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Effect of extrusion conditions on physicochemical characteristics and anthocyanin content of blue corn third-generation snacks

Efecto de las condiciones de extrusión sobre características físico-químicas y contenido de antocianinas de alimentos botana de tercera generación de maíz azul

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“Doctorado en Ciencias en Ingeniería Bioquímica, Instituto Tecnológico de Durango, Durango, México; bMaestría en Ciencia y Tecnología de Alimentos, Universidad Autónoma de Sinaloa, Sinaloa, México; cCentro de Investigaciones Químicas, Universidad Autónoma del Estado de Hidalgo, Hidalgo, México

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The aim of this study was to evaluate the effect of barrel temperature (BT, 98.8–141.2 °C) and feed moisture (FM, 19.93–34.07%) as independent factors on physicochemical characteristics of microwave-expanded extruded third-generation (3G) snacks obtained from blue corn and corn starch. Single-screw laboratory extruder and a central, composite, rotatable experimental design were used. Both independent factors showed significance (p ≤ 0.01) on most of the analyzed responses. The mathematical models showed values of $R^2_p ≥ 0.76$ and $p$ of $F_{(model)} ≤ 0.001$. The optimum area of the extrusion process ranged from 120 °C to 126 °C for BT and from 23.8% to 25.2% for FM. In optimal conditions, the product showed an expansion index of 4.8, a penetration force of 12.42 N, a specific mechanical energy of 169.08 kJ/kg, and 71.09 mg of total anthocyanin content/kg. The developed 3G snack presented high-quality physicochemical characteristics, with the potential health benefits derived from nutraceutical characteristics (dietary fiber and anthocyanins) of the whole blue corn used.

Keywords: extrusion; blue corn; third-generation snack; anthocyanin

El objetivo de este estudio fue evaluar el efecto de la temperatura de barril BT (98.8–141.2 °C) y la humedad de alimentación FM (19.93–34.07%) como factores independientes, sobre características físicoquímicas de botanas extrudidas, de tercera generación (3G), expandidas por microondas, obtenidas a partir de maíz azul y almíndon de maíz. Se utilizó un extrusor de laboratorio de tornillo simple y un diseño experimental central compuesto, rotatable. Ambos factores independientes mostraron significancia ($p ≤ 0.01$) en la mayoría de las respuestas analizadas. Los modelos matemáticos mostraron valores de $R^2_p ≥ 0.76$ y $p$ de $F_{(modelo)} ≤ 0.001$. La zona óptima para el proceso de extrusión varió de 120–126 °C para BT y de 23.8% a 25.2% para FM. En condiciones óptimas el producto mostró un índice de expansión de 4.8, una fuerza de penetración de 12.42 N, una energía mecánica específica de 169.08 kJ/kg y 71.09 mg de contenido total de antocianina/kg. La botana 3G desarrollada presentó características físico-químicas de alta calidad, con los beneficios potenciales para la salud, derivados de las características nutraceuticas (fibra dietaria y antocianinas) del maíz azul integral utilizado.

Palabras clave: extrusión; maíz azul; botana de tercera generación; antocianina

Introduction

A snack is defined as a small, lightweight food that is easy to manipulate, ready to eat, accessible, and, most importantly, able to satisfy the appetite sensation for a moment (Hurtado, Escobar, & Estévez, 2001). Snack foods are widely consumed, regardless of social status, age, or gender. The industrial sector of snacks in Mexico is booming with an annual market value of 3419 million dollars, offering various kinds of snacks, mainly the potato and corn (dough and tortilla) derivatives (http://inegi.gob.mx). Among the main types of snacks are the third-generation (3G) snacks, also known as intermediate snacks or pellets, which are cheap and easy to prepare at home (Hollingsworth, 2001). In the processing of 3G snacks, the dry ingredients are mixed with water (22–35%) to form a dough. The 3G snacks are prepared by extrusion, formed at low pressure to avoid expansion, and dried to a final moisture content of 10–14% to form a glassy pellet. The extrusion process consists of a 3-step temperature profile, starting with a low-temperature step at the feed zone (70–80 °C), continuing with a high-temperature step at the mixing and cooking zone (90–145 °C), and ending with a low-temperature step at the output die (75–95 °C) (Bastos-Cardoso, Zazueta-Morales, Martínez-Bustos, & Yoon, 2007; Delgado-Nieblas et al., 2012). The 3G snacks have a long shelf life, being capable of retaining a good quality for at least one year, provided that a proper storage is given. As pellets, they require less storage space due to their less volume in relation to their size after expanding when compared with directly expanded snacks (Arias-García et al., 2007). However, they require a further expansion process, which may be done by hot oil, hot air, or microwave exposure. During this latter intensive heating step, the moisture in the pellet will start to boil and vapor bubbles are formed, which will expand the pellet. The expansion gives the snack a porous structure (Boisichot, Moraru, & Kokini, 2003). Taking advantage of the greater consumer acceptance for 3G snacks, they can be used as nutrient carriers in order to offer

