Pet Food Processing—Understanding Transformations in Starch during Extrusion and Baking

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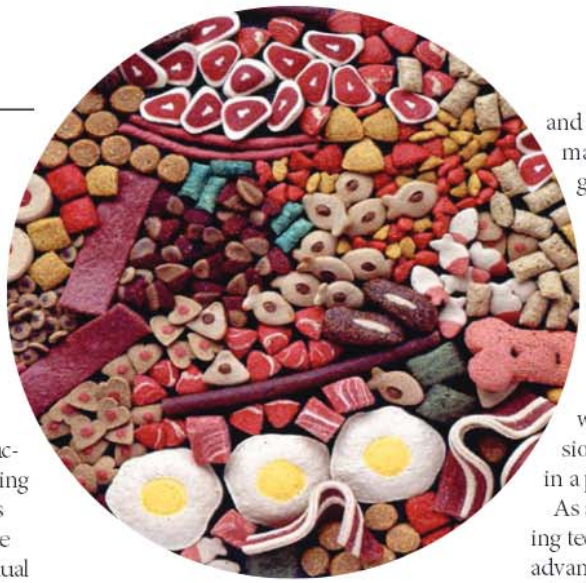

According to the American Pet Products Association, there are ≈73 million U.S. households that contain at least one pet. The pet food industry must continually innovate to meet the ever-changing demands of consumers. Due to the success of the pet food industry in meeting consumer demands, the industry has experienced constant growth over the past 10 years. It is estimated that annual pet food sales will grow to $21.26 billion in the United States in 2013 (1).

Pet foods differ from human foods in that a pet is usually fed only one type of food that must satisfy all of its daily nutritional requirements, including carbohydrates, protein, fat, and micronutrients. To meet these nutritional requirements, a multitude of ingredients are utilized in any given product. Ingredients range from cereal grains (e.g., corn, rice, and wheat) and meat products (fresh meat, as well as rendered and dried products or meals) to fat sources (e.g., chicken fat and beef tallow) and micro-ingredients (e.g., vitamins and minerals). All of these ingredients are combined and processed to make a very complex food matrix. Most pet food research focuses on nutrition and palatability. The interactions of ingredients during various processing steps have not been explored in-depth in the context of pet food production.

Processing Technologies

Most pet food products can be divided into three broad categories based on moisture content: dry, semiwet or soft-moist, and canned. Dry pet food is typically processed either by baking or extrusion. Both of these methods are also commonly used for processing human foods. Extrusion has been used in industrial applications such as rubber, plastics, and metal parts since the 19th century and was first applied to food products in the 1930s. This technology has gained widespread use in the food processing industry because of several benefits, including economy and versatility. Today, extruded products comprise a multibillion dollar market in the United States alone and include human foods such as breakfast cereals, snacks, pastas, confectionery, and texturized vegetable proteins and products for animal consumption such as pet foods and aquatic feeds. Food extrusion is a cooking, forming, and often a puffing process that adds immense value to a variety of materials, especially grains such as corn, wheat, rice, sorghum, and oats and soybeans (6). Grain-based raw materials can be in the form of whole grain flours or coarser meals, dehulled, degermed, and defatted flours; starches; concentrated or isolated cereal and legume proteins; and sources of fiber such as bran. In the case of pet foods, other materials such as fat and meat can be easily processed in combination with grain ingredients using extrusion. Fat and palatants often are added in a postextrusion coating step.

As a multifaceted continuous processing technology, extrusion has several advantages over conventional batch methods. Unlike batch processing, in which several pieces of equipment may be needed to make the final product, a single extruder performs several functions, including mixing and unitizing ingredients, kneading, cooking, forming the product to the desired shape, expansion, texture alteration, sterilization, and dehydration (due to flash-off of water vapor at the die). In addition, a wide variety of products can be processed using the same equipment by simply altering the processing conditions, screw profile, or die and using different combinations of ingredients. There is also better control over the process and product quality and much greater production capacity or throughput (up to several tons per hour).

