

Oil Absorption Characteristics of a Multigrain Extrudate During Frying: Effect of Extrusion Temperature and Screw Speed¹

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ABSTRACT

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The oil absorption characteristics of a multigrain extruded and fried snack product were studied as a function of extruder screw speed and cooking temperature using a central composite response surface methodology (RSM). The extruded product was produced using a corotating twin screw extruder, dehydrated to a uniform moisture content, and subsequently deep-fat-fried at $192 \pm 1^\circ\text{C}$ for 10–40 sec to complete expansion. Significant RSM models were developed for oil absorption and extrudate water absorption index (WAI). According to the lowest oil

model, absorption (19.9%) was obtained with an extruder screw speed of 218.6 rpm and a cooking temperature of 117.8°C . WAI reached a maximum at a screw speed of 221.9 rpm and a cooking temperature of 109°C . Oil absorption characteristics and extrudate WAI were significantly correlated ($r = -0.84$, $P = 0.0002$). The data suggest that extrusion conditions can be optimized to influence the physicochemical structures in the extrudate matrix so that oil absorption can be minimized.

The introduction of third-generation snacks that are often manufactured by frying extruded products has opened new avenues for snack food product introductions. In the manufacture of these snacks, semiprocessed extrudates, sometimes referred to as half products, are prepared in different shapes, sizes, or textures by extrusion and subsequent deep fat frying or air puffed to form a finished product (McWard 1994). A wide variety of cereal grain ingredients, including mixtures of grains, flour, and starch, can be used to produce these extruded snacks. In addition, dried half product extrudates can be stored for several months before final processing (Toft 1979).

When an extruded half product is deep-fat-fried, oil absorption and linear expansion are primarily influenced by frying time, oil temperature, and initial half product moisture (Nair et al 1996). It has also been suggested that extrudate characteristics such as oil absorption and expansion during frying may be influenced by extrusion conditions (Meuser et al 1982, Van Lengerich 1990). Empirical evidence has suggested that at constant initial moisture, oil absorption during frying of extruded half products may be influenced by extrusion screw speed, screw configuration, and extruder barrel temperature (G. R. Huber, *personal communication*).

The present study was designed to investigate the effect of two extrusion variables, screw speed and extrusion temperature, on oil absorption characteristics of a deep-fat-fried extrudate, when other process variables such as extrudate moisture and frying conditions are held constant. A multigrain snack product was formulated and extruded using a pilot-scale twin-screw extruder, dehydrated to a uniform moisture in a continuous drier, and deep-fat-fried to form a crispy product. Response surface methodology (RSM) was used to study the effect of screw speed and extrusion temperature on oil absorption characteristics. RSM was also used to establish the optimum screw speed and cooking temperatures at which oil absorption was minimized.

MATERIALS AND METHODS

Product Formulation

A multigrain formulation was developed to produce the extrusion formed and fried product (Table I). All the ingredients were mixed for ≈ 15 min in a ribbon blender (model 61001-000, Wenger Mfg., Inc., Sabetha KS) before feeding in the preconditioner. A distilled monoglyceride extract (Myvaplex, Eastman Kodak Co.) was added as a processing aid.

Extruder Configuration

A corotating pilot-scale twin-screw extruder with a preconditioner and volumetric bin feeder (Wenger TX-52 extruder) was used to produce the multigrain half product. The premixed ingredients were fed into the volumetric bin feeder. A nine-head extruder barrel was used. The barrel was configured into three zones on the basis of the screw configuration. Heads 1–3 formed the feed zone containing a pair of wide-flighted screws to facilitate raw material entry into the barrel. Heads 4–6 formed the cooking zone containing three pairs of reverse shear locks. Each lock was made of three segments designed to impart shear during conveying of ingredients. Positioned between the shear locks were conveying screws designed for moving the extrudate forward. Heads 7–9 formed the final, forming zone containing conveying screws and a pair of conical screws at the end. Cooking-zone heads (4–6) were set at the desired extrusion temperature. At the middle of the head 6, a vacuum venting apparatus was attached to release steam, thereby cooling the extrudate and reducing the head and die pressures. The last three heads (7–9) were actively cooled, forming heads. Head temperature range was 61 – 107°C , depending on cooking-zone temperatures and screw speeds.

TABLE I
Ingredients, Formulation Percentage and Materials Vendors
of the Multigrain Product

Ingredients	% of Formulation ^a
Degermed corn flour CCF 600 (Lauhoff Grain Co.)	40
Whole wheat flour (ConAgra Grain Products)	20
Wheat bran (ConAgra Grain Products)	10
Rice flour 7598 1584JA1 (Rice Land)	13.25
Sugar-extra fine granulated sugar (Domino)	6
Oat flour Lab 16 (National Oats)	10
Myvaplex (Eastman Kodak)	0.75

^a As-is weight basis.