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an added value product with high nutritional/nutraceutical properties. Balasubramanian, Borah, Singh, and Patil (2012), Delgado-Nieblas et al. (2012), Limón-Valenzuela, Martínez-Bustos, Aguilar-Palazuelos, Caro-Corrales, and Zazueta-Morales (2010) have reported studies aiming this purpose, where milk proteins, legume seeds, and vegetable flour have been used.

Blue corn composition is similar to white corn, with the advantage of containing anthocyanin and phenolic compounds (Pedreschi & Cisneros-Zevallos, 2007; Yan & Zhai, 2010). These are phytochemicals that are synthesized in plants by secondary metabolism, and there is great interest in them because of their antioxidant and bioactive properties. Their consumption has been correlated with health benefits, chronic, and degenerative illness prevention, such as cancer, cardiovascular diseases, and cataracts (He & Giusti, 2010).

The extrusion process has become very important in food processing because of its extensive technical advantages of cost, in addition to being a high-temperature short-time process, which allows for less destruction of heat-sensitive components (White, Howard, & Prior, 2010). Furthermore, extrusion technology has been successfully used in the production of both directly (second generation) or indirectly expanded snack (3G). Studies have been conducted about the addition of anthocyanin to directly expanded extruded foods. Khanal, Brownmiller, Howard, and Prior (2009) studied an extrusion process (temperature 160–180°C and screw speed 150–200 rpm) using mixtures of grape seed, cranberries, and white sorghum flour. In this report, the extrusion process reduced the anthocyanin content up to 42% at the high-temperature range. Camire, Chaovanalikit, and Dougherty (2002) reported a total anthocyanin loss, in the range of 64–90% caused by the extrusion process, when concentrated cranberry was incorporated into extruded breakfast cereals. Zazueta, Martínez, Jacobo, Ordorica, and Paredes (2001) studied the effect of the addition of calcium hydroxide on some characteristics of extruded directly expanded blue corn. They found that it is possible to obtain an extruded directly expanded blue corn product, fortified with calcium. However, the scientific literature on the development of blue corn-based 3G snacks, and the effect on extrusion processing on their physicochemical, structural, and nutritional properties, is scarce. The aim of this study was to evaluate the effect of extrusion variables on physicochemical characteristics and anthocyanin content of 3G snacks elaborated from blue corn flour and corn starch.

Materials and methods

Materials

Blue corn (Zea mays L.), “Chalqueño” race, from the local market of Pachuca, Hidalgo, and corn starch produced by IMSA (Industrializadora de maíz S.A de C.V. Puebla, México) were used.

Preparation of samples

Integral flour (≤250 μm) from blue corn was obtained using a hammer mill (Mini 100 Pulvex S.A de C.V. México) and was mixed with corn starch in a 65:35 proportion. The criteria used for the selection of the mixture was to obtain a product with high expansion, maximum blue corn content, and minimum addition of corn starch, which was established in preliminary studies. The mixture was added to 0.1% of monoglycerides (Bioproceso Company, Culiacán, México). The addition of emulsifiers, such as saturated monoglycerides, contributes to the lubricant effect, which decreases the mechanical degradation produced by the extruder and improves the texture of the cooked product (Bastos-Cardoso et al., 2007). This monoglyceride concentration was chosen because, in a preliminary study, it showed desirable effect for 3G snacks. The prepared mixtures were homogenized at medium speed (~8 min) in a laboratory mixer (Kitchen Aid, model KSS, Michigan, USA); they were stored in sealed polyethylene bags and kept under refrigeration (8–10°C) for 12 h before processing.

