Relationships between the gelatinization of starches and the textural properties of extruded texturized soybean protein-starch systems

Wei Zhang [a], Shujing Li [a, b], Bo Zhang [a, *], Silvina R. Drago [c], Jinchuang Zhang [a]

[a] Institute of Food Science and Technology, Chinese Academy of Agricultural Sciences/Key Laboratory of Agricultural Product Processing, Ministry of Agriculture, Beijing 100193, China
[b] Chiping Food and Drug Administration, Liaocheng, Shandong Province 252100, China
[c] Institute of Food Technology, Chemical Engineering School, Universidad Nacional del Litoral, Santiago del Estero 2829, 3000 Santa Fe, Argentina

ABSTRACT

Starches from diverse sources have different thermal properties and, thus, show different gelatinization degrees under a specific extrusion condition, which affects the quality of the extrudates. To find the appropriate ingredients for extruding texturized soybean protein-starch mixtures, the thermal properties of commercial-grade starches (wheat starch, corn starch, potato starch, sweet potato starch, cassava starch, mung bean starch, pea starch, amylose from potato, and amylopectin from waxy corn), blends of starches with soybean protein isolate (SPI) and wheat gluten were assessed. The extrusion response parameters (torque, pressure change, specific mechanical energy (SME), and on-line apparent viscosity) during extrusion and the thermal and textural properties of the extrudates were determined. Pearson correlation analysis showed that the enthalpy changes of the blends were directly correlated with the torque, pressure change, specific mechanical energy, and on-line apparent viscosity, whereas those parameters were inversely correlated with the fibrous degree of the extrudates. The hardness, tensile strength, lengthwise strength, and fibrous degree of the extrudates were correlated with the enthalpy changes of the blends. The springiness and fibrous degree of the extrudates were correlated with the half-peak height of the blends. It was concluded that a higher enthalpy changes of blends leads to a higher SME and a pressure change, which results in a higher hardness and tensile strength and a lower fibrous degree of the extrudates.

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1. Introduction

USA Food and Drug Administration claimed that "25 g of soy protein a day, as part of a diet low in saturated fat and cholesterol, may reduce the risk of heart disease" and also granted recognition for soy in 1999, which popularized the foods made from soy or soy protein, such as texturized soybean protein. Texturized soybean protein shows obvious fibrous structure and a remarkable similarity in appearance, texture and mouth feel to meat, so those textural properties are the key factors to consumer acceptance (Ranasinghesagara et al., 2005, 2006). The extruded defatted soybean meal has a remarkable fibrous structure comparing with SPI, which indicates that the fiber was affected by introducing carbohydrate into the protein phase (Sheard et al., 2007).

The essential effects of the extrusion process are due to high shear and temperature. Thermo-mechanical action during extrusion cooking leads to the denaturation of proteins and the gelatinization of starches; these effects have been characterized by thermal properties of protein and starches (Alonso et al., 2000; Barron et al., 2002; Batterman-Azcona et al., 1999; Harper and Clark, 1979; Kitabatake et al., 1985; Liu et al., 2011; Zhang et al., 2001). Differential scanning calorimetry (DSC) has been used to study the enthalpy changes of the thermal denaturation of proteins and gelatinization of starches (Baeza and Pilosof, 2002; Boye and Alli, 2000; Galani and Apenten, 2000; Hendrix et al., 2000; Li et al., 2004a; Tufvesson et al., 2003; Yu and Christie, 2001). In the DSC curve of SPI, two peaks were observed at 90 °C and 109 °C, which probably correspond to the denaturation of the 7S and 11S, and the similar result was obtained at 80 °C and 95 °C (Li et al., 2014; Ortiz and Añón, 2001). One peak of acetic acid-soluble wheat gluten at 74 °C and two peaks of washed wheat gluten at 88 °C and 101 °C were observed (Eliasson and Hegg, 1980; Lawton and Wu, 1993). The gelatinization of various starches with different water content has been well studied. Starch thermal changes under

limited water content had been well described by so-called Flory law, which described the relationship between the melting point of a crystalline polymer with dilute concentration (Donovan, 1979). A large gelatinization endotherm was found at approximately 70 °C for waxy and maize starch (Russell, 1987), and a second endotherm referring to the phase transition within an amylose–lipid complex was also detected for maize starch at approximately 90 °C (Jovanovich and Añón, 1999; Raphaelides and Karkalas, 1988). Meanwhile, there is an endotherm for waxy starch with 55% water content, which reflected the non-equilibrium melting of crystallites (Liu et al., 2006; Shogren, 1992).

Great interest has been given to the thermal properties of protein–starch mixtures. The thermal transition temperature of wheat-flour/potato-starch mixture with 30% moisture content increased from 62 to 66 °C and 64–66 °C separately, when the addition of two varieties potato starch increased from 10% to 50% (Zaidul et al., 2008). The peak temperatures of the starch gelatinization increased from 70 to 83 °C in a starch-gluten system with 60% moisture content, with the increasing addition of Hard Red Spring wheat protein extract from 5% to 50% (Mohamed and Rayas-Duarte, 2003). The starch gelatinization has a significant effect on the physical properties of the extruded products. The water solubility index of corn starch extrudate increased with the gelatinized corn starch content increasing, since only starch granules degraded beyond gelatinization could participate in the formation of a stable, expanded structure (Gomez and Aguilera, 1984). Asaoka et al. (2006) found that the bulk density decreased as gelatinization of the cassava starch increased, and the minimum bulk density occurred between 55% and 75% gelatinization.

