ABSTRACT: Corn-based expanded extruded snacks containing wheat bran as dietary fiber source were evaluated with respect to instrumental hardness, expansion index and color (L* - lightness). Internal cell structure was observed through Scanning Electron Microscopy (SEM). Snacks were produced following a 2^3 complete factorial design, in a single screw extruder (model GNF 1014/2, BRABENDER, Germany). The three independent variables studied were: moisture (from 16.3 to 29.7%); temperature of the 2nd and 3rd extruder zones (from 104.8 to 155.2ºC); and wheat bran content (from 0 to 24.6%). An increase in temperature resulted in lower extrudate hardness values, which varied from 1.6 to 4.8kgf. Higher moisture and lower wheat bran contents resulted in snacks with greater hardness. Expansion index, that varied from 1.7 to 3.7, was mainly influenced by moisture and temperature, being that higher moisture values combined to higher temperatures resulted in lower expansion indexes. The snacks presented lightness (L*) values between 42.77 and 64.41, being the temperature the variable that most influenced the values, because higher values of temperature resulted in higher L* values. Observing the snacks through Scanning Electron Microscopy, the influence of wheat bran could be observed, as higher contents of wheat bran contributed to the formation of cells with reduced sizes.

INTRODUCTION

The thermoplastic extrusion process is used to produce expanded snacks also known as second generation snacks. These snacks may have different characteristics (high fiber content, low caloric content, high protein content, etc.); and can be produced from different raw-materials (flours and/or starches from cereals, roots and tubers). Corn, as a flour or as grits, has been widely used to produce expanded extruded snacks, as it contains high starch content (between 65 and 70%, wet basis) and significant protein content (between 8 and 10%, w.b.); apart from presenting good sensory acceptance. Wheat bran appears as an important dietary fiber source. Bran represents from 12 to 15% of the wheat kernel and is composed of 45 to 50% dietary fiber, of which 95% is insoluble fiber. It has been highlighted that dietary fibers, as those present in wheat bran, improve intestinal function; as well as being effective in the reduction of the risk of degenerative diseases, such as colon cancer, diabetes and obesity.1, 12, 25

Thermoplastic extrusion is a continuous process, in which mixing, shear, cooking, and modeling occur simultaneously. Thus, the raw-material that is extruded is submitted to various changes, notably: hydration of starch and proteins, homogenization, starch gelatinization, fat liquefaction, protein denaturation, destruction of anti-nutritional factors, enzyme inactivation, plasticizing and expansion of the processed material. This type of process makes it possible, with little or no modification of the basic equipments and with appropriate process control, to produce a great variety of final products, such as expanded snacks.17, 18, 27

Extrusion parameters (temperature, screw rotation, die diameter, etc.) and raw-material characteristics (moisture content, particle size distribution, type of material used, etc.) have great influence on hardness, expansion, color and internal structure of expanded snacks, with direct consequences on their acceptance.15, 24

KEYWORDS: Thermoplastic extrusion; snacks; wheat bran; experimental hardness; expansion index; scanning electron microscopy.

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Introduction of dietary fiber in expanded extruded snacks has increased, because the inadequate ingestion of dietary fiber is related to occurrence of several diseases, emphasizing: heart diseases, diabetes, obesity and cancer.

Expanded extruded snacks generally are poor in dietary fiber, but have a good acceptance, especially among children and adolescents. According to Collucci & Bassette, in 2005, 35% of people between 7 and 12 years old were above the recommended weight in Brazil. Due to the good acceptance, snacks can be used as way to supply dietary fiber in significant amounts, aiming to reach part of DRI (Dietary Reference Intakes).

Snacks containing wheat bran as dietary fiber source can be classified as functional foods. Functional foods are those which present not only nutritional functions, due to the presence of substances that act into the organism regulating biochemical/physiological functions, but also contribute to higher protection to health, because they help to postpone pathological processes that result in chronic and degenerative diseases.

According to Cho et al., wheat bran represents a dietary fiber concentrated source. Bran consists of external layers of wheat grains and can be separated from the germ during the milling process. Wheat bran generally comprehends around 12 to 15% of wheat grain and is composed by 45 to 50% of dietary fiber, being approximately 95% of it insoluble. The authors emphasize wheat bran as the dietary fiber source to improve intestinal activity. Besides, they cite wheat bran as effective to decrease the risk of colon cancer, diabetes and obesity. They also recommend the use of wheat bran in nutritional education programs.

The objective of this study was to evaluate the influence of raw-material moisture content, barrel temperature in the 2nd and 3rd zones of the extruder, and of the quantity of added wheat bran on experimental hardness, expansion index (EI) and color (L* - lightness) of snacks; as well as to characterize the internal cell structure of extrudates, establishing a relationship between the experimental measurements (technological parameters) and the structures visualized through Scanning Electron Microscopy (SEM). Besides, the sensory acceptance of expanded extruded snacks with and without wheat bran, respectively described as optimum and control samples, was evaluated.

