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Physical characteristics of extrudates from corn flour and dehulled carioca bean flour blend

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ABSTRACT

Extruded products were prepared from a corn flour and dehulled carioca bean (*Phaseolus vulgaris*, L.) flour blend using a single-screw extruder. A central composite rotate design was used to evaluate the effects of extrusion process variables: screw speed (318.9–392.9 rpm), feed moisture (10.9–21.0 g/100 g) and bean flour level (4.8–55.2 g/100 g) on the specific mechanical energy (SME), sectional expansion index (SEI), longitudinal expansion index (LEI), volumetric expansion index (VEI) and density (*D*) of the extrudates. The instrumental texture was also analyzed. The independent variables had significant effects on the physical properties (SEI, VEI and density) of extrudates, with the exception of SME and LEI. SEI increased with increasing screw speed, but a higher moisture and bean flour content resulted in decreasing SEI and VEI. The increase of moisture and bean flour increased the density of extrudates. According to texture analysis, some treatments with 30 and 45 g/100 g bean flour did not show significant differences when compared to commercial brand snacks. However, when combined with higher moisture content (≥19 g/100 g) and lower screw speed (≤333 rpm), the results of the expanded product were not satisfactory.

1. Introduction

Aside from soybean (*Glycine max*), dry edible beans, or common beans (*Phaseolus vulgaris*, L. of the Fabaceae family), are the legume with the highest economic value in the world. Dry beans contain, on a 100 kcal basis, 80% less total fat than lean ground beef, and they are low in sodium, cholesterol free and high in protein and soluble fiber content (Berrios, 2006). In addition to these nutritional benefits, beans are also gluten-free, so products made from bean flours provide alternatives to wheat flour based products (Siddiq, Kelkar, Harte, Dolan, & Nyombaire, 2013). Additionally, they are a main source of protein for low-income populations (Nyombaire, Siddiq, & Dolan, 2011). Beans are usually purchased dry and raw; preparation is time consuming, which makes them less competitive than semi-ready or ready products (Gomes, Silva, Costa, & Pirozi, 2006).

Currently, the yearly consumption of beans in Brazil is approximately 3.5 million tons (CONAB, 2010). Carioca beans occupy more than 85% of the national market, while black beans corresponds to 10% of sales. Moreover, the carioca bean is cheaper and is emerging in biofortification food programs in the context of conventional crossing of cultivars with high levels of iron and zinc. This cultivar's resistance to drought is a positive factor for productivity, especially in the Northeast area of Brazil.

Snack foods have become a significant part of the diet of many individuals, particularly children, and can influence overall nutrition (Meng, Threinen, Hansen, & Driedger, 2010). The most widely consumed extruded snacks are made primarily with cereals/grains due to their good expansion characteristics; however, they tend to be low in protein and many other nutrients. As a result, demand from consumers for more nutritious snacks has been increasing (Giménez et al., 2012).

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Corn flour is widely used to elaborate expanded extrudates. However, as with other cereals, corn flour's nutritional value does not satisfy the needs of health-conscious consumers (Rampersad, Badrie, & Comissiong, 2003). It is well known that the addition of legumes to cereals produces an increase in both the amount and the quality of the protein mix (Anton, Fulcher, & Artnfield, 2009; Chillo et al., 2010; Pérez et al., 2008). Extruded legumes have been reported to have good expansion and are regarded as highly feasible for the development of value-added high nutrition, low calorie snacks (Berrios, 2006; Berrios, Camara, Torija, & Alonso, 2002; Berrios, Morales, Camara, & Sanchez-Mata, 2010; Berrios, Wood, Whitehand, & Pan, 2004).

The main objectives of this study were as follows: (a) to optimize extrusion processing conditions for production of extruded snacks from corn flour and carioca bean flour; (b) to determine the effect of extrusion variables such as screw speed, feed moisture content and bean content on physical properties of the extrudates; and (c) to evaluate the texture properties of the products on select extrudates.

