains produced during extrusion processing can also affect the complex interactions

TABLE III
Effect of Temperature and Screw Speed on Nutritional Characteristics of Resulting By-Product Blend Extrudates (n = 6)[a]

		80-90-100 (ºC)				100-110-120 (ºC)			
		50 rpm		100 rpm		50 rpm		100 rpm	
Property	**CMB[b]**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
Moisture content (%, wb)	0	19.82fg	2.45	20.39ef	3.45	18.78hi	0.65	19.33gh	1.24
	10	20.60de	1.12	19.49g	1.42	19.42g	5.00	18.53ij	2.13
	20	21.04d	0.68	20.54de	3.13	18.17j	2.57	18.13j	2.54
	30	25.79a	3.25	25.18b	0.52	23.48c	2.11	23.63c	1.69
Water activity	0	0.70de	5.15	0.66e	4.54	0.82a	2.25	0.81ab	2.75
	10	0.80ab	2.08	0.76bc	4.67	0.82a	3.12	0.81a	2.33
	20	0.74cd	4.41	0.68e	9.78	0.80ab	2.37	0.80ab	2.83
	30	0.75cd	19.71	0.60f	9.12	0.85a	2.09	0.84a	2.79
Protein (%, db)	0	48.39a	0.48	48.35a	0.56	48.29a	0.31	48.42a	0.39
	10	47.60b	0.56	47.60b	0.70	47.49b	0.61	47.52b	0.65
	20	47.32b	0.50	47.36b	0.54	47.15b	0.25	47.24b	0.47
	30	46.35c	0.44	46.19c	0.56	47.06b	0.54	47.06b	1.08
Protein digestibility (%, db)	0	83.65a	0.33	80.88b	3.20	80.82b	3.28	83.79a	0.21
	10	83.74a	0.10	80.62b	3.38	80.93b	2.82	83.83a	0.09
	20	83.79a	0.16	80.89b	2.74	80.46b	3.68	83.79a	0.17
	30	83.82a	0.11	80.62b	3.23	79.73b	4.57	83.59a	0.47
Fat (%, db)	0	1.24b–d	3.54	1.17cd	6.07	1.11de	4.97	1.12c–e	5.88
	10	1.24bc	1.95	1.10de	7.55	1.10de	15.31	1.06de	6.25
	20	1.24bc	10.43	1.08de	8.14	1.02e	13.21	1.00e	14.32
	30	1.23b–d	11.93	1.19b–d	12.59	1.40a	12.45	1.31ab	6.86
Ash (%, db)	0	6.81b	0.81	6.77b	1.16	10.13a	29.42	10.11a	24.10
	10	8.39ab	20.59	7.59b	6.17	9.77a	29.46	7.98b	9.71
	20	7.82b	16.05	7.13b	5.91	7.17b	7.15	7.53b	13.43
	30	6.93b	1.08	6.91b	0.92	6.95b	2.41	8.77ab	36.50

[a] Values followed by the same letter within the same property are not significantly different ($P < 0.05$).
[b] Fraction of corn masa byproduct in the blend (%, wb).

TABLE IV
Effect of Temperature and Screw Speed on Physical Characteristics of Resulting By-Product Blend Extrudates (n = 6)[a]

