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A novel *in-situ* enhanced blasting extrusion technique — Extrudate analysis and optimization of processing conditions with okara

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ABSTRACT

A novel *in-situ* enhanced extrusion with the aim to improve the solubility of dietary fiber in okara (OKP) was developed. Wet OKP was blended with a CO_2-producing reagent (a mixture of $NaHCO_3$ and $C_6H_8O_7$) and subjected to extrusion. Processing variable optimization showed that the highest SDF fraction was obtained when the feed (containing 35.50 g/100 g moisture and 35 g/100 g reagent) was extruded with barrel temperature at 50-70-110-170 °C and screw speed at 191 rpm, respectively. The SDF fraction of the extrudate (21.35 g/100 g) was higher than that of untreated OKP (2.30 g/100 g) and the extrudate without reagent (4.67 g/100 g). The monosaccharide composition indicated that the increase of SDF in novel extrusion was mainly reflected in the redistribution of IDF to SDF. The novel extrusion improved the water and oil holding as well as swelling capacities of OKP when compared to untreated and reference extrudates.

Industrial relevance: This article provided a novel and an effective way to improve the solubility of okara dietary fiber. It focused on the feasibility of this technique by optimizing conditions and evaluating the physicochemical properties of the resulting extrudates. This method could increase the soluble fraction (g/100 g) of other rich-in-insoluble dietary fiber plant food by-products, which could be used as valuable ingredients for new functional foods.

1. Introduction

Since scientists identified dietary fiber (DF) as "the seventh basic nutrient", it had attracted a wide range of research and received a considerable level of public attention. Dietary fibers are classified as soluble dietary fiber (SDF) or insoluble dietary fiber (IDF), based on whether they form a solution when mixed with water or not (AACC, 2001; Elleuch et al., 2011). SDF and IDF are known to have distinct technological and physiological effects. IDF such as cellulose, lignin and hemicelluloses, are characterized by their porosity, low density and ability to increase fecal bulk (Elleuch et al., 2011; Gajula, Alavi, Adhikari, & Herald, 2008). On the other hand, SDF, which includes oligosaccharides, pectins, β-glucans and galactomanan gums, is characterized by its capacity to increase viscosity, reduce glycemic response and plasma cholesterol (Tosh & Yada, 2010). Compared to IDF, SDF has higher capacity to form gels or act as emulsifiers. It is easier to be incorporated into foods (Jenkins et al., 2006; Mateos-Aparicio, Redondo-Cuenca, Villanueva-Suárez, Zapata-Revilla, & Tenorio-Sanz, 2010; Rodríguez, Jiménez, Fernández-Bolaños, Guillén, & Heredia, 2006). In these contexts, an ideal DF is expected to have up to 20–30 g/100 g SDF content. This is to ensure that it effectively carried out its technological and physiological activities.

Disposal of by-products presents a major challenge for plant food processing industries. However, many of those by-products are potential sources of functional compounds, mainly DF which may be utilized in food fortification. Okara is a major solid residue from the production of various soybean products such as protein isolate, soymilk and tofu. Approximately, 2.5 kg fresh okara with moisture content of over 80 g/100 g could be obtained from 1 kg of dry soybean seeds. When okara is not used as animal feed or fertilizer, it is usually discarded. One of the problems associated with this practice is that discarding okara as a waste poses an environmental problem because it is highly susceptible to putrefaction. Okara is rich in DF (50–60 g/100 g db), mainly as IDF. The high fraction of IDF in okara DF makes it difficult for it to be used to fiber-fortified food products.

In order to increase the SDF fraction of fiber-rich plant food by-products, different approaches were investigated. These approaches were classified into three categories: chemical, biological and physical (Tosh & Yada, 2010). Physical approach is safer than the other two approaches. Physical modification can be achieved through different ways such as dehulling, soaking, grinding, pressurizing and extruding

Abbreviations: OKP, okara powder; DF, dietary fiber; SDF, soluble dietary fiber; IDF, insoluble dietary fiber; TFA, trifluoroacetic acid; NS, neutral sugar; UA, uronic acid; RSM, response surface methodology; BBD, Box–Behnken design; SEM, scanning electron micrographs; WHC, water holding capacity; OHC, water holding capacity; SC, swelling capacity.

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(Björck, Nyman, & Asp, 1984; Mateos-Aparicio, Mateos-Peinado, & Rupérez, 2010; Wennberg & Nyman, 2004). Among these methods, extrusion is regarded as the most effective and time-saving in addition to its wide application.

Extrusion has been applied successfully to increase the SDF fraction of fiber-rich plant food by-products such as sugar beet pulp (Rouilly, Jorda, & Rigal, 2006) and potato peels (Camire, Violette, Dougherty, & McLaughlin, 1997). During extrusion processing, the extent of SDF increment largely depended on the temperature and pressure in the extruder barrel. The higher the temperature and pressure, the higher the success of breakdown of polysaccharides' glucosidic bonds was. This led to the release of oligosaccharides and eventually to the increase in SDF (Björck et al., 1984; Esposito et al., 2005; Guha, Ali, & Bhattacharya, 1997). However, very high temperature (≥200 °C) deteriorated the nutritional and sensory quality of the extrudate. The high temperature was limited in the improvement of extrusion (Singh, Gamlath, & Wakeling, 2007). Consequently, high pressure extrusion at low or normally used temperature holds more potential. This was shown with the blasting extrusion, which was carried out at an enhanced pressure. The extruded biomass underwent a rapid decompression at the outlet of the extruder, which made the fibrous material to "explode" into fiber pieces and fiber bundles and thereby improved the performance of extrusion. The enhanced pressure was achieved by introducing pressured gas directly into the barrel of the extruder. Jeong and Toledo (2004) developed this method by directly injecting pressured CO_2 (0.1–0.6 MPa) into the barrel of a twin-screw extruder. This method markedly increased the operation pressure. This led to the increase in water solubility index of rice flour from 1.82% to 10.39%. The injection of pressured gas into the barrel is dangerous and capital intensive as it demands the use of sophisticated equipment. Theoretically, CO_2 could also be introduced *in-situ* by the feed itself into the barrel of the extruder. This was highlighted in the following chemical equation: $3NaHCO_3 + C_6H_8O_7 = C_6H_5O_7Na_3 + 3H_2O + 3CO_2$. This reaction was widely used in various solids projected to be effervescent tablets. It produced CO_2 when the tablet was subjected to water. This has led us to the hypothesis that the introduction of the same reaction in the barrel will improve the performance of the blasting extrusion as far as the producing H_2O and CO_2 were concerned.