Baking is another process widely utilized for production of dry pet food kibbles. We are all familiar with the use of baking for making products such as breads or chocolate chip cookies in the

Table I. Experimental dog food formulations (0–20% fresh meat)

	% in Formulation		
Components	**0% Fresh Meat**	**10% Fresh Meat**	**20% Fresh Meat**
Mechanically deboned frozen chicken	–	10.00	20.00
Chicken by-product meal	20.94	14.42	10.91
Chicken fat	5.32	4.04	2.34
Major ingredients (brewers rice, corn, etc.)	70.63	68.23	63.52
Minor ingredients (vitamins, minerals, etc.)	3.11	3.32	3.25

Photo courtesy of Wenger Manufacturing

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home setting. Industrial-scale baking of pet food is not much different. All dry ingredients are weighed in batches and transferred to a mixer. Because pet food formulations also require substantial proportions of fat and meat, these ingredients are added to the mixer and allowed to homogenize for a few minutes. After mixing, the pet food mash is brought up to around 35% moisture on a wet basis with the addition of water, and the material is kneaded to a dough or paste-like consistency. The dough is then sheeted, cut, and formed into the desired shapes. In industrial settings, this set of operations is performed using a rotary molder. During rotary molding, the pet food dough is pressed into a die with the desired shape and depth. The shaped kibbles pass through a tunnel oven with temperature settings ranging from 350 to 450°F for 7–15 min or until the kibbles have reached a shelf-stable moisture content. The baked kibbles are allowed to cool to room temperature and packaged. Due to the nature of the baking process, it is a much lower throughput process compared with extrusion processing. Although there are obvious fundamental differences between extrusion and baking processes for making dry pet food kibble, scant scientific data are available in the literature that quantify these differences or draw contrasts between the transformations and properties of the final products.

Impact of Processing on Starch

Starch is an important part of a typical dry pet food formulation and undergoes several important changes during processing that impact the digestibility, palatability, and physical attributes of the final product. A study was designed to examine transformations in starch during pet food processing using extrusion and baking. Three dog food formulations based on an adult maintenance diet were used in the experiments (Table I). The three formulations were isonutritional with regard to carbohydrate, lipid, protein, and sodium content. They differed from each other with respect to the addition of fresh meat (0, 10, or 20% mechanically deboned chicken), chicken by-product meal, and chicken fat. Each formulation was extruded using a pilot-scale single-screw extruder (X-20, Wenger Manufacturing, Sabetha, KS) (Fig. 1) at two screw speeds (353 and 453 rpm). A typical screw configuration for producing dry, expanded kibble was used (Fig. 2). A 30 ft experimental baking oven set at 425°F was used to produce dry kibble from the three formulations. Proximate analysis confirmed the kibbles obtained after baking or extrusion were isonutritional at the meat inclusion levels tested.

Fig. 1. Pilot-scale single-screw extruder (Wenger model X-20).

Differential Scanning Calorimetry

As mentioned above, pet food formulations are much more complex than human food formulations and so are the interactions between the various components and physicochemical transformations that take place during processing. It is important to understand these interactions and changes, and one useful and sensitive tool for studying these interactions is differential scanning calorimetry (DSC) (Fig. 3). This technique is commonly used in cereal and polymer science and can detect and quantify both reversible and irreversible thermal events, including state changes (e.g., melting), phase changes (e.g., glass transition), starch gelatinization, protein denaturation, and interactions between biomolecules. Comparison of DSC data corresponding to a control or unprocessed sample with any given treatment can yield information on processing effects. The basic principle in DSC involves subjecting a specified, carefully weighed sample (usually a few milligrams) in a sealed pan to temperature ramping at a constant rate. In the case of biopolymer samples, a suitable amount of water is usually added to facilitate component transformations and interactions. Heat flow into or out of the sample pan is monitored using sensors. Heat flow data are typically plotted against temperature in a DSC thermogram. These thermograms are analyzed using software to yield information such as melting point,

Fig. 3. Differential scanning calorimeter.

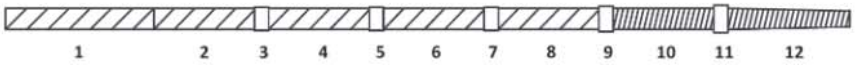

Fig. 2. Extruder screw profile:1 = inlet screw, single flight; 2 = single pitch, single flight, uncut; 3 = small shear lock; 4 = single pitch, single flight, uncut; 5 = small shear lock; 6 = single pitch, single flight, uncut; 7 = small shear lock; 8 = single pitch, single flight, uncut; 9 = medium shear lock; 10 = half pitch, double flight, uncut; 11 = large shear lock; 12 = half-pitch cone, double flight, uncut.

