Extrusion Research for Addressing the Obesity Challenge[1]

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Extrusion is an important technology for processing grain-based products and adds immense value to raw materials ranging from corn, wheat, and rice to sorghum, oats, and soybeans. These raw materials can be in the form of whole-grain flours, dehulled flours, starches, concentrated or isolated cereal and legume proteins, or bran. Extrusion has been used for industrial applications such as rubber and plastics since the late 19th century and has been applied to food products since the 1930s. This technology has gained widespread use in the food industry because of its several benefits, including its economics and versatility. Today extruded products comprise a multibillion dollar market in the United States alone. These products include foods such as breakfast cereals, savory snacks, pastas, confectioneries, and texturized vegetable proteins, as well as products for animal consumption such as pet foods and aquatic feeds.

- Innovations in extrusion can be used to improve the health benefits of cereal-based food products.
- Addition of high-fiber pomaces from fruits and vegetables to extruded products increases nutritional value and addresses dietary shortfalls.
- Sensory analyses highlight challenges and opportunities for extruded products as acceptable carriers of nutrition.

As a multifaceted continuous-processing technology, extrusion has several advantages over conventional batch-processing methods. Unlike batch processing, where several pieces of equipment might be needed to make the final product, the same extrusion equipment performs several functions, including mixing and unitizing ingredients, cooking, forming the product into the desired shape, expansion, texture alteration, sterilization, and dehydration (due to steam flash-off). By altering the processing conditions, screw profile, or die and using different ingredients, a wide variety of products can be processed by the same equipment. There also is better control over the process and product quality and much greater processing capacity (ranging from a few hundred kilograms to several tons per hour).

The Nutrition Shortfall

Despite the high prevalence of overweight and obesity in the United States, several food groups and, consequently, nutrients are lacking in the American diet. The report issued by the 2010 Dietary Guidelines Advisory Committee (DGAC) (20) identifies the intake of dietary fiber, vitamin D, calcium, potassium, and unsaturated fatty acids as insufficient. These are termed "shortfall nutrients." Fruits and vegetables can be good sources of dietary fiber, calcium, and potassium; however, average intake of this food group has consistently been below recommended levels. On average, consumption is <50% of the recommended intake for fruits and <60% for vegetables.

The DGAC report (20) maintains that health outcomes, such as protection against myocardial infarction and certain cancers, can be promoted by consumption of at least five daily servings of fruits and vegetables. Furthermore, the low calorie density of fruits and vegetables is an important tool in energy balance and weight management, which also provide

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various health benefits. Although the DGAC calls for minimal processing of fruits and vegetables, it also calls for the engagement of academia and industry in changing the food environment. Technological innovations in the use of fruits and vegetables may be a route for increasing consumption.

Fruits and Vegetables in Extruded Products

Increasingly, research efforts are being focused on utilization of extrusion for production of nutritious processed foods. In addition, the inherent economies of scale and process efficiencies associated with extrusion make it a highly viable technology for delivery of enhanced nutrition. The addition of fruits and vegetables to extruded snacks has been studied since the 1980s, with the first published work in 1989 by Maga and Kim. Researchers have since studied the addition of fruit juice, paste, powders, pomace, peels, and seeds to extruded products (2,4,12,21). Such additions greatly increase dietary fiber content, as well as several micronutrients and antioxidant capacity. Furthermore, starch digestibility patterns have been shown to improve with the addition of fruit and vegetable materials.

Despite the favorable nutritional impact, there is commonly a negative effect on quality parameters related to texture. Studies that include sensory analysis find that texture is the parameter with lower acceptability, while taste is usually acceptable. This is true even with the addition of pomace and other fruit and vegetable by-products (2,15,21).

The use of by-products is a growing trend. One motivation is the addition of value to food-processing residues and reduction of waste (22). Other drivers are the concentrated nutrient content of by-products (especially in terms of bioactive compounds) and growing interest in increasing the dietary fiber content of foods (13,14,16).

