Extrusion Cooking of Corn Meal with Soy Fiber, Salt, and Sugar[1]

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ABSTRACT

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Soy fiber (0–40%), sugar (0–12%), and salt (0–2%) were mixed with corn meal and extruded with a twin-screw extruder at 150–350 rpm screw speed. The effects of fiber, sugar, salt, and screw speed on extrusion parameters and extrudate properties were studied using a central-composite, rotatable, response-surface methodology. Increasing the fiber content raised the product temperature, extruder torque, die pressure, and specific energy. It also resulted in greater axial expansion but less radial expansion in extrudates. The net result was an increase in bulk density. Sugar increased the extrudate bulk density and decreased both axial and radial expansions. An increase in the screw speed raised the product temperature and specific energy but reduced die pressure. Increasing the salt content enhanced the lightness and increased the bulk density of extrudates but had no significant effects on the extrusion processing variables.

High-temperature, short-time (HTST) extrusion cooking technology has almost limitless application in the processing of cereal-based products of various blends for food as well as for feed. In recent years, increasing attention has been directed to incorporate dietary fiber into food (Colonna et al 1989).

An increase in dietary fiber intake is believed to be beneficial to human nutrition and health. Cancer of the colon, diabetes, hypercholesterolemia-atherosclerosis, diverticulosis, constipation, hypertension, obesity, and gallstones are frequently related to inadequate consumption of dietary fiber (Gordon 1989). This situation is therefore of great concern to nutritionists, food processors, and health-conscious consumers. According to the Food and Drug Administration Nutrition Labeling Guidelines, to make "a good source of fiber" claim the product must contain 10–19% of the daily reference value (DRV) per serving, which is equal to 2.5–4.75 g per serving; to claim "a high source of fiber" the product must contain 20% or more of the DRV, or 5.0 g or more per serving (Anonymous 1993). In fact, many products on the market today contain less than 2.5 g of dietary fiber per serving and will require an increase in the fiber content to make these claims to meet the needs of consumers (Hegenbart 1992).

During manufacturing of ready-to-eat (RTE) cereals and snack foods, sugar and salt are often added to impart or enhance their flavors. Recent U.S. surveys of RTE cereals revealed maximum contents of 16 g of sugar and 370 mg of sodium (941 mg of salt) per serving (28.4 g) (Hsieh et al 1990).

For extrusion cooking, changes in feed ingredients such as sugar, salt, and fiber, or processing parameters such as screw speed can affect the extrusion system variables and product characteristics. Hsieh et al (1989, 1991) examined the effects of dietary fiber and screw speed on corn meal extrusion processing and product variables. It was found that increasing either fiber content or screw speed increased the axial expansion but decreased the radial expansion. The net results were a decrease in the specific volume but an increase in the bulk density and breaking force of the extrudates. Therefore, the attempt to incorporate high levels of fiber in extruded products often resulted in a compact, tough, noncrisp, and undesirable texture in extrudates, as a result of reduced expansions (Lue et al 1991). Moore et al (1990) studied the effect of three additives (bran, sucrose, and magnesium carbonate) on the extrudates. An increase in apparent density occurred when the concentration of any of the additives was increased. However, most of the literature deals with relatively simple raw materials such as corn meal with either sugar or fiber. Little has been discussed about more complex mixtures, involving their implications on extruder performance and product characteristics. The objectives of this study were to investigate the effects of sugar, salt, fiber, and screw speed, and the interaction of these variables on the extrusion system variables and product properties.

MATERIALS AND METHODS

Materials

Yellow corn meal was obtained from Lauhoff Grain Company (Danville, IL). Soy fiber (Fibrim 1250) was purchased from Protein Technologies International (St. Louis, MO). The powdered sugar was from Imperial Sugar Company (Sugar Land, TX) and contained 3% corn starch. Iodized salt was a product of Morton International, Inc. (Chicago, IL). The proximate compositions of corn meal and Fibrim 1250 are shown in Table I. Table II shows the particle-size distributions for corn meal, soy fiber (Fibrim 1250), sugar, and salt. All the ingredients, in predetermined ratios, were mixed with yellow corn meal in an 18.9-L Hobart mixer (model A-200-F, Hobart Corp., Troy, OH) with a wire whip operating at a speed of 120 rpm for 10 min before extrusion to ensure homogeneity.

Extrusion Conditions

Extrusion experiments were performed using an APV Baker MPF 50/25, 28.0 kW, corotating and intermeshing twin-screw extruder (APV Baker Inc., Grand Rapid, MI) with a smooth barrel. An length-to-diameter ratio of 15:1 was used to ensure gelatinization and expansion of the corn meal (Hsieh et al 1989). The screw profile is shown in Figure 1. The temperatures of the six barrel zones were maintained at 26.7, 26.7, 51.7, 93.3, 121.1, and 121.1°C, respectively, from the feeding port to the die section. The die plate has two circular dies, each with one hole. The diameter of each hole was 27.25 mm initially, tapered to 3.18 mm downstream in a distance of 15.46 mm, and then 3.18 mm in diameter for another 3.08 mm further downstream.

TABLE I
Proximate Compositions (%) of Yellow Corn Meal and Soybean Fiber

Component	Yellow Corn Meal	Fibrim 1250
Moisture	12.0	7.0
Protein	7.0	12.0
Oil	0.7	0.2
Fiber	0.5	75.0
Ash	0.4	4.5
Nitrogen-free extract	79.4	nt[a]

[a] Not tested.

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Raw materials were fed into the extruder with a K-tron type T-35 twin-screw volumetric feeder with a series 6300 controller (K-tron Corp., Pitman, NJ). The feed rate was maintained at 45.4 kg/hr throughout the experiments. The moisture content of feed was adjusted to 20% (wb) by injecting water at ambient temperature into the extruder with a pump. The adjustable die face cutter with four blades was operated at 325 rpm.