2. Material and methods

2.1. Material

Corn flour (degermed) was obtained from the local market (Rio de Janeiro, RJ, Brazil). Carioca beans (*P. vulgaris*, L. (BRS Pontal)) were provided by Embrapa Rice and Bean (Goiânia, GO, Brazil).

The carioca beans were dehulled in order to promote the expansion of the snack. First, the bean grains were submersed in warm water (four times their weight) at 40 °C for 4 h. They were then dried in a forced-air drier (model Fabbe-Primar, Sao Paulo, SP, Brazil) at 100 °C for 1 h. The hulls were separated from the seeds by passing them through two rotating stone discs, followed by sieving. The dehulled seeds were milled into flour on a disc mill in order to obtain most particles between 853 and 1200 μm in size, similar to those of corn flour (Perten, Laboratory Mill 3600, Hägersten, Sweden).

2.2. Proximate composition and particle size distribution

The proximate composition of each raw material was determined according to AOAC (2000) standards: moisture (method 930.15), protein (method 990.03), fat (method 920.39), ash (method 942.05) and crude fiber (method 962.09). Carbohydrates were calculated by difference (100−moisture + protein + fat + ash + crude fiber). Calories were calculated with the following formula: (carbohydrates × 4 kcal) + (protein × 4 kcal) + (fat × 9 kcal). The particle size distribution of each raw material was determined by sifting 100 g of flour per 10 min through a plan sifter equipped with seven sieves with different opening sizes (1200, 1000, 853, 710, 422, 354 and 297 μm), according to ASAE Standards method S319.2 (1995).

2.3. Blend preparation

The two raw materials were mixed in proportions established by the experimental design. Bean flour was mixed with corn flour in proportions of 4.8–55.2 g/100 g. The appropriate amount of water was added to adjust the flour moisture content of the blend to the required level of 10.9–21 g/100 g. Then, the moisture of the blend was equilibrated overnight under refrigerated conditions to guarantee homogeneity and dispersion of the water throughout the dough before extrusion.

2.4. Extrusion processing

Extrusion was performed on an Inbra RX50 single screw extruder (Ribeirão Preto, São Paulo, Brazil) equipped with a circular die of 3.0 mm. The corn/bean flour blend was fed into the extruder operating at a screw speed of 318–393 rpm. A production rate of 50 kg/hr and die cutting knife rotation of 33 rpm were used as constant extrusion parameters. The extrudates were collected 5 min after the process was stable. The extrudates were immediately dried at 52 °C overnight in a forced-air drier. The final dried samples, containing approximately 5 g/100 g (wb) moisture, were stored in polyethylene bags at room temperature for further analysis.

2.5. Physical extrusion properties

Specific mechanical energy (SME) was calculated following the methodology described by Mesa et al. (2009) using the following equation:

$$\mathrm{SME} = \frac{\frac{\tau-\tau 0}{100} \times P_{\mathrm{rated}} \times \frac{N}{N_{\mathrm{rated}}}}{m} \tag{1}$$

Eqn. (1). Specific mechanical energy.

where τ is the measured torque, $\tau0$is the no-load torque (assumed to be 0%), P_{rated} is the rated power for the extruder (7.5 kJ/s), N is the measured extruder screw speed in rpm, N_{rated} is the rated extruder screw speed and m is the mass flow rate.

The sectional expansion index (SEI), longitudinal expansion index (LEI) and volumetric expansion index (VEI) were determined using the proposed methodology of Alvarez-Martinez, Kondury, and Harper (1988). Triplicate measurements were made on 10 randomly chosen pieces of extrudates from each run to calculate these indexes. For each test, the diameter of the extrudates was measured with a vernier caliper.

