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Research Article

Yield and Physicochemical Properties of Soluble Dietary Fiber Extracted from Untreated and Steam Explosion-Treated Black Soybean Hull

Meng Shen,[1] **Yunfei Ge**,[1] **Ziyue Kang**,[1] **Zhigang Quan**,[1] **Juan Wang**,[1] **Jinling Xiao**,[1] **Weihao Wang**,[2] **and Longkui Cao**[1,2]

[1]*College of Food Science, Heilongjiang Bayi Agricultural University, Daqing 163319, Heilongjiang, China*
[2]*National Coarse Cereals Engineering Research Center, Heilongjiang Bayi Agricultural University, Daqing 163319, Heilongjiang, China*

Correspondence should be addressed to Longkui Cao; caolongkui20190606@163.com

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Black soybean hull was subjected to steam explosion (SE) treatment under different conditions to improve the yield and properties of soluble dietary fiber (SDF) extract. Optimal conditions for SE treatment were found to be moisture content of 15%, pressure level of 1.0 MPa, and treatment time of 80 s. Under these conditions, the yield of SDF increased from 10.20% to 17.49%. In addition, structural and functional properties of SDF from untreated and SE-treated black soybean hull were investigated. Soluble dietary fiber extracted from SE-treated hull exhibited lower molecular weight and improved functional properties, such as cholesterol-binding capacity, when compared to SDF extracted from untreated soybean hull. In addition, SDF extracted from SE-treated black soybean hull showed a rough surface structure, while a smooth surface structure was found for SDF extracted from the untreated hull. The obtained results indicate that SE treatment can be successfully used to enhance the yield and the property of yolk cholesterol absorption of SDF adsorption of yolk cholesterol functional properties of SDF from black soybean hull.

1. Introduction

Black soybean is an economic crop in China, with an estimated average cultivation area of 13,333.33 square kilometers and a total production of 220,000 tons [1]. Black soybean hull, by-products of black soybean processing, is usually used as animal feed and is rich in nutrients and bioactive compounds such as proteins, polysaccharides, pigments, and polyphenols [2–5]. Also, anthocyanins of black soybean hull showed antioxidant and antidiabetic effects in rats [6]. Recently, bioactive compounds in black soybean hull received more attention from researchers and scientists. For example, black soybean hull beverage was prepared, and its free radical scavenging ability was measured [7]. However, studies performed on extracts of functional soluble dietary fiber (SDF) from black soybean hull are limited.

Dietary fiber (DF) attracts much attention for its functional characteristics and potential health benefits, such as the effect against heart diseases, atherosclerosis, hyperglycemia, hyperlipidemia, obesity, and other diseases [6]. Dietary fiber is a carbohydrate polymer that cannot be completely digested by human digestive enzymes but has shown important physiological functions in the body [8]. According to solubility, DF is divided into SDF and insoluble dietary fiber (IDF) [9]. Soluble dietary fiber consists of pectin, hemicellulose, and vegetable gum, while IDF consists of cellulose, hemicellulose, and lignin [9]. Several potential health benefits were noted for SDF. These include antioxidant activity, cholesterol-lowering effect, adsorption and α-glycosidase inhibition, and antidiabetic effects [10–15]. Furthermore, SDF may enhance the functional properties of food, such as water-holding capacity, oil-holding capacity, emulsification, and gel formation. Studies have shown that

SDF can reduce postprandial blood glucose, increase insulin secretion, improve food intake and body weight, and reduce plasma glucose concentration in diabetic rats; it can also reduce the concentration of cholesterol, triglyceride, and low-density lipoprotein cholesterol in plasma [16–19].

The steam explosion (SE) method is used to soften materials such as wood under a high temperature and pressure environment. This high temperature and pressure damages the binding force of fibers and results in dissolution or degradation of large molecular carbohydrate polymers to small molecular polysaccharides [20]. When compared with other treatment methods, the advantages of SE included considerably lower energy consumption, lower capital investment, and less hazardous process chemicals [21]. Kang [22] showed SE treatment effectively increased SDF content in bean dregs. Also, Sun et al. [23] found that SE treatment of apple dregs increased pectin yield and the surface of pectin became softer. Using Fourier infrared spectrum research, Zhang et al. [24] found that SE processing of corn husk dissolved lignin. The destruction of its structure has a certain effect, and this is shown by nuclear magnetic resonance (NMR) spectrometry. The SE treatment of corn husk can degrade cellulose, hemicellulose, and lignin into small molecules, indicating that SE treatment can promote the degradation of corn husk. This work aimed at studying the efficiency of SE treatment in the enhancement of dietary fiber conversion and SDF extraction from black soybean hull. The effect of SE treatment on the functional properties of extracted SDF was also investigated.