TABLE II
Particle-Size Distributions for Corn Meal, Soy Fiber (Fibrim 1250), Sugar, and Salt

Particle size, μm	Distribution, %
Corn meal	
> 1,000	0.3
710–1,000	23.2
500–710	72.0
400–500	2.8
300–400	1.1
< 300	0.1
Recovery	99.5
Soy fiber (Fibrim 1250)	
> 710	0.1
500–710	1.4
400–500	3.1
300–400	9.1
250–300	11.6
150–250	47.4
80–150	23.6
< 80	2.5
Recovery	98.8
Sugar	
> 300	1.1
250–300	4.4
150–250	73.2
80–150	19.4
< 80	1.3
Recovery	99.4
Salt	
> 710	0.1
500–710	5.4
400–500	40.3
300–400	47.8
250–300	3.9
< 250	2.4
Recovery	99.9

All parameters, including barrel and product temperatures, die pressure and temperature, extruder torque, screw speed and cutter speed shown in the control panel, were automatically collected by an MACS PL-1000 data acquisition system (Elexor Associates, Morris Plains, NJ), and displayed simultaneously on an IBM PC-AT/XT compatible computer (Northgate, Plymouth, MN) and stored on hard disk. Steady-state extrusion conditions were assumed to have been reached when there were no visible drifts in product temperature at the die and extruder torque for at least 5 min. Samples were collected during the next 5-min sampling time and then dried in a fluidized bed drier at 65°C for approximately 5 min. Final product moisture was about 7.0% (wb).

Specific energy was calculated using the following formula:

$$\text{Specific energy} = \text{RPM(run)}/500\ \text{rpm} \times \%\ \text{torque(run)}/100 \times 28\ \text{kW}/\ \text{feed rate} \quad (1)$$

Experimental Design

The experiment design was based on a rotatable, central-composite, response-surface model (Mullen and Ennis 1979) with four variables and five levels. The response-surface design allows for the prediction of dependent variable values with a minimum number of experimental treatments. The four independent variables were sugar, salt, fiber contents, and screw speed. The five levels were coded as −2, −1, 0, 1, and 2 (Table III) for statistical analyses.

The values of the independent variables in each treatment are shown in Table IV. Other process variables such as feed rate, feed moisture content, and barrel temperatures were kept constant.

TABLE III
Independent Variable Levels and Codes

Variables	Levels				
Sugar, %	0	3	6	9	12
Salt, %	0	0.5	1	1.5	2
Soy fiber, %	0	10	20	30	40
Corn meal, %	100	86.5	73	59.5	46
Screw speed, rpm	150	200	250	300	350
Code	−2	−1	0	1	2

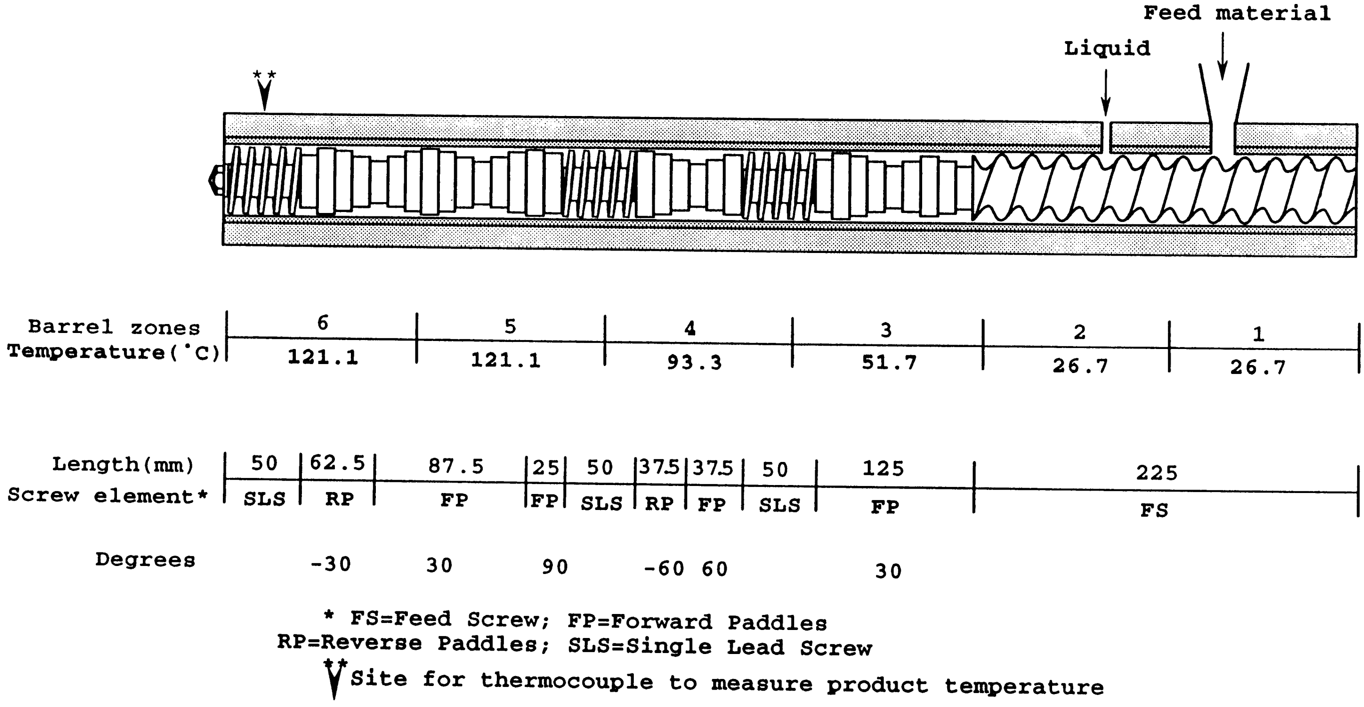

Fig. 1. Screw profile of the twin-screw extruder.