Density (ρ_e) was evaluated using the method described by Fan, Mitchell, and Blanshard (1996). Equations for the calculation of the different expansion indices and density are presented below:

$$\mathrm{SEI} = \left[\frac{D}{D_o}\right]^2 \tag{2}$$

Eqn. (2). Sectional expansion index (SEI).

$$\mathrm{LEI} = \left[\frac{\rho_d}{\rho_e}\right]\left[\frac{1}{\mathrm{SEI}}\right]\left[\frac{1-M_d}{1-M_e}\right] \tag{3}$$

Eqn. (3). Longitudinal expansion index (LEI).

$$\mathrm{VEI} = \mathrm{SEI}{*}\mathrm{LEI} \tag{4}$$

Eqn. (4). Volumetric expansion index (VEI).

$$\mathrm{Density}(\rho_e) = \frac{4m}{\pi D^2 L} \tag{5}$$

Eqn. (5). Density (ρ_e).

where m is the mass of a length L of extrudates with diameter D after cooling and D_o is the diameter of the die. Bulk density of the dough (ρ_d) behind the die was considered to be 1400 kg m^{-3} and ρ_e is the density of the extrudates. The moisture content (M_e, wb) of the extrudates and the moisture content of the dough inside the extruder (M_d, wb) were measured by drying 2–3 g samples in a forced-air drier at 105 °C until constant weight was reached. An average of three measurements was used in all calculations.

Table 1
Proximate composition[c] of corn flour and dehulled carioca bean flour.

Samples	Moisture[a]	Protein[a]	Fat[a]	Ash[a]	Crude fiber[a]	Carbohydrate[b]	Calorie (kcal)
Corn flour	10.6 (0.09)	7.0 (0.05)	0.5 (0.08)	0.2 (0.06)	0.1 (0.09)	81.6 (0.40)	358.9 (0.81)
Carioca bean	6.3 (0.08)	23.5 (0.06)	1.9 (0.08)	3.6 (0.05)	1.5 (0.10)	63.2 (0.50)	363.9 (0.90)

[a] g/100 g (dry weight basis).
[b] Calculated by difference.
[c] Means (standard deviation).

2.6. Texture analysis

The texture of the extrudates was determined based on the methodology described by Bouvier, Bonneville, and Goullieux (1997), although it was modified according to the sample characteristics. Texture testing was accomplished on a Texture Analyzer TA.XT2i (Stable Micro Systems, Surrey, UK) interfaced with computer software. The equipment was fit with a 10 kg load cell and a 2 mm diameter stainless steel cylinder probe. Before the test, samples were dried at 105 °C in a forced-air drier until constant weight was obtained. The samples were punctured by the probe to a depth of 4 mm, corresponding to approximately 60% of the diameter of the extrudates. The cross head speed was 1 mm/s. A force–time curve was recorded and analyzed by Texture Exponent 32 (Surrey, UK) to calculate the peak force, area and distance. Ten measurements were performed on each sample, each of which was chosen based on its SEI value (>10) to ensure the probe could puncture the sample easily.

In accordance with Bouvier et al. (1997), the following criteria were applied to evaluated crispness:

$$N_{sr} = \frac{N_o}{d} \tag{6}$$

Eqn. (6). Frequency of structural ruptures (mm^{-1}).

$$F_{sr} = \sum \frac{\Delta F}{N_o} \tag{7}$$

Eqn. (7). Average specific force of structural ruptures (N).

$$F = \frac{A}{d} \tag{8}$$

Eqn. (8). Average of compression force (N).

$$W_c = \frac{F}{N_{sr}} \tag{9}$$

Eqn. (9). Crispness work (N mm).

where N_o is the total number of peaks in the Texture Analyzer force deformation curve output, d is the distance of compression (mm), ΔF is the individual force drop for each peak (N), A is the area under the force deformation curve (mm^2), N_{sr} is the frequency of ruptures, F_{sr} is the average specific force of ruptures, F is the average compression force and W_c is the crispness work.

