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A new technique for cross-sectional density profiling of extruded foods by X-ray scanning

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ABSTRACT

A wide variety of snack and cereal products are manufactured using extrusion. Often, these products are produced by direct expansion upon exiting the extruder by utilizing a raw material that is predominately starch. The density of extruded food products is an important quality parameter that determines its sensory and physical characteristics, as well as the appropriate packaging. Direct expanded products often shrink differentially with cooling after their initial expansion resulting in different localized densities within a product. We developed a novel technique to determine these localized cross-sectional density differences within an extruded product using an X-ray density profiler. Commercial, direct expanded products were characterized using this technique. All products demonstrated significantly higher densities near the edge, compared to the center of the product. Density profile data provided a means to rapidly characterize and image density variations axially and radially, offering a viable alternative to currently used density methods, while also providing more information. Different extruded foods can have significantly different localized densities. SEM images confirmed that the density differences in the products are visible through a smaller, more collapsed cell structure near the edge compared to the center. X-ray density profiling can provide insight into the eating characteristics of extruded products and will be a useful tool in product development and quality assurance.

1. Introduction

Snack foods and cereal products are becoming increasingly popular with consumers. Texture can play an important role in the consumer acceptance of these foods (Duizer, Campanella, & Barnes, 1998) and can vary widely depending upon the extrusion processing conditions and how well this process is controlled. Texture variations are even more important within multi-textured products that may have both crunchy and smooth components within the product.

Extrusion is a continuous, high pressure, high shear, and high temperature process. By altering the extrusion processing parameters, including screw speed, feed rate, feed moisture, and temperature, extrusion enables the creation of highly diverse food products within the directly expanded food category, as well as the ability to create a wide variety of textures (Alvarez-Martinez, Kondury, & Harper, 1988). Products can become more diverse with the wide array of ingredients that are used such as corn (Thymi, Krokida, Pappa, & Maroulis, 2005), wheat (Hagenimana, Ding, & Fang, 2006), rice (Hagenimana et al., 2006), and other cereal grains (Robin et al., 2010).

With the wide variety of food products that can be created through extrusion, the need to characterize these products has become an important issue affecting quality (Campbell & Mougeot, 1999). Currently, extruded food products can be characterized by various quality parameters including radial expansion, bulk density, true density, water solubility and water absorption properties (Ali, Hanna, & Chinnaswamy, 1996) (Anderson, Conway, Pfeifer, & Griffin, 1969) (Lazou & Krokida, 2010).

Density is a key quality measure that can directly affect the textural properties of the product (Liu, Hsieh, Heymann, & Huff, 2000) by having a correlation to crispness (Roudaut, Dacremont, Valles Pamies, Colas, & Le Meste, 2002). A model of crispness in extruded products directly correlates density to the cell area of an extrudate (Barrett, Cardello, Lesher, & Taub, 1994). A higher density product can be crunchier compared to low density product which is crispier (Luyten, Plijter, & van Vliet, 2004). Due to this density correlation with textural properties, products can have very

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different perceptions by a consumer with small fluctuations in density.

Density is also strongly correlated with expansion ratio of the extrudate. Expansion ratios can be affected by various independent extrusion variables. Modeling of extrudate expansion and its relation with density has been studied by Alvarez-Martinez et al. (1988). When the extrudate melt exits the extruder, a sudden change from high pressure to low pressure causes the release of water vapor that results in a large initial expansion throughout the extrudate until the pressure equilibrates with the atmosphere (Della Valle, Vergnes, Colonna, & Patria, 1997). A slower change then occurs from high temperature to low temperature, causing the product to shrink through a negative pressure difference (Fan, Mitchell, & Blanshard, 1994). Additionally, the cells near the edge can rupture during formation due to the high pressure differential. The rupturing, combined with moisture diffusing from the inside of the starch matrix to the outside, can also lead to the more collapsed structure seen near the edge of extrudates. However, the collapse and shrinkage of the product can be affected by variables such as moisture, temperature, and various mechanical properties (Wang, Ganjyal, Jones, Weller, & Hanna, 2005).

Current methods to determine the density of directly expanded products focus on the average density of the entire product and do not often identify the density differences within the cross-section of the extrudate caused by the expansion process. Most commonly, the densities are reported as bulk density or unit density and are determined by the ratio of mass of the product to volume (Ali et al., 1996). Density of the solid material, not including the pores, of an extrudate can also be identified with displacement of air or fluid, but these methods fail to give an accurate representation of differences within the product (Bisharat, Oikonomopoulou, Panagiotou, Krokida, & Maroulis, 2013).

