Original paper

Effect of Calcium Stearyl Lactylate on Physicochemical Properties of Texturized Wheat Gluten

Wen Yang¹, Xin-Sheng Qin¹, Shui-Zhong Luo¹,², Yan-Yan Zhao¹,², Xi-Yang Zhong¹,², Dong-Dong Mu¹,², Shao-Tong Jiang¹,² and Zhi Zheng¹,²*

¹School of Food Science and Engineering, Hefei University of Technology, Hefei 230009, China
²Key Laboratory for Agricultural Products Processing of Anhui Province, Hefei University of Technology, Hefei 230009, China

Received September 2, 2016 ; Accepted December 21, 2016

In order to improve the processing properties of texturized wheat gluten (TWG), we studied the effect of calcium stearyl lactylate (CSL) (0 – 0.12%, w/w) on the physicochemical properties and structure of TWG using a twin screw extruder. Results showed that the hardness, adhesiveness, and chewiness of TWG significantly increased by 161.55%, 225.06% and 138.54%, respectively, with addition of 0.08% CSL during twin-screw extrusion processing. Moreover, Raman spectroscopy indicated that CSL encouraged new disulfide bond formation during extrusion treatment. Infrared spectroscopy and reducing electrophoresis demonstrated that CSL inhibited the Maillard reaction. Increasing the amount of CSL resulted in shifts from α-helix and β-turn structures into β-sheet and random coil structures, as evidenced by secondary structure analyses. Overall, features of TWG were modified by CSL which made TWG a valuable material can be used for the development of fibrous meat alternatives, thus widening the application of wheat gluten products for meeting consumer requirements.

Keywords: wheat gluten, calcium stearyl lactylate, extrusion, physicochemical properties, structure

Introduction

Extrusion cooking is widely used in the production of expanded snack foods, breakfast cereals, meat analogues, modified starches, and other food products (Brennan et al., 2013; Burey et al., 2009; Tran et al., 2008). The process of extrusion cooking is a promising operation involving high temperature, pressure, and shear force to get highly expanded, low-density, and fibrous meat-like products (Osen et al., 2014; Pitts et al., 2014). However, despite its increasing use in the food industry, the extrusion process is still a complex system that remains to be mastered (Ding et al., 2006). Slight variations in processing conditions affect the quality of the extruded products (Desrumaux et al., 1999). Many research groups have focused on the twin screw extrusion process to optimize the extrusion conditions for soy protein isolates, pea protein isolates, corn flour, rice flour, barley flour, and other products (Meng et al., 2010; Osen et al., 2014; Yu et al., 2012).

Wheat gluten, which has protein content up to 76%, is the main economic by-product of the wheat starch industry. It is a relatively inexpensive vegetable protein whose use has progressively increased in the food industry due to abundant resources (Dadzie et al., 2013). The functional properties of wheat gluten can be improved via extrusion cooking technology, thus enlarging wheat gluten’s application in the food industry. Most of the research pertaining to extrusion technology has focused on extrusion conditions, such as the control of extrusion temperature and feed moisture content in order to obtain optimized extrudates (Rathod and Annapure, 2016). Calcium stearyl lactylate (CSL) has been approved by the European Food Safety Authority (EFSA) and
Food and Drug Administration (FDA) standards for use as an emulagtor. CSL has good emulsifying and anti-aging properties, which are mainly used for production of spicy puffed foods, dairy creamers, breads, pasta, noodles, dumplings, milk, and other food items. In addition, CSL has excellent strengthening and good tissue softening effects on wheat gluten (Mei and Lee, 1996). Although, the primary application of CSL for food is to improve the sensory properties of extruded foods, the ingredient also has specific functions that can contribute to the processing characteristics and textural qualities of the extruded food products (Murayama and Tomida, 2004). Nonetheless, there is currently minimal research surrounding the effect of CSL on extrusion processing.

The aim of the presented study was to investigate the effect of CSL on the physicochemical properties of wheat gluten by twin-screw extrusion treatment. The resultant protein structures were studied using Raman spectroscopy, Fourier transform infrared spectroscopy (FTIR), sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE), and scanning electron microscopy (SEM), enabling clarification of changes in the texture profile analyses (TPA), of the products.

Materials and Methods

Materials Wheat gluten on a dry basis was supplied by Ruifuxiang Food Co., Ltd. (Bozhou, China). The wheat gluten was comprised of 76.70% protein, 6.16% moisture, 0.88% fat, and 0.62% ash.