Expansion process

The extrusion process was performed using a single-screw laboratory extruder (Brabender 20DN, model 8-235-00, Duisburg, Germany). A rectangular aperture output die with internal measures of 20 mm wide × 1.0 mm high × 100 mm long, a screw with 2:1 compression ratio, a screw speed of 80 rpm, and feed rate of 2.8–3.0 kg/h, were used. Temperatures in both the feed zone and in the output die were 75°C, while temperatures of the intermediate zone (mixing/cooking zone) and feed moistures varied according to the experimental design (Table 1). The extruded materials (pellets) were manually cut into approximately 2.5 cm long strips, dried at room temperature (24–26°C, 50–70% relative humidity) for 48 h, up to a moisture content of about 9–13%, stored in sealed plastic bags, and kept in darkness under refrigeration (6–8°C) until analysis.

Extrusion process

The cut and extruded pellets were expanded using a commercial microwave oven (LG®, R-501CW, Monterrey México, 900 W and 2450 Hz) for 26 s, according to preliminary tests.

Proximate analysis

Official methods of AOAC (1999) were used to analyze moisture (925.09), protein (979.09), ash (923.03), lipids (923.05), and 2450 Hz) for 26 s, according to preliminary tests.

Table 1. Experimental design used for blue corn extrusion.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>$X_1$</th>
<th>$X_2$</th>
<th>BT (°C)</th>
<th>FM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>−1</td>
<td>−1</td>
<td>105</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>−1</td>
<td>135</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>−1</td>
<td>1</td>
<td>105</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>135</td>
<td>32</td>
</tr>
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<td>0</td>
<td>98.79</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>1.414</td>
<td>0</td>
<td>141.21</td>
<td>27</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>−1.414</td>
<td>120</td>
<td>19.93</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>1.414</td>
<td>120</td>
<td>34.07</td>
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<td>9</td>
<td>0</td>
<td>0</td>
<td>120</td>
<td>27</td>
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<td>10</td>
<td>0</td>
<td>0</td>
<td>120</td>
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Note: BT = Barrel temperature (°C); FM = Feed moisture (%).

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<td>0</td>
<td>0</td>
<td>120</td>
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</tbody>
</table>

Note: BT = Barrel temperature (°C); FM = Feed moisture (%).
and fiber (962.09). The carbohydrate content was calculated by difference.

**Expansion index (EI) and bulk density (BD)**

Expansion index (EI) and bulk density (BD) were determined using the specific volume of non-expanded (Vnep) and expanded (Vep) pellets as EI = (Vep–Vnep)/Vnep. The specific volume was determined using the seed displacement test, according to Penfield and Campbell (1990) and Boischat, Moraru and Kokini (2003). Results were the mean of 30 determinations by treatment.

**Penetration force (PF)**

Penetration force (PF) was measured in microwave-expanded products with a penetrometer (Chatillon, model TCD 200, Surrey, UK). A 2 mm diameter flat-tip probe with a penetration speed of 0.8 mm/s was used. The required force (N) to penetrate a depth of 3 mm was registered, with 30 replicates for treatment.

**Specific mechanical energy (SME)**

The energy required for extruder screw rotation (kJ/kg) was calculated from values of torque (t, N·m), screw extruder speed (ss, rpm/min), and feed flow (F, kg/h), according to Butteman-Azcona, Lawton, and Hamaker (1999).

\[
SME = \frac{2\pi \times ss}{F}
\]

**Water absorption index (WAI) and water solubility index (WSI)**

They were performed in the microwave-expanded products using 2.5 g of sample according to Anderson, Conway, Pfeifer, and Griffin (1969), where the quantity of dissolved material and the proportion of absorbed water are gravimetrically calculated after stirring a suspension at room temperature.