MATERIAL AND METHODS

Material

Corn grits (“quirera”) and wheat bran were purchased at the local market (Campinas, SP, Brazil). Corn grits were milled to flour by passing them through the break and reduction sections of a laboratory roller mill (Quadramat Senior, BRABENDER, Germany).

Particle size distribution of the raw materials

Corn flour and wheat bran were characterized as to their particle size distribution according to AOAC method 965.22.

Proximate composition of the raw materials

Moisture, protein (N x 6.25) and ash content determinations were carried out according to AACC methods 44-15A, 46-13 and 08-01, respectively. Lipid content was determined according to the methodology described by the Adolfo Lutz Institute, using petroleum ether for extraction. Total dietary fiber content was determined through the AOAC enzymatic-gravimetric method 985.29. Total carbohydrate content includes dietary fiber and was calculated by difference, subtracting from 100% the sum of moisture, protein, lipid and ash contents.

Extrusion process

The experiments were carried out using a single-screw laboratory extruder (model GNF 1014/2, BRABENDER, Germany), with an L/D ratio of 20:1 (380mm length and 19 mm diameter). The extruder had three heating zones, which were heated by electric resistances. Cooling and temperature of the different extruder zones were controlled.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>Screw compression ratio</td>
<td>3:1</td>
</tr>
<tr>
<td>Screw speed (rpm)</td>
<td>150</td>
</tr>
<tr>
<td>Die diameter (mm)</td>
<td>4</td>
</tr>
<tr>
<td>Temperature in the 1st extruder zone (ºC)</td>
<td>80</td>
</tr>
<tr>
<td>Feeding rate (g/min)</td>
<td>70</td>
</tr>
<tr>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>Temperature in 2nd and 3rd extruder zones (ºC)</td>
<td>104.8 to 155.2</td>
</tr>
<tr>
<td>Raw material moisture content (%)</td>
<td>16.3 to 29.7</td>
</tr>
<tr>
<td>Wheat bran (%)</td>
<td>0.0 to 24.6</td>
</tr>
</tbody>
</table>

Table 1 – Parameters used for the production of the snacks using different ratios of corn grits and wheat bran.
using compressed air. Process parameters were divided in fixed and variable and are described in Table 1.

For each assay, 1.3 kg raw material was used, and the extruded material was collected 10 minutes after the beginning of the run, that is, after the stabilization of process conditions. Extrudate diameter was measured after cooling at room temperature for 30 minutes. The material was then oven-dried at 90ºC for 1 h. The extrudates were cooled to room temperature and stored in polyethylene bags in a dry place until analyses.

**Experimental design and data analysis**

To evaluate the combined effect of the independent variables (raw material moisture content, temperature in the 2nd and 3rd extruder zones and wheat bran addition) on the dependent variables or responses (extrudate hardness, expansion index and L* lightness) and characterize cell structure (cell wall thickness and integrity), a 2nd order central composite rotational design (CCRD) was used, aiming at analyzing the results through the Response Surface Methodology (RSM). A 23 complete factorial design was used, composed of 17 assays: 8 factorial points (combinations of levels −1 and +1); 6 axial points (one variable at level +α and two at 0; and one variable at level −α and two at 0); and 3 central points (all three independent variables at level 0). The variation ranges and the values of the central points of the three independent variables were chosen based on preliminary trials and on the data presented by Booth. The coded value of α (axial point) was calculated and was equal to 1.682. The independent variables and their respective variation ranges are shown in Table 2. The assays carried out according to the experimental design and their respective coded values are described in Table 3.

**Table 2** – Independent variables and variation ranges of the experimental design for the production of snacks using different ratios of corn grits and wheat bran.

<table>
<thead>
<tr>
<th>CODED LEVELS</th>
<th>INDEPENDENT VARIABLES</th>
<th>(Real values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>Factorial</td>
<td>x1</td>
</tr>
<tr>
<td>- α = -1.682</td>
<td></td>
<td>16.3</td>
</tr>
<tr>
<td>-1</td>
<td></td>
<td>19.0</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>23.0</td>
</tr>
<tr>
<td>+1</td>
<td></td>
<td>27.0</td>
</tr>
<tr>
<td>+α = 1.682</td>
<td></td>
<td>29.7</td>
</tr>
</tbody>
</table>

X1, x1 = Raw material moisture content (%); X2, x2 = Temperature in the 2nd and 3rd extruder zones (ºC); X3, x3 = Wheat bran (%).

**Table 3** – Assays of the experimental design (levels in coded values and corresponding decoded or real values) for the production of snacks using different ratios of corn grits and wheat bran.