2. Materials and Methods

2.1. Materials and Reagents. Black soybean hull was obtained from Bozhou Runbang Food Sales Co., Ltd (Anhui, China); soybean oil was obtained from Beijing Hualian Supermarket (Daqing, China); α-amylase (heat-stable) (A3306), protease from *Bacillus licheniformis* (P3910), and amyloglucosidase solution from *Aspergillus niger* (A9913) were purchased from Sigma (St. Louis, MO, USA). Other chemical reagents used in this study were obtained from Damao Chemical Reagent Factory (Tianjin, China).

2.2. Steam Explosion Treatment of Black Soybean Hull. Black soybean hull samples (250 g) for each group of tests were placed into a SE vessel, and the extraction ratio of SDF was taken as the test index. Different pressure levels, treatment times, and moisture contents were applied to determine optimal conditions. At a moisture content of 15% and time of 80 s, pressure levels of 0.5 MPa, 0.75 MPa, 1.0 MPa, 1.25 MPa, 1.5 MPa, and 1.75 MPa were applied to investigate the effect of different pressures on the extraction ratio of SDF. On the other hand, at a pressure level of 1.0 MPa and moisture content of 15%, treatment times of 20 s, 40 s, 60 s, 80 s, 100 s, and 120 s were applied to study the effect of different treatment times on the extraction ratio of SDF. Furthermore, at a pressure of 1.0 MPa and time of 80 s, moisture contents 9%, 11%, 13%, 15%, 17%, and 19% were applied to study the effect of different moisture contents on the extraction ratio of SDF [24]. All experiments and tests were performed in triplicate.

2.3. Extraction of Soluble Dietary Fiber (SDF). One gram of black soybean hull powder (60 mesh, 8–10% water content) was weighed and suspended in distilled water at a solid-to-water ratio of 1 : 30 (w/v). The pH was adjusted to 6.0, and 100 μL of α-amylase (heat-stable) was added. The reaction mixture was incubated at 95°C to 100°C for 20 min in a water bath. Then, the pH was adjusted to 7.0 and 100 μL protease from *Bacillus licheniformis* was added. The mixture was then incubated at 60°C for 30 min. Thereafter, the pH was adjusted to 4.5 and 100 μL amyloglucosidase solution from *A. niger* was added and the mixture was incubated at 60°C for 30 min. The mixture was then filtered under vacuum and concentrated by rotary evaporation. Ethanol (95%) was added to the concentrate at a concentrate/ethanol ratio of 1 : 4 (v/v). After 10 h of precipitation, the mixture was centrifuged at 3,200 rpm for 30 min and freeze-dried at −108°C for 8 h to get soluble dietary fiber (SDF) [25]:

$$\text{SDF extraction ratio}\,(\%) = \frac{M_2}{M_1} \times 100\%, \tag{1}$$

where M_1 is the weight of the dried hull sample and M_2 is the weight of the dried SDF.

2.4. Measurement of Cellulose and Hemicellulose

2.4.1. Measurement of Acid Detergent Lignose (ADL) Content. Dried hull was ground to pass through a 40-mesh sieve, and 1 g of sample was weighed in a crucible. The sample crucible was placed in a FIWE6 cellulose analyzer host device (VELP Scientifica, Milan, Italy), and 100 mL acid detergent (prepared by dissolving 20 g hexadecyl trimethyl ammonium bromide (CTAB) in 1,000 mL 1 mol/L sulfuric acid solution) was added with three drops of octanol ($C_8H_{18}O$) at 25°C. Thereafter, the mixture was boiled for 60 min, filtered, washed three times with boiling water, and then washed twice with cold acetone. A volume of 25 mL of 72% sulfuric acid was added at room temperature to dissolve cellulose, and cold extraction was performed for 3 h. The mixture was filtered and the residue washed with boiling water three times until it cooled down to ambient temperature, dried at 105°C for 8 h, cooled in a drying jar, and weighed [26]:

$$\text{ADL}\,(\%) = \frac{M_3 - M_2}{M_1} \times 100\%, \tag{2}$$

where M_1 is the weight of the dried hull sample, M_2 is the weight of the crucible, and M_3 is the weight of the crucible and dried residue.

