Study on Physicochemical and Functional Properties of Soluble Dietary Fiber from Apple Pomace

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Abstract [**Objectives**] This study was conducted to investigate the physicochemical and functional properties of soluble dietary fiber (SDF) from apple pomace. [**Methods**] Soluble dietary fiber (SDF) from apple pomace was extracted by direct water extraction (W), lactic acid bacteria fermentation (F) and steam explosion (SE) respectively, and the extraction methods and physicochemical and functional characteristics were compared and analyzed. [**Results**] The solubility, water holding capacities, oil holding capacities and swelling capacities of W-SDF, F-SDF and SE-SDF were (2.13, 3.95 and 5.13 g/g), (9.02, 13.75 and 15.88 g/g), (2.13, 4.08 and 5.11 g/g), and (10.82, 14.03 and 15.77 ml/g), respectively. Their emulsifying activity, emulsifying stability and least gelation concentration were (30.28, 47.95 and 58.72 ml/100 ml), (37.88, 45.25 and 57.13 ml/100 ml), and (12.11, 11.25 and 9.87%), respectively. The adsorption capacities of W-SDF, F-SDF and SE-SDF for heavy metals (Pb, As and Cu) in the intestinal environment (pH 7) were (162.7, 183.5 and 197.3 μmol/g), (132.8, 156.7 and 168.9 μmol/g), and (57.2, 63.5 and 89.2 μmol/g) respectively. In the gastric environment (pH 2), they were (72.8, 110.5, 138.9 μmol/g), (82.1, 112.5, 135.7 μmol/g), and (38.9, 42.7, 55.1 μmol/g) respectively. [**Conclusions**] The study can provide a theoretical basis for functional modification and comprehensive utilization of dietary fiber from apple pomace.

Key words Apple pomace; Soluble dietary fiber; Extraction method; Physicochemical characteristics; Functional performance

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In recent years, people pay more and more attention to the important role of dietary fiber in food nutrition and clinical medicine, and it is called the "seventh largest nutritional element" of humans[1-3]. Although dietary fiber has no nutritional value, its physical and chemical characteristics make it have unique physiological functions and nutritional and health care functions. According to its solubility, it can be roughly divided into soluble dietary fiber (SDF) and insoluble dietary fiber (IDF)[4-8]. Soluble dietary fiber can exert its metabolic function better than insoluble dietary fiber in physiological function, and has special effects in promoting the growth of intestinal probiotics and preventing diabetes, obesity, coronary heart disease, arteriosclerosis and hyperlipidemia[9-15].

China is a big country in the production, consumption and export of apples in the world, and its planting area and annual output rank among the top in the world. The large amount of pomace left after deep processing of apples is a potential dietary fiber resource. If this part of resources is not fully utilized, it will cause serious waste of resources and pollution to the environment. Therefore, processing these byproducts of apple industry into natural dietary fiber can not only improve the added value of apple industry, but also bring huge social and economic benefits[16]. In this study, the extraction methods and physicochemical and functional characteristics of apple dietary fiber were compared and analyzed in detail, and it was pointed out that apple dietary fiber, as a functional food, has a wide development and application prospect in China.

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Materials and Methods

Experimental materials and reagents

Apple pomace was provided by Beijing Huiyuan Food Co., Ltd.

Soluble dietary fiber products:

W-SDF: After removing starch by high temperature-resistant α-amylase and protein by neutral protease, the apple pomace was directly extracted by water. The supernatant was precipitated by alcohol, and SDF was obtained by centrifugation. After drying and crushing, it was screened by a 80-mesh sieve to obtain white powder.

F-SDF: After removing starch by high temperature-resistant α-amylase and protein by neutral protease, the apple pomace was mixed with water at a ratio of 1 : 15 (*v/v*), and ground twice with a colloid mill. After sterilization, *Lactobacillus bulgaricus* and *Streptococcus thermophilus* were inoculated to ferment the pomace at 42 ℃ to pH 4.0, which was then adjusted to neutral pH. The supernatant was precipitated by alcohol, and fermented SDF was obtained after centrifugation and freeze-drying.

SE-SDF: After removing starch by high temperature-resistant α-amylase and protein by neutral protease, the apple pomace was added with deionized water according to a material-to-liquid ratio of 1 : 7 (g/ml). After stirring to mix well, the apple pomace was ground twice with a colloid mill. Next, it was treated with steam explosion equipment at a pressure of 4.0 MPa for 3 min, and centrifuged. The supernatant was precipitated by alcohol and centrifuged. The obtained filter residue was dried in a drying box at 40 ℃ at low temperature to obtain SDF.