**Total anthocyanin content (TAC)**

Total anthocyanin content (TAC) was measured in raw materials and microwave-expanded snacks, using the method described by Abdel-Aal and Huel (1999). TAC was expressed in mg of cyanidin-3-glucoside/kg (db).

**Experimental design**

A central, composite, rotatable experimental design for response surface methodology, with 13 treatments and value \(a = 1.414\) (Table 1), was used.

The response surface superposition methodology was utilized to find the optimal processing conditions, in order to obtain a high-quality and high expanded product, using the Design-Expert software (7.0). Pearson correlations were performed using Statistica 7.0 software (Stat-Ease, Inc., Minneapolis, MN).

**Results**

**Proximate composition**

Table 2 shows the proximate composition of blue corn, corn starch, and the mixture of blue corn flour and corn starch. The proximate composition of blue corn is consistent with values reported by Zazueta-Morales et al. (2001) and Escalante-Aburto et al. (2013), who used blue corn for developing a directly expanded second-generation snack. The results are also consistent with those reported by Nava, Jimenez, and Hernandez (2008) and Hoover and Manuel (1996) for blue corn and corn starch.

**Regression coefficients and ANOVA**

The Regression coefficients for the responses analyzed are shown in Table 3. Both factors, barrel temperature (BT) and feed moisture (FM), showed a highly significant effect \((p \leq 0.01)\) in their linear \((b_1)\) and quadratic \((b_{11})\) terms on the majority of the responses studied, except \(b_2\) and \(b_{22}\) to WSI and \(b_{23}\) for BD. Furthermore, for TAC in the microwave-expanded extruded snacks, only the terms \(b_{22}\) and \(b_{23}\) of the mathematical model had a significant effect. The interactions terms of the models, in general, were significant on various responses. Additionally, Table 4 shows the analysis of variance (ANOVA) for the analyzed response variables. The models were accurate enough for all responses, with values of \(R^2_{\text{Adj}} > 0.76, p\) of \(F_{\text{model}} < 0.001,\) and variability coefficient (VC) < 14.78 (except for PF, 20.41). However, it can be seen that BD, SME, and WAI showed lack of fit \((p > 0.082)\).

**Expansion index (EI)**

The effect of BT and FM on expansion index (EI) is shown in Figure 1. It can be seen that in almost the entire experimental interval of FM, EI increased with increasing BT from 98°C to 125°C. BT higher than 125°C favored a decrease in values of EI. Furthermore, at low BT (<115°C), EI values increased as FM increased, and the highest EI values were obtained at low FM (~20%) and intermediate BT (120–125°C). These results are in agreement with Moraru and Kokini (2003), who mention that the expansion usually occurs at high BT and low FM as a result of several events such as structural transformations of biopolymers, phase transitions and nucleation, swelling, growth, and collapse of air bubbles, all of them contributing to the expansion phenomenon. Furthermore, Lee, Lim, Lim, and Lim (2000) observed that starch gelatinization degree and the moisture content of the pellets are two important factors in determining the shape, bulk density, and expansion of microwave-expanded products. These authors found higher expansion values when BT...
The expansion of the extruded products is enhanced by an increase in temperature up to a peak and decreases thereafter. This is due to the physicochemical changes in starch-protein systems induced by temperature increment (Amaya-Llano, Morales-Hernández, Castaño-Tostado, & Martínez-Bustos, 2007; Moraru & Kokini, 2003). The temperature of maximal expansion is dependent on the ingredients being used. The decrease in EI may also be related to dietary fiber content of the mixture.

In our study, EI ranged from 1.91 to 4.80 (a commercial sample showed an EI of 4.75). These values are close to those reported by several authors for 3G microwave-expanded snacks (Bastos-Cardoso et al., 2007; Delgado-Nieblas et al., 2012), and the differences that were found in BT for maximum expansion of the mixture.