		80-90-100 (°C)				100-110-120 (°C)			
		50 rpm		100 rpm		50 rpm		100 rpm	
Property	**CMB[b]**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
Diameter (mm)	0	3.33ab	1.29	3.36ab	2.08	3.39a	2.61	3.40a	2.02
	10	3.32ab	0.93	3.37a	1.16	3.39a	1.19	3.35ab	2.81
	20	3.29bc	1.49	3.37ab	1.21	3.34ab	2.06	3.36ab	3.05
	30	3.15e	2.27	3.16de	1.58	3.24b–d	5.80	3.24cd	2.38
CSEI[c]	0	1.10ab	2.63	1.12ab	4.14	1.14a	5.22	1.15a	4.05
	10	1.09ab	2.01	1.13a	2.33	1.14a	2.39	1.11ab	5.66
	20	1.07bc	2.98	1.12ab	2.44	1.11ab	4.15	1.12ab	6.08
	30	0.98e	4.54	0.99de	3.16	1.05cd	11.52	1.04cd	4.72
LEI[d]	0	0.80d	1.99	0.84cd	4.69	0.87bc	7.26	0.89b	4.84
	10	0.81d	2.61	0.83d	3.97	0.88bc	3.14	0.88bc	3.89
	20	0.84cd	1.90	0.81d	3.46	0.89b	1.75	0.88bc	5.48
	30	0.82d	4.19	0.85cd	2.54	0.90b	6.29	0.95a	5.53
VEI[e]	0	0.88de	1.94	0.94bc	5.02	1.00ab	6.87	1.02a	5.11
	10	0.88de	1.85	0.93cd	5.11	1.01a	5.07	0.98ab	4.99
	20	0.90cd	4.11	0.91cd	2.20	0.99ab	3.79	0.98ab	9.57
	30	0.80f	7.12	0.84ef	4.86	0.93cd	8.41	0.99ab	9.83
Unit density (g/cm^3)	0	1.26bc	1.68	1.19c	4.86	1.10c	7.67	1.08c	5.26
	10	1.28bc	1.66	1.19c	5.57	1.10c	5.63	1.12c	5.17
	20	1.26bc	4.22	1.23c	2.05	1.10c	3.93	1.11c	9.77
	30	1.40a	7.74	1.33ab	4.87	1.17c	8.77	1.11c	9.85
True density (g/cm^3)	0	1.39bc	1.14	1.40a	1.57	1.39bc	1.68	1.38bc	1.85
	10	1.40a	1.03	1.41a	0.52	1.38c	2.24	1.38bc	2.28
	20	1.40a	0.57	1.40ab	0.61	1.40ab	0.99	1.39ab	0.98
	30	1.38bc	1.18	1.37c	0.66	1.36c	0.98	1.36c	0.56
WAI[f]	0	4.27ab	5.89	4.10bc	12.09	4.11bc	5.22	4.37ab	3.74
	10	4.32ab	8.32	4.44a	3.72	4.50a	6.49	4.41ab	7.06
	20	4.34ab	4.99	4.36ab	4.02	4.32ab	5.57	4.40ab	3.97
	30	4.28ab	3.00	4.04bc	3.59	4.15bc	6.73	3.98c	8.32

[a] Values followed by the same letter within the same property are not significantly different ($P < 0.05$).
[b] Fraction of corn masa byproduct in the blend (%, wb).
[c] Cross-sectional expansion index.
[d] Longitudinal expansion index.
[e] Volumetric expansion index.
[f] Water absorption index.

between the chemical constituents and alter the resulting internal cellular structures that occur during water evaporation upon die exit (Miller 1985), reflected in the expansion of the material as it passes through the extruder die, and can be quantified through expansion ratios (Moore et al 1990). Extrudate expansion is dependent on the rheological properties of the thermoplastic melt in the extruder channel, where radial expansion is a function of melt elasticity, and elongation depends on melt viscosity. Overall, there was a slight expansion in the radial direction (CSEI >1) and a contraction in the longitudinal dimension (LEI <1), resulting in a total volumetric expansion (VEI) of ≈1 (0.80–1.02). In general, the HTP produced extrudates with greater radial expansion, elongation, and overall volumetric expansion than those produced with the LTP. The LEI depends on melt viscosity (Kokini et al 1992). For these results, the combination of lower temperature and screw speed led to higher melt viscosities, which resulted in less elongated structures upon die exit.

Radial expansion was lower than that observed for many extruded foods and feeds, with diameter values only slightly greater than the die diameter (3.175 mm [0.125 in.]). Similar results were obtained by Cumming et al (1972), who extruded SBM and produced extrudates with relatively constant diameters. Radial expansion is highly dependent on the starch composition of the extruded material, which is key to product expansion by starch gelatinization (Nielsen 1976). Products high in starch generally exhibit high expansion. SBM, however, essentially has no starch, so it was not surprising that little radial expansion occurred during extrusion processing in this study. The carbohydrate fraction of CMB also has negligible starch, being almost entirely cellulose and hemicellulose (Rosentrater et al 1999). Low radial expansion can also be attributed to the high protein value of SBM, which can incur heat damage during processing and thus further restrict expansion (Cumming et al 1972; Nielsen 1976).