Experimental methods

Determination of water holding capacity Water holding capacity (WHC) refers to the amount of water bound by a certain amount of sample without external force (except gravity and atmospheric pressure). Specific operation: A 1.0 g of sample was accurately weighed in a 50 ml centrifuge tube, and added with 20 ml of deionized water. After mixing well and standing at 4 ℃ for 24 h, the mixture was centrifuged at 4 200 r/min for 15 min, and then, the sample was weighed.

Water holding capacity (g/g) = (Wet weight of sample saturated with water − Weight of sample powder)/Weight of sample powder

Determination of oil holding capacity Oil holding capacity (OHC) refers to the amount of olive oil that a certain amount of sample can bind. Specific operation: A 1.0 g of sample was accurately weighed in a 50 ml centrifuge tube, and added with 10 ml of olive oil. After mixing well and standing at 4 ℃ for 1 h, the mixture was centrifuged at 4 200 r/min for 15 min, and then, the sample was weighed.

Oil holding capacity (g/g) = (Wet weight of sample saturated with oil − Weight of sample powder)/Weight of sample powder

Determination of swelling capacity Swelling capacity (SC) refers to the difference between the volume occupied by a certain amount of sample when it is immersed in excessive water and reaches equilibrium and its actual volume. Specific operation: A 0.2 g of sample was accurately weighed and added in a graduated test tube, and its volume was recorded. Next, 5.0 ml of distilled water was added. After mixing well and standing at 4 ℃ for 18 h, the volume of the sample after water absorption was recorded.

Swelling capacity (ml/g) = (Sample volume after swelling − Volume of sample powder)/Weight of sample powder

Determination of water solubility For the determination of water solubility (WS), A 1.0 g of sample was weighed in a centrifuge tube and added with deionized water according to a ratio of 1 : 10. After mixing well and standing at 4 ℃ for 1 h, centrifugation was performed at 3 000 r/min for 10 min to collect supernatant and residue, which were dried and weighed, respectively.

WS (%) = (Weight of supernatant after drying/Weight of sample powder) × 100

Determination of emusifying activity (EA) Specific operation: A 2.0 g of sample was weighed and dissolved in 100 ml of deionized water. The sample was sheared at 2 000 × g for 2 min, and then added with 100 ml of corn oil and sheared again at a high speed for 1 min. The obtained emulsion was added into a 15 ml graduated test tube and centrifuged at 3 000 r/min for 10 min. The volume of the emulsion was recorded.

EA (ml/100 ml) = Volume of emulsion layer/100 ml original emulsion volume

Determination of emusifying stability (ES) Specific operation: A 2.0 g of sample was weighed and dissolved in 100 ml of deionized water. The sample was sheared at 2 000 × g for 2 min, and then added with 100 ml of corn oil and sheared again at a high speed for 1 min. The obtained emulsion was heated at 80 ℃ for 30 min, cooled to room temperature, and centrifuged at 3 000 r/min for 10 min. The volume of the emulsion was recorded.

ES (ml/100 ml) = Volume of emulsion layer/100 ml original emulsion volume

Determination of least gelation concentration (LGC) Specific operation: Sample solutions with concentrations of 2%, 4%, 6%, 8%, 10%, 12% and 14% were prepared with deionized water, and 5 ml of each sample solution was added into a test tube, heated in a water bath at 100 ℃ for 1 h, and then cooled in a water bath for 1 h. LGC was based on the fact that the sample solution did not slide off when the test tube was reversed.

Evaluation of binding capacity (BC) Specific operation: Into 250 ml triangular flasks, 10 mmol/L of heavy metal solutions ($Pb(NO_3)_2$, $CuSO_4$, $NaAsO_2$) and 1.0 g of dietary fiber samples were added, respectively. In order to simulate the environment of the stomach and intestines *in vitro*, the pH value was adjusted to 2.0 and 7.0, respectively, and oscillation was performed at 37 ℃ and 120 r/min for 3 h. After adsorption, in order to precipitate the sample, 8 ml of absolute ethanol was added to 2 ml of sample collection solution, and centrifugation was performed at 4 000 r/min for 10 min. The supernatant was determined for concentrations of residual heavy metal ions by atomic absorption spectrometry.

Data processing

Design-Expert 7.0 was employed for experimental design and data processing.

