**Original paper**

Twin-Screw Extrusion of Hairtail Surimi and Soy Protein Isolate Blends

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In this study, hairtail surimi (HS) and soy protein isolate (SPI) blends were extruded using a co-rotating twin-screw extruder. The effects of feed moisture, screw speed, and barrel temperature on the texture and water-holding capacity of the extrudates were investigated using response surface methodology. HS and SPI were mixed at a ratio of 1:4; the screw speed was tested at three levels between 80 and 120 rpm; the barrel temperature was set between 140°C and 160°C, and the feed moisture was set between 30% and 50%. The digestibility and microstructure of the extrudate produced by optimum conditions were also studied. The results demonstrated that the physical properties were significantly (p < 0.05) affected by the three process variables. Water-holding capacity and extrudate texture were found to mainly depend on barrel temperature and feed moisture, respectively. In vitro protein digestibility of the blends was improved by the extruding process.

Keywords: extrusion, hairtail surimi, soy protein isolate, response surface methodology

**Introduction**

Surimi-based products, such as kamaboka, tempura, and chikuwa are very popular in Asian markets (Jiang et al., 2000). Due to the overfishing of Alaska pollack, some previously underutilized species with low-value protein such as hairtail are now being used for surimi production (Heywood et al., 2002). Hairtail is one of the most important fish species, both economically and ecologically, in the East China Sea (Chakraborty et al., 2007; Liu et al., 2009). Thus, it is necessary to study the use of hairtail in surimi-based products. Since texture properties play a vital role in the perceived quality of these products (Endres, 2001; Kaewudom et al., 2013), some previous research have focused on developing methods to improve the texture functionality of hairtail surimi (HS). For instance, Hsu and Chiang (2002) demonstrated that the addition of soybean oil up to 8% could increase the breaking force of hairtail surimi gels. Hsieh JF group reported that the combined use of enzymes and an inhibitor substantially improved the gel-forming ability of HS (Hsieh et al., 2002; Jiang et al., 2000). However, there is no literature about the application of extrusion in the improvement of HS texture. Extrusion could perform a high temperature and a high shear rate to quickly restructure the material into fiber-like products, improving the

**List of abbreviations**

HS ; Hairtail Surimi, SPI ; Soy Protein Isolate, WHC ; Water-holding Capacity, TC ; Texture Characteristic, IVPD ; In Vitro Protein Digestibility, SEM ; Scanning Electron Microscopy, OWHC ; Optimum of Water-holding Capacity, OTC ; Optimum of Texture Characteristic, OEC ; Optimum Extrusion Condition, F ; Factor

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textured and protein utilization of products (Cheng et al., 2007; Silva et al., 2010; Singh et al., 2007), and recently several studies have reported fish (e.g. Indian major carp) based snack food with a unique texture produced by the extrusion process (Singh et al., 2012a; Singh et al., 2012b). Therefore, the aim of this work was to develop a hairtail surimi-based snack food using extrusion, which had a highly fibrous texture simulating meat, thus contributing to a new use for a low-value marine protein.

The independent process parameters for extrusion, such as temperature, screw speed, feed composition, and moisture content, require close control because they influence not only the textural but also the functional properties of the extrudates, such as water-holding capacity. In particular, feed composition is a dominant parameter (Pansawat et al., 2008). Many researchers have examined which starch-based feed composition to produce fish flesh snack-type products that are acceptable by consumers (Jaya Shankar and Bandyopadhyay, 2005; Pansawat et al., 2008; Tumuluru et al., 2013; Wianecki, 2007). As soy protein isolate (SPI) can improve the physical and chemical properties of surimi products (Draganovic et al., 2011; Fang et al., 2012; Kumar et al., 2012), this study incorporated SPI blends into the extrusion processing of HS, and investigated the effect of three process parameters on the physical properties (texture and water-holding capacity) of the extrudates.

Materials and Methods

Materials Low-grade HS was purchased from Anioy Foods Works Co., Ltd, Xiamen, China, and was stored at −20°C until being used. The SPI was received from Yu Xin Foods Works Co., Ltd, Jinan, China. The food mix during extrusion corresponded to an HS: SPI ratio of 1:4 (wet basis), and the moisture content of HS and SPI was 78.78% and 6.50%, respectively. Water was then added in order to adjust the mixture to the required moisture content required (30%, 40%, 50%, respectively). The blends were kept for equilibration at 4°C for 24 h before extrusion.