Table II. Differential scanning calorimetry gelatinization data (average ± SD)

Treatment	Peak Temperature(°C)	Enthalpy of Gelatinization (J/g)	Degree of Gelatinization (%)
0% Fresh meat			
Raw	79.2 ± 0.3	3.1 ± 0.1	0.0 ± 0.0
Baked	79.7 ± 1.7	1.7 ± 0.6	45.4 ± 15.8
Extruded	–	0.0 ± 0.0	100.0 ± 0.0
10% Fresh meat			
Raw	78.5 ± 0.8	3.0 ± 0.0	0.0 ± 0.0
Baked	75.6 ± 9.2	2.0 ± 0.1	32.3 ± 1.7
Extruded	–	0.0 ± 0.0	100.0 ± 0.0
20% Fresh meat			
Raw	79.1 ± 0.3	2.2 ± 0.0	0.0 ± 0.0
Baked	79.9 ± 0.9	1.3 ± 0.2	38.0 ± 8.3
Extruded	–	0.0 ± 0.0	100.0 ± 0.0

Table III. Glucoamylase test results for three pet food formulations and processing treatments

Treatment	Degree of Gelatinization (%)		
	0% Fresh Meat	10% Fresh Meat	20% Fresh Meat
Baked	57.00 ± 3.67	57.02 ± 2.81	55.39 ± 0.39
Extruded at 353 rpm	98.88 ± 0.92	94.77 ± 3.31	93.46 ± 6.55
Extruded at 453 rpm	98.14 ± 4.85	98.40 ± 4.55	93.50 ± 2.36

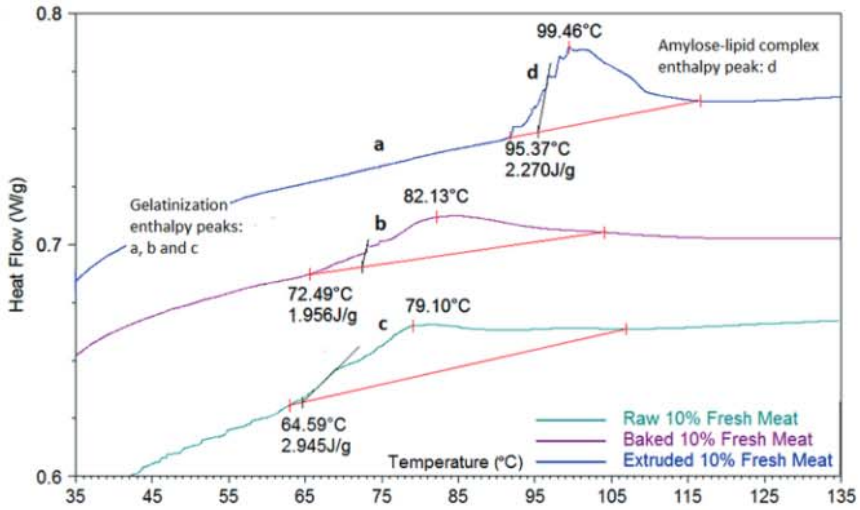

Fig. 4. Differential scanning calorimetry thermograms for a raw pet food formulation and corresponding baked and extruded dry pet food products. Quantitative data extracted from the thermograms relate to the particular test and are not averages.