Within each temperature setting, the LSS generally produced slightly lower expansion ratios than the HSS. As previously noted, products with the LSS had higher moisture levels. These results are therefore consistent with the conclusions of Alvarez-Martinez et al (1988), who predict lower CSEI for higher moisture materials due to softening of molecular structures and thus a reduction of elastic properties. Increasing the by-product blend ratio also increased moisture, similarly decreasing both extrudate diameter and CSEI.

Extrudate Density

Another measure of internal structure is unit density, which quantifies a material's mass per unit volume, and includes the air entrapped within interior pores. As both processing temperature and screw speed increased, resulting unit density values decreased. Unit density generally decreases as processing temperature increases due to increased product expansion, which thus produces a more porous extrudate structure (Cumming et al 1972; Badrie and Mellowes 1991). Bouvier et al (1987) extruded soy dough and found extrudates with unit density values of ≈1.25 g/cm^3, similar to values found in this study. True density, on the other hand, can be used to quantify the structure of a material by accounting for internal pores (Stroshine and Hamann 1995). Generally, true density values were slightly higher than the corresponding unit density values, indicating that many of these entrained pores were open to the surface.

Extrudate Color

From the color analysis, it was determined that, although no significant differences resulted from the various treatment levels, the extruded products were all substantially darker in appearance than the raw ingredient blends, with the *L* values (mean 40.54, CV 11.46%), *a* values (mean 2.75, CV 13.71%), and *b* values (mean 11.53, CV 12.02%) being much lower than their respective values before processing. These results essentially described the extruded products as brown in appearance. They were darker and browner than the raw ingredient blends primarily because of the high-temperature heat treatment during the extrusion cooking process. High-temperature processing exacerbates protein reaction with reducing sugars in nonenzymatic (e.g., Maillard) browning processes, which can lead to not only darker products but also products with reduced nutritional quality (i.e., destruction of amino acids) (Badrie and Mellowes 1991; Dahl and Villota 1991).

Extrudate WAI and WSI

Relationships between extruded products and water are vital to the ultimate functionality of these materials and can be quantified through the water absorption index (WAI) and the water solubility index (WSI). No clear effects due to processing treatment were evident for WAI results. WSI results (mean 0.2, CV 24.22%) were not significantly affected by processing conditions or blend ratios, but overall, the ability of the extruded CMB/SBM blends to solubilize in water was quite low. Typically, water absorption ability of an extrudate increases with increasing processing temperature, which results in a higher expansion, and thus produces a more porous structure (Maga and Lorenz 1978). Bressani et al (1978) extruded blends of corn and soybean materials and found resulting WAI values of 4.6–5.1, which compare favorably to the results obtained in this study. As processing temperature increases, however, proteins within a soy-based thermoplastic melt (in an extruder) are increasingly altered and redistributed and these molecules can become insoluble (Cumming et al 1973).

Extrudate Durability

Durability results were not significantly affected by any processing conditions or blend ratios, and the resulting values for the extruded products in this study were quite high (≈97–99%, mean 98.38%, CV 0.58%). Thus, the extruded CMB/SBM blends were highly resistive to the destructive forces commonly encountered by feed materials, which is highly desirable in resisting potential damage during handling and storing and thus maintaining feedstuff quality and value.

