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Waxy flour degradation – Impact of screw geometry and specific mechanical energy in a co-rotating twin screw extruder

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ABSTRACT

Dextrinization of starch using extrusion processing is crucial to the quality of direct expanded products. To determine the extent of dextrinization, flour samples were extracted from a twin-screw extruder that had been brought to a sudden stop and molecular weights were determined by intrinsic viscosity. The screw profile and moisture feed content had the most significant impact on molecular weight reduction, reducing intrinsic viscosity from 1.75 to 0.70 dL/g at the most. The breakdown, as shown by a reduction in intrinsic viscosity, had a strong negative correlation ($r = -0.96$) with specific mechanical energy. However, the extruder die did not have a measurable impact on the molecular weight reduction of waxy flour. Size exclusion chromatography confirmed intrinsic viscosity measurements were associated with reduction of the size of amylopectin molecules to approximately 1/10 the original molecular weight while native gliadin was nearly eliminated from the waxy flour following the extrusion treatments.

1. Introduction

Extrusion is widely used throughout the food and polymer industries because of the ability to design continuous processes with short processing times, and the ability to produce a wide array of unique products (Chinnaswamy & Hanna, 1988; Kowalski, Morris, & Ganjyal, 2015). During extrusion of directly expanded foods, often either flour or starch is subjected to large amounts of shear, heat, and pressure, all of which can change the properties of the flour (Alvarez-Martinez, Kondury, & Harper, 1988; Kowalski, Medina-Meza, Thapa, Murphy, & Ganjyal, 2016). The change in flour properties can also be utilized to produce pregelatinized starch, or other types of modified flours and starches, using an extruder (Hagenimana, Ding, & Fang, 2006).

Flour is a primary ingredient used in many extrusion processes and is composed mainly of starch with protein also being present at a lower level. Starch is built of two main polymer components consisting of amylose, which are linear chains built by α-(1 → 4) glycosidic linkages, and amylopectin, which contains branch points with α-(1 → 6) glycosidic linkages. Molecular weights of amylose can range from 10^4 to 10^5 Da (Hizukuri & Takagi, 1984) while amylopectin is around 10^8 Da (Buleon, Colonna, Planchot, & Ball, 1998). Secondary structures caused by hydrogen bonding between polymers, such as helix shapes in amylose, also contributes to granule structure and polymer stability. During extrusion, the high shear and high pressure environment can break apart these molecular structures within the starch and cleave the bonds holding the polymers together.

The extent to which the starch bonds are cleaved, as well as how other components that are within flour are affected, in extrusion processing can be a key factor in determining manufacturing parameters of extruded starch ingredients and starch based foods with varying textures. Quick measurements of breakdown often involve determining how soluble the extrudates are since smaller polymers should more readily dissolve in water than larger ones (Anderson, Conway, Pfeifer, & Griffin, 1969; Gomez & Aguilera, 1984). By analyzing the degree of starch gelatinization, further conclusions about starch dextrinization can be developed since it has been found that dextrinization (identified through water solubility index) and degree of gelatinization can correlate (Gomez & Aguilera, 1983).

More detailed descriptions of starch breakdown during extrusion have evolved through the use of intrinsic viscosity, which can be correlated with molecular weight through the Mark-Houwink relation (Millard, Dintzis, Willett, & Klavons, 1997). By doing so, first order degradation models of breakdown have been developed for single screw extruders (Davidson, Paton, Diosady, & Rubin, 1984; Diosady, Paton, Rosen, Rubin, & Athanassoulias,

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1985). Davidson, Paton, Diosady, and Larocque (1984) also concluded that the highly branched large polymer amylopectin is more susceptible to breakdown during extrusion compared to the linear polymer, amylose. Similar conclusions have been reached for purified starch studies utilizing twin-screw extruders (Della Valle, Colonna, Patria, & Vergnes, 1996).

Breakdown of starch as measured by intrinsic viscosity is highly correlated with specific mechanical energy in an extruder with multiple models being developed to describe this breakdown (Barron, Bouchet, Della Valle, Gallant, & Planchot, 2001; Berzin, Ahmed, Tighzert, & Vergnes, 2010; Van Den Einde, Van Der Goot, & Boom, 2003; Willett, Millard, & Jasberg, 1997). As changes with specific mechanical energy are usually affected more by the feed moisture content than by temperature, breakdown of starch has also been determined to be impacted more by feed moisture than extruder temperature. Often it has been seen that lower feed moistures lead to increased breakdown or dextrinization which may be due to the higher melt viscosity associated with lower feed moistures (Van Den Einde, Akkermans, Van Der Goot, & Boom, 2004; Van Den Einde, Van Der Veen, Bosman, Van Der Goot, & Boom, 2005). While these findings have concluded that shear is the main contributing factor to starch breakdown, researchers have speculated that there is a limit as to how much shear can break down starch in extrusion (Zheng & Wang, 1994). Shear rates within an extruder have also been shown to increase quickly with a decrease in feed moisture, which can influence the starch breakdown (Lai & Kokini, 1990).