2.4.2. Measurement of Acid Detergent Fiber (ADF) Content. Dried hull was ground to pass through a 40-mesh sieve, and 1 g of sample was weighed. A volume of 100 mL acid solvent, prepared by dissolving 20 g of cetyltrimethylammonium bromide ($C_{19}H_{42}BrN$) in 1 N/L sulfuric acid (H_2SO_4, 49.04 g/L, 1 L), was added with several drops of octanol

($C_8H_{18}O$) at room temperature. The mixture was then boiled for 60 min and filtered. The residue was washed three times with boiling water and twice with cold acetone. The residue was then dried at 105°C for 8 h, cooled in a drying jar, and weighed [26]:

$$\text{ADF}(\%) = \frac{M_3 - M_2}{M_1} \times 100\%, \quad (3)$$

where M_1 is the weight of the dried hull sample, M_2 is the weight of the crucible, and M_3 is the weight of the crucible and dried residue.

2.4.3. Measurement of Neutral Detergent Fiber (NDF) Content. Dried hull was ground to pass through a 40-mesh sieve, and a 1 g sample was weighed at room temperature and added to100 mL of NDF containing 0.5 g Na_2SO_3 and 1 mL acetone. The mixture was boiled for 60 min and filtered, and the residue was washed three times with boiling water and twice with cold acetone. The washed residue was dried at 105°C for 8 h, cooled in a drying jar, and weighed [26]. The NDF configuration was prepared by dissolving 6.81 g of pure sodium tetraborate decahydrate and 18.61 g ethylenediaminetetraacetic acid (EDTA) in distilled water while heating. Thereafter, 30 g of sodium dodecyl sulfonate and 10 mL glycol ether were added. Disodium hydrogen phosphate (4.56 g) was dissolved separately and then mixed with the NDF configuration solution. A volume of 1 L was used and the pH was adjusted to 6.9 to 7.1:

$$\text{NDF}(\%) = \frac{M_3 - M_2}{M_1} \times 100\%, \quad (4)$$

where M_1 is the weight of the dried hull sample, M_2 is the weight of the crucible, and M_3 is the weight of the crucible and residue.

The formulas for hemicellulose, cellulose, and lignin are as follows [25]:

$$\begin{aligned} \text{hemicellulose}(\%) &= \text{NDF} - \text{ADF}, \\ \text{cellulose}(\%) &= \text{ADF} - \text{ADL}, \\ \text{lignose}(\%) &= \text{ADL}. \end{aligned} \quad (5)$$

2.5. Measurement of Physicochemical Properties of Treated and Untreated Black Soybean Hull

2.5.1. Measurement of Water-Holding Capacity. Ground hull samples (1.0 g each) were weighed and suspended in a deionized solid/water ratio of 1 : 20 (w/v) and mixed well. The mixture was kept at room temperature for 24 h and centrifuged at 2000 rpm for 10 min, the excess water discarded, and residue weighed. All experiments were performed in triplicate, and the water-holding capacity (WHC) was calculated by the following equation [27, 28]:

$$\text{WHC}(\text{g/g}) = \frac{M_2 - M_1}{M_1}, \quad (6)$$

where M_1 is the weight of the dried hull sample and M_2 is the weight of the wet sample.

2.5.2. Measurement of Swelling Capacity. One gram of sample was weighed and placed into a tube and the volume recorded. Then, deionized water was added at a solid/water ratio of 1 : 30 (w/v) and mixed well. The sample tubes were left at room temperature for 20 h and the volume of samples was recorded after swelling upon water absorption. All experiments were performed in triplicate, and the swelling capacity (SWC) was calculated by the following equation [29]:

$$\text{SWC}(\text{mL/mL}) = \frac{V_2 - V_1}{V_1}, \quad (7)$$

where V_1 is the volume of the dried hull sample and V_2 is the volume of the sample after swelling upon water absorption.

2.5.3. Measurement of Water-Binding Capacity. A 0.1 g sample was soaked in 25 mL of deionized water for 1 h. The mixture was centrifuged at 4000 rpm for 1 h and the supernatant discarded. The residue was put into a G-2 sand core crucible for 2 h, weighed, and dried at 105°C for 3 h and then weighed again. Experiments were performed in triplicate, and the water-binding capacity was calculated by the following equation:

$$\text{WBC}(\text{g/g}) = \frac{M_2 - M_3}{M_1}, \quad (8)$$

where M_1 is the weight of the dried sample, M_2 is the weight of the wet sample after soaking in water, and M_3 is the weight of the sample after water-soaking and drying.