Despite the information available on the effects of fruits and vegetables on the quality parameters of extrudates, the mechanisms of structure formation are still poorly understood for systems containing fruit and vegetable materials. This article describes these mechanisms based on novel rheological and imaging techniques employed for characterization and analysis of corn flour and apple pomace systems. Thorough analyses and a conceptual model for such systems are presented in an upcoming publication (9).

Incorporation of Apple Pomace

Apple pomace is a by-product of the apple processing industry and consists of dried and ground peels and core. The typical composition is 1.2–10.8% moisture, 0.5–1.9% ash, 2.4–7.3% protein, 1.6–4.5% fat, and 51.1–89.8% total dietary fiber (36.5–81.6% insoluble and 4.14–14.6% soluble) (6,19). Apple pomace has a high total phenolic content and antioxidant activity, which, along with its high fiber content, is the main reason it has been extensively studied in recent years as a potential food ingredient (5,10,18,19).

Blends were formulated with degermed yellow corn flour and dried apple pomace in ratios of 100:0, 83:17, 78:22, and 72:28. These levels were chosen with the aim of delivering 15–25% of the recommended daily value for dietary fiber (25 g) in a 30-g serving. Each blend was hydrated to three different moisture levels: 17.5, 20, and 25% (wet basis). The required amount of water was added, and the material was mixed on a bench-top mixer. The hydrated blends were refrigerated and allowed to equilibrate overnight in sealed plastic bags.

Rheology of Pomace-containing Blends

The flow temperature (T_f) of the hydrated blends was determined using a phase-transition analyzer (PTA, Wenger Manufacturing, Inc., Sabetha, KS), which is useful for studying physical changes associated with glass and melt transitions in biopolymers (3,11,17). A 2-g sample was loaded in the temperature-controlled chamber of the analyzer, with a 2-mm capillary die underneath. The sample was heated at a rate of 10 degrees Celsius/min under a constant pressure of 6 MPa. T_f was determined as the temperature at which the sample started to flow through the capillary and provided a very useful insight into the flow properties of the blend under extrusion-like conditions (Fig. 1).

Pomace level (0–28%) did not have a significant impact on T_f, which ranged between 159 and 168°C, 147 and 151°C, and 124 and 130°C at hydration levels of 17.5, 20, and 25% (wet basis), respectively. The starch present in corn flour is the primary contributor to the viscosity of the melt. It was obvious that as the proportion of corn flour decreased, the decrease in the shear viscosity of the melt was compensated for by the increased resistance to flow due to higher levels of apple pomace fiber. The result was no net change in the overall resistance to flow as measured by T_f. Overall resistance to flow did decrease, however, with increasing moisture due to the plasticizing effect of the latter. These properties had a significant impact on process dynamics during extrusion of these blends (Fig. 2).

The development of a cellular matrix in expanded extrudates depends on the expansion and subsequent collapse of the bubbles in the melt, which in turn is governed by a complex balance between forces driving and resisting deformation and the

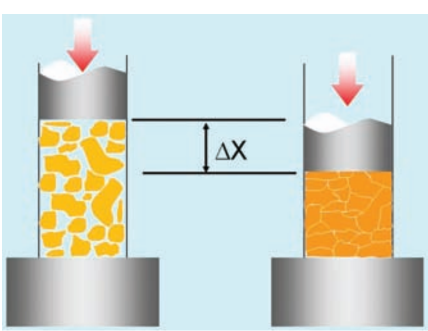

Fig. 1. Measurement of flow temperature (T_f) or temperature of initiation of flow (displacement [ΔX] beyond a set threshold) under constant compressive pressure using a phase-transition analyzer. (Schematic courtesy of Wenger Manufacturing, Sabetha, KS)