Size exclusion chromatography is also an effective method for monitoring starch breakdown and from such studies, it has been concluded that amylopectin, not amylose, is the component most affected by extrusion processing, likely due to amylopectin being unable to align the entire molecule and all side chains in a high shear environment (Davidson, Paton, Diosady, & Larocque, 1984). Additionally, size exclusion chromatography has shown that amylopectin tends to break apart more towards the inner region of the molecule than near the edges as demonstrated by the even sized fragments of amylopectin formed (Li, Hasjim, Xie, Halley, & Gilbert, 2014; Liu, Halley, & Gilbert, 2010; Orford, Parker, & Ring, 1994).

The objective of this research was to further analyze how refined flour breaks down as it travels through an extruder by using a systematic approach of increasing shear in screw profiles and recovering extrudates along the length of the screw and measuring the degree of starch breakdown. The decision to use refined flour was to see if a full flour system behaves differently from isolated starch systems in previous literature (Davidson, Paton, Diosady, & Larocque, 1984; Van Den Einde et al., 2005; Willett et al., 1997). How the flour breaks down in relation to specific mechanical energy inputs due to changes in the screw design was of focus in this study. Since amylose is not anticipated to be affected to a great degree and can impact how the entire starch fraction degrades, a waxy flour was utilized to obtain a better understanding of the effects on amylopectin in the absence of amylose, and properties of the extrudate, such as viscosity and component solubility, that would affect quality of extrudates in a food item.

2. Materials and methods

2.1. Raw materials and sample preparation

The refined waxy wheat flour used was of the variety Waxy Sagitario (protein content 15.3% d.b.) and was obtained from the USDA Western Wheat Quality Laboratory (Pullman, WA, U.S.A.). The waxy wheat flour was confirmed to have an undetectable amount of amylose via colorimetric analysis (Chrastil, 1987). Flour particle size distribution was determined by sieving to have 0.8% <10 μm, 22.3% 10–100 μm, and 76.9% >100 μm. All flour used for extrusion experiments was hydrated to a moisture content of 14.0 ± 0.5, 18.0 ± 0.5, or 22.0 ± 0.5% w.b. according to the experimental design in Table 1. Hydrated samples were stored in airtight containers overnight at 4 °C to allow for further moisture equilibration.

2.2. Extrusion and process conditions

Extrusion was performed using a 20 mm co-rotating twin screw extruder (TSE 20/40, CW Brabender Instruments Inc., S. Hackensack NJ, USA). The extruder had a L/D ratio of 20:1 giving the screw section a length of 400 mm. The extruder setup utilized four individual heating regions with two being located along the barrel, one for the transition zone connecting the screws and die, and one for the die. The temperature profile was kept at 50 °C for the first zone and 100 °C for the second zone while the other two zones were varied according to the experimental design (120, 140, or 160 °C). A cylindrical shaped die with a diameter of 3.0 mm was used for all trials and the screw speed was fixed at 200 rpm. Flour was fed into the extruder at a rate of 5.0 kg/hr using a pre-calibrated twin-screw volumetric feeder (DDSR20-5, Brabender Technologie Inc., Mississauga, Ontario, CA). The screw profile was varied between 3 different profiles that correspond to varying amounts of shear input into the material. This was accomplished by either the addition or removal of kneading block geometries to the screw. While exact shear rates cannot currently be calculated in the twin screw system due to its complexity, altering the geometry to increase mixing is known to increase shear input. These screw profiles were labeled SP1, SP2, and SP3 as shown in Fig. 1.

The extruder used had a clamshell style barrel which allowed for easy sample collection along the course of the screws. To collect samples, extrusion was started and the given sample conditions were run for a minimum of 3 min to obtain steady-state runtime conditions. The extruder was then brought to a sudden dead stop and the barrel was opened 4 min after the stop for every sample. Samples were collected along the extruder screws at designated locations (Fig. 1). The first area, designated zone 1, was from a screw length range of 280–300 mm, the second area, designated zone 2, was from a screw length range of 320–340 mm, and the third area, designated zone 3, was from a screw length range of 360–380 mm. The fourth collection area, designated zone 4, was at the transition zone between the screws and the die and had a length of 32.5 mm. The final collection area, designated zone 5, was the final product collected. All collected samples were then dried at 45°C for 18 h to equilibrate the moisture level to approximately 5% w.b. Every dead stop trial (Table 1) was repeated in duplicate.

While the extruder was running, process data was collected continuously including pressure, motor torque, and barrel temperature using a data acquisition system designed for use with an Intelli-Torque extruder (CW Brabender, S. Hackensack, NJ, USA). One data point for each process factor monitored was taken every 20 s and values of pressure and motor torque were calculated from an average of 5 random data points while the extruder was running the specified sample.

2.3. Analysis of extrudate properties

2.3.1. Extrudate analysis

Specific mechanical energy was calculated according to Godavarti and Karwe (1997) using the torque values obtained from the extruder. The diameter of the extrudates was measured using a digital caliper (Mitutoyo America Corp., Aurora, IL, USA) and was