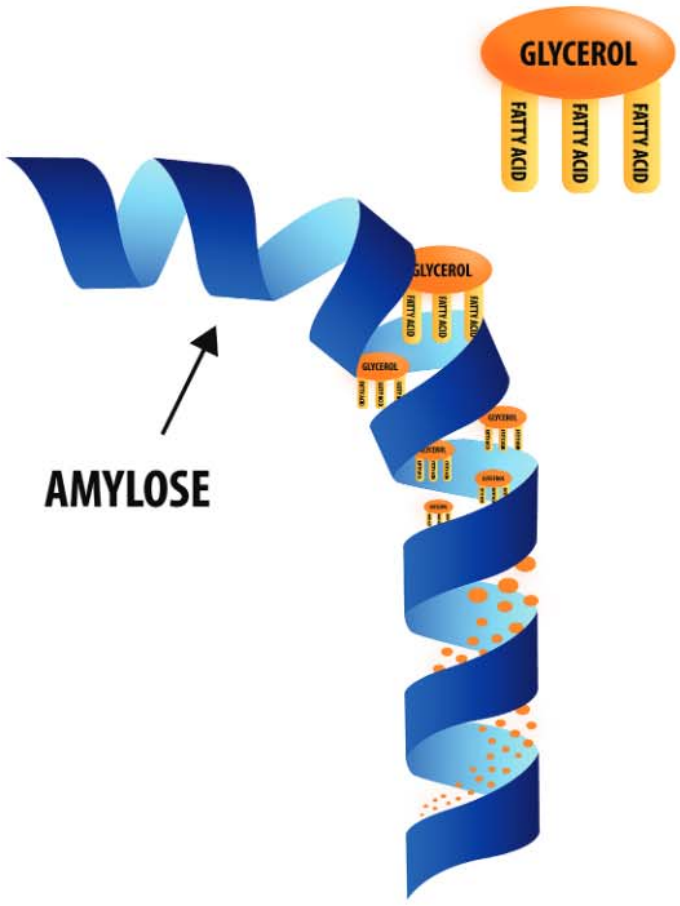

Fig. 5. Schematic depiction of amylose-lipid complex formation during pet food processing.

glass transition temperature, denaturation temperature, heat of melting, and heat of denaturation.

Because starch and its interactions and transformations were the primary focus of this study, DSC was used to characterize the degree of starch gelatinization and amylose-lipid complexation in both baked and extruded products. These phenomena and their quantification are described in detail below.

Starch Gelatinization

Starch requires heat, moisture, and time to gelatinize. Gelatinization is an endothermic reaction that leads to disruption of the crystalline structure, absorption of water, swelling, and increased accessibility for digestion by enzymes such as amylase. Although gelatinization takes place over a temperature range (e.g., 70–80°C) that is dependent on the type and source of the starch, only a small proportion of the energy absorbed during the process effects temperature increase (sensible heat). The area under the endothermic peak in the DSC thermogram of a starch sample heated over a temperature range of 35 to 130°C provides an estimate of enthalpy or heat of gelatinization. The temperature range for gelatinization can also be obtained.

This test works especially well when there is a limited number of components other than starch in the sample being tested and the sample is more or less homogeneous in terms of hydration and various components. Pet food products, however, are very complex formulations that contain 20–30 different components, including multiple starch sources, meat, lipids, fiber, vitamins, and minerals. This, in turn, affects the DSC-based gelatinization data. Typical DSC thermograms for an unprocessed formulation and corresponding extruded and baked products are shown in Figure 4. The gelatinization enthalpy and temperature range for the phenomenon are labeled on the thermograms. Comparison of the gelatinization enthalpies for the raw and processed samples allows calculation of degree (or percentage) of gelatinization. Gelatinization data for all treatments in the current study are summarized in Table II and indicate complete starch gelatinization (100%) for the extruded kibble and a lower degree of gelatinization for the baked kibble (32–45%).

Other methods have also been explored to quantify this important phenomenon. One such alternate method for determi-

nation of starch gelatinization is based on enzymatic digestion. The processed pet food kibble (both extruded and baked treatments) was first ground and subjected to a chemical solubilization procedure as follows. Samples were simmered in sodium hydroxide for 20 min, and then hydrochloric acid was added to balance the pH and complete the solubilization process. The solubilized sample and corresponding nonsolubilized control were subsequently taken through an enzymatic digestion procedure using glucoamylase. Enzymatic digestion breaks down starch chains or biopolymers into the smaller constituent compound or monomer glucose. The glucose concentration obtained after enzymatic digestion is measured with a glucose analyzer, and comparison between the solubilized and nonsolubilized samples yields the degree of starch gelatinization. Table III summarizes the gelatinization data obtained from the enzymatic digestion test for all treatments, and the trends were similar to those shown by the DSC-based data. However, the standard derivations were much lower in the case of the glucoamylase test, underscoring the variability of DSC data in the case of complex formulations.