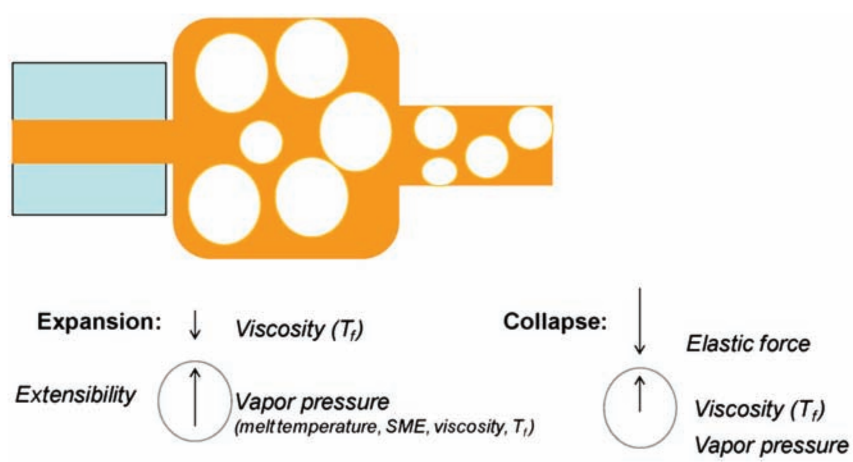

Fig. 2. Dynamics of bubble expansion and collapse during extrusion processing. T_f = flow temperature; SME = specific mechanical energy.

extensibility or film-forming ability of the melt. The water vapor pressure inside nucleated bubbles is the driving force for expansion, which in turn is a function of the melt temperature. The latter is mainly impacted by the specific mechanical energy (SME) input during the extrusion process, which depends on the resistance to flow or T_f of the melt. The experimental data verified this relationship, since higher in-barrel moisture led to a decrease in SME, but apple pomace level did not have a significant impact, which was in keeping with the trends observed for T_f. At the same time, flow temperature also represents the primary resistance to both expansion and collapse, but this cancels out in the net impact on expansion. Based on these findings, T_f has a dominant role in the overall process dynamics and, in general, should correlate well with measures of expansion such as piece density and void fraction, as long as the extensibility of the melt is not impacted. This was verified by the experimental results discussed below.

Extrusion of Corn Flour/Apple Pomace Blends

Lab-scale extrusion was used in a model study for understanding the impact of pomace on corn-based extrudates in terms of process dynamics, structure formation, and mechanical properties. Analysis of the cellular structure in combination with macro-level structural and mechanical properties was used to gain insight into micro-level mechanical properties. Hydrated blends of corn flour and apple pomace were extruded using a twin-screw extruder (Micro-18, American Leistritz Extruder Corp., Somerville, NJ) with a barrel diameter of 18 mm and L/D ratio of 29.3. A circular die with a diameter of 3.1 mm was used. The feed rate was ≈2 kg/hr, and the screw speed was 350 rpm for all treatments. Extrudates were dried in a convection oven (Fig. 3).

Figure 3 clearly shows that radial expansion of extrudates was reduced as apple pomace content increased. This trend was observed irrespective of the in-barrel moisture. However, apple pomace level did not have a significant impact on the piece density of the extrudates ($P = 0.09$), which is an indirect measure of overall or volumetric expansion. Piece density did increase significantly with in-barrel moisture ($P < 0.0001$), which was consistent with T_f data and the earlier discussion on process dynamics. The only mechanism by which the observations for radial expansion and piece density can be reconciled is by postulating an increase in longitudinal expansion of the extrudates with an increase in apple pomace. This is a common observation in extrudates with high levels of fiber and was verified in our study by specific length (m/kg) measurements. Thus, as the level of apple pomace increased, overall expansion did not change, but the extrudate expanded less in the radial direction and more in the direction of extrusion. Noninvasive X-ray microtomography images of transverse cross-sections of extrudates bear this out (Fig. 4).

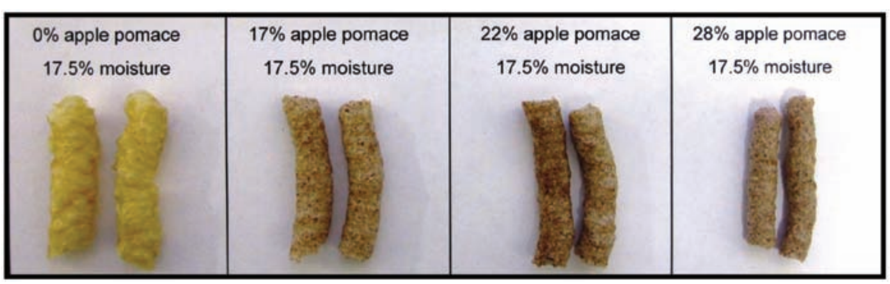

Fig. 3. Expanded corn-flour extrudates (17.5% [wet basis] in-barrel moisture) with different levels of apple pomace. The same formulations were also processed at 20 and 25% (wet basis) in-barrel moisture levels.