2.7. Regression modeling and statistical analysis

A 3^2 central composite design was used to study the effects of interactions of screw speed (333, 355, 378 rpm), feed moisture content (13, 16,19 g/100 g) and bean content (15, 30, 45 g/100 g) on the sectional expansion index, longitudinal expansion index, volumetric expansion index, density and specific mechanical energy of the extrudates. Overall, 20 experimental runs were conducted, each with eight factorial points studied in three levels (−1, 0, +1); six star corner points (two for each variable), using $\alpha = 1.68$ as rotability; and six central points to meet the statistical design requirements. Actual levels were selected according to the preliminary studies and literature data for suitable extrusion cooking. The second order polynomial equation fitted with coded variables was the following:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} {X_1}^2 + \beta_{22} {X_2}^2 + \beta_{33} {X_3}^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \xi \tag{10}$$

Eqn. (10). Second order polynomial equation.

where Y is the experimental response; β_0 is the coefficient for intercept; β_1, β_2, β_3 are linear coefficients; β_{11}, β_{23}, β_{33} are quadratic coefficients; β_{12}, β_{13}, β_{23} are the interactive coefficients; X_1, X_2 and X_3 are independent variables (X_1 = screw speed, X_2 = moisture, X_3 = bean level); and ξ is the experimental error. The whole model includes linear, quadratic and cross product terms. The effect of each term and their statistical significance for the response variables were analyzed from the standardized Pareto chart. Once the polynomial model fit to the response variables was obtained, the optimization process was performed using the technique proposed for dependent variables (Derringer & Suich, 1980). This definition is based on a function of desirability (di) restricted within the range $0 \leq di \leq 1$, in which $di = 1$ is the desired response and $di = 0$ indicates that the response is outside the acceptable region. The independent variables were chosen to maximize overall desirability: $D = (d_1\ d_2 \ldots d_m)^{1/m}$, where m is the number of response variables. Tukey's test was performed to compare the means of texture analysis, at a confidence of 95%. All analysis was performed using the software "Statistica" version 6.0 (Statsoft Inc., Tulsa, OK, USA).

3. Results and discussion

The proximate composition of the selected raw materials is presented in Table 1. It can be observed that, even when dehulled, carioca beans contain (dry basis) 23.5 g/100 g protein content, 3.6 g/100 g ash content and 1.9 g/100 g crude fiber content. Corn grits exhibited typical proximate compositional values, similar to those reported by Reyes-Moreno et al. (2003). The particle sizes of raw materials are presented in Table 2. It was verified that 90.6% of the particles in the corn flour fall within the particle size range of 853–1200 μm, while 72.7% of the bean flour particles fall within the same range. Moreover, the fact that 71.5% of the largest particles in the corn flour and 49.8% in the bean flour were concentrated within the narrower range of 853–1000 μm demonstrated that the

Table 2
Particle size distribution of corn flour and carioca bean flour.

Sieve size (μm)	Corn flour (%)	Carioca bean flour (%)
1200	19.1	22.9
1000	31.6	22.7
853	39.9	27.1
710	8.1	8.0
422	0.6	5.7
354	0.1	2.4
297	0.1	3.1

particles of bean flour were somewhat better distributed. Carvalho, Takeiti, Onwulata, and Pordesimo (2010) observed that there was an increase in expansion of extruded products made with corn meal when the process was made with raw materials with particle sizes in the range of 500–710 μm. Additionally, Bassinello et al. (2011) obtained extruded snacks with crunchy textures and large cell structures using flour with particle sizes in the range of 710–1000 μm, similar to the range of particle sizes presented in this study.