Commercial CSL was obtained from Yihang Chemical Products Co., Ltd. (Henan, China). The CSL meets the Chinese National quality standard for edible ingredients.

Extruder and experimental configurations A twin screw extruder (Wenger TX-85, USA) was used in this study. The Tx-85 has a length to barrel diameter ratio of 19.5:1 (barrel diameter 85 mm), and the barrel was segmented into the feeding zone and four controlled temperature zones, which were heated by a steam heating system and cooled with running water. The temperature, screw speed and feed rate were monitored from a control panel. The die had six openings with dimensions of 23×1.5×28 mm (W×H×L). A knife holder was installed at the end of the extruder die, and two hard blades were used to cut the samples to approximately 2.0 cm long.

Extrusion cooking The wheat gluten were then combined with CSL (0%, 0.04%, 0.08%, or 0.12%) prior to extrusion cooking. The raw material for each treatment consisted of batches blended using a mixer (Wenger Manufacturing, USA) to ensure even distribution of the ingredients. The moisture content of samples used in the extruder feed was adjusted to approximately 32%, water at ambient temperature was pumped (Lead Fluid Manufacturing, China) into the pre-conditioner and extruder with flow of 60 kg h\(^{-1}\) and 54 kg h\(^{-1}\), respectively. The extrusion parameters used were based on previous optimization experiments, and the orthogonal table is shown in Table 1. Barrel zone temperatures were kept constant at 40, 90, 140 and 110°C throughout the experiments, while die temperatures varied according to the experimental design. Screw configuration were shown in Fig. 1. The residence time of wheat gluten in the barrel was about 30 s. Wheat gluten was extruded at a feed rate of 300 kg h\(^{-1}\) and a screw speed of 400 rpm. The extrudates were maintained in a steady state condition for about 5 min before sample collection. Extruded products were immediately dried at 40°C overnight in a forced-air drier (DHG-9240A, Hengkexue Instrument Co., Ltd., China). The final dried samples contained a maximum of 6% moisture. Dried samples were stored in polyethylene bags at room temperature and used for further analysis. Hereafter, we refer to the raw wheat gluten as WG and the extruded wheat gluten products with different CSL contents (0%, 0.04%, 0.08% and 0.12% w w\(^{-1}\)) as TWG-0% CSL, TWG-0.04% CSL, TWG-0.08% CSL, and TWG-0.12% CSL.

Texture properties The samples were immersed in water at 25°C, set on sieve for 10 min, and then split into 50 mm cubes with a knife. The TWG were then characterized including the hardness, gumminess, cohesiveness, springiness, chewiness, and texturization using the TA-XT2i texture analyzer (Stable Micro Systems, U.K.) at 25°C, according to the method described by Fang et al (2014), with slight modifications. The texture analyzer conditions were set as follows: probe P50, pretest speed: 1.0 mm s\(^{-1}\), testing speed: 2.0 mm s\(^{-1}\), posttest speed: 2.0 mm s\(^{-1}\), and compressed distance: 75% of its original height. The hardness, gumminess, cohesiveness, springiness and chewiness data were then recorded. The samples

| Table 1. Process parameter factor level of texturized wheat gluten |
|----------------|----------------|----------------|----------------|
| factors        | moisture content/% | Temperature/℃ | screw speed/ rpm | feed rate/kg h\(^{-1}\) |
| levels         |                  |                |                |                        |
| 1              | 31               | 130            | 400            | 285                    |
| 2              | 32               | 135            | 410            | 300                    |
| 3              | 33               | 140            | 420            | 315                    |
were cut using an A/CKB probe to 75% of its initial thickness at a speed of 1 mm s\(^{-1}\), along the vertical orientation and then parallel to the direction of extrusion. The degree of texturization can be used to indicate the formation of fibrous structures, and is expressed as the ratio of vertical strength and parallel strength. All measurement indices from 6 pieces of treatment were recorded and averaged.