<table>
<thead>
<tr>
<th>Assay</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
<th>x1</th>
<th>x2</th>
<th>x3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>19</td>
<td>115</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>27</td>
<td>115</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>19</td>
<td>145</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>27</td>
<td>145</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>19</td>
<td>115</td>
<td>19.6</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>27</td>
<td>115</td>
<td>19.6</td>
</tr>
<tr>
<td>7</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>19</td>
<td>145</td>
<td>19.6</td>
</tr>
<tr>
<td>8</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>27</td>
<td>145</td>
<td>19.6</td>
</tr>
<tr>
<td>9</td>
<td>-α</td>
<td>0</td>
<td>0</td>
<td>16.3</td>
<td>130</td>
<td>12.3</td>
</tr>
<tr>
<td>10</td>
<td>+α</td>
<td>0</td>
<td>0</td>
<td>29.7</td>
<td>130</td>
<td>12.3</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>-α</td>
<td>0</td>
<td>23</td>
<td>104.8</td>
<td>12.3</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>+α</td>
<td>0</td>
<td>23</td>
<td>155.2</td>
<td>12.3</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>-α</td>
<td>23</td>
<td>130</td>
<td>0.0</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0</td>
<td>+α</td>
<td>23</td>
<td>130</td>
<td>24.6</td>
</tr>
<tr>
<td>15 (C)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>23</td>
<td>130</td>
<td>12.3</td>
</tr>
<tr>
<td>16 (C)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>23</td>
<td>130</td>
<td>12.3</td>
</tr>
<tr>
<td>17 (C)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>23</td>
<td>130</td>
<td>12.3</td>
</tr>
</tbody>
</table>

X1, x1 = Raw material moisture content (%); X2, x2 = Temperature in the 2nd and 3rd extruder zones (ºC); X3, x3 = Wheat bran (%); (C) Central point.
The results were analyzed using the Statistica software, version 5.5 (StatSoft, USA). To show the response surfaces and visualize the effect of the independent variables on experimental hardness, expansion index and lightness (L*), one of the independent variables was maintained fixed at the central point, while the other two varied within the ranges proposed in the experimental design.

**Hardness**

The determination of the hardness of the extrudates was carried out using a texture analyzer (model TA-XT2, STABLE MICRO SYSTEMS, United Kingdom), maximum load of 25kg, with the Texture Expert software for data collection. Samples of 40mm length were evaluated, disposed horizontally on a support with an opening. This opening permitted the passage of a rectangular steel blade (Warner Bratzler) of 12x7cm (HDP/BS), that ruptured the sample on the support, acting as a guillotine. The results were expressed in kgf (kilogram-force) and represent the average of 10 rupture force determinations for samples from the same extrusion condition. The conditions used in the hardness analysis were: measurement of force in compression; force threshold of 1.0g; pre-test speed of 4.0mm/s; test speed of 1.0mm/s; post-test speed of 5.0mm/s; rupture distance of 15mm.

**Expansion index (EI)**

The expansion index (EI) was determined according to the methodology proposed by Batistuti et al., where this index represents the ratio between the diameter of the extrudate and the diameter of the die of the extruder. The diameter measurements of snacks were done using a digital pachymeter (model CD-6”BS, MITUTOYO, Japan). For the calculation of the EI, the average of 10 diameter measurements at different parts of the sample for each extrusion condition was considered.

**Color - lightness (L*)**

Color (L* - lightness) of snacks was determined using a spectrophotometer (model COLOR QUEST II, HUNTERLAB, USA). The evaluation was based on (L*a*b* CIELab). In this system, L* represents the lightness, which varies from zero (black) to 100 (white); while a* and b* represent chromatic coordinates, being that +a* indicates tendency to red and -a* tendency to green; +b* indicates tendency to yellow and -b* tendency to blue. For color measurements, snacks were disposed in a bundle form, with around 15 extrudates of 100mm length each.

The obtained results for several evaluations were used to determine L* value. This value was determined for the 17 assays proposed in the experimental design, and for snacks with and without wheat bran, aiming to verify the influence of wheat bran and operational conditions in browning or not of snacks.

**Evaluation of the snacks by Scanning Electron Microscopy (SEM)**

The snacks were fractioned into pieces of 3.0mm thickness and placed on aluminum stubs. The material was covered with a gold-palladium layer (covering rate of 0.5 Angstrom’s), of 92 Å thickness. The samples were introduced in the scanning electron microscope (model LEO 440i, LEICA, Germany) and the visualization of the structures was done using variable magnifications, so as to best characterize the extrudates.

**Choice of optimum and control points**

The experimental point considered as control was the one proposed for assay 13 of experimental design (moisture = 23%; temperature in the 3rd zone of extruder = 130°C; and wheat bran content = 0.0%). This choice was done in function of the use of intermediate conditions of experimental design (central) in terms of moisture and temperature and by representing a product with no wheat bran addition, like is more common to be found in the market.