2.5.4. Measurement of Oil-Holding Capacity. A 1.0 g sample was weighed in a centrifugal tube, to which 10 mL edible soybean oil was added and mixed well. The sample tube was kept for 1 h at room temperature and subsequently centrifuged at 4000 rpm for 20 min. Excess oil was discarded and residue weighed. All experiments were performed in triplicate, and the oil-holding capacity (OHC) was calculated by the following equation [30]:

$$\text{OHC}(\text{g/g}) = \frac{M_2 - M_1}{M_1}, \quad (9)$$

where M_1 is the weight of the dried hull sample and M_2 is the weight of the sample after oil absorption.

2.6. Scanning Electron Microscopy (SEM) Analysis. A small amount of dried ground SDF sample was deposited on an aluminum stub lined with carbon tape, coated with gold, and viewed using a scanning electron microscope (Hitachi Limited, Tokyo, Japan) at an acceleration voltage of 15 kV [31]. The appearance of SDF before and after treatment was observed.

2.7. Measurement of Molecular Mass Distribution of SDF. Samples (10 mg each) of SDF, extracted from treated or untreated black soybean hull, were weighed, and 1.0 mL of 0.1 mol/L $NaNO_3$ solution was added. The mixture was set at

45°C for 4 h and subsequently diluted four times. Thereafter, the mixture was filtered using a 0.22 μm filter membrane and 100 μL of filtrate was analyzed. Gel permeation chromatography analysis conditions were as follows: moving phase was 0.1 mol/L $NaNO_3$, flow rate was 0.4 mL/min, column temperature was set at 60°C, analytical column model was Waters Styragel HMW 6E (Beijing Lvbaicao Science and Technology Development Co., Ltd, Beijing, China), and analysis column type: Ohpak SB-805 HQ, Ohpak SB-804 HQ, and Ohpak SB-803 HQ. The data were input into ZP software, and the appropriate fitting mode was selected according to the different conditions of the polymer, namely, Zimm, Berry, and Debye. The Zimm figure was used to obtain the average molecular weight, Rg, and the coefficient A_2 in the second dimension [32].

2.8. Monosaccharide Composition Analysis. Samples of SDF (5 mg each), extracted from treated or untreated black soybean hull, were weighed, and 500 μL of 2.5 mol/L trifluoroacetic acid (TFA) was added to each sample. Samples were hydrolyzed at 121°C for 2 h in an oven, cooled to room temperature, blow-dried with nitrogen, dissolved in methanol, and continually blow-dried with nitrogen. Thereafter, 1 mL of deionized water was added for dissolution and dilution, and 25 μL of the solution was taken for analysis. Ion chromatography apparatus specifications and analysis conditions are as follows: ICS5000 (Dionex); detector: PAD (pulse ampere detector); analytical column model: CarboPacPA10; column temperature: 30°C; flow rate: 1.0 mL/min; and moving phase: 0–40 min: 5 mmol/L NaOH, 40–45 min: 100 mmol/L NaOH and 100 mmol/L NaOAc, 45–50 min: 200 mmol/L NaOH, and 50.2–55 min: 5 mmol/L NaOH.

Monosaccharide content was calculated as follows:

$$\text{monosaccharide content}\,(\mu\text{g/mg}) = \frac{\text{sugar concentration} \times \text{dilution ratio}}{\text{sample mass}}. \quad (10)$$

2.9. Cholesterol-Binding Capacity of SDF. Since cholesterol is difficult to dissolve in water, even after addition of emulsifiers, egg yolk was used as a model system. Fresh egg yolk (16.4 g/egg, on average), containing 14.26 mg/g cholesterol, was whipped with nine volumes of deionized water. A mixture of 2.0 g SDF and 50 mL of diluted yolk at pH 7.0 or 2.0 (similar to pH conditions in the stomach and small intestine, respectively) was shaken at 80 rpm for 2 h in a 37°C water bath. Diluted yolk without SDF was used as the blank. At the end of adsorption, 4 mL of the sample and 16 mL of absolute ethanol were added to precipitate the SDF. The mixture was then centrifuged at 4000 rpm for 20 min; ethanol in the supernatant was removed using a vacuum evaporator (Shanghai Senxin Laboratory Instrument Co. LTD, Shanghai, China) at 40°C. One milliliter of the concentrate was diluted five times with 90% acetic acid. Color was developed by adding 0.1 mL of *o*-phthalaldehyde reagent and 2 mL of concentrated H_2SO_4, according to the method by Park [33]. Absorbance was read 20 min after addition of H_2SO_4 at 550 nm against a reagent blank. The cholesterol concentration in samples was determined against a standard curve generated using a standard cholesterol solution.