For each objective response, analysis of variance was conducted to determine significant differences among different treatment combinations by the SAS response-surface regression procedure (SAS 1989). The generalized regression model was:

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 + \epsilon$$

where Y = objective response, x_1 = sugar, x_2 = salt, x_3 = fiber, x_4 = screw speed, and ϵ = random error in which the linear, quadratic, and interaction effects were involved. Also, the data were tested using multiple regression procedures and backward elimination procedure. The terms that were not significant ($P > 0.05$) were deleted. Others were kept for the statistical analyses and three-dimensional plots.

For each response, three-dimensional plots were produced from the equations by holding the two variables with the least and the second-least effects on the response constant (central points) and changing the other two variables.

Determination of Product Properties

Specific length and expansion ratio. Fifty extrudate samples collected at random were weighed. Their diameters and lengths were measured with a pair of digital vernier calipers (500-215, Mitutoyo Co., Tokyo, Japan), and an average was determined. The expansion ratio (diametral) was defined as the ratio between the diameter of the extrudate and the diameter of the die (3.18 mm), while the specific length of the extrudate (L_{se}) was defined as the length of the extrudate per unit mass.

Extrudate specific volume and bulk density. The specific volume of the extrudates were determined using the rapeseed displacement method (Hsieh et al 1991). For apparent bulk density, the weight of extrudate that could be placed in a 1-L container was determined and expressed as grams per liter. There was a total of three measurements for each treatment. The average was calculated and recorded.

Colors. The color of the ground extrudate was measured in a Hunter D25L Colorimeter (Hunter Associates Lab., Reston, VA). The extrudate was milled to pass through a 20-mesh sieve with a Wiley Laboratory mill. The ground extrudate was placed in a plastic petri dish to the rim and then leveled off with a spatula. Then the plastic petri dish was covered with a clear glass plate and placed into the colorimeter. The L, a, and b values were reported: L = lightness, a = redness, and b = yellowness. For each sample, two readings were taken. The second reading was obtained by rotating the plastic petri dish approximately 90°. Ten readings from five samples of each treatment were collected and formatted into an SAS readable data file for statistical analyses.

TABLE IV
Rotatable Response-Surface Design

	Sugar		Salt		Fiber		Screw Speed	
Sample	Code	%	Code	%	Code	%	Code	rpm
1	−1	3	−1	0.5	−1	10	−1	200
2	−1	3	−1	0.5	−1	10	1	300
3	−1	3	−1	0.5	1	30	−1	200
4	−1	3	−1	0.5	1	30	1	300
5	−1	3	1	1.5	−1	10	−1	200
6	−1	3	1	1.5	−1	10	1	300
7	−1	3	1	1.5	1	30	−1	200
8	−1	3	1	1.5	1	30	1	300
9	1	9	−1	0.5	−1	10	−1	200
10	1	9	−1	0.5	−1	10	1	300
11	1	9	−1	0.5	1	30	−1	200
12	1	9	−1	0.5	1	30	1	300
13	1	9	1	1.5	−1	10	−1	200
14	1	9	1	1.5	−1	10	1	300
15	1	9	1	1.5	1	30	−1	200
16	1	9	1	1.5	1	30	1	300
17	2	12	0	1.0	0	20	0	250
18	−2	0	0	1.0	0	20	0	250
19	0	6	2	2.0	0	20	0	250
20	0	6	−2	0.0	0	20	0	250
21	0	6	0	1.0	2	40	0	250
22	0	6	0	1.0	−2	0	0	250
23	0	6	0	1.0	0	20	2	350
24	0	6	0	1.0	0	20	−2	150
25[a]	0	6	0	1.0	0	20	0	250

[a] Central point repeated seven times.

RESULTS AND DISCUSSION

Extrusion Process Variables

The effects of independent variables on the extrusion process variables are summarized in Table V. Regression analyses showed that extruder torque, specific energy, and product temperature were significantly ($P < 0.001$) affected by the screw speed and the additions of sugar and fiber, but not by the addition of salt. Die pressure was mainly influenced by the screw speed ($P < 0.001$), but not by any additives (salt, sugar, or fiber). It also appeared that the screw speed was the most important factor affecting the extrusion process variables.

TABLE V
Regression Equation Coefficients[a] for Product Temperature, Die Pressure, Percent of Torque, and Specific Energy

	Product Temperature (°C)	Die Pressure (kPa)	Torque (%)	Specific Energy (kJ/kg)
Intercept	164.29	3501.68	54.02	611.3
Sugar	-2.92^{***} [b]	ns[c]	-1.99^{***}	-21.1^{***}
Salt	ns	ns	ns	ns
Fiber	1.93^{***}	ns	2.97^{***}	33.9^{***}
Screw speed	3.54^{***}	-247.5^{***}	-6.64^{***}	54.2^{***}
Sugar × sugar	ns	ns	ns	ns
Salt × sugar	ns	ns	ns	ns
Salt × salt	ns	ns	ns	ns
Fiber × sugar	ns	ns	ns	ns
Fiber × salt	ns	ns	ns	ns
Fiber × fiber	ns	ns	-0.91^{*}	-11.1^{*}
Speed × sugar	ns	ns	ns	ns
Speed × salt	ns	ns	ns	ns
Speed × fiber	ns	ns	ns	ns
Speed × speed	0.80^{*}	ns	1.87^{***}	ns
R^2	0.88	0.35	0.92	0.88

[a] Coded.

[b] *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[c] Not significant at 5% level.