The optimum point choice took into account the amount of dietary fiber supplied by the product, because it reaches the minimum established by Brazilian legislation to consider it as “high fiber content”. Therefore, a wheat bran content of 12.3% was used in the formulation, that represents 8.7% of dietary fiber in the final product (wt basis). It is important to emphasize that the minimum determined by the Brazilian food legislation for a product to be considered as “high fiber content” is 6g of dietary fiber per 100g of product.

The values used for moisture and temperature in the optimum point were the same used for the control point, aiming to avoid that these variables could contribute to not true conclusions in terms of wheat bran influence in the quality of final product.

**Sensory analysis**

The expanded extruded snacks (optimum and control) were sensorially evaluated through an acceptance test, using a 9-point hedonic scale (mixed structured), where the value 1 corresponded to “disliked very much” and 9 to “liked very much”. In the evaluation, 40 people tasted the samples, which were evaluated in the same session, but using two forms (one for the control and other for the optimum) in relation to the following attributes: color, appearance, texture (hardness), taste and global evaluation. Before the evaluation, snacks were coated with salt (saline solution 10%).

It is important to emphasize that the sensory evaluations were carried out in individual cabinets, under
white fluorescent light, with water for the evaluators between the samples.

The evaluators were students and employees of the University of Campinas (UNICAMP, Brazil), men and women, between 18 and 45 years old.

The results from sensory analysis were evaluated by Variance Analysis (ANOVA), being the averages compared by the Tukey test, at 5% of probability.

RESULTS AND DISCUSSION

Particle size distribution of the raw materials

Corn flour presented, predominantly (85%), particle size between 0.15 and 0.42mm. Wheat bran presented larger particles, with 96.5% greater than 0.5mm. According to Mercier et al., very small particles of starch or flour are more easily molten, resulting in a sticky mass, difficult to displace within the extruder. On the other hand, particles greater than 0.5mm may be incompletely molten. Both, very small and very large bran and starch-based particles directly influence expansion, reducing it; with direct consequences on the hardness of the extrudates, usually increasing it. The authors also state that large particles, as in the case of wheat bran, tend to rupture the cell walls of the extrudates, as they do not undergo gelatinization as corn starch does (they act as inert material), contributing to reduce expansion and increase hardness.

Proximate composition of the raw materials

The results obtained for the chemical composition of the raw materials are presented in Table 4, with values in wet basis.

Corn flour presented a high carbohydrate content and low dietary fiber and protein contents. The results found for corn flour are close to those found in the literature, except for ash content (0.3%, w.b.), lower than the values reported by the previously mentioned authors (between 0.7 and 0.9%, w.b.).

Wheat bran presented a high dietary fiber content, as well as a significant protein content. The proximate composition of wheat bran is very close to that found in the USDA data-base.

Hardness

The experimental values for snack hardness are presented in Table 5.

The influence of the independent variables on snack hardness can be represented by the coded mathematical model presented in Equation 1, which includes only the significant regression coefficients. The coefficients proposed for the equation presented significance at P≤0.05. Also, the model proposed was well adjusted, with R²=0.83, especially considering such a complex process as thermoplastic extrusion.

\[
\text{Hardness (kgf)} = 2.82 + 0.25 X_1 - 0.69 X_2 - 0.22 X_3 + 0.16 X_1 X_2 + 0.19 X_2 X_3 + 0.18 X_2^2
\]

Where:

- \(X_1\) = Raw material moisture content (%);
- \(X_2\) = Temperature in the 2^nd and 3^rd extruder zones (ºC);
- \(X_3\) = Wheat bran (%).

To be used as coded values.

The effects of extrusion conditions on snack hardness are shown in Figures 1, 2 and 3.

According to the model and the figures, temperature presented the most significant effect on snack hardness, with an increase in this extrusion parameter, resulting in a decrease in the values of experimental hardness, which is in accordance with the observations of some works found in the literature. These works explain that the increase in temperature reduces the viscosity of the material within the extruder, thus favoring bubble growth in the molten material, consequently increasing extrudates expansion and reducing hardness. In this study, the increase in expansion was not observed, probably due to a greater fragility of the structure due to the presence of bran.