Pepsin and pancreatin were purchased from Yuan Ju Biotechnology Co., Ltd, Shanghai, China. HCl, NaOH, CaCl2 and NaNO3 were purchased from Sinopharm Chemical Reagent Co., Ltd, Shanghai, China.

Extrusion Process The extrusion was performed in a co-rotating twin-screw extruder (DS32-II, Jinan Saixin Food Machinery, Jinan, China), which had three independent zones of controlled temperature in the barrel. The diameter of the screw was 30 mm. The length to diameter ratio of the extruder barrel was 20:1. The diameter of the hole in the die was 5 mm, with a die length of 27 mm. The screw speed and the temperature of the third barrel section (metering section) were adjusted to the required levels. The extruder was fed manually through a conical hopper, which kept the flights of the screw fully filled and avoided an accumulation of the material in the hopper.

Experimental Design and Data Analysis Response surface methodology (RSM) was applied to design the experiment. An experimental design of three levels and three factors with three replicates at the center point based on Box and Behnken was chosen (Box and Behnken, 1960), and the independent variables considered in this study were feed moisture (A) (30%, 40%, 50%), screw speed (B) (80, 100, 120 rpm), barrel temperature (C) (140, 150, 160°C). These actual levels were selected based on our preliminary studies and on the date literature data available in the extrusion cooking literature. The coded values for the independent variables are shown in Table 1.

The experimental data for WHC and TC from different treatments was analyzed using multiple regression analysis by statistical software (Design-Expert 8.05b). The fitting was done to a second-order model for each response. This model can be expressed with the coded variables (A, B, C) with the following equation:

\[ Y = \beta_0 + \beta_1A + \beta_2B + \beta_3C + \beta_{12}AB + \beta_{13}AC + \beta_{23}BC + \beta_{1^2}A^2 + \beta_{2^2}B^2 + \beta_{3^2}C^2 + \epsilon \]

with \( Y \) representing the estimated response of WHC or TC, \( \beta_0 \) representing the equation parameters for the constant term, \( \beta_i \) representing the linear terms, \( \beta_{ij} \) (i = 1 – 3, j = 1 – 3) representing the cross terms, \( \beta_{ii} \) representing the quadratic terms for a single variable, and \( \epsilon \) representing the random error. These coefficients of regression were estimated using least square method conducted by Design-Expert 8.05b. Based on the model, the response surface plots were then developed as a function of two independent variables while keeping the other independent variable at a certain value. The effects of barrel temperature, screw speed and feed moisture content on water-holding capacity and texture of extrudates were investigated through RSM, and RSM was also conducted to determine the optimum conditions of products with water-holding capacity and texture characteristic to be as high as possible.

Physical Properties

Water-holding Capacity (WHC) The water-holding capacity (WHC) of the extrudate was evaluated as previously described (Esposito et al., 2005). Five grams of the extrudate was suspended in 25 mL of distilled water and stirred for 30 min at room temperature. After centrifugation for 10 min at 2500 g using a centrifuge (Universal 320/320R, Hettich Co., Ltd, Kirchlengern, Germany).
Germany), the samples were weighed and the amount of held water was calculated by the difference in weight. The data are reported as grams of water retained for each gram of product. Three independent measurements were conducted for each sample.

**Texture Characteristic (TC)** Each sample (1 cm × 1 cm × 3 mm) was analyzed for texture characteristic with a TA.XT Plus Texture Analyser (Stable Micro System Co., Ltd, London, UK) at room temperature. The test was conducted using the razor blade shearing methods (Aussanasuwannakul et al., 2010; Lee et al., 2008; Meullenet et al., 2004). A/CKB Craft Knife Adapter & Blades (Stable Micro System Co., Ltd, London, UK) was performed to shear the sample perpendicularly to the transversal and longitudinal fiber orientation (the transversal orientation referred to the flow direction of extrudates in the die of the extruder), and the test speed was 1.0 mm/s. The transversal shear force (TF) and longitudinal shear force (LF) were measured, and the value of TC was expressed as the ratio of the transversal shear force and longitudinal shear force (TF/LF), which was an indicator to assess the fibre formation of meat products (Thiébaud et al., 1996). Twenty independent measurements were conducted for each sample.