The binding capacity (BC) was calculated as follows:

$$\text{BC}\,(\text{mg/g}) = \left[C_{\text{yolk}} - \left(C_{\text{blank}} - C_{\text{d}}\right) \times F\right] \times \frac{50}{w}, \quad (11)$$

where C_{yolk}, C_{blank}, and C_{d} are the concentrations of cholesterol in the yolk, the yolk without SDF, and the mixture of yolk with SDF, respectively; F is the dilution factor (10); 50 is the adsorption volume (mL); and w is the weight of SDF.

2.10. Statistical Analysis. Each experiment was performed in triplicate, and obtained data were statistically analyzed and expressed as means ± standard deviation (SD). Statistical analysis was conducted using Microsoft Excel (2003), where $p < 0.05$ was used as the standard for significance.

3. Results and Discussion

3.1. Single Factor Analysis of SDF Extraction Ratio. As shown in Figure 1(a), the extraction ratio of black soybean hull SDF increased as the pressure level increased to 1.0 MPa. However, at pressure levels higher than 1.0 MPa, the extraction ratio decreased. This increase in extraction ratio may be attributed to the fact that pressure destroyed the tissue structure of black soybean hull and made it easy for SDF to dissolve out [28]. In other words, at pressure levels between 0.25 and 0.75 MPa, the soybean hull fiber may have lost their compact structure and some substances bound with fiber depolymerized and macromolecular polysaccharides degraded. Therefore, their molecular weight decreased and resulted in a greater extraction ratio of SDF. On the contrary, at higher pressure levels (of 1.25 MPa to 1.50 MPa), greater degradation in cellulose, hemicellulose, and other substances in the soybean hull was noted, which produced monosaccharides or oligosaccharides with smaller molecular weights, and thus, the extraction ratio of SDF was decreased [13, 34].

As shown in Figure 1(b), the extraction ratio of SDF from black soybean hull increased with an increase in SE treatment time and reached a maximum value at 80 s. These results indicate when SE treatment time was short, the compact structure of black soybean hull fiber was slightly damaged, resulting in a lower SDF extraction ratio [28]. However, when SE treatment time was prolonged, greater degradation in soybean hull structure occurred and monosaccharides or oligosaccharides with smaller molecular weights were produced. This resulted in a decrease in the SDF extraction ratio [35, 36].

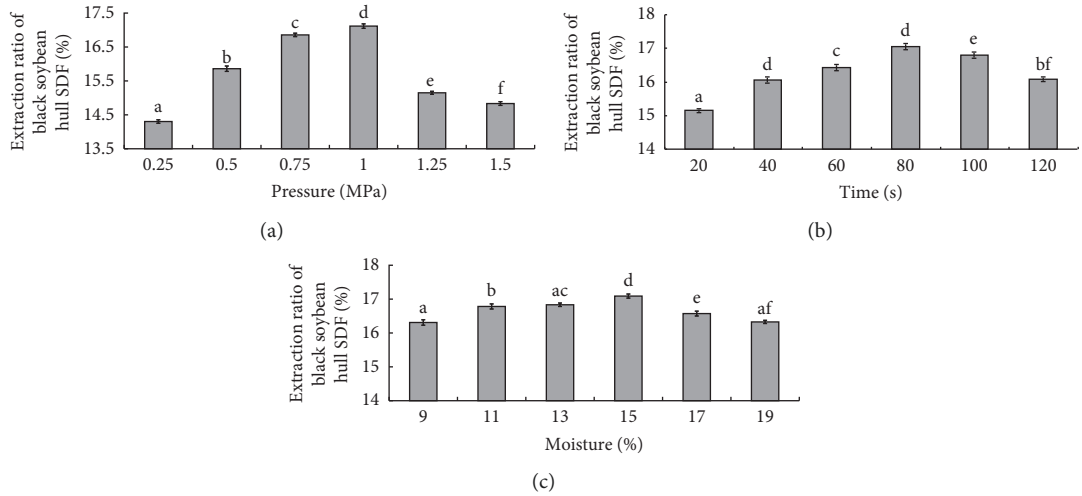


Figure 1: Extraction yield of SDF at different steam explosion (SE) treatment conditions: (a) black soybean hull (500 g) treated by SE at different steam pressures for 80 s and 15% moisture; (b) black soybean hull (500 g) treated by SE at 1.0 MPa and 15% moisture at different times; (c) black soybean hull (500 g) treated by SE at 1.0 MPa and 80 s at different moisture contents. Different letters on the top of a column indicate significant differences ($p < 0.05$), and the same letters on the top of a column indicate differences that are not significant ($p > 0.05$); $n = 3$.