Raw material moisture content and wheat bran addition also presented significant effects on extrudates hardness, however at a lower intensity. Increasing raw material moisture content resulted in harder snacks, while increasing wheat bran addition, opposite to what was expected, contributed to lower hardness values. According to Ding et al., water acts as a plasticizer of the starch material inside the extruder. Increasing raw material moisture content under low extrusion temperature

<table>
<thead>
<tr>
<th>Components</th>
<th>Corn flour</th>
<th>Wheat bran</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>11.3 ± 0.1</td>
<td>11.7 ± 0.1</td>
</tr>
<tr>
<td>Protein</td>
<td>7.4 ± 0.2</td>
<td>15.3 ± 0.2</td>
</tr>
<tr>
<td>Lipids</td>
<td>3.6 ± 0.3</td>
<td>4.0 ± 0.3</td>
</tr>
<tr>
<td>Ash</td>
<td>0.3 ± 0.05</td>
<td>5.5 ± 0.03</td>
</tr>
<tr>
<td>Dietary fiber</td>
<td>2.8 ± 0.2</td>
<td>46.3 ± 0.1</td>
</tr>
<tr>
<td>Carbohydrates*</td>
<td>77.4 ± 0.5</td>
<td>63.5 ± 0.3</td>
</tr>
</tbody>
</table>

*Include dietary fiber.
conditions, reduces the viscosity of this mass. Thus, starch gelatinization is reduced and bubble growth is suppressed, resulting in a denser, harder and less crunchy final product. The increase of hardness as a function of the increase of raw material moisture content was also observed when extruding cassava flour.4

The reduction of hardness values as a function of the increase of the addition of wheat bran is not in accordance with some works,28,30 as these works relate the presence of dietary fiber, as that in wheat bran, to the reduction of the expansion of the extruded products, indicating as a consequence an increase in their hardness.

Expansion index (EI)

The experimental values for snack expansion index (EI) are presented in Table 5 and the snacks obtained for each experimental condition can be visualized in Figure 4.

Table 5 – Observed values (responses) for instrumental hardness, expansion index and lightness (L*) to productions of snacks using different ratios of corn grits and wheat bran.

<table>
<thead>
<tr>
<th>Assay</th>
<th>Hardness (kgf)</th>
<th>EI</th>
<th>L*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.9</td>
<td>3.6</td>
<td>54.69</td>
</tr>
<tr>
<td>2</td>
<td>4.0</td>
<td>2.9</td>
<td>46.51</td>
</tr>
<tr>
<td>3</td>
<td>1.6</td>
<td>3.3</td>
<td>50.93</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>1.9</td>
<td>64.41</td>
</tr>
<tr>
<td>5</td>
<td>2.8</td>
<td>3.1</td>
<td>42.77</td>
</tr>
<tr>
<td>6</td>
<td>3.2</td>
<td>2.5</td>
<td>48.20</td>
</tr>
<tr>
<td>7</td>
<td>1.7</td>
<td>2.9</td>
<td>55.31</td>
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<tr>
<td>8</td>
<td>2.2</td>
<td>1.8</td>
<td>61.37</td>
</tr>
<tr>
<td>9</td>
<td>3.4</td>
<td>3.0</td>
<td>48.93</td>
</tr>
<tr>
<td>10</td>
<td>3.6</td>
<td>1.7</td>
<td>52.83</td>
</tr>
<tr>
<td>11</td>
<td>4.8</td>
<td>3.4</td>
<td>44.97</td>
</tr>
<tr>
<td>12</td>
<td>2.4</td>
<td>2.2</td>
<td>62.19</td>
</tr>
<tr>
<td>13</td>
<td>3.0</td>
<td>3.7</td>
<td>60.59</td>
</tr>
<tr>
<td>14</td>
<td>2.8</td>
<td>2.4</td>
<td>52.84</td>
</tr>
<tr>
<td>15 (C)</td>
<td>2.8</td>
<td>2.7</td>
<td>49.84</td>
</tr>
<tr>
<td>16 (C)</td>
<td>2.6</td>
<td>2.5</td>
<td>48.30</td>
</tr>
<tr>
<td>17 (C)</td>
<td>2.6</td>
<td>2.7</td>
<td>53.87</td>
</tr>
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</table>
The influence of the independent variables on snack expansion index (EI) can be represented by the coded mathematical model presented in Equation 2, which includes only the significant regression coefficients. The coefficients proposed for the equation presented significance at $P \leq 0.05$. Also, the model proposed was well adjusted, with $R^2 = 0.87$, especially considering such a complex process as thermoplastic extrusion.

$$EI = 2.73 - 0.48 X_1 - 0.32 X_2 - 0.27 X_3$$

Equation 2

Where:

- $X_1 =$ Raw material moisture content (%);
- $X_2 =$ Temperature in the 2nd and 3rd extruder zones ($^\circ$C);
- $X_3 =$ Wheat bran (%). To be used as coded values.