Still there is insufficient research on enthalpy changes during the extrusion process, such as (1) how the thermal transition properties of proteins and starches change after mixing and extrusion, and (2) what is the relationship between the enthalpy changes of blends and textural properties of texturized soybean protein? The purpose of this research is to study the relationships among the enthalpy changes of the blends, extrusion response parameters, and textural properties of the extrudates. The results will help to select the ingredients and optimize the formula of extruded textured soybean protein-starch mixtures.

2. Materials and methods

2.1. Materials

Soybean protein isolate (Injected 5100) was purchased from Yuxin Group Ltd. (Shandong Province, China). The moisture content was 6.98%. The protein content was 94.44% (dry basis). Wheat gluten was purchased from Ruixiang Group Ltd. (Shandong Province, China). The moisture content was 7.21%. The protein content was 85.73% (dry basis). Wheat starch, corn starch, potato starch, sweet potato starch, cassava starch, mung bean starch, pea starch, potato amylose and corn amylopectin were acquired in a market. The total starch content of the starches from different botanical sources, measured according to Chinese standard method GB/T 5009.9-2003 by third-party inspection companies (Silliker, Shanghai), are specified in Table 1. Soybean protein isolates and wheat gluten were mixed with 9 different starches at a ratio of 65:15:20, respectively.

2.2. Extrusion

2.2.1. Extruder

All of the extrusion experiments were conducted using a pilot-scale, co-rotating and intermeshing twin-screw DSE-25 extruder (Brabender GmbH and Co., Germany). The screw profile from feed

Table 1
Total starch content of starches from different botanical sources.

Starch	Starch content (%. d.b)[a]	Moisture content (%)
Wheat starch	94.52 ± 0.00d	12.16% ± 0.15b
Corn starch	99.51 ± 0.00a	10.85% ± 0.16d
Potato starch	98.44 ± 0.74a	15.99% ± 0.03a
Sweet potato starch	99.23 ± 0.57a	11.55% ± 0.07c
Cassava starch	93.98 ± 0.02d	10.76% ± 0.02d
Mung bean starch	97.37 ± 0.42b	12.51% ± 0.59b
Pea starch	95.75 ± 0.55c	12.14% ± 0.08b
Potato amylose	98.66 ± 0.63a	12.05% ± 0.02b
Corn amylopectin	92.90 ± 0.31e	12.06% ± 0.01b

[a] Means ± standard deviations; different letters mean significant differences ($P < 0.05$).

to the die is with CE/37.5/37.5/8 and CE/25/45/8, which represented 8 conveying elements with 37.5 mm length and 37.5° helix angle together with another 8 conveying elements with 25 mm length and 25° helix angle, respectively. The extruder parameters were 25 mm screw diameter (D); 20:1 screw length/diameter ratio; and $2 \times 20 \times 100$ mm cooling die attached to the end of the extruder. The barrel was segmented into a feeding zone and five temperature-controlled zones, which were heated by an electric cartridge heating system and cooled with running water. The temperature and screw speed were monitored from a control panel. The extruder responses, including the motor torque and die pressure, were recorded on-line once every 10 s automatically.

2.2.2. Extrusion conditions

The blends were fed into the extruder at a speed of 30 g min^{-1} (dry basis). Based on preliminary experiments and the working stability of the extruder, the feed moisture content was selected as 50% (dry basis), the screw speed was 160 r min^{-1}, and the extruder barrel temperatures were kept at 60, 80, 145, 137 and 70 °C from the first zone to the fifth zone (die), respectively.

2.2.3. Specific mechanical energy

The specific mechanical energy (SME, kJ kg^{-1}) was calculated from the screw speed (n = 160 r min^{-1}), motor torque (T, N·m, recorded automatically by computer) and mass flow rate (MFR, g min^{-1}, determined by the output of the extrudate within 1 min), according to the following formula (Chen et al., 2010; Godavarti and Karwe, 1997):

$$SME = \frac{2\pi \times n \times T}{MFR}$$

2.2.4. On-line viscosity

The on-line viscosity at the die of each treatment was calculated according to the method described by Li et al. (2004b), using the equation below:

$$\eta = \frac{\tau}{\dot{\gamma}} = \frac{\Delta PH}{2L} \bigg/ \frac{6V}{BH^2} = \frac{\Delta PBH^2}{12LV} = \frac{\Delta PBH^3}{12L(s \times B \times H)} = \frac{\Delta PH^2}{12Ls}$$

where η is the apparent viscosity (Pa·s); τ is the shear stress (Pa); $\dot{\gamma}$ is the shear rate (s^{-1}); ΔP is the die pressure drop (Pa); H, L, and B are the known geometries of the viscometer channel (mm); and s is the velocity of the extrudates coming out from the die (mm s^{-1}), which was measured according to the lengths of the extrudates within 2 min.

2.2.5. Sample collection

When the extruder reached a steady state, as indicated by the