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The die design was largely proprietary, consisting of five large die inserts. Each die insert had three 0.06-cm wide and 3.8-cm long double-S-shaped slits (two letter S's connected top to bottom). An air-powered knife assembly was used to cut the extruded mass. Extrudate was pneumatically conveyed to a gas-fired double-pass drier (Wenger model 42001-000) for subsequent drying. All the extrudates were dehydrated to $10 \pm 0.5\%$ moisture for storage and deep fat frying.

Snack Preparation: Operational Parameters

Mass flow rate of raw material conveyed to the preconditioner was set at ≈ 1 kg/min by adjusting the feed screw speed to 12 rpm. Water and steam input to the preconditioner was set at 9.6 and 23.0 kg/hr, respectively. Mass flow output from the preconditioner was estimated to be ≈ 1.29 kg/min.

Inflow of steam and water to the extruder was set at 6 and 6.2 kg/hr, respectively. Extruder screw speed and cooking zone temperature (temperature of barrel heads 4–6) were set for each experimental trial as outlined in the experimental design (Table II). For drying the extrudate, oven temperature was set at 71°C. The top and bottom conveyor retention times in the drier were 5 and 25 min, respectively. The extruder was allowed to run at a steady thermal state for ≈ 10 min before sample collection. Approximately 11 kg of dried extrudate per trial was collected. The collected samples were stored in covered 121-L plastic drums lined with plastic liners for analysis and frying.

A 6-L kitchen kettle fryer (model 0600003, Presto, Eau Claire, WI) containing partially hydrogenated soybean oil (FryMax, Procter and Gamble, Cincinnati, OH) was used for frying the product. The extrudate was fried at $192 \pm 1^\circ\text{C}$ for 10–40 sec for optimum cooking and expansion. The extrudate was considered optimally cooked when it had fully expanded in the fryer. Oil temperature was controlled by an oil-immersed thermocouple connected to a temperature controller (Thermoelectric 100, Japan) to within 1°C of the set temperature at 192°C .

Raw Material, Extrudate, and Fried Product Characterization

Raw ingredient and preconditioned material moistures were determined by Approved Method 44-19 (AACC 1995). Bulk densities of the ingredient mixture and extrudate were determined by weighing material collected in a volume of $2.83 \times 10^{-3} \text{ m}^3$. Extrudate proximate compositional analyses were conducted for fat (Approved Method 30-10), ash (Approved Method 46-08), protein (Approved Method 46-08), dietary fiber (Total Dietary Fiber Kit, Megazyme, Warriewood, Australia), and moisture (Approved Method 44-19). Length, width, and thickness of the extrudate and fried product were measured (average of 20 measure-

ments for each trial) using a digital micrometer. Water absorption index (WAI) and water solubility index (WSI) of extrudate was determined as outlined by Anderson et al (1969). Oil absorption during frying was determined by estimating the increase in extrudate (chip) fat content after frying (Approved Method 30-10).

Experimental Design and Statistical Analysis

A rotatable central composite RSM with two factors and five levels was generated using SAS response surface regression procedures (Statistical Analysis Software, version 6.08, SAS Institute, Inc. Cary, NC). Screw speeds and extruder barrel temperatures (temperatures in the three cooking zones at heads 4–6) were the two independent variables. The design consisted of a total of 14 experiments with four star points, four axial points, and six central points (Table II). RSM graphs were generated for response variables that exhibited significant models with high correlations. All the experiments and analyses were conducted in triplicate. Mean values with coefficient of variation (CV) are reported.

A random number table was used to randomize the frying order of the extruded samples. A 20-g sample from each treatment was fried. Four replicates of the frying test were performed. Each frying session was designated as a separate block (to give a total of four blocks). Each block consisted of one fried sample from each of the 14 extrusion treatments.

RESULTS AND DISCUSSION

Snack Production

The ingredient mixture had an average moisture content of 9.7% (CV 1.6%), protein content of 9.23% (CV 0.7%) and an ash content of 1.10% (CV 2.4%). The preconditioned ingredient mixture had 29.8% (CV 2.4%) moisture. From the mass flow and moisture input data collected from the preconditioner, it was calculated that water vapor loss during preconditioning was ≈ 15 kg/hr. The average moisture content of the chip pellets exiting the extruder die was 33.9% (CV 4.7%). The average extrudate mass flow rate, measured by weighing pellets that were extruded in 1 min, was 86.5 kg/hr. Although screw speed was varied in 14 experimental trials, there was no significant difference in the extrudate mass flow rate between treatments. ($P = 0.428$). Three replicate weights were obtained for the 14 treatments.