Results and Analysis

Effects of different extraction methods on water holding capacity, oil holding capacity, swelling capacity and solubility of SDF

It can be seen from Table 1 that the physicochemical properties of apple SDF were improved after fermentation by lactic acid bacteria and steam explosion. The solubility, water holding capacity, oil holding capacity and swelling capacity of W-SDF were 2.13 g/g, 9.02 g/g, 2.13 g/g and 10.82 ml/g, respectively. The solubility, water holding capacity, oil holding capacity and swelling capacity of F-SDF increased to 3.95 g/g, 13.75 g/g, 4.08 g/g and 14.03 ml/g, respectively; and the values of SE-SDF increased to 5.13 g/g, 15.88 g/g, 5.11 g/g and 15.77 ml/g, respectively. The results showed that the solubility, water holding capacity, oil holding capacity and swelling capacity of SE-SDF samples were significantly higher than those of W-SDF and F-SDF samples. The reason was that during steam explosion treatment, the material tissue was spongy, and the volume increased, and some structural tissues such as fiber bundles were destroyed, leading to the exposure of the inclusions, which was beneficial to the dissolution of the target substance. As a result, the content of pectin-type soluble dietary fiber was increased, and the ability to bind water molecules was improved. Meanwhile, macromolecular substances such as cellulose and hemicellulose were cut off, resulting in various small molecular fragments, which might expose some hydrophilic active sites of dietary fiber, which was beneficial to the combination of water molecules, and the number of dietary fiber particles increased. When dissolved in water, the particles expanded and stretched to produce a larger volume, which led to the increase in solubility, water holding capacity and swelling capacity of modified SDF.

Table 1 Effects of different extract methods on physicochemical properties of SDF

Sample	WS//%	WHC//g/g	OHC//g/g	SC//ml/g
W-SDF	2.13^a	9.02^a	2.13^a	10.82^a
F-SDF	3.95^b	13.75^b	4.08^b	14.03^b
SE-SDF	5.13^c	15.88^c	5.11^c	15.77^c

Different letters following data in the same column indicate significant differences ($P<0.05$).

Effects of different extraction methods on emulsifying activity, emulsifying stability and least gelation concentration of SDF

Emulsification activity (EA) refers to the ability of a substance to promote the dissolution or dispersion of two immiscible liquids. Emulsification stability (ES) refers to the ability to limit the rupture of emulsion[17]. Table 2 shows that the emulsifying activity and emulsifying stability of W-SDF were 30.28 and 37.88 ml/100 ml, respectively. The emulsifying activity and emulsifying stability of F-SDF increased to 47.95 and 45.25 ml/100 ml, respectively. The values of SE-SDF increased to 58.72 and 57.13 ml/100 ml, respectively, both reaching a significant level ($P<0.05$). Compared with SDF before treatment, SDF after steam explosion treatment can be used as a good emulsifier for functional foods with long shelf life and physical and chemical stability[18]. Moreover, SDF with high emulsifying activity is very beneficial to maintaining human health. Because bile acid is the precursor of cholesterol synthesis, the content of cholesterol in blood can be reduced by adsorption of bile acid in small intestine[17, 19]. The least gelation concentration (LGC) is an index for judging the gelation ability of a substance. It can be seen from Table 2 that lactobacillus fermentation and steam explosion treatment significantly reduced LGC from 12.11% to 11.25% and 9.87%, indicating that lactobacillus fermentation and steam explosion treatment increased the viscosity of SDF of apple pomace.

Table 2 Effects of different extraction methods on emusifying properties of SDF

Sample	EA//ml/100 ml	ES//ml/100 ml	LGC//%
W-SDF	30.28^a	37.88^a	12.11^a
F-SDF	47.95^b	45.25^b	11.25^b
SE-SDF	58.72^c	57.13^c	9.87^c

Different letters following data in the same column indicate significant differences ($P<0.05$).

Effects of different extraction methods on adsorption capacities of SDF for heavy metals

Lead (Pb), arsenic (As) and copper (Cu) are a class of chemical substances that are harmful to human health. Due to environmental pollution, these heavy metal elements can be detected in many foods. They are not easy to excrete, and all of them have the potential crisis of enrichment in organisms. When the amount reaches a certain level, it can lead to poisoning and cancer. The binding of dietary fiber to heavy metal ions mainly depends on chemical adsorption, and physical adsorption also exists. Chemical adsorption mainly depends on the binding of carboxyl groups from uronic acid and phenolic acid groups from lignin in the fiber with heavy metal ions, so it is greatly influenced by pH. With the increase of pH value, these groups dissociate more and can bind with positively charged heavy metal cations by ionic bonds. On the contrary, the decrease of carboxyl dissociation may reduce the adsorption effect, that is, the acidic environment is not conducive to the adsorption of heavy metal ions by dietary fiber. Physical adsorption is the result of van der Waals force, and the reaction rate is generally very fast due to the influence of temperature[20].