**Raman spectroscopy**  Samples of the powder were retrieved from the 100-mesh sieve after grinding by the QSB-200 grinder (Yongkang fun Ltd., Zhejiang, China) and then the powder were used for Raman spectroscopy analyses. Raman spectra for the TWG were collected to analyze molecular structure and chemical composition by a LABRAM-Aramis spectrometer (Horiba Jobin-Yvon, France) according to previous methods with modifications (Cui et al., 2011; Tang and Ma, 2009). The apparatus was operated with excitation at 632.8 nm (He/Ne laser) and the results were read at 25°C. The wheat gluten samples were placed on microscope slides for focusing the laser to obtain Raman measurements. The following detection conditions were used: 30 s laser irradiation, 80 scans, 2 s exposure time, and 2 cm\(^{-1}\) resolution. The resulting Raman intensity ratios were based on the averaged spectral data from the scanned samples. Raman spectra were normalized, baseline calibrated, and smoothed to minimize errors caused by surface roughness.

**FTIR spectroscopy**  FTIR of the texturized wheat gluten was performed as previously described (Kong and Yu, 2007), with modifications, using a Nicolet 6700 FTIR spectrometer (Thermo Nicolet Co., USA). To avoid the interference of moisture, the sample powder was dried using the drying lamp. The ratio of sample powder and KBr was 1:200. After mixing evenly using an agate mortar and pestle, the powder was formed into slice (1 – 2 mm thick) using a 10 t hydraulic press. The powder samples were measured by determining the attenuated total reflectance (ATR) from 4000 to 400 cm\(^{-1}\) with a resolution of 4 cm\(^{-1}\) and a total of 64 scans. Changes in the Amide I band from 1600 to 1700 cm\(^{-1}\) were analyzed using Omnic 6.0 and Peakfit v4.12 software. The Amide I band procedure was applied to the linear baseline correction, the Fourier self-deconvolution and the Gaussian curve fit. The relative amounts of the different secondary structures of sample were determined from the second derivative of the Amide I. The corresponding relationships between absorption peaks and secondary structures were as follows: 1650 – 1660 cm\(^{-1}\) for α-helices; 1610 – 1640 cm\(^{-1}\) and 1670 – 1690 cm\(^{-1}\) for β-sheets; 1660 – 1670 cm\(^{-1}\) and 1690 – 1700 cm\(^{-1}\) for β-turns; and 1640 – 1650 cm\(^{-1}\) for random coils (Murayama and Tomida, 2004; Muyonga et al., 2004).

**Reducing SDS-PAGE**  SDS-PAGE was used to visualize changes in the wheat gluten subunit molecular weights using a vertical mini-gel System (Mini-PROTEAN Tetra Cell, Bio-Rad Laboratories, Shanghai, China). SDS-PAGE was conducted using the modified method described by Steffolani et al. (2010). WG, TWG and TWG-CSL powder (2 mg) were solubilized in 0.5 mL of Tris-HCl buffer (0.0625 M, pH 6.8) containing glycercol (10%), SDS (2.3%), and 2-mercaptoethanol (5%). The solubilized samples were then heated in boiling water for 5 min. The resulting solution was cooled to room temperature, and centrifuged at 7,000 rpm for 10 min. The sample supernatants (10 µL) were added to a 12% (pH 8.8) separating/5% (pH 6.8) stacking gel, and separated using a constant voltage of 80 V for electrophoresis. The gel was stained for 50 min with 0.25% Coomassie Brilliant Blue-R250 (0.1 g/100 mL Coomassie brilliant blue R-250, 10 mL/100 mL acetic acid, and 45 mL/100 mL methanol), and washed in acetic acid-methanol-distilled water solution (1:8:5, v:v:v). The stained bands were measured using a Chemi Doc TM MP Imaging System (Bio-Rad Laboratories, Shanghai, China).

**Scanning Electron Microscope (SEM)**  Microstructure analysis was carried out according to the method described by Wang et al. (2016). The samples were sprayed with gold prior to detection. Microstructures were visualized using a JSM-6490 LV scanning electron microscope (JEOL, Japan). A representative photomicrograph was selected for all samples.

**Statistical analysis**  All experiments were conducted in triplicate, with the resulting data presented as the mean ± standard deviation (mean ± SD) for the samples. All analysis of variance (ANOVA) and significant difference tests were performed using SPSS Statistic 10.0 software. Statistical significance was determined as P < 0.05.