The effects of extrusion conditions on snack expansion index (EI) are shown in Figures 5, 6 and 7. Analyzing the model and the figures related to the expansion index (EI), it can be observed that this index varies in a linear form with the variation of each of the parameters evaluated; with an increase in the values of raw material moisture content, temperature and wheat bran.

\[ \text{FIGURE 3 – Effect of wheat bran and extrusion temperature on snack hardness using different ratios of corn grits and wheat bran. (*) The third independent variable was maintained fixed at the central point.} \]

\[ \text{FIGURE 4 – Visualization of the snacks obtained for each experiment using different ratios of corn grits and wheat bran.} \]
addition resulting in lower EI values. The most significant effects on the EI were those of moisture and temperature.

According to Figure 5, the highest EI values were obtained with the lowest moisture and temperature values. Usually, an increase in temperature results in an increase in expansion, however, according to Lue et al.24 at very high temperatures, the molten mass of material is not able to retain the vapor generated when exiting the die, due to starch dextrinization and the weakening of the structure. Thus, the EI is reduced. In this study, the presence of wheat bran could have further influenced the weakening of the structure.

Ding et al.16 found that moisture is the main factor that affects the density of the extrudates and their expansion. In this work, moisture was the variable that most affected the EI. According to the authors mentioned, the high dependence of expansion in relation to moisture would be the result of its influence on the elastic characteristics of the materials. High raw material moisture contents can reduce the elasticity of the mass through plasticization of the molten material, resulting in reduction of the specific mechanic energy, with a consequent reduction of gelatinization.

In Figure 6, it can be observed that for low raw material moisture content and wheat bran addition values,
EI values were higher. According to Riaz,\textsuperscript{30} particles in the form of bran tend to rupture extrudate cell walls, causing a reduction in the EI. The behavior shown in Figure 6 is in accordance with Berglund et al.\textsuperscript{7} that evaluating barley extrudates with high fiber contents, found that their expansion was inhibited. Increasing the dietary fiber content, the authors point out that there was a reduction of the starch content, interfering with product expansion. Chang et al.,\textsuperscript{11} developing extruded snacks using mixtures of “jatobá” flour (rich in fibers) and cassava starch, found that the EI was reduced linearly with the increase of the concentration of “jatobá” flour, moisture content and extrusion temperature.

Figure 7 shows clearly, as does Figure 6, that the increase of wheat bran in the formulation tends to reduce the EI. Relating wheat bran and temperature, it is observed that the lowest EI values were found at high temperatures (above 140°C) and high wheat bran contents (above 20%). The reduction of the EI due to the increase of wheat bran content and process temperature is in accordance to the found by Berglund et al.\textsuperscript{7}

Color - lightness (L*)

The experimental values for snack color (lightness – L*) are presented in Table 5. The influence of the independent variables on L* values can be represented by the coded mathematical model presented in Equation 3, which includes only the significant regression coefficients. The coefficients proposed for the equation presented significance at $P \leq 0.05$. Also, the model proposed was well adjusted, with $R^2 = 0.76$, especially considering such a complex process as thermoplastic extrusion and as the snacks are not homogeneous when displaced in a bundle form when evaluated.

$$L^* = 15.52 + 0.25 \times X_2 - 1.05 \times X_3 + 0.004 \times X_1X_2 + 0.03 \times X_3^2$$ \hspace{1cm} \text{Equation 3}

Where:

- $X_1 = $ Raw material moisture content (%);
- $X_2 = $ Temperature in the 2nd and 3rd extruder zones (°C);
- $X_3 = $ Wheat bran (%). To be used as coded values.

The effects of extrusion conditions on the color of snacks (L* - lightness) are shown in Figures 8, 9 and 10. The color of extruded snacks is influenced by temperature, raw material composition, residence time, pressure and shear stress.\textsuperscript{20, 28}

Color is an important visual quality (attribute) of food products. There are several reactions that happen during the extrusion and can affect the color. Among them, the most common are the non-enzimatic browning reactions (Maillard reaction and caramelization) and pigments degradation. Processing conditions used in extrusion (high temperature and low moisture) are recognized to favor the reaction between reducing sugars and aminoacids, that results in the formation of colored compounds and in the reduction of lysine aminoacid. If browning is too intense, colors and undesirable tastes may come up. Besides, the color changes during the process can be considered as an indicator to evaluate the intensity of the process in terms of chemical and nutritional changes.\textsuperscript{21}

Observing Figure 8, it is possible to verify that an increase of moisture, when compared to temperature, had little influence on L* value. Therefore, higher temperature in the process resulted in lighter snacks. It can be related to the loss of color as a function of the severity of thermal treatment. It is important to emphasize that it could be
noted visually that snacks obtained with high temperatures were whitened.

According to Figure 9, for the same wheat bran content, an increase in moisture indicated a tendency to increase L* values, or better, lighter snacks. It is also noticed that lower L* values were obtained for low moisture in association with intermediate wheat bran content (between 10 and 15%). The results are not in accordance by the proposed by Liu et al., which evaluated oat flour and corn flour based extrudates and found that an increase in the moisture content contributed to the reduction of L*, or better, a browning of the material happened. Nevertheless, Ilo & Berghofer proposed that high temperatures and low moisture favor the occurrence of non-enzymatic browning reactions.