The expansion of the extruded products is enhanced by an increase in temperature up to a peak and decreases thereafter. This is due to the physicochemical changes in starch-protein systems induced by temperature increment (Amaya-Llano, Morales-Hernández, Castaño-Tostado, & Martínez-Bustos, 2007; Moraru & Kokini, 2003). The temperature of maximal expansion is dependent on the ingredients being used. The decrease in EI may also be related to dietary fiber content of the mixture.
the pellets might be attributed to raw material formulations as well as to different types of extruders used.

**Bulk density (BD)**

Increasing BT from 98°C to ~125°C resulted in a decreased BD throughout the whole FM experimental interval. Above 125°C, the BD of the expanded products tends to increase. Furthermore, it can be seen that at lower BT (<110°C), BD decreased when FM increased. The values of BD in this study ranged from 178.2 to 428.6 kg/m³ (a commercial sample showed a BD of 130 kg/m³). The lowest values of BD of expanded pellets were shown at BT ~125°C, in about the whole FM range studied (Figure 2). In this work, an inverse behavior can be observed between BD and EI. The BD showed a high negative Pearson-correlation with EI ($r = -0.95$, $p < 0.05$). According to Ramírez-Ascheri, Ciacco, Riaz, and Luñas (1995), BD of 3G extruded products is inversely related to expansion degree and starch gelatinization degree, thereby lower BD values corresponded with higher EI values. These authors correlated extrusion variables with starch gelatinization degree, finding that the best product, with the highest degree of gelatinization, showed approximately 50% gelatinization. Aguilar-Palazuelos et al. (2006) elaborated a 3G snack, and they found that BD decreased by an interaction effect between BT and FM. Several authors have reported that when the extrusion temperature is increased, BD values tend to decrease, which is attributed to starch degradation as an effect of thermal process (Altan, McCarthy, & Maskan, 2008).

Özer, Ibanoglu, Ainsworth, and Yagmur (2004) reported that by decreasing the moisture content the BD decreased, while in the present study the effect of FM was significant only at BT lower than 110°C. Ding, Ainsworth, Plunkett, Tucker, and Marson (2006) found that as FM in the samples increased, BD values of the expanded snack products elaborated from wheat also increased. These authors attributed this behavior to a smaller starch gelatinization, leading to a lower EI and a high BD. In addition, Stojceska, Ainsworth, Plunkett, and Ibanoglu (2009) reported a similar behavior in extruded snacks made from wheat flour and corn starch added with red cabbage and by-products from brewing beer process.

**Penetration force (PF)**

Figure 3 shows the effect of BT and FM on PF. It can be seen that in the range from 18–26% of FM, PF decreased by increasing BT from 98°C to ~120°C. Above that temperature, PF tended to increase. On the other hand, at low BT (<110°C) and high BT (>130°C), as FM increased, PF decreased. The lowest experimental value of PF showed in this study was 8 N; this value was higher than the PF of a commercial sample (3.52 N). It has been documented that the incorporation of dietary fiber in the extruded products significantly reduces expansion volumes and increases density of extruded products, leading to harder textures (Robin, Schuchmann, & Palzer, 2012). The high PF values reported in the present study, could be due to a relatively high dietary fiber content contained in whole blue-corn flour used. In this work, PF showed moderate negative Pearson correlation with EI ($r = -0.63$, $p < 0.05$) and an important negative correlation with BD ($r = 0.71$, $p < 0.05$), thereby the low PF values corresponded with higher EI values and lower BD values. It is also observed that PF is a dependent variable of BT and FM, as reported by Martinez-Bustos et al. (1998). These behaviors can be related to starch gelatinization degree and the dietary fiber content present in the corn pericarp and interactions between lipids and proteins that make up the corn grain. These findings are consistent with those reported by Arias-García et al. (2007), who reported on products made from mixtures of wheat flour and corn starch. Those with higher EI and lower BD were the softer products. PF is a strength that reflects the resistance of bubble walls to be broken, which depends on the number of bubbles formed per volume unit and on the resistance of the formed cell-wall-type structures which are thinner as EI is increased (Pérez-Navarrete, Cruz-Estrada, Chel-Guerrero, & Betancur-Ancona, 2006). Several authors have reported a relationship between PF and EI of extruded products, since softer...
products have a higher EI (Delgado-Nieblas et al., 2012; Hsieh, Mulvaney, Huff, Lue, & Brent, 1989).