**In Vitro Protein Digestibility (IVPD)** The in vitro digestibility of the extrudates was determined by modifying the method of Monsoor and Yusuf (2002). The extruded product (200 mg) was suspended in 15 mL (0.1N) HCl solution containing 2 mg of pepsin. The suspension was incubated at 37°C for 3 h and then neutralized with 0.2N NaOH before adjusting the pH to 7.5 – 8.0. A phosphate buffer (7.5 mL, pH 7.4) containing 4 mg of pancreatin, 1 mM CaCl₂ and 0.01% NaN₃ were added to the suspension. The mixture was then precipitated by adding 30% trichloroacetic acid (TCA) solution and separated by ashless filter paper. The amount of undigested protein was measured using a Kjeldahl analyzer (DT208, FOSS Scinos Co., Ltd, Bern, Switzerland), and IVPD was calculated using the following equation. Three independent measurements were conducted for each sample.

\[
IVPD = \frac{\text{Total protein in 200 mg extruded product} - \text{undigested protein}}{\text{Total protein in 200 mg extruded product}} \times 100\% 
\]

**Scanning Electron Microscopy (SEM)** The extrudates from all diets were cut in half using a razorblade, mounted on aluminum stubs, sputter coated with gold/palladium (JEOL Fine Coat Ion Sputter JFC-1100, Tokyo, Japan), and examined with a JEOL JSM 840 SEM. Micrographs of cross sections were acquired at a primary magnification of X20, using a working distance of 12.8 mm and an accelerating voltage of 5 keV (Sørensen et al., 2009).

**Results and Discussion**

Table 2 showed the Box-Behnken design and the responses of the dependent variables (i.e., water-holding capacity (WHC) and texture characteristic (TC) of the extrudates), together with the predicted values according to the second-order response surface models. The regression analysis was employed to fit a full response

### Table 2. Box-Behnken for optimizing the extrusion condition for TC and WHC of the extrudates in coded units together with experimental date and their predicted value according to the second-order response surface models

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Coded level of variables</th>
<th>WHC (g water/g sample)</th>
<th>TC (N/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Experimental</td>
<td>Predicted</td>
</tr>
<tr>
<td>1</td>
<td>-1/-1/0</td>
<td>3.91 ± 0.14</td>
<td>3.95</td>
</tr>
<tr>
<td>2</td>
<td>1/-1/0</td>
<td>6.94 ± 0.11</td>
<td>6.58</td>
</tr>
<tr>
<td>3</td>
<td>-1/1/0</td>
<td>4.50 ± 0.12</td>
<td>4.86</td>
</tr>
<tr>
<td>4</td>
<td>1/1/0</td>
<td>5.75 ± 0.09</td>
<td>5.71</td>
</tr>
<tr>
<td>5</td>
<td>-1/0/-1</td>
<td>3.59 ± 0.06</td>
<td>3.33</td>
</tr>
<tr>
<td>6</td>
<td>1/0/-1</td>
<td>3.65 ± 0.16</td>
<td>3.79</td>
</tr>
<tr>
<td>7</td>
<td>-1/0/1</td>
<td>4.07 ± 0.14</td>
<td>3.93</td>
</tr>
<tr>
<td>8</td>
<td>1/0/1</td>
<td>6.69 ± 0.07</td>
<td>6.95</td>
</tr>
<tr>
<td>9</td>
<td>0/-1/-1</td>
<td>4.09 ± 0.09</td>
<td>4.31</td>
</tr>
<tr>
<td>10</td>
<td>0/1/-1</td>
<td>4.41 ± 0.12</td>
<td>4.31</td>
</tr>
<tr>
<td>11</td>
<td>0/-1/1</td>
<td>6.07 ± 0.05</td>
<td>6.17</td>
</tr>
<tr>
<td>12</td>
<td>0/1/1</td>
<td>6.42 ± 0.08</td>
<td>6.20</td>
</tr>
<tr>
<td>13</td>
<td>0/0/0</td>
<td>7.39 ± 0.12</td>
<td>7.42</td>
</tr>
<tr>
<td>14</td>
<td>0/0/0</td>
<td>7.23 ± 0.09</td>
<td>7.42</td>
</tr>
<tr>
<td>15</td>
<td>0/0/0</td>
<td>7.36 ± 0.11</td>
<td>7.42</td>
</tr>
<tr>
<td>16</td>
<td>0/0/0</td>
<td>7.36 ± 0.11</td>
<td>7.42</td>
</tr>
<tr>
<td>17</td>
<td>0/0/0</td>
<td>7.78 ± 0.08</td>
<td>7.42</td>
</tr>
</tbody>
</table>

WHC, water-holding capacity; TC, texture characteristic.
surface model for every response investigated including all linear (A, B, C), interaction (AB, AC, BC), and quadratic terms (A², B², C²). The regression analysis and the regression coefficients for the response surface model in terms of coded units were shown in Table 3, and the fitted models for WHC/TC were given in Table 4.