In the Figure 10, it is possible to verify again that the lowest values of L* were obtained for intermediate contents of wheat bran; and that an increase in temperature resulted in lighter snacks, showing loss of color of them. The results found are not in accordance to the found by Grenus et al., which studied the extrusion of rice bran and flour; the authors found that an increase in the levels of bran resulted in darker snacks. In the figure above can be clearly observed that the L* value was influenced by the temperature.

**Microscopic evaluation of the extrudates**

The internal structures of the expanded extruded snacks observed through SEM are shown in Figure 11. The micrographs are numbered from 1 to 17, according to the experimental design. Also, the internal cell structures were evaluated under different magnifications, so as to best characterize the structures. The magnifications used were the following: Assays 1 (24x), 9 (30x), 11 (30x) e 13 (30x) (bar = 1 mm); Assays 2 (40x), 3 (35x), 4 (60x), 5 (34x), 6 (50x), 7 (45x), 10 (70x), 12 (50x), 14 (50x), 15 (40x), 16 (60x) and 17 (50x) (bar = 300µm); Assay 8 (60x) (bar = 200µm).

Observing Figure 11, it can be verified that the different processing conditions used for the different assays had a great influence on the internal cell structure of extruded snacks. In general, high raw material moisture contents, 27% (Assays 2, 4, 6 and 8) and 29.7% (Assay 10) resulted in snacks with a dense structure and poor cell formation. This probably occurred due to a lower degree of starch gelatinization, which contributed to an inadequate formation of the extruded matrix. Liu et al. report that high moisture contents reduce the friction (mechanical shear) between the mass and the extruder internal surface, reducing its temperature and, consequently, presenting a negative impact on gelatinization. In the assays with the lowest raw material moisture content, 19% (Assays 1, 3, 5, 7 and 9), extrudates with a less dense structure and a tendency to form well structured cells, of sizes greater than or equal to 500µm, were obtained. The points with intermediate moisture content (23%) presented cells with intermediate characteristics (a tendency to higher density; however, with well defined cells). The lowest EI values were found at the highest raw material moisture contents and temperatures (Assays 4, 8 and 10). Temperature also had an important influence on extrudate structure. In Assay 3, it can be observed that high temperature, combined to low raw material moisture content, produced snacks with large cells (greater than 500µm) of thin walls. This probably occurred due to the reduced viscosity of the molten material. At other experimental points where high temperatures were used, such as Assays 4, 7, 8 and 12, the formation of large cells with thin walls was suppressed by other factors (high moisture and/or the presence of wheat bran). The snacks from Assay 11, produced at the lowest temperature (104.8°C) were those that presented the greatest hardness, when evaluated using a texture analyzer (4.8kgf).

**FIGURE 9**: Effect of moisture and wheat bran on lightness (L*) of snacks using different ratios of corn grits and wheat bran. (*) The third independent variable was maintained fixed at the central point.

**FIGURE 10**: Effect wheat bran and temperature on lightness (L*) of snacks using different ratios of corn grits and wheat bran. (*) The third independent variable was maintained fixed at the central point.
FIGURE 11 – Micrographs showing the internal structure of the extrudates. The magnifications used were the following: Assays 1 (24x), 9 (30x), 11 (30x) e 13 (30x) (bar = 1 mm); Assays 2 (40x), 3 (35x), 4 (60x), 5 (34x), 6 (50x), 7 (45x), 10 (70x), 12 (50x), 14 (50x), 15 (40x), 16 (60x) and 17 (50x) (bar = 300 μm); Assay 8 (60x) (bar = 200 μm).
Wheat bran addition also influenced cell formation within the extrudates, with high percentages of wheat bran, as in Assays 8 and 14 (19.6 and 24.6% wheat bran, respectively), contributing to the formation of dense structures; reduced average cell size (close to 300 μm) with a great number of holes in their walls. Assay 13, which represents a snack without wheat bran, showed few cells, but of a large size (greater than 1 mm), with a relatively smooth surface and without holes between adjacent cells.

According to the results, it is possible to verify that the degree of expansion was dependent on the quantity of wheat bran present in the formulation; and is associated to cell size. Lue et al.24 state that wheat bran in extrudates tends to rupture cell walls at a critical thickness before the cell has reached its maximum expansion. Also, they point out that, increasing the content of dietary fiber, a reduction in average cell size occurs, apart from an increase in the frequency of incomplete flakes and holes formed. Mercier et al.28 also report that large wheat bran particles, as those used in this work (96.2% particles greater than 0.50mm), contribute to a greater susceptibility to rupturing extruded cells. This can occur due to the fact that wheat bran dilutes starch and does not undergo gelatinization.