The extruded pellets, after expansion, can acquire a volume 2–9 times the original size (Mercier & Feillet, 1975). This expansion is related to the fragility of the piece being chewed. When the elaboration of the pellets is not within technological patterns, its expansion is very low and the product is very hard (Ramírez-Ascheri & Carvalho-Wanderley, 1997).

**Specific mechanical energy (SME)**

Figure 4 shows the effect of BT and FM on the SME. It is observed that with increasing FM at low temperatures (≤110°C), SME decreased. This is due to a reduced shear force and mechanical energy input. On the other hand, at low FM (<25%), BT increased and SME decreased. These results agree with those reported by Chang et al. (1999), who reported that an increase in BT causes a decrease in the SME. This was attributed to the increased temperature in the extrudate by increasing BT, which resulted in a decrease of the material viscosity and the required equipment energy. In addition, various authors have reported that an increase in FM during extrusion resulted in a decrease in material viscosity and in the required SME for the process (Rosentrater, Muthukumarappan, & Kannadhason, 2009; Singh, Smith, & Frame, 1998). In this study, SME showed a moderate positive correlation with PF (r = 0.58, p < 0.05). SME value is indicative of the extrusion process severity, and it has been reported that this parameter is correlated with properties of extruded products such as EI, BD, and PF (Altan et al., 2008; Onwulata, Konstance, Smith, & Holsinger, 2001). Furthermore, it has been reported that SME is dependent on the process parameters such as FM, BT, screw speed, and feed rate, FM being the most significant factor (Ding, Ainsworth, Tucker, & Marson, 2005).

The starch gelatinization degree varies with the SME applied by the extruder. High SME facilitates intermolecular rupture of hydrogen bonds, and the hydrophilic groups of starch are exposed to water, thereby the gelatinization is favored (Gropper, Moraru, & Kokini, 2002). The SME decrement by moisture effect is mainly due to the lubricating effect of water. FM plays an important role in controlling the extrusion process because of its impact on mixing, on viscosity, and on the retention time of the dough in the extruder barrel. Additionally, it has been reported that a reduction in the FM at low BT increases the SME required for the extrusion process, which is explained by the high viscosity of the dough processed under these conditions (Ryu, 2001). This behavior is consistent with the data obtained in this study. The experimental values of SME for the different treatments of the present study were within the range of 80.4–316.7 kJ/kg. SME values for different materials processed by extrusion ranged from 160 to 2108 kJ/kg (Bastos-Cardoso et al., 2007; Delgado-Nieblas et al., 2012; Gropper et al., 2002). It has been documented that, in efficiency terms, the SME values for extrusion process must be lower than 1000 kJ/kg.

**Water absorption index (WAI)**

The effect of BT and FM on WAI is shown in Figure 5. It can be seen that throughout the studied FM range WAI increased, reaching its highest level at approximately 130°C and decreasing thereafter. The highest WAI increment rate was shown between the range of 20–27% of FM. This effect could be explained by the rearrangement in the starch structure, which facilitates water absorption. Some researchers have suggested that when the temperature is increased in the presence of moisture, the chains of amylose and amylpectin are separated and form an extended matrix, which results in a higher water absorption capacity (Balandrán-Quintana, Barbosa-Cánovas, Zazueta-Morales, Anzaldúa-Morales, & Quintero-Ramos, 1998; Colonna, Tayeb, & Mercier, 1989; Kokini, Lai, & Chedid, 1992).