Extrudate Characteristics

There was no significant statistical difference ($P < 0.05$) between sizes and thickness of extrudate produced in the 14 experimental trials. Extrudate had a rectangular corrugated chiplike shape, with average dimensions of 37.6 (CV 2.5%) by 31.1 mm (CV 4.0%). The average thickness was measured at 0.8 mm (CV 10.7%). The dried extrudate in all the trials appeared semitranslucent with specks of opaque bran pieces.

Moisture, fat, protein, ash contents and bulk density of extrudate did not exhibit significant regression models with process parameters, indicating that extrudate composition and bulk density were independent of screw speed and extrusion temperature. Extrudate bulk density did not change with processing variables because, due to pressure venting, the extruder primarily cooked and formed the product without significant expansion.

Extrudate WAI exhibited a significant second-order quadratic regression model ($P = 0.0105$, $R^2 = 0.74$, lack of fit = 0.18) with process variables (Fig. 1). WAI reached a maximum value of 7.2 with a barrel temperature of 109°C and a screw speed of 221.9 rpm. Harper (1979) observed that WAI reached a maximum value before gradually decreasing as the extruder cooking temperature was continuously increased. When extruding pinto and navy bean flour, Gujska and Khan (1990) noted a significant increase in WAI as the barrel temperature was increased from 110 to 132°C ($P < 0.05$). However, a further increase in temperature to 150°C ,

TABLE II
Experimental Points Used to Model Response Variables^a

Experimental Points	Extrusion Temperature (°C)	Screw Speed (rpm)	Run Order
Corner points	85	140	5
	85	270	4
	155	140	1
	155	270	6
Center points	120	205	2
			3
			7
			8
			9
Axial points	71	205	13
	170	205	12
	120	113	11
	120	297	10

^a Extrusion temperature (setting for heads 4–6) and screw speed were the two independent factors, levels used are indicated. Samples were randomized and run in the order indicated.

resulted in a decline of WAI. Gujska and Khan (1991) concluded that besides starch gelatinization, protein denaturation and swelling of fiber during extrusion contributed to increase in WAI. However, no specific explanation was given for the phenomenon.

The initial increase in extrudate WAI with increases in barrel temperature and screw speed can be attributed to an increase in starch gelatinization concomitant with increasing energy input. However, it appears that further increases in barrel temperatures and screw speeds created harsh enough conditions for complete starch gelatinization that decreased the WAI value.

Partial starch depolymerization has been reported to occur during extrusion under harsh conditions that decreases the WAI values (Chinnaswamy and Hanna 1990, Rodis et al 1993). HPSEC of the extrudates starch polymers (data not shown) and WSI values did not conclusively indicate starch depolymerization in our samples. It appears that the presence of extrusion-lubricating and amylose-complexing monoglyceride (Myvaplex) in the formulation may have prevented extensive depolymerization, complicating the interpretation of the HPSEC profiles.

Colonna et al (1989) observed that the compact starch structures formed during extrusion restrict water accessibility into the matrix, resulting in low WAI. Under excessive harsh extrusion conditions of high barrel temperatures and high screw speed, decrease in WAI can be attributed to formation of such compact starch structures that limit water penetration. We could not, however, observe any significant correlation ($P < 0.05$) between extrudate bulk density and WSI.

Oil Absorption Characteristics of Extrudate

Deep fat frying of the multigrain extrudate at $192 \pm 1^\circ\text{C}$ for 10–40 sec results in $\approx 10\times$ expansion in volume and an oil absorption of 20–35%. Percent oil absorption exhibited a significant quadratic model ($P = 0.0001$, $R^2 = 0.82$, lack of fit = 0.77) with process variables, indicating that extruder screw speed and barrel temperature significantly influenced oil absorption characteristics. The RSM equation (Fig. 2) indicates that the multigrain product would absorb the least amount of oil (19.9%) when processed at 117.8°C with extruder screw speed of 218.6 rpm. This point of minimum oil absorption was considered the stationary point of the RSM. Extruder barrel temperatures or screw speed above and below the stationary point increased oil absorption, indicating that the extrusion process can be optimized for minimizing oil absorption. A strong inverse relationship was observed ($r = -0.84$, $P = 0.0002$) between the degree of oil absorption during frying and extrudate WAI, which is evident when comparing Figs. 1 and 2.