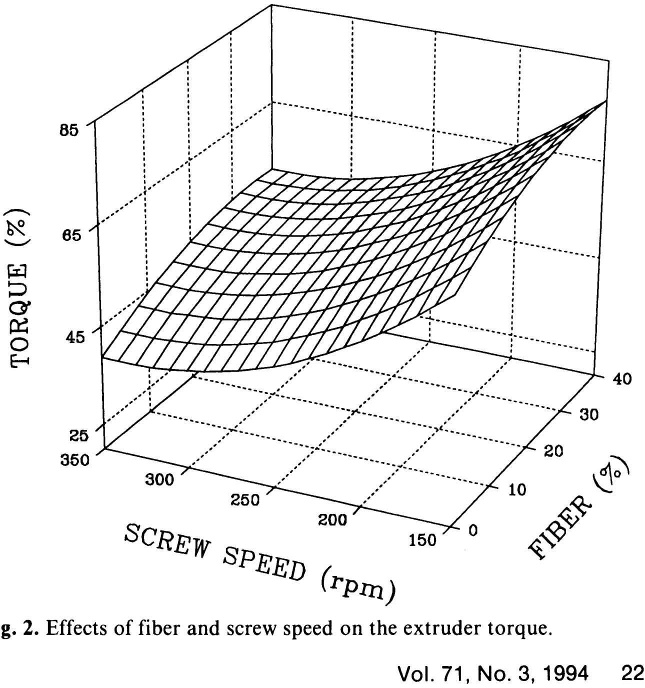

Fig. 2. Effects of fiber and screw speed on the extruder torque.

The decreases in the extruder torque with increasing screw speed (Fig. 2) could be attributed to the changes in the length of filled flights in the extruder barrel. At a constant feed rate, an increase in screw speed decreased the length of filled flights (Martelli 1983). This resulted in a decrease in the load on the screw shaft motor. Thus, the extruder torque was reduced. In addition, the product temperature was greater at a greater screw speed (Table V and Fig. 3), which indicated that the temperature of dough mass in the extruder barrel was greater, and hence, the viscosity of dough mass was less (Harper et al 1971, Colonna et al 1989). A reduced dough mass viscosity also decreased the load on the extruder motor, and therefore the torque. Bhattacharya and Hanna (1987a) also found that an increase in the dough mass viscosity increased the torque requirement. They concluded that any variable affecting the dough mass viscosity would correspondingly affect the extruder torque.

According to Martelli (1983), the total power (Z_t in kW) transmitted from the main motor to the screws is:

$$Z_t = C_1 \bar{\mu} N \omega^2 + Q^2 \mu / K_f \qquad (2)$$

where C_1 = a constant based on screw geometry, ω = screw speed (1/sec), N = number of filled flights, Q = output rate (m^3/sec), K_f is the die conductance (m^3), $\bar{\mu}$ is melt viscosity, and μ is average viscosity (N × sec/m^2) of the dough mass over the filled channels. The feed rate was kept constant so that N was inversely proportional to ω (Martelli 1983). Also, the output rate was constant at a fixed feed rate. Thus, the power consumption or specific energy increased with either increasing screw speed or increasing dough mass viscosity. As mentioned earlier, an increase in the screw speed reduced the dough mass viscosity. Therefore, the specific energy might increase or decrease with increasing screw speed, depending on the relative contribution of the screw speed and dough mass viscosity (Hsieh et al 1991).

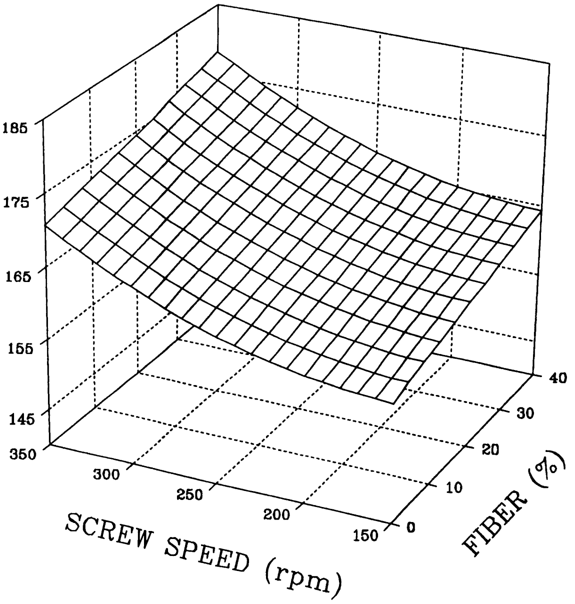

Fig. 3. Effects of fiber and screw speed on the product temperature.

As shown in Figure 3, increasing the screw speed from 150 to 350 rpm increased the product temperature approximately 15°C, and the average product temperature was approximately 165°C. The reduction in the dough mass viscosity could be estimated as (Hsieh et al 1991):

$$\mu_2/\mu_1 = \exp\,(\Delta E/R)(\Delta T/T^2) = \exp\,(2{,}500)[-15/(165+273)^2] = 0.822 \qquad (3)$$

where $\Delta E/R$ varied from 990K to 4,390K, and a value of 2,500K was assumed (Harper et al 1971). Thus, as the screw speed increased from 150 to 350 rpm, the dough mass viscosity reduced about 17.8% (or a 17.8% decrease in the second term on the right hand side of Equation 2. Assuming that changes in the average dough mass viscosity were the same as those in the melt viscosity $\bar{\mu}$, an increase of screw speed from 150 to 350 rpm would cause (Hsieh et al 1991):

$$\mu_2 N_2 \omega_2{}^2/\mu_1 N_1 \omega_1{}^2 = (0.822)(150/350)(350/150)^2 = 1.918 \qquad (4)$$

or 91.8% increase in the first term on the right hand side Equation 2. Thus, the specific energy increased with increasing screw speed (Fig. 4), because the effect of screw speed dominated the effect of dough mass viscosity. Similar results have been reported (Fletcher et al 1985; Hsieh et al 1989, 1990, 1991).