The effects of different extraction methods on the heavy metal adsorption capacities of apple pomace SDF are shown in Table 3. In the process of adsorbing the same kind of heavy metal ions, the adsorption effect under the condition of pH 7.0 was better than that under the condition of pH 2.0, which showed that the small intestine environment was more suitable for the adsorption of heavy metal ions by dietary fiber.

Under the simulated intestinal environment *in vitro* (pH 7.0), the adsorption capacities of W-SDF for Pb, As and Cu was 162.7, 132.8 and 57.2 μmol/g, respectively. The adsorption capacity for Pb was the strongest, followed by the adsorption capacity for As taking the second place, and the adsorption capacity for Cu was weaker. After the treatment with lactic acid bacteria fermentation and steam explosion, the adsorption capacity of SDF for heavy metal ions was enhanced, and the adsorption capacities were 183.5, 156.7 and 63.5 μmol/g, and 197.3, 168.9 and 89.2 μmol/g, respectively. Under the condition of gastric environment (pH 2.0), the adsorption of SDF to Cu was weak, but the adsorption to Pb and As was much stronger than that of Cu. Under the condition of pH 2.0, the adsorption capacity of SE-SDF for heavy metals was higher than those of W-SDF and F-SDF. The results of this study showed that after the SDF of apple pomace was treated by steam explosion, the sample particles were highly broken, leading to an increased specific surface area and loose structure, which made SDF more fully contact with heavy metal ions and thus enhanced the adsorption of heavy metal ions. Agnieszka *et al.* [21] found that the adsorption capacity of dietary fiber to metal ions is related to its chemical composition and the proportion of special components, and the adsorption capacities of the same dietary fiber to different metal ions are also different. Sangnark *et al.* [22] reported that cellulose and lignin have the ability to bind heavy metal ions, and their ability is related to their sources and particle sizes.

Table 3 Effects of different extract methods on binding capacities of SDF for Pb, As and Cu at pH 2.0 and 7.0

Sample	pH	BC//μmol/g		
		Pb	As	Cu
W-SDF	2.0	72.8	82.1	38.9
	7.0	162.7	132.8	57.2
F-SDF	2.0	110.5	112.5	42.7
	7.0	183.5	156.7	63.5
SE-SDF	2.0	138.9	135.7	55.1
	7.0	197.3	168.9	89.2

Conclusions and Discussion

(1) The solubility, water holding capacities, oil holding capacities and swelling capacities of water-soluble dietary fibers W-SDF, F-SDF, and SE-SDF obtained from apple pomace by the three extraction methods were (2.13, 3.95 and 5.13 g/g), (9.02, 13.75 and 15.88 g/g), (2.13, 4.08 and 5.11 g/g), and (10.82, 14.03 and 15.77 ml/g), respectively. Lactic acid bacteria fermentation and steam explosion treatment improved the solubility, water holding capacity, oil holding capacity and swelling capacity of SDF from apple pomace.

(2) The emulsifying activity, emulsifying stability and least gelation concentration of water-soluble dietary fibers W-SDF, F-SDF and SE-SDF from apple pomace obtained by the three extraction methods were (30.28, 47.95 and 58.72 ml/100 ml), (37.88, 45.25 and 57.13 ml/100 ml), and (12.11, 11.25 and 9.87%), respectively. After lactic acid bacteria fermentation and steam explosion treatment, the emulsifying activity and stability of SDF were enhanced, and the least gelation concentration was reduced.

(3) The results showed that the adsorption effect on the same heavy metal ion was better at pH 7.0 than at pH 2.0. In the intestinal environment (pH 7), the adsorption capacities of W-SDF, F-SDF and SE-SDF obtained by the three extraction methods for heavy metals (Pb, As and Cu) were (162.7, 183.5 and 197.3 μmol/g), (132.8, 156.7 and 168.9 μmol/g), and (57.2, 63.5 and 89.2 μmol/g) respectively. In the gastric environment (pH 2), they were (72.8, 110.5, 138.9 μmol/g), (82.1, 112.5, 135.7 μmol/g), and (38.9, 42.7, 55.1 μmol/g) respectively. After lactic acid bacteria fermentation and steam explosion treatment, the adsorption capacity of SDF on heavy metal ions was enhanced.

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