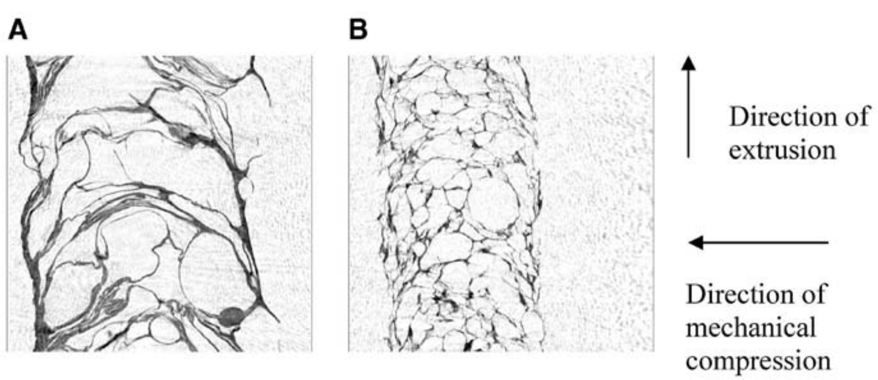

Fig. 4. Noninvasive X-ray microtomography images of transverse sections of corn-flour extrudates processed at 17% (wet basis) in-barrel moisture: **A,** no apple pomace, and **B,** 28% apple pomace.

It is clear from Figure 4 that cellular anisotropy in the radial direction was very high for extrudates with no apple pomace. Radial expansion in general was favored because of elastic recovery forces. This anisotropy almost vanished in the presence of apple pomace, leading to lower radial expansion and increased axial expansion from a macroscopic point of view. The latter was a result of a dramatic increase in the number of nucleation sites due to the discontinuities in the melt introduced by the pomace particles. The insoluble fiber component of the pomace (cellulose, lignin, and some hemicelluloses) was incompatible with starch and existed in a dispersed phase. These particles probably were aligned longitudinally due to the shear field in the extruder die and hindered radial extensibility and expansion, which would be against the grain or orientation of the fibers and would cause the rupture of air cells.

Compression tests in the transverse direction (perpendicular to the direction of extrusion) using a texture analyzer (TA-XT2, Stable Micro Systems, Godalming, U.K.) revealed quantitative data on a common drawback of fiber incorporation in expanded cellular matrices. Average crushing stress significantly increased with an increase in apple pomace ($P < 0.0001$) and also in-barrel moisture ($P = 0.0046$). It was obvious that mechanical strength was inversely related to the cell wall length in the radial or transverse direction. Further analysis led to the conclusion that the strength of the cell wall material also increased with apple pomace levels. This is in accordance with the accepted theory for mechanical properties of brittle cellular foams (1,7):

$$\frac{E}{E_s} \propto \frac{t_{\text{wall}}}{l}$$

where E is the mechanical property of the cellular foam, E_s is the corresponding cell wall mechanical property, l is the cell wall length, and t_{wall} is the cell wall thickness. It can be inferred from the above equation that lower l and higher E_s would lead to an increase in crushing stress. All of this translates nicely into the real-life sensory perception of expanded snacks loaded with pomace as described below.