Die pressure decreased with increasing screw speed (Fig. 5). According to Yacu (1985), die pressure P is related to the output rate Q and melt viscosity μ of dough as:

$$P = Q \times \mu / K_f \qquad (5)$$

An increase in the screw speed increased the product temperature, and hence the dough mass viscosity, which in turn decreased the die pressure because of a constant output rate and die conductance. Della Valle et al (1987) reported an increase

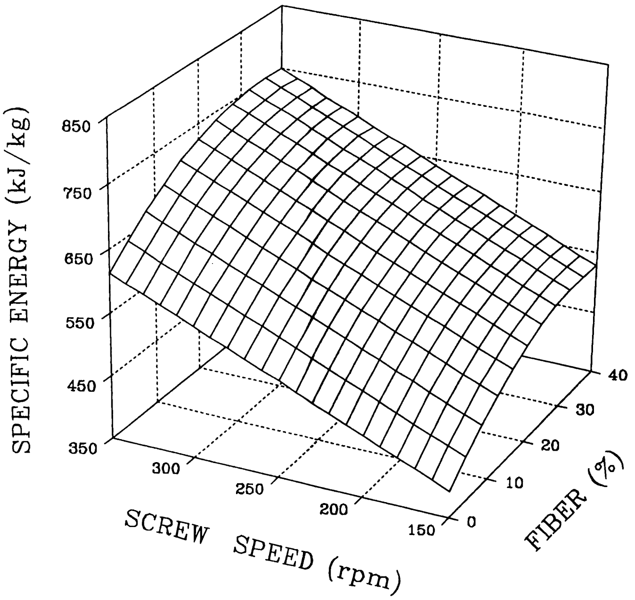

Fig. 4. Effects of fiber and screw speed on the specific energy.

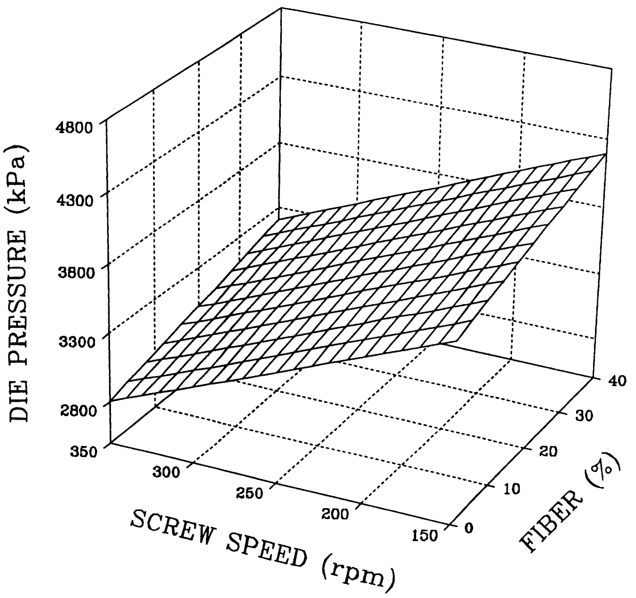

Fig. 5. Effects of fiber and screw speed on the die pressure.

of 10° C product temperature in the melting zone and a decrease of 2,000 kPa in the die pressure when the screw speed was increased from 130 to 250 rpm using a Clextral BC-45 twin-screw extruder. Fletcher et al (1985) also reported that increasing the screw speed increased shear in the barrel, which reduced the viscosity measured at the die. Thus, die pressure was lower.

An increase in added fiber tended to increase all of the four dependent processing parameters (Fig. 2–5), although die pressure increases were not significant ($P > 0.05$) (Table V). Slight increases in the extruder torque and die pressure with increasing fiber content probably resulted from an increased viscous dissipation of the dough mass. Increasing the fiber content increased the viscosity of the dough mass and increased the friction between the feed material and the barrel surface. Thus, a greater extruder torque was required to turn the extruder shaft. Also, die pressure was greater because of the increased dough mass viscosity (Equation 5). An increase in specific energy and increased product temperature with increasing fiber content could also be explained by the increased dough mass viscosity (Equation 2).

Increases in the sugar content, on the other hand, decreased the extruder torque, specific energy, and product temperature, but die pressure was not affected (Table V). Meuser and Wiedmann (1989) suggested that the effects of sugar probably resulted from the liquefaction of the sugar in the feed via a melting process. An increase in the sugar content reduced the melt viscosity, which in turn decreased the die pressure (Equation 5). Using a "dead stop" method, Sopade et al (1991) observed a gradual reduction of the length of filled flights in the extruder barrel as the sugar content was increased. The lower degree of fill reduced the heat transfer surface between the dough mass and heated barrel surface. Therefore, less heat would be transferred from the barrel surface to the product. Thus the product (melt) temperature was reduced. Because there was a reduction in the melt viscosity and the length of filled flights as the sugar content was increased, lower specific energy and extruder torque were observed. Similar results have been reported (Hsieh et al 1990, Sopade et al 1991). The effects of salt were not significant ($P > 0.05$) (Table V), although its effects were negative on these parameters (data not shown).

Extrudate Specific Volume and Bulk Density

Statistical analyses indicated that all four processing variables affected the extrudate expansion as did the interaction between sugar and fiber (Table VI). The additions of sugar and salt increased the bulk density and reduced the specific volume. Increasing the fiber content reduced the bulk density. Screw speed increases raised the specific volume but decreased the bulk density. The specific volume was negatively correlated with the bulk density ($P < 0.001$, $r = -0.93$).