To verify this hypothesis, this study was meant to determine the feasibility of a novel blasting extrusion with $NaHCO_3$ and $C_6H_8O_7$ buried in the feed to increase the SDF fraction in OKP. In addition to that, the operating parameters were optimized and the physicochemical properties of the extrudate were analyzed.

2. Materials and methods

2.1. Materials

Okara was provided as a fresh by-product of soymilk by a local company (Yuanmo, Chongqing, China) with a moisture content of 85 g/100 g. The fresh okara was centrifuged at 3000×*g* for 10 min followed by drying in oven at 60 °C. This was meant to decrease its moisture content to about 5 g/100 g. After grinding dried okara to pass through a 1.0 mm mesh, the resulting okara powder (OKP) was tightly packaged in a polyethylene bag prior to use.

2.2. Chemicals

Sodium bicarbonate ($NaHCO_3$) and citric acid ($C_6H_8O_7$) were purchased from Kelong Reagent Chemical Co. (Chengdu, China). Trifluoroacetic acid (TFA) and 3,5-dimethylphenol of analytical grade were purchased from Solarbio Reagent Chemical Co. (Beijing, China). Monosaccharide standard Kit, D-(+)-galacturonic acid monohydrate (no. 48280, purity ≥97.0%), protease (no. 5459, 7–15 U/mL) and amyloglucosidase (no. 9913, 320 U/mL) were purchased from Sigma Chemicals Co. (St. Louis, USA). One unit of protease has the capacity to hydrolyze casein to produce color equivalent to 1.0 μmol (181 μg) of tyrosine per min at pH 7.5 and 37 °C (color by Folin–Ciocalteu reagent). One unit of amyloglucosidase has the capacity to liberate 1.0 mg of glucose from starch in 3 min at pH 4.2 and 60 °C. All the other chemicals and reagents used in the experiment were also of analytical grade.

2.3. Feed preparation

OKP (400 g) was mixed with previously grounded citric acid powder (0–22.5 g/100 g OKP). It was made wet by adding water to obtain a moisture content that ranged from 30 g/100 g to 40 g/100 g. The resulting mixture was allowed to equilibrate at 25 °C for 20 min. Before feeding it into extruder, the wet OKP containing citric acid was thoroughly mixed with $NaHCO_3$ powder (0–22.5 g/100 g OKP) to obtain the feed. The proportion of $NaHCO_3$ and $C_6H_8O_7$ was determined as 1:1 (w/w) by preliminary experiments. To perform reference extrusion, OKP was made wet to maintain a moisture level of 35.50 g/100 g.

2.4. Extrusion process

Extrusion experiments were carried out on a laboratory-scale co-rotating and closely intermeshing twin-screw extruder (SYSLG30-LV, Saibainuo Scientific Ltd., Jinan, China). The extruder was equipped with 4 barrel zones, each 128 mm in length. The screw diameter (D) and its length to diameter ratio (L/D) were 57 mm and 24:1, respectively. The diameter of circular die was 3.5 mm. The feed was extruded at a rate of 200 g/min. Temperatures of the first three zones were maintained at 50, 70 and 110 °C, respectively. Once the equipment was functioning at a stabilized rate, the feed was processed continuously and the extrudate was collected and placed on trays to cool for 10 min. Reference extrusion was carried out at the optimized conditions for blasting extrusion without adding $NaHCO_3$ and $C_6H_8O_7$. Moisture content of the extrudate was measured immediately after extrusion. The extrudate was conditioned at 60 °C until they attained moisture content about 5 g/100 g and hermetically packaged in polyethylene bags for further researches.

2.5. Experimental design

Based on the results of preliminary experiments the Box–Behnken design (BBD) was used to arrange CO_2 blasting extrusion experiments for the subsequent response surface methodology (RSM) optimization study. The evaluated factors and levels were die temperature (X_1, 150, 160 and 170 °C), screw speed (X_2, 180, 190 and 200 rpm) and moisture (X_3, 30, 35 and 40 g/100 g db) with a feed rate of 200 g/min and CO_2 producing reagent fraction of 35 g/100 g OKP. Seventeen experiments were organized randomly and conducted three times. An experiment carried out at the center point was used to evaluate the margin of error. Regression analysis was performed on the data obtained using multiple analysis for each of the independent variables. Response surface analysis was also applied on the data from BBD for modeling and prediction of optimum conditions of extrusion for the soluble fiber fraction in OKP.

A second-order polynomial regression model was used to express the fraction as a function of the independent variables as Eq. (1):

$$Y = \alpha_0 + \sum_{i=1}^{3} \alpha_i X_i + \sum_{i=1}^{3} \alpha_{ii} X_i^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \alpha_{ij} X_i X_j \quad (1)$$

where Y represents the response variables, α_0 is a constant, α_i, α_{ii} and α_{ij} are the linear, quadratic and interactive coefficients, respectively. X_i and X_j are the levels of the independent variables.