3.1. Specific mechanical energy (SME)

The values of specific mechanical energy (SME) of extruded products under experimental conditions are presented in Table 3. SME values ranged between 32.20 and 58.88 kJ/kg. According to Meng et al. (2010), a higher SME usually results in a greater degree of starch gelatinization and extrudate expansion. Hence, an increased SME is desired for expanding products. Fig. 1 shows that none of the variables studied (screw speed, moisture and bean level) significantly influenced SME values, and Table 4 indicates that SME did not have any significant correlation with the other variables. This could suggest, for example, that the addition of beans in percentages up to 55 g/100 g would not significantly affect the energy spent during processing. The same would be true of the other variables. In contrast to the data offered by this study, some authors observed that feed moisture content and screw speed significantly affected SME values of protein-fortified expanded extruders (Meng et al., 2010; Mesa et al., 2009; Ruiz-Ruiz et al., 2008). According to these authors, increased SME with increased screw speed was attributed to higher shear rates affecting macromolecular degradation. The same effect was observed by Meng et al. (2010). Alternately, Carvalho et al. (2010) noted that SME was significantly affected by the average particle size and that increasing particle size decreased the SME input.

3.2. Expansion indices

The SEI values of the extrudates ranged from 4.54 to 35.33 (Table 3). It is noted that all independent variables (screw speed, feed moisture content and bean content) significantly influenced SEI values in a linear fashion, except for the interaction between the independent variables (Fig. 1). It was observed that feed moisture was the variable that most influenced the sectional expansion values, having a negative effect ($p < 0.05$), followed by bean content and screw speed. The increase of water content, together with applied heat, promotes gelatinization of the material. However, higher moisture content promotes a lubricant effect inside the extruder, reducing shear rate as well as the internal temperature of the equipment. As a consequence, a decrease in the cooking of raw material and lower expansion can occur. The addition of bean flour caused a negative linear effect on snack expansion ($p < 0.05$). Beans, despite being a starchy material, have approximately 20 g/100 g protein content, which reduces the total amount of starch in the mixture. Screw speed had a positive linear effect ($p < 0.05$) on SEI. This means that snack expansion increased in accordance with screw speed increases. The highest screw speed caused an increase in shear rate, implying a higher degree of material degradation and/or cooking. However, as a consequence of the speed increase, a smaller material residence time in the extruder was observed, which may indicate that less cooking of the material occurred. All parameters must be collectively studied in order to obtain the quality of the final product. The same effect was observed by Meng et al. (2010) and Ding, Ainsworth, Tucker, and Marson (2006). For the experimental data for LEI (Table 3), the values ranged between 1.31 and 3.41. It can be observed that LEI values were not influenced by screw speed, feed moisture content or bean level oscillations (Fig. 1). The values of VEI ranged between 10.8 and 67.0 (Table 3). The increases in bean content and feed moisture affected VEI values, reducing this index (Fig. 1). As expected, SEI was negatively correlated with LEI ($r = -0.648$; $p < 0.05$) and positively correlated with VEI ($r = 0.797$; $p < 0.05$) (Table 4). As LEI is inversely proportional to SEI (Alvarez-Martinez et al., 1988), higher SEI value resulted in lower LEI values. The factors that affect those last indices will, in turn, affect VEI.

3.3. Density

The resulting values for density ranged between 0.05 and 0.55 g/cm^3 (Table 3). Feed moisture was the variable that most influenced the density values, having a positive effect ($p < 0.05$), followed by bean content and its interaction (Fig. 1). This same condition was verified by Saeleaw, Dürrschmid, and Schleining (2012). Density is usually related to SEI, but in this case, density was negatively

Table 3

Experimental design with coded and real values for screw speed, moisture, bean flour level and results obtained in the experiment for specific mechanical energy (SME), sectional expansion index (SEI), longitudinal expansion index (LEI), volumetric expansion index (VEI) and density.