TABLE VI
Regression Equation Coefficients[a] for Specific Volume, Bulk Density, Specific Length, and Expansion Ratio

	Specific Volume (cm^3/g)	Bulk Density (g/L)	Specific Length (mm/g)	Expansion Ratio
Intercept	20.74	71.72	95.28	3.94
Sugar	$-1.87^{***\,b}$	19.98^{***}	-9.77^{***}	-0.23^{***}
Salt	-0.47^{**}	6.47^{**}	-1.70^{**}	-0.095^{*}
Fiber	ns[c]	-8.63^{***}	16.65^{***}	-0.28^{***}
Screw speed	0.33^{*}	-6.51^{**}	12.96^{***}	-0.18^{***}
Sugar × sugar	ns	5.74^{**}	1.46^{**}	-0.12^{**}
Salt × sugar	ns	6.29^{*}	-1.75^{**}	ns
Salt × salt	ns	ns	ns	ns
Fiber × sugar	1.04	-10.36^{***}	1.69^{**}	0.19^{***}
Fiber × salt	ns	-5.36^{*}	1.24^{*}	ns
Fiber × fiber	-0.54^{**}	7.98^{***}	ns	-0.13^{**}
Speed × sugar	ns	-5.27^{*}	−1.51	0.11^{*}
Speed × salt	ns	ns	ns	ns
Speed × fiber	ns	ns	3.32^{**}	-0.12^{*}
Speed × speed	ns	ns	5.76^{***}	-0.11^{**}
R^2	0.89	0.93	0.99	0.91

[a] Coded.

[b] *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[c] Not significant at 5% level.

Several researchers demonstrated that the expansion of extruded cereals or starch-based materials depended on the degree of gelatinization, which in turn was determined by process temperature, shear rate, and moisture content of the feed material (Lawton et al 1972, Chiang and Johnson 1977, Guy and Horne 1988). Starch gelatinization temperature can be markedly altered by additives. While some additives enhance gelatinization, others inhibit gelatinization (Bhattacharya and Hanna 1987b). The presence of sugar and salt tended to reduce the availability of water or water activity (Moore et al 1990), because the sugar and salt absorbed more water than the starch did from the corn meal. Sterling (1978) reported that an increase in sugar content would effectively cause competition for the limited moisture available in the system for gelatinization. As mentioned above, the sugar and salt additions reduced the product temperature (Fig. 3), which might have also decreased or delayed the starch gelatinization. Hence, the bulk density increased but the specific volume reduced as the sugar or salt content was increased.

An increase in the specific volume and a decrease in the bulk density, caused by an increased screw speed have been well documented (Guy and Horne 1988; Hsieh et al 1989, 1990). Onwulata et al (1992) found that the extrudate bulk density varied as a function of the screw speed and was dependent on the final temperature of the dough behind the die. This was expected, because at the higher screw speed there was a greater amount of mechanical work (specific energy) (Fig. 4) and frictional heat, which caused an increase in the product temperature (Fig. 3). As the shear force and the product temperature increased, more starch granules were dispersed into a polymer phase, and the extrudate expansion increased (Guy and Horne 1988).

Statistically, the square of fiber content had significant effects on specific volume ($P < 0.01$) and bulk density ($P < 0.001$). The square of sugar content also had a significant effect on bulk density ($P < 0.01$). These results suggested that the effects of these two independent variables were nonlinear within the range of experimental conditions. Without sugar, increasing the fiber content resulted in extruded products of higher bulk density and lower specific volume (Figs. 6 and 7). This was because the fiber particles tended to rupture the cell walls before the gas bubbles had expanded to their full potential (Guy and Horne 1988, Lue et al 1991). This was found by many researchers (Breen et al 1977, Andersson et al 1981, Lawton et al 1985, Hsieh et al 1989).

It is interesting to note that the effects of sugar addition on the extrudate specific volume and bulk density were dependent

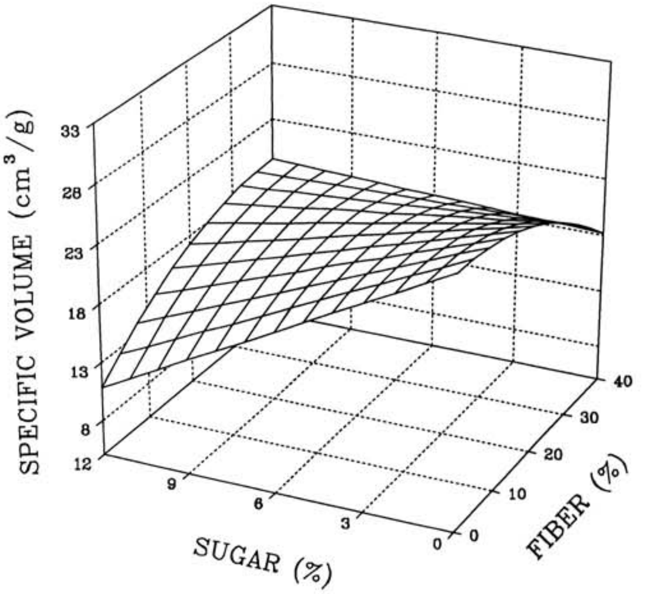

Fig. 6. Effects of sugar and fiber on extrudate specific volume.

on the fiber content (Figs. 6 and 7). While the specific volume and bulk density were essentially independent of sugar addition at 40% fiber content, they changed dramatically at lower fiber contents. In fact, the most dense extrudate (lowest specific volume and highest bulk density) occurred at 0% fiber and 12% sugar contents, not at 40% fiber and 12% sugar levels. This was probably due to the opposite effects of sugar and fiber additions on the product temperature (Table V). Without fiber, the product temperature was reduced with an increase in sugar content, which reduced the extrudate expansion. The product temperature increased progressively with increasing fiber content, and its effect probably dominated the effect of increasing fiber content on the extrudate expansion.