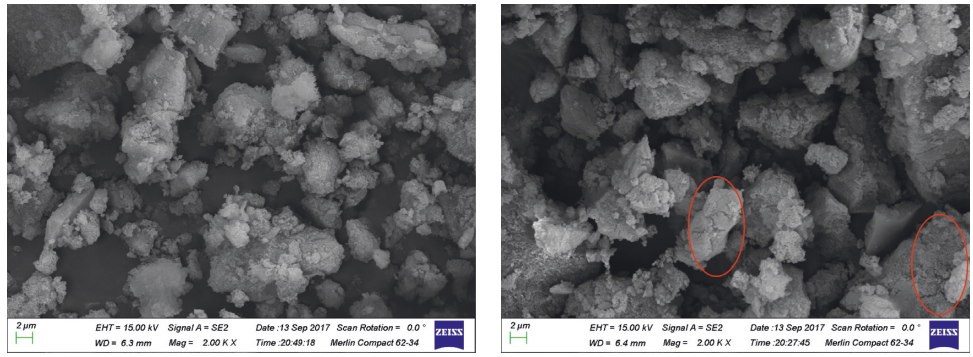
As shown in Figure 1(c), the SDF extraction ratio increased as the moisture content of the soybean hull increased by up to 15% during SE treatment. However, when the moisture content of soybean hull was greater than 15%, the SDF extraction ratio decreased. These results indicate at a lower moisture content (<15%), the temperature of the soybean hull increased during SE treatment and that resulted in the evaporation of water present in the hull. Therefore, the expansion was not sharp and the explosive force was small causing slight damage in cellulose and hemicellulose bundles, resulting in a lower SDF extraction ratio. On the other hand, greater damage in cellulose and hemicellulose structure may have occurred in soybean hull at a greater moisture content (>15%) with high temperature and pressure; therefore, the SDF extraction ratio also decreased.

3.2. Microstructure of SDF. Micrographs of SDF, extracted from untreated and SE-treated soybean hull, as obtained from SEM are shown in Figure 2. From the micrographs (Figure 2(b)), it can be seen that surface of SDF, extracted from black soybean hull after explosion treatment, is rough with large diameter pores and damaged internal structure, while SDF extracted from the untreated soybean hull showed a smooth surface with smaller diameter pores and compact internal structure (Figure 2(a)). These results may be attributed to the evaporation of water during SE treatment from the hull. The steam caused rapid expansion; therefore, the surface and internal structures of the fiber bundles were damaged [28]. In addition, some substances bound with fiber were depolymerized at high temperature and high pressure; therefore, pores appeared on the surface structure of SDF extracted from steam explosion-treated black soybean hull.

3.3. Cellulose, Hemicellulose, and Lignose Contents. From Table 1, it can be seen that cellulose, hemicellulose, and lignose contents in black soybean hull decreased by 2.06%, 20.53%, and 18.56% after SE treatment compared to those in the untreated black soybean hull, respectively. This can be attributed to the fiber bundle structure, i.e., the ordered structure of hydrogen bonds and arrangement in cellulose, hemicellulose, and lignose in black soybean hull destroyed due to the high temperature and pressure during the SE treatment [37].

3.4. Physicochemical Properties of Black Soybean Hull. As shown in Table 1, water-holding capacity, swelling capacity, water-binding capacity, and oil-holding capacity of black soybean hull increased by 19.06%, 137.50%, 116.77%, and 4.96% after explosion treatment, respectively. This can be attributed to the degradation and conversion of macromolecular cellulose and hemicellulose to SDF and monosaccharides or oligosaccharides with smaller molecular weights under high temperature and pressure during SE treatment. Cellulose and hemicellulose molecules contain hydrophilic groups with strong water-holding and swelling capacities. Also, cellulose and hemicellulose molecules become gel after water absorption and expansion and can absorb oil and cholesterol in food. Therefore, fiber is expected to possess cholesterol-lowering effects in the human body and reduce blood fat [38]. These results indicate that SE treatment increased the short-chain SDF and the SDF surface area, which is reflected in the improvement of the water-holding capacity, swelling capacity, and water-binding capacity of black soybean hull.