Density has also occasionally been measured using X-ray tomography (Robin et al., 2010) (Babin, Della Valle, Dendievel, Lourdin, & Salvo, 2007), an X-ray diffraction method, to identify correlations with crispness (Agbisit, Alavi, Cheng, Herald, & Trater, 2007). X-ray tomography can identify localized densities and create an image of the product in a three dimensional space (Trater, Alavi, & Rizvi, 2005). However, X-ray tomography is used primarily as an imaging technique for structural analysis and has not been widely used as a density method. Additionally, other density methods are often utilized even when X-ray tomography is being used for analysis (Parada, Aguilera, & Brennan, 2011; Zhu et al., 2010). Additionally, the equipment cost, size, as well as time, for testing and analysis, have been the reasons that X-ray tomography has not been used as the primary method for measuring product density.

In order to better characterize extruded product densities, an X-ray density profiler was evaluated as a method. Currently, the X-ray density profiler is utilized in forestry research areas (Yu et al., 2006). The equipment works by rapidly moving a polarized X-ray along the length of a sample. The intensity differences in absorbance of the X-ray as it passes through the sample can then be related to the product density. This method differs from tomography in that it is designed to rapidly provide a cross-sectional density and two dimensional profile instead of a three dimensional image of the product. With regard to extruded products, it may provide a better understanding of the cross-sectional densities and help explain the expansion phenomenon.

Therefore, the objective of this study was to evaluate if X-ray density scanning could characterize cross-sectional densities of extruded products sufficiently to predict factors associated with physical properties including expansion and texture for several extruded products of different composition produced under different extrusion conditions.

2. Materials and methods

2.1. Raw materials

The following extruded products were purchased from a local supermarket and used as purchased, for all density determinations without any further treatments: a) cereal puffs including Coco Puffs (Lot #AL090703 B, Use by 02/12/2014, 334 g), Cocoa Cool (Lot#P02, Use by: 05/14/2014, 335 g), Coco Roos (Lot #18290 1203, Use by: 02/18/2014, 1070 g), Cap'n Crunch's Oops! All Berries (Lot #L2 19, Use by: 01/29/2014, 437 g), which have been labeled "Cereal Puff 1" (CP1), "Cereal Puff 2" (CP2), "Cereal Puff 3" (CP3), and "Cereal Puff 4" (CP4), respectively, and b) cheese snacks such as Cheetos Crunchy (Lot# 346316353 77, Use by: 08/13/2013, 524 g), Cheetos Puffs (Lot # 546216554 51, Use by: 08/13/2013, 269 g), Cheese Puffs (Lot# N08183G, Use by: 08/25/2013, 283 g), which have been labeled "Cheese Snack 1" (CS1), "Cheese Snack 2" (CS2), "Cheese Snack 3" (CS3), respectively. All density measurements and determinations were done before the use by date of each extruded product.

2.2. Bulk density

Samples were accurately weighed and then placed in a 600 mL beaker, filling it to a level of approximately 450 mL. The beaker was manually shaken back and forth ten times to allow the extruded products to settle and pack. The final volume was recorded and sample density was obtained using a mass to volume ratio. All samples were tested in triplicate and analyzed via ANOVA and separated using Tukey's HSD ($p < 0.05$) using Minitab software (Minitab 17, Minitab Inc., State College, PA, U.S.A.).

2.3. Apparent density

Apparent density of all the samples was measured using displacement with 1.0 mm glass beads(Cole-Parmer, Vernon Hills, IL, U.S.A.) according to a method by Ali et al. (1996). The densities of the extrudates were then calculated using the following equation,

$$\rho_d = (W_{ex}/W_g)\rho_{gb} \quad (1)$$

where ρ_d is the density found through glass bead displacement method (g/cm^3), W_{ex} is the extrudate mass (g), W_g is the mass of the glass beads displaced (g), and ρ_{gb} is the density of the glass beads (g/cm^3). Each product was tested ten times and analyzed via ANOVA and separated using Tukey's HSD ($p < 0.05$) using Minitab software (Minitab 17, Minitab Inc., State College, PA, U.S.A.).

2.4. Solid density

Density of the solid material within the extruded products was defined as mass per unit of volume. The volume of each sample was determined using a pycnometer (Quantachrome, Multipycnometer, Quantachrome Instruments, Boyton Beach, FL, U.S.A.) to measure the amount of air displaced. This allowed air to penetrate the pores of the extrudates so that only the volume of the solid material was found. Three replicates of each sample were analyzed via ANOVA and separated using Tukey's HSD ($p < 0.05$) using Minitab software (Minitab 17, Minitab Inc., State College, PA, U.S.A.).

2.5. X-Ray density profile

Density scanning profiles were obtained using an X-ray tree ring scanner (QTRS-01X Tree Ring Scanner, Quintek Measurement Systems, Knoxville, TN, U.S.A.) originally designed to test density