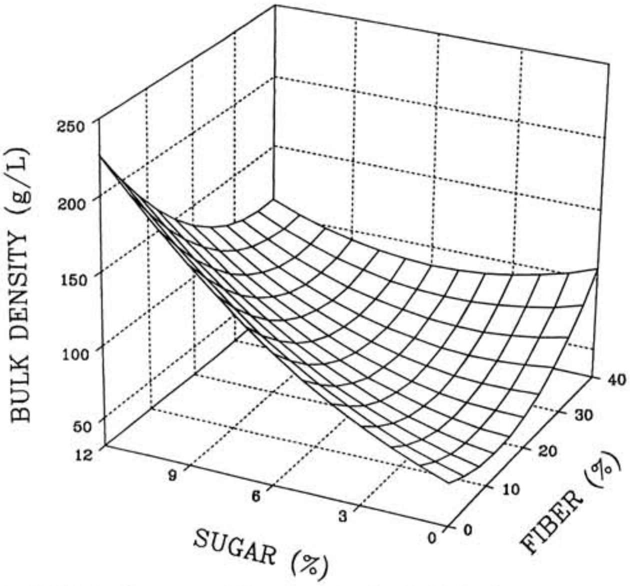

Fig. 7. Effects of sugar and fiber on extrudate bulk density.

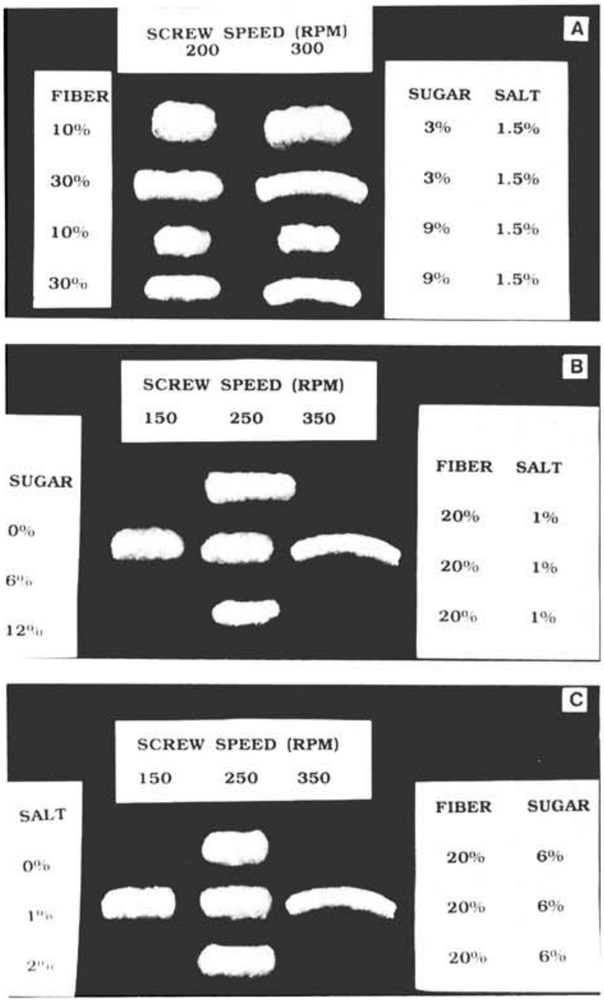

Fig. 8. Shape of the extrudates affected by fiber and screw speed (A), sugar and screw speed (B), and salt and screw speed (C).

Expansion Ratio and Specific Length

Table VI shows that the specific length and expansion ratio of extrudates were significantly affected by the four independent variables in linear, quadratic, and crossproduct terms. The effects of these variables on the shape of the extrudates are shown in Figure 8.

An increase in the sugar or salt content decreased the extrudate's expansion ratio and specific length. This is because sugar and salt decreased or delayed starch gelatinization, resulting in a reduced specific volume and an increased bulk density, as discussed earlier. Increasing the fiber content in feed resulted in a reduced expansion ratio but longer specific lengths of extrudates (Figs. 8–10). Similar results have been reported (Breen et al 1977; Hsieh et al 1989, 1991; Moore et al 1990; Andersson et al 1991). It has been reported that the extrudate's longitudinal expansion and melt viscosity were inversely related (Launay and Lisch 1983). Thus, a longer specific length, with greater fiber contents, was due to an increase in product temperature (Table V and Fig. 3), which reduced the melt viscosity. On the other hand, the presence of fiber ruptured the cell walls and prevented the gas bubbles from expanding to their full potential (Guy and Horne 1988, Lue et al 1991). Thus, the expansion reduced with the fiber addition.

An increase in the screw speed increased the specific length but decreased the expansion ratio. As mentioned above, an increase in the screw speed decreased the melt viscosity of the dough mass because of increased shear. A reduced melt viscosity resulted in a longer specific length (Launay and Lisch 1983). However, the product temperature increased with increasing screw speed, which imparted a greater elastic effect on the extrudates and increased the radial expansion (Fletcher et al 1985, Guy and Horne 1988). Again, similar results have been reported (Hsieh et al 1989, 1990, 1991).

Colors

Table VII shows that the fiber content and screw speed were the major factors influencing the colors of extrudates. Also, the interactions between fiber and sugar, and between fiber and salt were significant on the lightness of extrudates. Increased fiber