Property Relationships

Relationships between all measured physical, nutritional, and extruder operational properties were investigated using correlation analysis. Fifty-five of the resulting 1,156 Pearson product-moment correlations (Speigel 1994) were significant ($P < 0.05$); the remainder of the correlations were not. The correlation coefficient (r) quantifies the strength of the linear relationship between two variables. As shown in Table V, 37 of the variable combinations had resulting $r > |0.80|$, while 17 had $r > |0.90|$, and thus exhibited fairly strong linear relationships. Several of these correlations, however, were expected before analysis because of the relationships defined by Equations 1–7: CSEI and diameter; material throughput and product throughput; unit density and dough density in the die; dough viscosity and torque; CSEI and VEI; diameter and VEI; die temperature and dough density in the die; dough viscosity and extruder speed; and unit density and VEI.

Several other correlations were intuitively anticipated before analysis. A high moisture content should allow more water to be available for microbial use, thus the high correlation between raw ingredient moisture content and raw ingredient a_w was observed. A high initial feed ingredient moisture level should produce a final product with high moisture, thus the strong correlation between extrudate moisture content and raw ingredient moisture content was logical. The strong correlation between die temperature and dough temperature was also expected, as were the strong correlations between raw ingredient blend and both raw moisture content and raw a_w because the 30% CMB blend was initially at a higher moisture content and a_w than the other blends. Furthermore, the relatively strong correlations between dough density in the die and both the extrusion temperature profile and the dough temperature were likely because dough density in the die depends on die temperature and die temperature depends on the extrusion temperature profile, as does the dough temperature. As dough temperature increases, extrudate expansion increases; as expansion increases, both the unit density and the dough density in the die decrease due to a more porous structure that is developing in the extrudate. Moreover, as moisture content increases, expansion decreases due to a softened extrudate texture.

Several correlations involved the color (*L,a,b*) values and are appealing because they hold potential for developing prediction relationships between product color and other variables with which they are associated. A more thorough quantification could lead to low-cost visual sensing strategies for process quality control and property monitoring.

To further investigate the relationships and interactions between raw ingredients, extrusion processing, and resulting extrudate properties, a principal components analysis was conducted using all variables in the study. This type of analysis is typically used to reduce the dimensionality of multivariate data by summarizing the observed variance and projecting it into a set of uncorrelated, orthogonal linear combinations (eigenvectors) based on the original variables, which have the form:

$$y_{P.C.} = a_1 X_1 + a_2 X_2 + ... + a_Z X_Z \tag{8}$$

where $y_{P.C.}$ is a principal component value or score; a_1 through a_Z are principal component coefficients (eigenvectors); and X_1 through X_Z are the original property variables in vector form (Everitt and Dunn 1991). A scree plot of the resulting principal component eigenvalues (Fig. 1) and a plot of the error explained through the use of these principal components (Fig. 2) determined that the use of seven principal components should be adequate to summarize the multivariate data in the study. Results from the principal components analysis are presented in Table VI, which provides the resulting eigenvectors and eigenvalues for the first seven principal components, as well as the proportion of variation explained through the use of each principal component. These first seven principal components accounted for 81.17% of the total variability in the data, and thus provide both a convenient and comprehensive summary of the information contained in all the original variables in the study but utilize a reduced dimensionality of only seven variables. Although the interpretation of principal components is often very subjective, it appears that the first principal component may be an indication of raw ingredient properties, while the second principal component might be an indication of extrusion processing characteristics.

Another benefit to using principal components analysis to summarize multivariate data is the ability to identify curvature, outliers, and clustering through examination of low-dimensional scatterplots of the calculated principal component scores (Fig. 3). Using this approach, no curvature was indicated in this data set but it did appear that an outlier did exist (plots of PC 1 vs. PC 3 and PC 2 vs. PC 3).

Investigation into the cause of this determined that it was actually the point mentioned in the previous SME discussion (0% CMB-LTP-HSS). Thus, more investigation into the cause of this outlying data point is warranted. Furthermore, the plot of PC 1 vs. PC 2 shows a distinct separation in the data. It was subsequently determined that this clustering was due to the higher moisture content of the 30% blend.