**Water-holding capacity (WHC)** Previous studies of surimi-based extrudates used to produce crispy snack food have investigated the characteristics of color, unit density, bulk density, and expansion ratio (Choudhury and Gautam, 2003; Majumdar et al., 2011). In our pre-experiments, the effects of the process parameters on these characteristics were also studied, however, in this study the extrudates were intended to be a snack food with a fibrous texture simulating meat, thus the more important property water-holding capacity (WHC) was investigated, since the water-holding capacity is one of the most important quality characteristics of meat, furthermore, the low WHC would result in an unacceptable deterioration in the texture of meat products (Huff-Lonergan and Lonergan, 2005; Kristensen and Purslow, 2001). Hence, the higher value of WHC represented the better quality of the products.

WHC is the ability of a protein matrix to absorb and retain bound, hydrodynamic, capillary, and physically entrapped water against gravity (Damodaran and Paraf, 1997). It is an important functional property reflecting the protein-water interaction (Traynham et al., 2007), and can affect sensory attributes of protein products (Heywood et al., 2002). The mean values of the WHC of the extruded products are shown in Table 2. The regression analysis for WHC and the fitted model are given in Tables 3 and 4, respectively. The model indicated the quadratic effects of all three variables, and the regression analysis of the water-holding capacity demonstrated that barrel temperature and feed moisture were highly significant (P < 0.01).

The barrel temperature was the most significant factor affecting WHC; the value of WHC significantly increased with increasing barrel temperature. This result was in agreement with observations made in previous studies. For instance, in their study of blends of soy protein isolate (SPI) and wheat starch, Lin et al. (2002) found that the water-holding capacity of extrudates increased with higher cooking temperatures. Park et al. (1993) studying the extrusion of soy flour-corn starch-raw beef blends using a single-screw extruder, reported that increasing process temperature from 140°C to 180°C contributed to a 26% increase in WHC, perhaps because samples conducted by higher barrel temperatures seem to expand slightly upon exiting from the cooling die, creating more vacuoles in the inner structure of the extrudates. As a result, these samples absorb more water when rehydrating (Lin et al., 2002).

Fig. 1 (a-c) was the response surface plot of WHC vs. two independent variables with the third taken at the ‘coded 0’ level.

### Table 3. Regression coefficients for the second-order response surface models in terms of TC and WHC of the extrudates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Term</th>
<th>WHC (g water/g sample)</th>
<th>TC (N/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coefficient</td>
<td>P-value</td>
</tr>
<tr>
<td>β₀</td>
<td>Intercept</td>
<td>-352.853</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>β₁</td>
<td>Feed moisture(A)</td>
<td>0.5081</td>
<td>0.0007</td>
</tr>
<tr>
<td>β₂</td>
<td>Screw speed(B)</td>
<td>0.4342</td>
<td>0.9408</td>
</tr>
<tr>
<td>β₃</td>
<td>Barrel temp.(C)</td>
<td>4.2614</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>β₁₂</td>
<td>Feed moisture × Screw speed(AB)</td>
<td>-0.002225</td>
<td>0.0277</td>
</tr>
<tr>
<td>β₁₃</td>
<td>Feed moisture × Barrel temp.( AC)</td>
<td>0.0064</td>
<td>0.0053</td>
</tr>
<tr>
<td>β₂₂</td>
<td>Screw speed × Barrel temp.( BC)</td>
<td>0.0000375</td>
<td>0.9641</td>
</tr>
<tr>
<td>β₁₁</td>
<td>Feed moisture × Feed moisture(A²)</td>
<td>-0.01448</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>β₂₁</td>
<td>Screw speed × Screw speed(B²)</td>
<td>-0.001752</td>
<td>0.0029</td>
</tr>
<tr>
<td>β₃₃</td>
<td>Barrel temp × Barrel temp.(C²)</td>
<td>-0.01476</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Lack of fit</td>
<td></td>
<td>0.0992</td>
<td>4.22</td>
</tr>
</tbody>
</table>

WHC, water-holding capacity; TC, texture characteristic; Feed moisture (%), Screw speed (rpm), Barrel temp. (°C);