**Results and Discussion**

**Analysis of orthogonal array testing**  Orthogonal array testing was applied to optimize the parameters of extrusion condition. The set of experiments performed and the corresponding results obtained are shown in Table 1 and 2. The orthogonal table L9 (3\(^4\), four factors and three levels for each factor) arrayed factors used in the experiments and the response variables is the texturization degree. The results shown in Table 2 demonstrated that temperature and moisture content displayed the most significant effect on the texturization degree, followed by the feed rate and the screw speed exhibited the least. Table 2 illustrated that the optimal extrusion condition of texturized wheat gluten was found to be 32% moisture content, 140°C, 400 rpm and 300 kg h\(^{-1}\) feed rate.

Results revealed that the hardness was significantly dependent on the screw speed and feed rate. The hardness increased with the increasing of screw speed and feed rate. The moisture content showed significantly effect on the adhesiveness. Except for that, the chewiness of TWG were significantly affected by the moisture content, screw speed and feed rate.

**Texture properties**  The effects of CSL on the degree of hardness, adhesiveness, springiness, chewiness and texturization of TWG are shown in Table 3. ANOVA tests indicate that the addition of CSL significantly affected the hardness, chewiness, and texturization of the extruded products (P < 0.05). Increasing the amount of CSL from 0 to 0.08% resulted in a sharp increase in...
TWG hardness from 6125 to 7870 g, with an average increase of approximately 20.19% hardness for every 0.01% increase in CSL. This change could be related to the formation of a CSL-WG network (Marti et al., 2010). Changes in adhesiveness and chewiness were similar to those of hardness, also increasing with the amount of CSL. The degrees of chewiness and adhesiveness of TWG increased to maximums of 138.54% and 225.06%, respectively. Increases in adhesiveness may be attributed to CSL-enhanced formation of new WG structures combined with the degree of fibrosis, restricting swelling of the WG during extrusion cooking (Tudorica et al., 2002). The observed increases in chewiness may be associated with the effect of CSL on the extrusion pressure, which is reduced when CSL is used as an emulsifier. This may enhance the continuity of the wheat gluten network, resulting in increased chewiness (Meng et al., 2010).

In contrast, increasing amounts of CSL appeared to decrease springiness in the TWG extrusion product. Increasing the amount of CSL from 0 to 0.12% resulted in a decrease in the degree of springiness from 0.721 to 0.59, or approximately 18.17%. This suggests that CSL input lead to poorer springiness. Likewise, higher amounts of CSL also appeared to cause a decrease in the degree of texturization. Increasing CSL from 0 to 0.04%, led to a decrease in texturization from 1.63 to 1.46, thus indicating that the addition of CSL resulted in a poor fiber structure. Overall, the above results indicate that the addition of CSL leads to a more compact TWG structure.

Analysis on FTIR  FTIR spectroscopy can accurately measure protein secondary structure. Each protein can be associated with specific bands and wavenumber intensities. The total FTIR spectra (400 – 4000 cm⁻¹) of wheat gluten samples are displayed in Fig. 2.
Hydrogen bonding stretching vibration can be detected by the presence of characteristic bands at about 2930 cm\(^{-1}\). In the present study, we observed an increase in these 2930 cm\(^{-1}\) absorption bands associated with addition of CSL, thus suggesting in increase in hydrogen bonds present in the TWG-CSL samples. In addition, absorption bands at 1447 cm\(^{-1}\), 1530 cm\(^{-1}\), and 1658 cm\(^{-1}\), representative of C-N, C = N, and C = O groups and associated with Maillard reaction products, were weakened (Gu et al., 2010; Li et al., 2016).

Thus, the addition of CSL appeared to inhibit the Maillard reaction in wheat gluten samples during the extrusion process; this result therefore was consistent with the SDS-PAGE analysis.

The Amide I region (1600 – 1700 cm\(^{-1}\)) reflects the secondary structure of protein samples (Raussens et al., 2003). Thus, the contents of secondary structures in the TWG products from our study were calculated as shown in Table 4. The Amide I region of the samples consisted of seven components (Fig. 3) located at 1608, 1623, 1643, 1654, 1670, 1687, and 1697 cm\(^{-1}\), representing an intramolecular \(\beta\)-sheet of protein aggregation, another intermolecular \(\beta\)-sheet of protein aggregation, a random coil, an \(\alpha\)-helix, a \(\beta\)-turn, a \(\beta\)-sheet, and an extended \(\beta\)-sheet, respectively, demonstrating that random coils and \(\beta\)-sheets were the major secondary structures present in the samples (Liao et al., 2012; Zhao et al., 2004).