Although Booth8 mentions that increasing fiber content, as done increasing wheat bran content, increases expanded extruded snacks hardness, in this work, the reduction of hardness observed when increasing wheat bran addition, even though an apparently denser structure was formed, is probably due to the weakening of the structure through ruptures in cell walls.

**Sensory analysis**

The results found for expanded extrudates snacks in optimum (with wheat bran) and control (without wheat bran) points are shown in Table 6.

The results obtained through the sensory evaluation of snacks (control and optimum points) showed that the samples were significantly different at 95% of significance in terms of color and appearance. The best results were attributed to the control sample, which was without wheat bran, that was clearer and yellower and with more expansion. It can be the consequence of the fact that consumers use as reference corn-based snacks commonly found in Brazilian market, which do not contain wheat bran in its composition, and are clear and well expanded. In terms of color, the control snack was classified as “liked moderately” and “liked very much”, while the optimum was classified as “liked only a little”. The appearance of snacks was classified between “liked only a little” and “liked moderately” for the control, and between “liked/disliked” and “liked only a little” for the optimum.

**CONCLUSION**

The process parameters (moisture, temperature and wheat bran content) interfered on corn-based snacks features, with main influence of temperature on hardness, predominant influence of moisture and temperature on expansion index, and temperature and wheat bran content on lightness (L*).

Relating the experimental results of hardness and expansion index (EI) with the micrographs obtained through SEM for the different processing conditions, it is possible to conclude that the different experimental conditions resulted in snacks with different characteristics, both quantitatively (instrumental texture and EI evaluations) and qualitatively (through SEM); with instrumental hardness and expansion results being corroborated by microscopy and vice-versa.

All the independent variables studied (raw material moisture content, temperature and wheat bran) influenced extrudate hardness and expansion measurements and extrudate internal structure, however in different intensities.

Although it is stated in literature that the presence of fibers, such as wheat bran, results in harder extruded snacks, as a function of lower expansion and greater density, in this work it was observed that the snacks did present a less expanded (denser) structure when greater quantities of wheat bran were added, however hardness values were relatively low, suggesting that wheat bran acted as inert material, contributing to the formation of holes in extrudate cell walls and a less rigid structure.

For sensory acceptance, the best results were achieved by control sample, as it resembles the kind of product commonly found in the Brazilian market. However, the results did not differ very much, indicating that it is

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**Table 6 – Results for sensory acceptance of snacks in control and optimum points (***).**

<table>
<thead>
<tr>
<th>Point</th>
<th>Color</th>
<th>Appearance (expansion)</th>
<th>Texture</th>
<th>Taste</th>
<th>Global acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average&lt;sup&gt;1,2&lt;/sup&gt;</td>
<td>SD</td>
<td>Average</td>
<td>SD</td>
<td>Average</td>
</tr>
<tr>
<td>Control</td>
<td>7.43&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.58</td>
<td>6.88&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.47</td>
<td>5.03&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Optimum</td>
<td>5.95&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.05</td>
<td>5.30&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.87</td>
<td>5.40&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

(* *) Conditions of control point: moisture = 23%; temperature in the 3rd zone of the extruder = 130°C; and wheat bran content = 0.0% / Conditions of optimum point: moisture = 23%; temperature in the 3rd zone of the extruder = 130°C; and wheat bran content = 12.3%.

1 Same letters in the same column indicate that there is no significant difference between the samples at 95 % of significance (p<0.05).

2 Values between 1 and 9 (1 = “disliked very much” and 9 = “liked very much”).

SD = Standard deviation.
possible to add wheat bran in corn-based expanded snacks formulation, emphasizing the functional properties and serving as an important source of dietary fiber, especially to children and adolescents. It is important to emphasize that these snacks were not coated with condiments normally used in commercial snacks production and this fact may have contributed to reduce their scores in the sensory analysis.


RESUMO: Snacks extrudados expandidos de milho contendo farelo de trigo como fonte de fibra alimentar foram avaliados em relação à dureza instrumental, ao índice de expansão e à cor (L* - luminosidade). A estrutura interna foi observada por meio de Microscopia Eletrônica de Varredura (MEV). Os snacks foram produzidos seguindo-se um planejamento fatorial completo 2⁴, em um extrusor mono-rosca (model GNF 1014/2, BRABENDER, Germany). As variáveis independentes foram: umidade (de 16,3 a 29,7%); temperatura da 2ª e 3ª zonas do extrusor (de 104,8 a 155,2°C); e teor de farelo de trigo (de 0,0 a 24,6%). Tem-}

PALAVRAS-CHAVE: Exclusão termoplástica; snacks; farelo de trigo, dureza instrumental; índice de expansão; microscopia eletrônica de varredura.

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