3.5. Molecular Mass Distribution of SDF. From the data shown in Table 2, it can be seen that weight average molecular weight of SDF extracted from SE-treated black soybean hull is lower than that of SDF extracted from



(a) (b)

Figure 2: SEM images of SDF extracted from black soybean hull before SE treatment (a) and after SE treatment (b). SE treatment conditions: pressure level of 1.0 MPa, moisture content of 15%, and treatment time of 80 s. The images were captured at 2000x magnification.

Table 1: Cellulose, hemicellulose, and lignose contents and physicochemical properties of black soybean hull before and after SE treatment.

	CE (%)	HE (%)	LI (%)	WHC (g/g)	SC (mL/g)	WBC (g/g)	OHC (g/g)
A	24.47 ± 0.59^{a}	16.34 ± 0.32^{a}	20.18 ± 0.15^{a}	3.41 ± 0.08^{b}	2.00 ± 0.16^{b}	4.34 ± 0.13^{b}	2.62 ± 0.13^{b}
B	22.06 ± 0.75^{b}	12.99 ± 0.34^{b}	16.44 ± 0.28^{b}	4.06 ± 0.14^{a}	4.75 ± 0.10^{a}	7.24 ± 0.22^{a}	2.75 ± 0.19^{a}

Note: data are means of triplicate ± standard deviation. Values in the same column with different letters are significantly different ($p < 0.05$). Values in the same column with the same letters are not significantly different ($p > 0.05$); $n = 3$. A: SE treatment of black soybean hull; B: untreated black soybean hull. CE: cellulose; HE: hemicellulose; LI: lignose; WHC: water-holding capacity; SC: swelling capacity; WBC: water-binding capacity; OHC: oil-holding capacity; SE: steam explosion. SE treatment conditions: pressure, 1.0 MPa; moisture, 15%; treatment time, 80 s.

Table 2: Molecular weight of SDF extracted from SE-treated and untreated black soybean hull.

Samples	Number average molecular weight (Mn) (kDa)	Weight average molecular weight (Mw) (kDa)	Polydispersity Pd (Mw/Mn)
SDF from untreated BSH	4.386×10^{4} (±9.485%)	2.815×10^{5} (±0.899%)	6.417 (±9.527%)
SDF from SE-treated BSH	4.886×10^{4} (±4.162%)	1.478×105 (±1.319%)	3.025 (±4.366%)

Note: the error upon the signal fluctuations caused by signal noise and small molecular mass is in the bracket behind the data. BSH: black soybean hull; SE: steam explosion. SE treatment conditions: pressure, 1.0 MPa; moisture, 15%; treatment time, 80 s.

untreated black soybean hull. This indicates that SE treatment shortened the molecular chain of SDF in black soybean hull and reduced the degree of polymerization. The smaller molecular weight and lower degree of polymerization indicate better solubility and lower viscosity of SDF [39]. The SE treatment under high temperature and pressure may have damaged the hydrogen bonds and ordered structure of cellulose, which made hydroxyl with a stable structure free and break the macromolecular crystal lattice at the molecular level [37]. In addition, high temperature and pressure during SE treatment may have degraded macromolecular sugars to soluble polysaccharides with small weight average molecular weight [40]. At the same time, some small polysaccharides may have cross-linked and the molecular weight increased during the SE treatment, which is reflected in the increase in the number for average molecular weight after treatment. Therefore, these results may indicate a potential production of functional polysaccharides with a small molecular mass in the SDF due to SE treatment of soybean hull.

3.6. Monosaccharide Composition of SDF. Monosaccharide composition of untreated and SE-treated SDF is presented in Table 3. Similar monosaccharide composition was found for SDF extracted from untreated or SE-treated black soybean hull. Both SDF extracts contained fucose, arabinose, galactose, glucose, xylose, and mannose, arabinose, galactose, and mannose. The high temperature and pressure during SE treatment may have destroyed some glucosidic bonds [41]. Therefore, changes in the monosaccharide content of SDF occurred after SE treatment, i.e., content of some monosaccharides in SDF decreased and others increased after SE treatment. For example, the content of arabinose and xylose increased, while the content of galactose, glucose, and mannose decreased in SDF after SE treatment of black soybean hull.