Data from both tests indicated that starch in baked pet food was only partially gelatinized or cooked, unlike starch in extruded pet food. In the case of baking, this was due to insufficient moisture (only 35% compared with a requirement of 67%) and the absence of mechanisms other than heat for breaking down the compact structure of the starch. In extrusion, the mechanical energy or shearing action in combination with high pressure (≈300–400 psi) can offset the lack of sufficient moisture. The gelatinization data also leads to the intriguing question of whether complete cooking is nutritionally nonessential in the case of pet food or even detrimental. This is discussed below in the context of a unique phenomenon called amylose-lipid complexation that makes starch potentially indigestible.

Amylose-Lipid Complexation

Gelatinization is not the only starch-related phenomenon observed during the heating of pet food formulations. Another thermal transformation that occurs is amylose-lipid complexation, which is often observed during the cooking of starch in the presence of a lipid. The formation and extent of amylose-lipid complexation is a function of heat, moisture content, type of starch, type of lipid, and degree of gelatinization (2). The multiple starch sources in pet food formulations resulting from the mixture of cereal grains used makes this phenomenon even more challenging to study. As the name suggests, the helical structure of amylose allows lipids to find their way into the center where they are "trapped" during processing (Fig. 5). When lipids are complexed with starch, the amount of free fat in the pet food matrix is decreased. By reducing the free fat available for oxidation, amylose-lipid complexation has been shown to extend the shelf-life of a product. In addition, a higher degree of complexation also slows the digestion of starch (4). Thus, this phenomenon has potential benefits in pet foods.

Identification and Quantification of Amylose-Lipid Complexation

Amylose-lipid complexes can be identified using DSC. These complexes have endothermic peaks around 100–120°C on a DSC thermogram (Fig. 4). However, DSC is not an adequate tool for quantification of amylose-lipid complexation. In the current study, the amount of fat entrapped in amylose-lipid complexes in the pet food products tested was quantified using two crude-fat extraction methods. The first method used was based on ether extraction. The crude fat determined by ether extraction was an estimate of the amount of free lipids or extractable fat in the pet food matrix (Fig. 6A). The second method of fat analysis was based on acid hydrolysis. This method hydrolyzed the