Run	Levels: coded and real values			Results obtained in the experiment				
	Screw speed (rpm)	Feed moisture (g/100 g)	Bean flour (g/100 g)	SME (kJ/kg)	SEI	LEI	VEI	Density (g/cm^3)
01	(−1) 333	(−1) 13	(−1) 15	44.83	26.62	2.46	65.49	0.05
02	(1) 378	(−1) 13	(−1) 15	40.55	35.33	1.63	57.68	0.06
03	(−1) 333	(1) 19	(−1) 15	41.80	16.90	2.52	42.53	0.12
04	(1) 378	(1) 19	(−1) 15	51.71	26.60	2.05	54.56	0.12
05	(−1) 333	(−1) 13	(1) 45	51.96	22.41	2.23	50.03	0.08
06	(1) 378	(−1) 13	(1) 45	44.98	23.24	1.67	38.78	0.10
07	(−1) 333	(1) 19	(1) 45	49.18	4.54	2.38	10.80	0.52
08	(1) 378	(1) 19	(1) 45	45.71	5.29	3.41	18.04	0.55
09	(0) 355	(0) 16	(0) 30	36.00	20.77	1.89	39.22	0.11
10	(0) 355	(0) 16	(0) 30	32.34	13.16	2.41	31.72	0.20
11	(0) 355	(0) 16	(0) 30	32.20	16.00	1.69	27.07	0.17
12	(0) 355	(0) 16	(0) 30	50.47	13.71	3.41	46.70	0.17
13	(0) 355	(0) 16	(0) 30	48.10	10.46	3.20	33.52	0.20
14	(0) 355	(0) 16	(0) 30	56.88	12.18	3.14	38.22	0.17
15	(−1.68) 318.2	(0) 16	(0) 30	48.70	12.85	2.19	28.17	0.17
16	(1.68) 392.9	(0) 16	(0) 30	44.88	21.90	2.74	59.94	0.11
17	(0) 355	(−1.68) 10.9	(0) 30	39.96	31.29	1.31	40.96	0.07
18	(0) 355	(1.68) 21.0	(0) 30	42.90	7.15	2.63	18.84	0.53
19	(0) 355	(0) 16	(−1.68) 4.8	49.61	21.16	3.17	67.01	0.10
20	(0) 355	(0) 16	(1.68) 55.2	58.88	7.66	2.89	22.17	0.31