TABLE V
Statistically Significant ($P < 0.05$) Correlation Coefficients > |0.80| Based on All Collected Multivariate Data

Variable Associations		Correlation Coefficient (r)
CSEI	Diameter	0.999
Material throughput	Product throughput	0.998
Unit density	Dough density in die	0.982
Raw fat	Raw Hunter *L* value	0.967
Raw moisture content	Raw water activity	0.962
Raw Hunter *b* value	Raw Hunter *L* value	0.955
Dough viscosity	Torque	0.953
Raw blend	Raw GMD	0.943
Raw GMD (geometric mean diameter)	Raw moisture content	0.937
Hunter *b* value	Hunter *L* value	0.922
Raw GMD	Raw water activity	0.919
Moisture content	Raw moisture content	0.898
Die temperature	Dough temperature	0.880
Protein	Raw Hunter *L* value	0.875
Moisture content	Raw a_w	0.865
Raw Hunter *b* value	Raw fat	0.865
Protein	Raw fat	0.861
Raw blend	Raw Hunter *a* value	0.859
Moisture content	Raw GMD	0.836
Raw Hunter *b* value	Raw protein	0.818
Protein	Raw GMD	–0.807
Dough density in die	Dough temperature	–0.816
Dough viscosity	Extruder speed	–0.823
Raw protein	Raw water activity	–0.834
Moisture content	Raw protein	–0.842
Raw blend	Raw Hunter *b* value	–0.843
Raw Hunter *a* value	Raw Hunter *L* value	–0.849
Raw Hunter *b* value	Raw moisture content	–0.849
Raw Hunter *b* value	Raw GMD	–0.867
Raw blend	Protein	–0.872
Raw GMD	Raw Hunter *L* value	–0.899
Raw blend	Raw fat	–0.927
Raw moisture content	Raw protein	–0.934
Raw blend	Raw Hunter *L* value	–0.951
Raw Hunter *a* value	Raw fat	–0.952
Dough density in die	VEI (volumetric expansion index)	–0.953
Unit density	VEI	–0.986

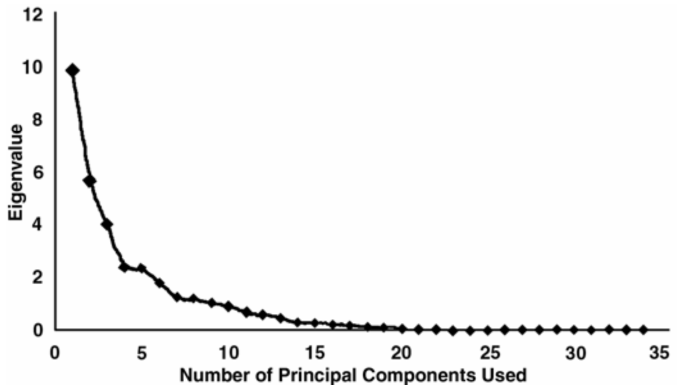

Fig. 1. Scree plot used to determine the number of principal components required to summarize the entire multivariate data set.

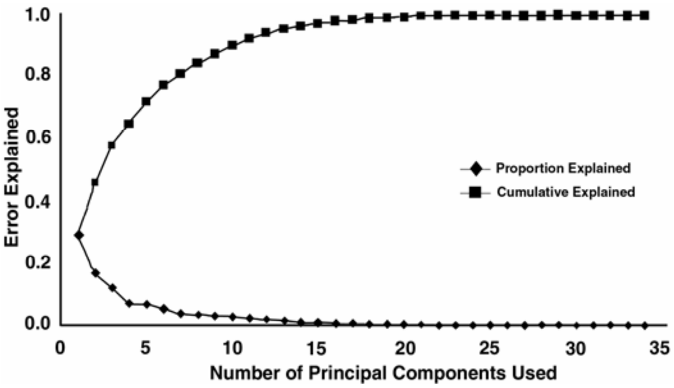

Fig. 2. Error explained through use of additional principal components to summarize the entire multivariate data set.