3.7. Cholesterol-Binding Capacity of SDF in Egg Yolk. Cholesterol-binding capacity of SDF extracted from untreated and SE-treated black soybean hull is shown in

Table 3: Monosaccharide composition of SDF extracted from untreated and SE-treated black soybean hull.

	SDF from untreated BSH			SDF from SE-treated BSH		
	Peak area	Concentration (μg/mL)	Monosaccharide content (mg/g)	Peak area	Concentration (μg/mL)	Monosaccharide content (mg/g)
Fuc	0.619	0.694	2.777	1.290	1.375	5.501
Ara	3.990	0.083	0.331	10.214	9.458	37.831
Gal	36.936	57.862	231.446	29.229	37.843	151.374
Glc	6.467	8.752	35.007	3.942	4.659	18.638
Xyl	0.793	0.621	2.483	3.1058	3.282	13.130
Man	39.459	114.432	457.727	27.154	54.814	219.258

Note: data are presented as means of independent experiments. Fuc: fucose; Ara: arabinose; Gal: galactose; Glc: glucose; Xyl: xylose; Man: mannose. BSH: black soybean hull; SE: steam explosion. SE treatment conditions: pressure, 1.0 MPa; moisture, 15%; treatment time, 80 s.

Table 4. From these data, it can be seen that the oil-binding capacity of SDF increased after SE treatment of black soybean hulls. On the contrary, the cholesterol-binding capacity of the SDF from untreated and SE-treated black soybean hulls at pH 7 is higher than that at pH 2. These results are in agreement with the findings of previous studies [42, 43]. In the acidic state, there are many hydrogen ions, which repel the positive charge carried by SDF and cholesterol. Since SDF contains arabinuronic acid and galacturonic acid, the carboxyl group does not dissociate in the acidic state, and when the pH value increases, the carboxyl group dissociates into carboxyl anion (RCOO), which has a stronger interaction with cholesterol, leading to a higher binding capacity between SDF and cholesterol [44]. The binding force between the two is weakened, resulting in a decrease in SDF binding capacity. Since cholesterol is a water-insoluble molecule, it exists as oils in nature. Therefore, factors such as surface properties, thickness, and the hydrophobic nature of fiber affect cholesterol-binding capacity. The SDF extract from SE-treated black soybean hulls showed higher WHC and SC than those of SDF from the untreated hull. The microcrystalline beam force is abating, and as the amorphous state or polar group exposed area increases, cholesterol chelation by the reactive group increases. In addition, after water absorption and expansion, gel formation occurs, which can remove more cholesterol from food, thereby leading to a body cholesterol-lowering effect [45]. The high cholesterol-binding capacity of SDF extracted from SE-treated black soybean hulls may indicate a high potential hypocholesterolemic effect of the hulls as it can reduce the concentration of cholesterol in the gastrointestinal tract and hence reduce the absorption of cholesterol.

Table 4: Cholesterol-binding capacity of SDF in egg yolk.

	pH = 2 (mg/g)	pH = 7 (mg/g)
SDF from untreated BSH	8.66 ± 0.13^{a}	9.34 ± 0.06^{a}
SDF from SE-treated BSH	13.53 ± 0.07^{b}	15.35 ± 0.04^{b}

Note: data are means of triplicate ± standard deviation. Values in the same column with different letters are significantly different ($p < 0.05$). Values in the same column with the same letters are not significantly different ($p > 0.05$); $n = 3$. SE: steam explosion. SE treatment conditions: pressure, 1.0 MPa; moisture, 15%; treatment time 80 s.

4. Conclusion

SDF was effectively extracted from black soybean hulls after SE treatment. In comparison with SDF from untreated black soybean hull, SDF from SE-treated black soybean hull exhibited good properties such as cholesterol-binding capacity. The molecular structure of SDF became more porous, and the average molecular weight decreased after SE treatment of black soybean hulls. In addition, the monosaccharide composition ratio changed, but the functional group structure of SDF did not change after SE treatment. The results obtained suggest that functional SDF with potential cholesterol-lowering effects can be successfully extracted from black soybean hull after treatment by SE. Our laboratory will continue to study the functional properties of SDF and conduct animal experiments. The above results showed that SDF has a high nutritional value, ideal physiological activity, and adsorption function, making it a potential functional ingredient in the food industry.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Extraction ratio of black soybean. (*Supplementary Materials*)

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