Sensory Perception of Corn Flour/Apple Pomace Snacks

The extrusion study was scaled up to a pilot-scale system consisting of a twin-screw extruder (TX-52, Wenger Manufacturing) and a dual-pass dryer (Series 4800, Wenger Manufacturing). The extruder screw diameter was 52 mm, with an L/D ratio of 16. The screw speed was fixed at 300 rpm for all treatments. The ingredients used were yellow degermed cornmeal and dried apple pomace. Two blends were prepared with cornmeal/apple pomace ratios of 73:17 and 68:22, with the balance composed of 10% pregelatinized cornstarch. Material was fed into the extruder at 80 kg/hr using a gravimetric system. A one-opening, 3.7-mm circular die was used. Product was cut at the die exit using a face-cutting rotary knife and dried at 115°C for 18 min, followed by a 7-min cooling step. Samples were coated with a proprietary cheddar cheese-based flavor. Although obtained from the same source, pomace composition was different in this case than the one used in the lab-scale study. The treatments with 17 and 28% apple pomace corresponded to 10 and 13% of the daily value for fiber, respectively.

Participants in the sensory evaluation were recruited from among seventh graders enrolled in middle schools in Manhattan, KS. This was part of an ongoing larger engagement project with middle-school children involving faculty and students from the Departments of Grain Science, Human Nutrition, and Journalism & Mass Communication at Kansas State University (see YouTube video: K-State Healthy Snack Products for Children). The total number of participants was 130. Participants were given the two apple pomace-based product samples, along with commercial snacks purchased from a local grocery store. The latter were two "healthy" snacks, i.e., low-fat salted popcorn and baked potato chips, and two "unhealthy" snacks, i.e., regular potato chips and cheese-flavored corn puffs. Based on the standards recommended by the Institute of Medicine for competitive foods in schools (8), a "healthy" snack was defined by the following criteria: <35% of total calories from fat or sugar, <200 mg of sodium, and <200 kcal per portion. Overall liking was assessed using a 7-point hedonic scale. The terms used for the scale were chosen to relate to terms commonly used by the age group. A check-all-that-apply (CATA) scale was used to identify specific descriptors: smells good, smells bad, puffy, hard/tough to bite, crispy, gritty, chewy, salty, cheesy, bitter, sour, tastes good, tastes bad, and sticks to my teeth. The results are summarized in Table I.

Table I. Middle-school study on acceptability of snacks using a 7-point hedonic scale

Sample Snack	Overall Liking
Cheese-flavored corn puff	5.74
Regular potato chip	5.26
Popcorn	5.02
Baked potato chip	4.87
Apple pomace snack:	
High-fiber, cheddar flavor	4.78
Apple pomace snack:	
Low-fiber, cheddar flavor	4.76

The cheese-flavored commercial corn puff had the highest acceptability among all snacks. The least liked commercial snacks were the healthy products—baked potato chips and low-fat salted popcorn. The experimental apple snacks were close to the healthy commercial snacks in overall acceptance scores. Principal components analysis of the CATA data revealed that the less preferred experimental samples were related to the term "hard." This was in accordance with the higher crushing force data recorded in the experiment. Other terms associated with low preference were gritty, bitter, sour, tastes bad, and smells bad. An intriguing aspect of the data was the lack of difference in acceptability of the low- and high-fiber apple pomace snacks. These data serve to highlight the challenges and opportunities for such products as acceptable carriers of nutrition.

Conclusions

Extrusion is a widely used technology for processing ready-to-eat snack and breakfast cereal products. Ingredients with high levels of starch contribute to optimal texture and consumer acceptance but, at the same time, limit the nutritional value of these products. One alternative for addressing this shortcoming is the incorporation of high-fiber pomaces from fruits and vegetables. This study presented an analysis of the process dynamics, mechanisms of structure formation, and structure-texture relationships in such products based on a corn/apple pomace system. Macrostructural properties and cellular architecture were largely determined by the phase-transition and extensional properties of the high-fiber melt. Inclusion of pomace increased nucleation and favored axial expansion. Cellular anisotropy and cell size explained the higher mechanical strength observed with pomace. A sensory study measuring acceptance by school children had encouraging results. Technical challenges exist with regard to commercialization of such products, but there are opportunities available. Increased awareness among consumers of the benefits of such products and gradual familiarization might help in bridging this gap. This is the focus of an ongoing middle-school project. Various other facets of such food systems need to be explored further, including the impact of individual carbohydrate components and the relationship between cellular architecture and digestibility. This is part of ongoing investigations by our research group.

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