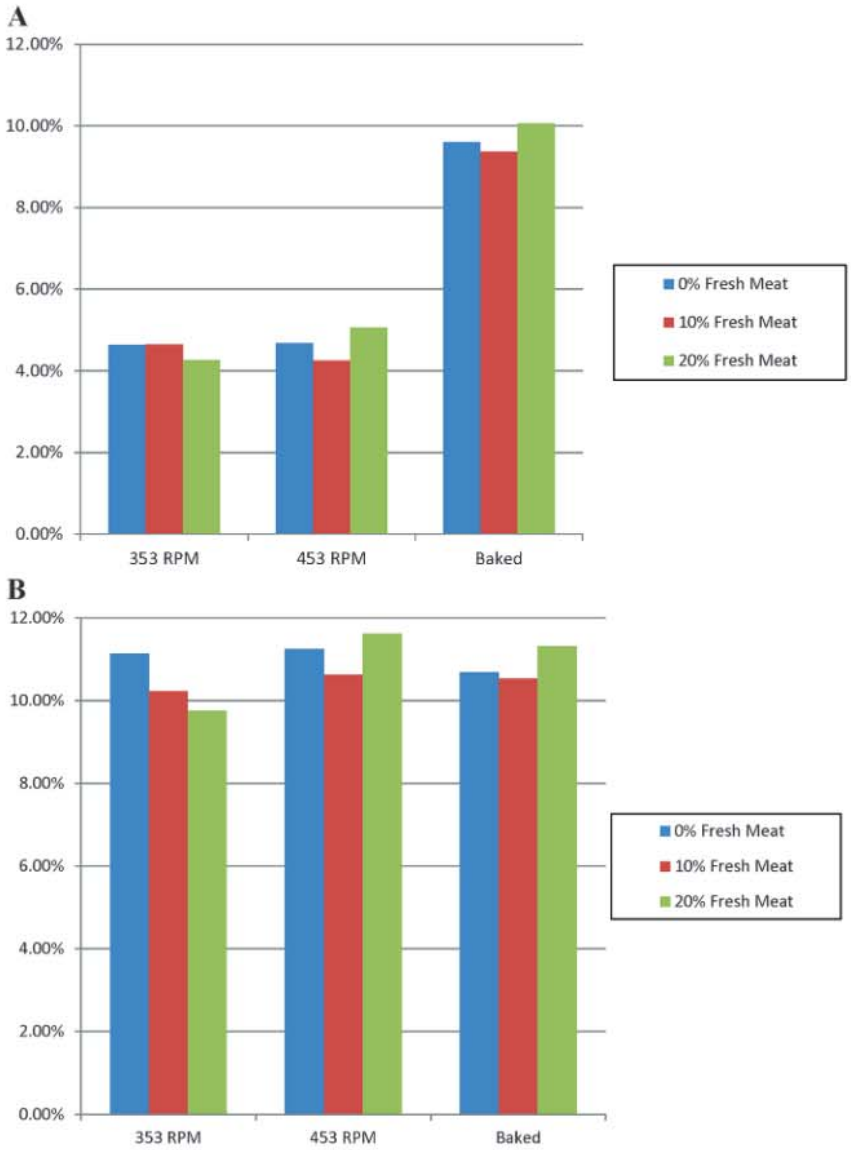

Fig. 6. A, Estimated crude fat using ether extraction method. **B,** Estimated crude fat using acid hydrolysis method. The descriptors 353 RPM and 453 RPM refer to extruded products processed at different screw speeds.

bonds within the amylose-lipid complexes and estimated the amount of total or crude fat (Fig. 6B). The difference between the two fat quantification methods gave the total amount of unextractable fat, which is also a measure of the extent of amylose-lipid complexation.

Extrusion clearly led to significant amylose-lipid complexation in all treatments, and the crude fat estimated by the ether extraction method was consistently lower than that estimated by acid hydrolysis. In the case of baked products, little or no difference was observed in the amount of crude fat estimated by the two methods, confirming the absence of amylose-lipid complexation, which was also observed in the DSC thermograms. The higher extent of complexation in extruded products was possibly due to the combination of thermal and mechanical energy involved in the process. Also the area (J/kg) under the peak in the DSC thermograms corresponding to amylose-lipid complexation decreased as the level of fresh meat inclusion increased from 0 to 20%. It was hypothesized that lower levels of external lipids (chicken fat) in formulations with higher levels of fresh meat might have led to a reduction in amylose-lipid complex formation. Moreover, internal fat in ingredients such as unrendered fresh meat might be "protected" from thermal and mechanical conditioning, thus preventing amylose-lipid complex formation. This needs to be verified with further experimentation and analyses.

Effects of Starch Gelatinization on Pets

The differences between gelatinization of baked and extruded pet foods was significant. Starch gelatinization in extruded kibble ranged from 90 to 100%, whereas starch gelatinization in baked pet food kibble was ≤60%. Gelatinization of starch increases starch digestibility and may increase available glucose in the blood stream (5). If a pet continually consumes an excess of calories the risk of obesity increases (3). However, higher levels of amylose-lipid complex formation may slow starch digestion, which leads to intriguing questions. For example, is less gelatinized starch with no amylose-lipid complex from baked pet food kibble healthier than highly gelatinized starch combined with an amylose-lipid complex from extruded pet food kibble? This is a question that needs to be explored in further studies and is the focus of ongoing work in our laboratory.

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References

1. American Pet Products Association. Pet industry market size and ownership statistics. Published online at www.americanpetproducts.org/press_industrytrends.asp. APPA, Greenwich, CT, 2013.
2. Eliasson, A. Interactions between starch and lipids studied by DSC. Thermochim. Acta 246:343, 1994.
3. Kelly, N., and Wills, J. The obese animal. Page 110 in: *Manual of Companion Animal Nutrition & Feeding*, 1st ed. Iowa State University Press, Ames, IA, 1996.
4. Muoki, P. N., de Kock, H. L., and Emmambux, M. N. Effect of soy flour addition and heat-processing method on nutritional quality and consumer acceptability of cassava complementary porridges. J. Sci. Food Agric. 92:1771, 2011.
5. Ross, S. W., Brand, J. C., Throburn, A. W., and Truswell, A. S. Glycemic index of processed wheat products. Am. J. Clin. Nutr. 46:631, 1987.
6. Yao, N., White, P. J., and Alavi, S. Impact of β-glucan and other oat flour components on physico-chemical and sensory properties of extruded oat cereals. Int. J. Food Sci. Technol. 46:651, 2011.

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