TABLE VI
First Seven Principal Components Based on All Collected Multivariate Data

Property	PC1[a]	PC2	PC3	PC4	PC5	PC6	PC7
Raw GMD[b]	–0.2931	0.1259	0.0400	–0.0555	–0.0306	0.0313	–0.0007
Raw moisture content	–0.2846	0.1351	–0.0942	0.0258	–0.0626	–0.0513	0.0811
Raw water activity	–0.2672	0.1198	–0.1101	–0.0006	–0.0868	–0.0168	0.0601
Raw protein	0.2494	–0.1336	0.1751	–0.1038	0.0625	0.1321	–0.1478
Raw fat	0.2382	–0.0969	–0.2500	0.1109	–0.0677	–0.0827	0.0084
Raw ash	–0.0619	–0.0120	0.3190	–0.2332	0.0493	0.2391	–0.2183
Raw Hunter *L* value	0.2741	–0.1195	–0.1607	0.0692	–0.0358	–0.0382	0.0325
Raw Hunter *a* value	–0.1844	0.0626	0.3300	–0.1644	0.0882	0.1439	–0.1464
Raw Hunter *b* value	0.2763	–0.1328	–0.0647	–0.0005	–0.0192	0.0353	–0.0362
Dough temperature	0.1045	0.3531	0.0365	–0.0371	0.0420	–0.1447	0.0130
Die temperature	0.0884	0.3324	0.0405	–0.0125	0.1531	–0.1373	–0.0803
Torque	0.0050	–0.1731	0.0570	–0.2669	0.4060	0.1747	0.2903
SME[c]	–0.0111	–0.0535	–0.3174	–0.1064	0.1643	0.2638	–0.0533
Product throughput	0.0456	–0.1208	0.3794	0.0232	–0.2758	–0.0650	0.1891
Material throughput	0.0426	–0.1192	0.3834	0.0078	–0.2765	–0.0549	0.1904
Dough viscosity	0.0155	–0.1434	0.0008	–0.2340	0.4836	0.1405	0.2347
Dough density in die	–0.1648	–0.3304	–0.0167	0.1317	0.0700	–0.0714	–0.0494
Moisture content	–0.2908	–0.0127	–0.1009	0.0442	–0.0607	–0.0383	0.1184
Water activity	0.0544	0.2186	0.0008	–0.0503	0.3030	–0.2582	–0.2831
Protein	0.2469	–0.0737	–0.2037	0.0929	–0.0067	–0.1144	–0.0275
Fat	–0.1306	0.0174	–0.2437	–0.1067	0.0548	0.0395	0.1187
Ash	0.0932	0.0709	–0.0036	–0.0821	0.1237	–0.3615	0.4333
Protein digestibility	0.0105	–0.0515	–0.0174	–0.0130	0.0881	–0.1849	–0.5052
Diameter	0.2528	0.0582	0.0239	–0.1579	–0.1095	0.1270	–0.0079
CSEI[d]	0.2510	0.0614	0.0238	–0.1562	–0.1144	0.1261	–0.0146
LEI[e]	0.0123	0.3345	–0.0015	–0.0538	–0.0009	–0.0010	0.1447
VEI[f]	0.1944	0.2822	0.0174	–0.1581	–0.0845	0.0918	0.0907
Unit density	–0.1948	–0.2931	–0.0193	0.1456	0.0787	–0.0978	–0.0696
True density	0.0967	–0.2146	0.0707	0.0474	0.0126	–0.0468	–0.0432
Hunter *L* value	0.0433	0.0636	0.1458	0.4810	0.1625	0.2540	0.1706
Hunter *a* value	0.0067	0.2113	0.1115	0.3745	0.1837	0.1325	–0.0610
Hunter *b* value	0.1035	0.1083	0.0998	0.4703	0.2085	0.2313	0.0634
WAI[g]	0.0641	–0.0906	0.2153	0.0708	0.2470	–0.3599	–0.1070
WSI[h]	0.0069	0.0345	–0.1928	0.0176	–0.1848	0.3928	–0.1727
Eigenvalue	9.9500	5.7800	4.0300	2.4400	2.3400	1.8100	1.2500
Proportion of variation (%)	29.2700	17.0100	11.8600	7.1700	6.8700	5.3100	3.6800
Cumulative variation (%)	29.2700	46.2800	58.1400	65.3200	72.1800	77.4900	81.1700

[a] Eigenvector value for the given principal component.
[b] Geometric mean diameter.
[c] Specific mechanical energy.
[d] Cross-sectional expansion index.
[e] Longitudinal expansion index.
[f] Volumetric expansion index.
[g] Water absorption index.
[h] Water solubility index.