### Table 4. The regression models for process variables and product properties using independent variables feed moisture (A), screw speed (B) and barrel temperature (C) of HS-SPI extrudates

<table>
<thead>
<tr>
<th>Response</th>
<th>Model</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHC (g water/g sample)</td>
<td>7.42 + 0.87A + 0.00875B + 0.94C - 0.44AB + 0.64AC + 0.0075BC - 1.45A² - 0.70B² - 1.48C²</td>
<td>0.9812</td>
</tr>
<tr>
<td>TC (N/N)</td>
<td>1.48 + 0.12A - 0.029B + 0.057C + 0.042AB - 0.035AC - 0.061A² - 0.19B² - 0.14C²</td>
<td>0.9893</td>
</tr>
</tbody>
</table>

WHC, water-holding capacity; TC, texture characteristic
Through the analysis of variance (ANOVA), the optimum WHC (the maximum of WHC, 7.792 g water/g sample) could be obtained when the barrel temperature was 154.06°C, and similar results have been reported in previous literature. For example, the optimum WHC of deboned meat-SPI blends after extrusion was obtained at 150°C (Megard et al., 1985). Yoshitomi (2004), who investigated the extrusion of fish meal-wheat flour-defatted soybean meal blends in a twin-shaft extruder, found that temperature of approximately 155°C maximized WHC. This phenomenon might result from an optimal equilibrium between protein unfolding and aggregation which would occur at around 150°C, resulting in a firm network (Megard et al., 1985).

In this work, it was noteworthy that ‘barrel temperature × feed moisture’ interaction displayed a highly significant effect on WHC (P = 0.0053), which were also found by other researchers (Lin et al., 2002; Thiébaud et al., 1996). It may be due to the less frequent protein-protein interactions and the better fiber alignment when feed moisture was at a high level (Thiébaud et al., 1996).

**Texture characteristic (TC)** Texture characteristic is an important physical property of extruded snacks made from feed mixtures containing meat and non-meat ingredients (Rhee et al., 2004). In this study, the materials (HS and SPI blends) were extruded to produce a snack food with a fibrous texture simulating meat. Therefore, the razor blade shearing method which has been widely applied to assess the texture of meat products was used (Aussanasuwannakul et al., 2010; Lee et al., 2008; Meullenet et al., 2004). The natural meat products were characterized by the structure of fibers (Yang, 1974), and the value of TC (the ratio of transversal shear force/longitudinal shear force) could evaluate the degree of the fiber formation (texturization) of the extrudates (Thiébaud et al., 1996), that is, the higher value of TC represents the better texture quality of the products (Taranto et al., 1978; Yao et al., 2004). The mean values of the TC of the extruded products are listed in Table 2. Table 3 indicated that the texture characteristic was a highly significant (P < 0.01) affected by the quadratic effect of all three variables.

It could be seen that feed moisture was the most significant factor affecting the value of TC, and that the interaction of moisture with the other variables was not dramatic. Sun et al. (2011) studied high humidity extrusion of SPI-defatted soybean meal-wheat gluten blends and found that the moisture content of the product textured degree (i.e., TC in this study) was the most important variable. Thiébaud et al. (Thiébaud et al., 1996) came to a similar conclusion in their study of the extrusion of surimi-soy protein concentrate blends. Fig. 2 (a-c) illustrates the response surface plot of TC vs. two independent variables with the third taken at the ‘coded 0’ level. The feed moisture showed a significant positive correlation with TC, and the optimum TC (i.e. the maximum of
TC, 1.544N/N) was obtained when the feed moisture was 49.99%. Many other researchers have concluded that water acts as a plasticizer in the extruder, and therefore higher feed moisture reduces the melt viscosity and the viscous dissipation, hence it promotes protein restructuring and the shaping of comminuted meat or fish, while at the same tie forming a fiber structure (Draganovic et al., 2011; Sun et al., 2011).

**Optimum extrusion condition (OEC)** A graphical multi-response optimization technique was applied to determine the optimum combination of temperature, screw speed and feed moisture of hairtail surimi and soy protein blends for maximum WHC and TC. In terms of the same two independent variables, two contour plots (i.e., the undersurface of response surface plots) of WHC and TC were superimposed. The following numeric limits were conducted: WHC of at least 7.5 g water/g sample (the maximum was 7.792 g water/g sample, obtained in the optimum process of WHC) and TC of at least 1.5 N/N (the maximum was 1.544N/N, obtained in the optimum process of TC).