Water absorption index determines the quantity of water (in grams) that is bound to one gram of dry sample and indicates the integrity of the starch in an aqueous dispersion (Anderson et al.,...
Water absorption index (WAI)

The effect of extrusion parameters on WAI is shown in Figure 6. At FM lower than 30%, WAI increases as BT increased, peaking approximately at 120°C. This may be due to the starch degradation, which causes a rise in WSI as a result of a reduction in the molecular size of starch fragments. WSI showed a moderate negative correlation with FM ($r = -0.62$, $p < 0.05$). This correlation may be due to the fact that an increase in FM reduces friction of the dough in the extruder, so the material fragmentation is limited. Furthermore, the lubricating effect supplied by the water causes the sample to pass faster through the extruder, and the shearing effect of the BT and the extruder screw is not high enough to degrade the starch in high levels, obtaining a lower WSI as a result. WSI also showed a moderate positive correlation with EI ($r = 0.71$, $p < 0.05$), a moderate negative correlation with BD ($r = -0.60$, $p < 0.05$), and a moderate negative correlation with WAI ($r = 0.57$, $p < 0.05$). At low moisture content, SME increased. WSI is related to the amount of soluble solids in a dry sample, allowing for the verification of the severity of the extrusion process, which depends on the degradation, gelatinization, and dextrinization of starch (Carvalho et al., 2002; Yang, Peng, Lui, & Lin, 2008). In this study, the highest WSI value (20.47%) was shown at BT = 120°C and FM = 20%, while the lowest WSI value (5.46%) was obtained at BT = 99°C and FM = 27%. These results agree with those reported by several authors (Colonna & Mercier, 1983; Colonna, Doublier, Melcion, De Monredon, & Mercier, 1984; Gomez & Aguiler a, 1983), who found that at low moisture content, SME increased. WSI increases with increasing temperature, regardless of the concentration of starch present. This increase in soluble solids content suggests a disintegration.

<table>
<thead>
<tr>
<th>Feed moisture (%)</th>
<th>Barrel temperature (°C)</th>
<th>Water solubility index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.0</td>
<td>109.0</td>
<td>1.0</td>
</tr>
<tr>
<td>19.0</td>
<td>110.0</td>
<td>1.6</td>
</tr>
<tr>
<td>20.0</td>
<td>111.0</td>
<td>2.3</td>
</tr>
<tr>
<td>21.0</td>
<td>112.0</td>
<td>3.0</td>
</tr>
<tr>
<td>22.0</td>
<td>113.0</td>
<td>3.7</td>
</tr>
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<td>23.0</td>
<td>114.0</td>
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<td>115.0</td>
<td>5.1</td>
</tr>
<tr>
<td>25.0</td>
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<td>26.0</td>
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<td>27.0</td>
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<td>7.9</td>
</tr>
<tr>
<td>29.0</td>
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<tr>
<td>31.0</td>
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</tr>
<tr>
<td>32.0</td>
<td>123.0</td>
<td>10.7</td>
</tr>
<tr>
<td>33.0</td>
<td>124.0</td>
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</tr>
<tr>
<td>34.0</td>
<td>125.0</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Figure 6. Effect of barrel temperature (°C) and feed moisture (%) on water solubility index (WSI) of blue corn microwave-expanded extruded products.

Figura 6. Efecto de la temperatura de barril (°C) y humedad de alimentación (%), el índice de solubilidad en agua (WSI) de productos extrudidos de maíz azul, expandidos por microondas.
of the starch granules (Palav & Seetharaman, 2006). Singh-Gujral, Singh, and Singh (2001) elaborated sweet corn grits by extrusion and found that WSI increased with increasing BT and that WSI decreased with increasing FM, showing a greater FM effect. This behavior was attributed to the fact that increasing FM decreases SME, and this leads to low starch solubility. Agustiniano-Osornio et al. (2005) and Yagi & Gojtis (2008) reported that the extrusion process produces a complete starch gelatinization at low FM, when BT is in the range of 110–135°C. According to these authors, a combination of heat treatment and mechanical shear could explain the disappearance of granular structure and crystallinity of starch in extruded materials. WAI and WSI are important parameters to define the possible application of extrudates. A high WSI is related to thicker characteristics of extruded products (Hashimoto & Grossmann, 2003).