SUMMARY AND CONCLUSIONS

This study has provided information essential to the development of livestock feed additives utilizing blends of CMB and SBM through extrusion processing. Blend ratio affected processing and product properties very little; most effects were due to screw speed and processing temperature. During processing, the dough melt in the extruder behaved pseudoplastically, which is typical of most food doughs and required less torque to convey the material as screw speed increased. Laboratory-scale extrusion produced extrudates with nutritional properties similar to those of the raw ingredient blends, with improved protein digestibility, which was

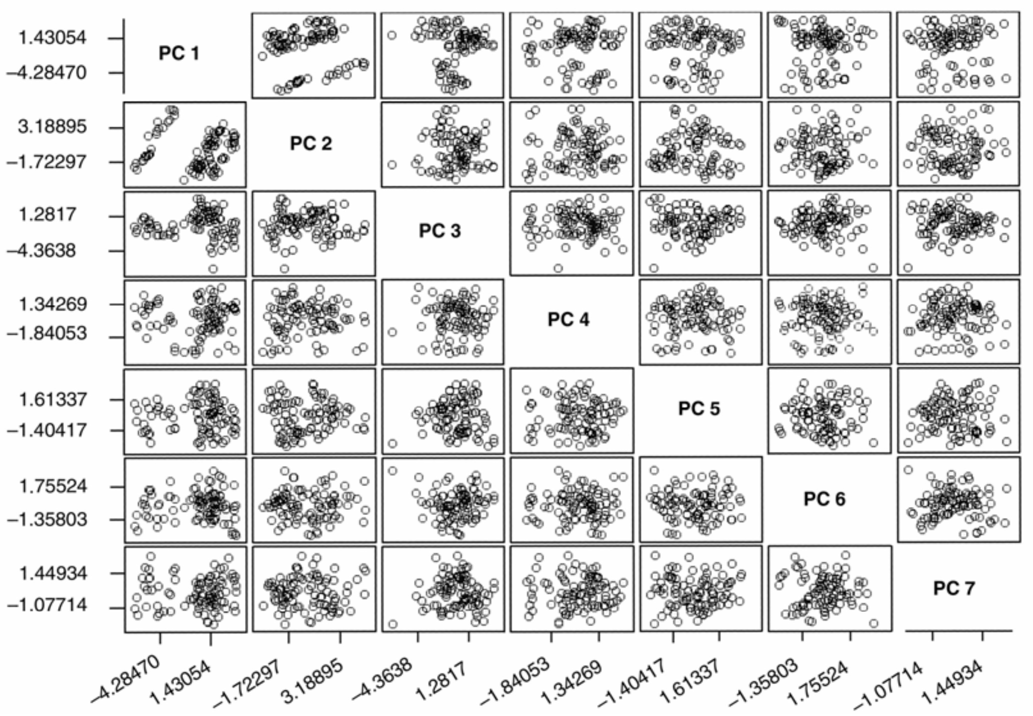

Fig. 3. Scatterplot matrix of calculated principal component (PC) scores for first seven principal components, based on all collected multivariate data.

due to the thermal effects of the extrusion cooking. Because SBM was used as a blending agent, little product expansion occurred at the extruder die, which was primarily due to lack of starch in the blends. Additionally, resulting products had low water absorption and solubility. All extrudates also had excellent durability, which is essential to retaining quality during transport and storage of pelleted feed ingredients. The next stage in developing livestock feed ingredients from CMB could logically follow three possible courses: 1) conducting a livestock feeding trial utilizing these extruded products, 2) developing an extrusion scale-up with blends of CMB and SBM, or 3) processing CMB with ingredients other than SBM.

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