The regions (shown by the shaded area in Figs.3 and 4) in the superimposed contour plots satisfied the constraints, and indicated the ranges of independent variables which could be considered as the optimum range for product with relatively high value of both WHC and TC, such as 91 – 107 rpm of screw speed, 41 – 48% of feed moisture at 153.02°C barrel temperature and 150 – 155°C of barrel temperature, 91 – 107 rpm of screw speed at 45.15% of feed moisture. The ‘optimum extrusion condition’ (feed moisture 45.16%, barrel temperature 153.01°C and screw speed 98.78 rpm) referred to the central point of the shaded area in the superimposed contour plots. The central point of the shaded area in the superimposed contour plots was feed moisture 45.16%, barrel temperature 153.01°C and screw speed 98.78 rpm.

**In vitro protein digestibility (IVPD)** The estimation of in vitro protein digestibility using enzymes is an acceptable and simple method for evaluating protein quality and utilization (Bhattacharya and Hanna, 1988). Thus IVPD can reflect the nutritional properties of products (Solanas et al., 2008). To investigate the changes in the IVPD of HS-SPI blends before and after extrusion, the IVPD of the raw materials and the extrudates produced by the optimum process of WHC (OWHC – moisture content 44.09%, barrel temperature 154.06°C, and screw speed 97.56 rpm), the optimum process of TC (OTC – moisture content 49.99%, barrel temperature 150.81°C, and screw speed 100.73 rpm) and the optimum extrusion condition (OEC – moisture content 45.15%, barrel temperature 153.02°C, and screw speed 98.79 rpm, which was the central point of the shaded area in superimposed contour plots) were compared. It can be concluded that the digestibility of the raw materials was improved 7.62% and 10.25% by the OWHC and OTC extrusions, respectively (Fig. 5), which was in agreement with previous
Fig. 3. Superimposed contours for product responses affected by feed moisture and screw speed at 153.02°C barrel temperature

Fig. 4. Superimposed contours for product responses affected by barrel temperature and screw speed at 45.15% feed moisture
Fig. 5. The in vitro protein digestibility of extrudate and non-extrudate
RM: Raw material; OWHC: Optimum of water-holding capacity; OEC: Optimum extrusion conditions
OTC: Optimum of texture characteristic

Fig. 6. Cross section SEM pictures of extrudates produced by (a) the optimum process of WHC (OWHC), (b) the optimum process of TC (OTC) and (c) the optimum extrusion condition (OEC)
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studies. For instance, Bhattacharya et al. (1988) studied the extrusion of fish meat and wheat flour blends and found that IVPD was improved by 5.84% after treatment. The value of the IVPD of faba beans increased from 75.4% in raw unsoaked seeds to 80.4% in soaked extruded seeds (Abd El-Hady and Habiba, 2003). This might be because the extrusion cooking is a typical high-temperature short-time process, therefore it is an effective way to improve digestibility by modifying enzymes and destroying anti-nutritional factors (Abd El-Hady and Habiba, 2003; Alonso et al., 2000; Harper, 1989). Compared with samples produced by OWHC, those produced by OTC had a slightly higher value of IVPD, which was probably due to differences in their process conditions. Higher temperatures seem to decrease the digestibility of proteins through non-enzymatic browning reactions and thermal cross-linking (Ainsworth et al., 1999), and higher screw speed might increase the shear stress to open up the protein structure, exposing new sites for enzyme attack (Ainsworth et al., 2007), thus leading to a larger value of IVPD, which was also found by Luo et al. (2011).

Scanning Electron Microscopy (SEM) Electron micrographs of cross sections of the extrudates produced by OWHC, OTC and OEC (labeled Sample A, Sample B and Sample C, respectively) are shown in Fig. 6 a-c. There was subtle difference among the three samples. Compared with Sample B and Sample C, the vacuoles (dark areas) in Sample A seemed to be a bit bigger, which might account for its higher water-holding capacity (Lin et al., 2002).

Conclusion

The RSM revealed the significant effects of all three important extrusion parameters (screw speed, feed moisture, and barrel temperature) on the WHC and TC of HS and SPI-blends extruded using a twin-screw extruder. Within the experimental range, barrel temperature had the most significant effect on the WHC of the extrudates, and feed moisture had the most significant effect on TC. The SEM did not reveal much microscopic distinction between the two samples produced by OWHC and OTC, however a slight difference existed in terms of IVPD.

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