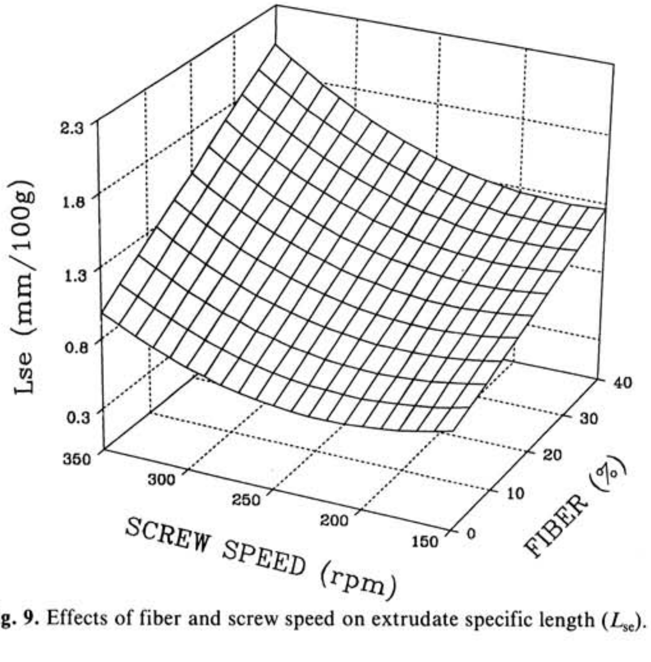

Fig. 9. Effects of fiber and screw speed on extrudate specific length (L_{se}).

contents resulted in lighter extrudates with less redness and yellowness, whereas higher screw speeds increased the lightness and reduced the redness and yellowness of extrudates.

One explanation of the effect of screw speed on extrudate colors is that an increase in the screw speed reduced the residence time and, hence, reduced the extrudate browning. On the other hand, the increased screw speed enhanced the shear and raised the product temperature, which could have led to more browning. The final effect was the result of the two opposite trends. In this study, the effect of residence time probably dominated, so the extrudates were lighter in color and had lower redness and yellowness at an increased screw speed.

The reduction in redness and yellowness with increasing fiber contents might have been caused by the pigments present in the fiber ingredient that not only had much less redness and yellowness but also was lighter in color than that of corn meal (data not shown). The decrease in lightness with increasing fiber might have resulted from more browning reaction because fiber additions increased the product temperature (Fig. 3).

When the salt content was increased, the extrudate became lighter, less red, and more yellow (Table VII). This was also reported by Hsieh et al (1990). Evidently, salt interfered with browning reactions such as caramelization and Maillard reactions, probably by lowering the water activity of the dough mass from an intermediate water activity where maximum browning reaction occurs (Whistler and Daniel 1985).

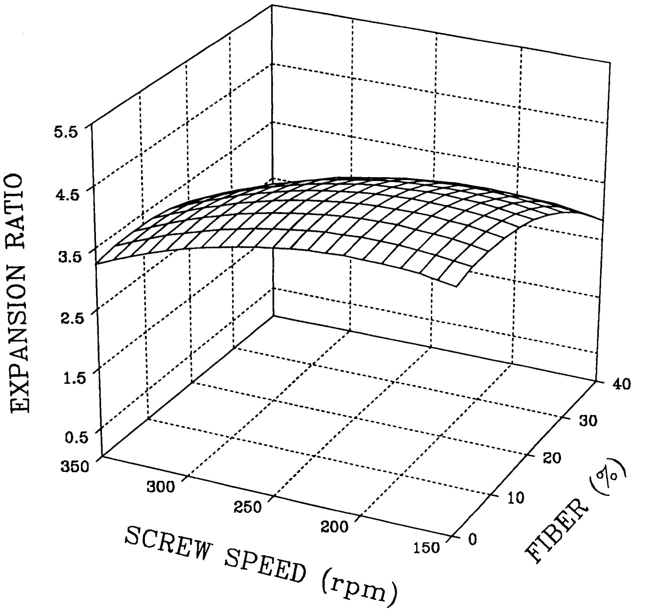

Fig. 10. Effects of fiber and screw speed on extrudate expansion ratio.

TABLE VII
Regression Equation Coefficients[a] for Lightness, Redness, and Yellowness

	Lightness (L)	Redness (a)	Yellowness (b)
Intercept	70.12	−0.062	34.03
Sugar	ns[b]	ns	0.37**[c]
Salt	0.39**	−0.18*	ns
Fiber	−0.62***	−0.33***	−2.35***
Screw speed	0.70***	−0.23**	−0.74***
Sugar × sugar	ns	ns	ns
Salt × sugar	ns	ns	ns
Salt × salt	ns	ns	ns
Fiber × sugar	−0.37*	ns	ns
Fiber × salt	−0.46**	ns	ns
Fiber × fiber	ns	ns	ns
Speed × sugar	ns	ns	ns
Speed × salt	ns	ns	ns
Speed × fiber	ns	ns	−0.41*
Speed × speed	ns	ns	−0.33**
R^2	0.82	0.53	0.95

[a] Coded.

[b] Not significant at 5% level.

[c] *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

Unexpectedly, the addition of sugar to corn meal had no appreciable effect on the lightness and redness of the extrudates. The reason is difficult to interpret and might have involved the physico-chemical characteristics of water and product temperature. Although an increase in the sugar content favored the browning reaction, an increased sugar content resulted in a reduced water activity and reduced the product temperature. Both inhibited the browning reaction. It appeared that there was a complex role of sugar in causing the browning reaction during extrusion processing.

CONCLUSIONS

The extruder torque, specific energy, and product temperature were significantly affected by sugar, fiber and screw speed, while the die pressure was affected by screw speed. Different ingredients and screw speed affected the viscous dissipation of the materials during the extrusion, which ultimately affected these extrusion system parameters.

The effects of fiber, sugar, salt, and screw speed were significant on the expansion and shape of extrudates. Changes in amounts of fiber, sugar, salt, or screw speed resulted in changes in the mass temperature, viscous dissipation, water availability, or residence time, which governed the degree of gelatinization. As a result, their changes affected the expansion of extrudates.

The interaction effects of ingredients, specifically those between sugar and fiber, were also significant on the expansion of extrudates. Sugar and fiber had an opposite effect on the product temperature, which was related to the expansion of the extrudate. The overall effect of adding fiber and sugar on the expansion was dependent on the ratio of their additions.

The colors of extrudates were mainly influenced by the initial color of the fiber and screw speed, whereas the effects of salt were not significant on the extrusion parameters.

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