**Total anthocyanin content (TAC)**

Blue corn flour showed a TAC of 374 ± 9.60 mg/kg db, whereas the mixture (BCF + CS) showed a TAC of 248.67 ± 4.33. TAC of blue corn flour is consistent with that reported by Del Pozo-Infran, Brenes, Serna, and Talcott (2007), but higher than TAC values reported by Aguayo-Rojas et al. (2012) and Mora-Rochin et al. (2010) for Mexican blue corn. The effect of BT and FM on TAC of microwave-expanded pellets is shown in Figure 7.

It can be seen that throughout the FM experimental interval, TAC decreases with increasing BT. This decrease may be due to the poor stability of anthocyanin to heat. On the other hand, at low BT (<110°C), in general, FM had no effect on TAC levels. However, above this temperature, at intermediate conditions of FM (~27%), highest TAC values were observed. It is probable that during the increase of FM from 18% to 27%, the severity of the extrusion process was reduced, due to the lubricant effect of water. However, an increase of FM higher than 27% provided moisture sufficient for starch gelatinization that causes paste formation, provoking the slowing of the material flow, and a longer exposure to the action of high temperatures and mechanical shear, conducive to TAC degradation. The minimum (41.16 mg/kg db) and maximum (82.3 mg/kg db) TAC values corresponded to 105°C of BT/22% of FM and 135°C of BT/32% of FM, respectively. These data indicate a TAC decrease in 70–85% in relation to the raw material (248.67 ± 4.33 mg/kg). Losses of 64–90% for TAC caused by extrusion have been reported where blueberry and cranberry concentrates were incorporated to extruded corn and extruded breakfast cereals (Camire et al., 2002; Chaovanalikit, Dougherty, Camire, & Briggs, 2003). Aguayo-Rojas et al. (2012) found a TAC loss of 53.5% in tortillas elaborated from lime-cooking extruded blue corn. Due to heat treatments, anthocyanin may suffer important structural changes such as conversion to colorless chalcones (Wrolstad, Durst, Giusti, & Rodriguez-Saona, 2002), and due to their thermolability, chalcones may be instantly degraded into phenolic acids (Sadilova, Carle, & Stintzing, 2007). On the other hand, polymerization and browning also lead to a decrease in TAC (Singh, Gamalath, & Wakeling, 2007).

**Optimization**

The optimization of the extrusion process was carried out by the response surface superposition methodology. The selected responses for this procedure were EI, PF, SME, and TAC. The main criteria for determining the optimal area of surface superposition was the finding of processing conditions corresponding to the highest values of EI and TAC and the lowest values of SME and PF.

The area corresponding to the optimal conditions for obtaining expanded snacks, elaborated from blue corn flour and corn starch, ranged from 120°C to 126°C of BT and from 23.80% to 25.20% of FM, selecting as the central point the following conditions: 122.3°C of BT and 25.20% of FM (Figure 8). To
validate the models, one experimental assay was carried out with the central point conditions. The predicted values by the mathematical models for each response were: EI = 4.10 ± 0.04, PF = 12.42 ± 0.31 N, SME = 169.08 ± 1.85 kJ/kg, and TAC = 71.09 ± 1.10 mg/kg. The experimental values of the obtained products (pellets) were: EI = 4.47 ± 0.07, PF = 11.45 ± 0.49 N, SME = 185 ± 5.5 kJ/kg, and TAC = 61 ± 1.74 mg/kg. There is no significant difference (p = 0.05) between the predicted and the experimental values, except for TAC. Therefore, the tested model showed a good fit in finding the best conditions of BT and FM for the elaboration of BCF + CS-expanded snacks by the extrusion process.

Conclusions
The mathematical models used in the analysis of responses showed suitable values ($R^2$ ≥ 0.76), although some responses showed lack of fit. BT and FM had a significant effect on all the studied responses, except for WAI and TAC. The EI values showed by expanded blue corn products were similar to those exhibited by a commercial product, while the BD and PF were higher. The dietary fiber and anthocyanin derived from the addition of whole blue corn flour confer eventually nutraceutical characteristics to the expanded snacks. However, studies are needed to evaluate their nutraceutical potential. To our knowledge, this is the first report about the utilization of blue corn for the elaboration of 3G snacks.

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