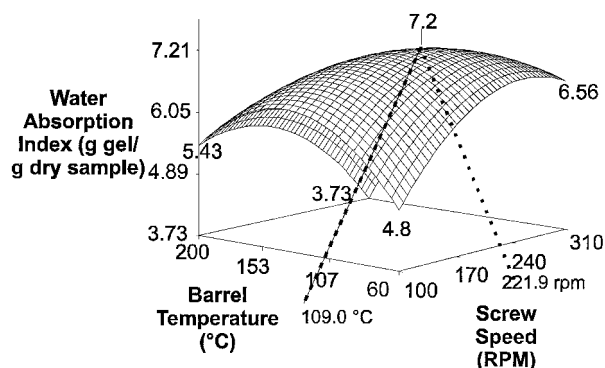


Fig. 1. Second-order response surface methodology (RSM) indicating effects of screw speed and extruder cooking zone barrel temperature on the water absorption index of multigrain product. Dotted lines indicate the parameters that give maximum water absorption index (7.2). Model was drawn based on the equation: $Y = -2.177862 + (0.07848 \times \text{temp}) + (0.045945 \times \text{rpm}) - [0.00024 \times (\text{temp} \times \text{temp})] - [0.000117 \times (\text{rpm} \times \text{rpm})] - [0.00007469 \times (\text{rpm} \times \text{temp})]$. $R^2 = 0.74$ ($P = 0.0284$).

It is generally observed that oil absorption during deep fat frying is essentially a quantitative water replacement process where higher initial moisture results in greater oil absorption during frying. Such a relationship has been demonstrated in extrusion-formed, deep-fat-fried tapioca chips (Nair et al 1996) and in tortilla chips (Moreira et al 1997). Gamble et al (1987), using a staining procedure, has demonstrated that oil uptake by a fried snack occurs primarily in areas that exhibit moisture loss. In this study, although all the extrudate formed in the 14 experimental trials was dehydrated to a constant initial moisture content before frying, oil absorption varied significantly, suggesting that extrusion variables critically influence oil absorption.

Colonna et al (1989) observed that a decrease in WAI of extrudates can be attributed to formation of compact starch structures that limit water penetration. However, in our study, samples with low WAI exhibited high oil absorption, suggesting that the same compact starch structures that resisted water absorption did not resist oil absorption.

Gomez and Aguilera (1983) observed that high WAI in gelatinized corn starch implies a greater number of available hydrophilic groups that could bind to the water molecules. As WAI was negatively related to oil absorption, we suggest that extent of oil absorption may be governed by the number of available hydrophilic groups (more hydrophilic groups resulting in less oil absorption) rather than initial moisture. It may also be suggested that oil absorption may not be a simple quantitative water replacement process.

CONCLUSION

RSM can be successfully used to optimize the oil absorption characteristics of an extruded multigrain snack product. Under uniform frying conditions, oil absorption characteristics of the extrudate dried to constant final moisture were primarily influenced by extruder barrel temperature and screw speed. It appears that the extrusion conditions may determine the number of free hydrophilic groups formed as a result of physical and chemical associations between molecules forming the extrudate matrix and influence its oil absorption characteristics.

WAI is an indicator of the water binding capacity of starch associated with starch gelatinization. Higher WAI may correspond to well-formed structurally coherent product matrices and an increased availability of hydrophilic groups in the starch molecules. Because WAI was inversely correlated with oil absorption, the number of free hydrophilic sites may influence the extent of oil absorption on frying. Commercially available multigrain extruded

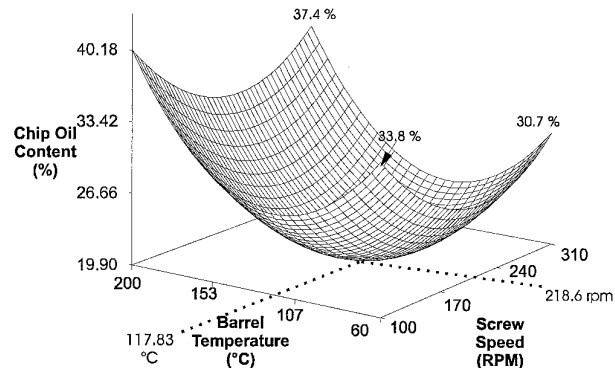


Fig. 2. Second-order response surface methodology (RSM) indicating effects of screw speed and extruder cooking zone barrel temperature on % of oil absorbed by deep-fat-fried multigrain product. Dotted lines indicate parameters that give minimum oil absorption (19.9%). Model was drawn based on the equation: $Y = 71.942723 - (0.457587 \times \text{temp}) - (0.229479 \times \text{rpm}) + [0.001932 \times (\text{temp} \times \text{temp})] + [0.000010273 \times (\text{rpm} \times \text{rpm})] + [0.000522 \times (\text{rpm} \times \text{temp})]$. $R^2 = 0.82$ ($P = 0.0006$).

snack products usually contain \approx 21.4% oil (based on nutritional label data). It appears possible to reduce the oil content of such products by optimizing the extrusion process.

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