As shown in Fig. 4B, the intensity of bands at 1230 – 1245 cm\(^{-1}\) increased with the addition of CSL, further supporting that the CSL led to the transformation of random coils into \(\beta\)-sheets in TWG. The intensity of Amide I bands at 1667 and 1655 cm\(^{-1}\) were markedly increased by addition of CSL to the extrusion cooking process. The increases in band intensity following extrusion indicate the disruption of secondary structures. The intensity of the band at 1668 cm\(^{-1}\), signaling the presence of random coils, also significantly increased with CSL. We hypothesize that the CSL triggered structural unfolding of the proteins during the extrusion process, enabling the denatured proteins to rearrange and/or re-associate their structures to form more stable intermediates (Ngarize et al., 2004; Tang and Ma, 2009).

According to a previous report, C = O groups have significant stretching vibrations in Raman wavenumbers between 1740 – 1800 cm\(^{-1}\) (Chen et al., 1991). As shown in Figure 4B, we did not observe a significant change in the intensity of C = O absorption peaks for TWG compared to WG, confirming that glutamine and asparagine deamidation reactions did not occur.

According to previous studies, Raman spectroscopy can

### Table 4. Effects of CSL on the secondary structure of TWG

<table>
<thead>
<tr>
<th>Sample</th>
<th>Intramolecular (\beta)-sheet of protein aggregation</th>
<th>Intermolecular (\beta)-sheet of protein aggregation</th>
<th>Random coil</th>
<th>(\alpha)-helix</th>
<th>(\beta)-turn</th>
<th>(\beta)-sheet</th>
<th>Extended (\beta)-sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Content</td>
<td>Content</td>
<td>Content</td>
<td>Content</td>
<td>Content</td>
<td>Content</td>
<td>Content</td>
</tr>
<tr>
<td>WG</td>
<td>5.1 ± 0.06(^a)</td>
<td>14.7 ± 0.13(^d)</td>
<td>21.8 ± 0.19(^b)</td>
<td>24.0 ± 0.05(^a)</td>
<td>20.7 ± 0.19(^b)</td>
<td>12.3 ± 0.16(^b)</td>
<td>0.9 ± 0.11(^c)</td>
</tr>
<tr>
<td>TWG-0.04</td>
<td>5.58 ± 0.07(^d)</td>
<td>15.99 ± 0.19(^c)</td>
<td>22.29 ± 0.09(^b)</td>
<td>23.59 ± 0.07(^b)</td>
<td>20.34 ± 0.31(^b)</td>
<td>10.88 ± 0.18(^d)</td>
<td>1.34 ± 0.06(^b)</td>
</tr>
<tr>
<td>TWG-0.08</td>
<td>6.56 ± 0.08(^b)</td>
<td>16.81 ± 0.15(^b)</td>
<td>21.40 ± 0.05(^c)</td>
<td>22.45 ± 0.1(^d)</td>
<td>19.02 ± 0.09(^b)</td>
<td>12.13 ± 0.22(^b)</td>
<td>1.64 ± 0.04(^d)</td>
</tr>
<tr>
<td>TWG-0.12</td>
<td>6.97 ± 0.04(^c)</td>
<td>17.24 ± 0.09(^a)</td>
<td>21.28 ± 0.07(^a)</td>
<td>22.71 ± 0.06(^b)</td>
<td>18.69 ± 0.08(^b)</td>
<td>11.52 ± 0.07(^b)</td>
<td>1.58 ± 0.02(^b)</td>
</tr>
</tbody>
</table>

Superscript letters indicate significant differences in the same column \((P < 0.05)\).
sensitively detect wheat gluten disulfide bonds (Cui et al., 2013). Disulfide bonds have a significant impact on tertiary conformational changes in proteins, such as by affecting folding and aggregation. Generally, disulfide bonds are not easily broken to generate sulfhydryl bonds (SH) under weak external conditions. Therefore, changes in the tertiary structure of a protein can be assessed based on the Raman spectra of vibration absorption peak intensity for disulfide bonds. As depicted in Fig. 4A, the presence of 521 cm\(^{-1}\) Raman stretching in TWG samples clearly proves the presence of disulfide bonds in texturized wheat gluten. The WG samples exhibited the least stretching in the Raman peaks in this wavenumber (521 cm\(^{-1}\)), followed by the TWG-0% CSL samples. Whereas the greatest stretching was observed in the TWG-0.08% CSL. Thus, TWG-0.08% CSL had the highest number of disulfide bonds. This proves that the spatial structure of TWG-0.08% CSL was stronger compared to that of WG and TWG-0% CSL. This may be attributed to interactions occurring between the CSL and

wheat gluten, combined with hydrophilic molecular bonds forming between gliadin and glutenin molecules, resulting in a stronger wheat gluten structure. Meanwhile, exposed -SH groups could be oxidized, creating S-S bonds (Pan et al., 2011). Therefore, our data indicate that the addition of CSL to the extrusion process resulted in a more compact protein structure in the texturized wheat gluten, improving the hardness and chewiness of TWG.

Analysis on reduced SDS-PAGE

According to previous reports, the electrophoretic pattern of original wheat gluten and texturized wheat gluten consists mainly of four subunits, namely: HMW-GS, \(\omega\)-gliadin, LMW-GS and a mixed group consisting of \(\alpha\), \(\beta\) and \(\gamma\)-gliadins subunits (Liao et al., 2010a; Steffolani et al., 2010). As can be seen in Fig. 5, dramatic distinctions could be observed between WG and TWG wheat gluten subunits. Electrophoretic analysis of TWG products following twin screw extrusion treatment resulted in a lower intensity of \(\omega\)-gliadin bands paired with a clear increase in the optical density of band P. This

Fig. 3. Deconvoluted FTIR spectra of wheat gluten samples in Amide I region. (A) WG; (B) TWG; (C) TWG-0.04; (D) TWG-0.08; (E) TWG-0.12.
change is indicative of the formation of many high-molecular-weight polymers in the extrudates that were too large to enter the resolving gel. However, no new bands (< 97.4 kDa) were observed in lanes 2, 3, 4 and 5, indicating that the wheat gluten molecules were not degraded under the powerful extrusion conditions, regardless of whether or not CSL was included as an additive. Interestingly, we found that the intensity of ω-gliadin bands at approximately 66.2 kDa in the TWG-0.04% CSL, TWG-0.08% CSL and TWG-0.12% CSL samples were higher than those in TWG without CSL samples. This may be attributed to the fact that the Maillard reaction was inhibited by addition of CSL. These results are consistent with those from FTIR spectroscopy.

Microstructures SEM can be used to investigate the spatial and network structures of different materials (Chen et al., 1991; Cui et al., 2013). For our study, we used SEM to analyze microstructure features present in WG and TWG, as shown in Fig. 6. Significant distinctions could be observed between the microstructures of wheat gluten samples. The WG consisted of irregular particles (Fig. 6A), while fibrous, meat-like elasticity could be observed for the TWG tissue proteins formed under extrusion with high temperature (140 – 150°C), high pressure (20 – 50 bar), and high shear force (torque 15 – 40 Nm) (Mei and Lee, 1996). As depicted in Fig. 6, the surface of TWG without CSL was coarser and more irregular, with fewer gluten fibrils and larger-sized pores (Fig. 6B) compared to TWG processed with CSL, which consisted of presented a more continuous, smooth, and compact gluten network structure (Fig. 6C, D, E). These changes in the TWG microstructures further support the function of CSL in improving the properties of wheat gluten texture, which must thus also affect its processing properties and taste.

Conclusions CSL is widely used in pasta industry and the effect on extrusion properties of wheat gluten has been studied less. This study found that the CSL had a great influence on physicochemical properties and structure of wheat gluten extrudates. CSL can significantly enhance the hardness, adhesiveness, and chewiness of extruded wheat gluten. The addition of CSL also resulted in the increase of fibrils and decrease in the pores size of the extrudates as described by SEM. In addition, FTIR and reducing SDS-PAGE analysis showed that CSL could inhibits Maillard reaction in the process of twin-screw extrusion. Moreover, a reduction in α-helix and β-turn and an obviously increase in β-sheet and disulfide bonds indicated wheat gluten structure unfolding in the process of extrusion. Compared with the TWG, TWG-CSL formed a more compact fibrous structure and enhanced the network structure, which enlarged the application of texturized wheat gluten in foodstuff.

Acknowledgements This research project was supported by funds provided by the Key Project of Science and Technology of Anhui Province (No. 1301031031), the National High Technology Research and Development Program of China (863 Program) (No.
References