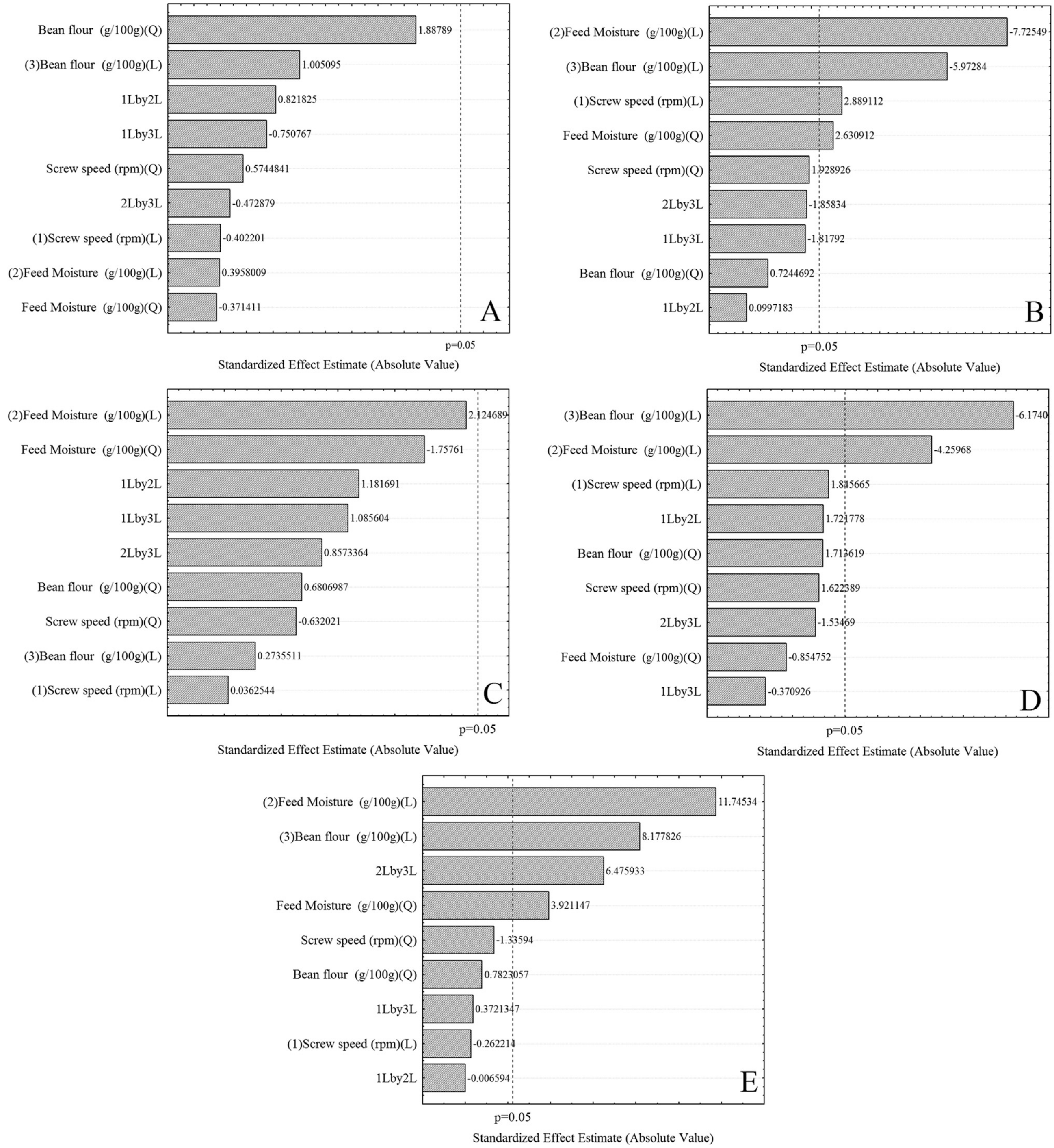

Fig. 1. Standardized Pareto chart plot with the effects of each independent variable, for the response variables (A: specific mechanical energy; B: sectional expansion index; C: longitudinal expansion index; D: volumetric expansion index; E: density). The vertical line in the chart tests the significance of the effects at 5% probability.

correlated with both SEI ($r = -0.825$; $p < 0.05$) and VEI ($r = -0.833$; $p < 0.05$) (Table 4). Extrudates with high sectional expansion indices tend to have lower densities because the formation of internal air bubbles in the material structure increases extrudate volume and therefore reduces its weight, enhancing crispness.

3.4. Texture analysis

In Table 5, results referring to texture analysis via puncture test of the extrudates can be observed. Regarding the frequency of structural ruptures, results varied between 0.12 and 0.25 mm^{-1}. These values are related to the specific mechanical energy applied during processing. Lower N_{sr} values are related to treatments in which the SME spent during the process was lower. The higher value of N_{sr} is related to treatment with high values of SME, as observed in this study. This finding is in accordance with Bouvier et al. (1997). It was also verified that treatments in which higher SME was spent processing the material did not exhibit significant differences when compared with a commercial snack brand made only with corn. Evidently, higher values of average specific force of

Table 4
Correlation coefficients between physical characteristics of corn and carioca bean extrudates.

	SME	SEI	LEI	VEI	Density
SME	1	−0.434^{ns}	0.436^{ns}	−0.182^{ns}	0.099^{ns}
SEI		1	−0.648*	0.797*	−0.825*
LEI			1	−0.115^{ns}	0.404^{ns}
VEI				1	−0.833*
Density					1

*Significant at $p < 0.05$; ^{ns}: not significant. SEI: sectional expansion index; LEI: longitudinal expansion index; VEI: volumetric expansion index; SME: specific mechanical energy.

structural ruptures (F_{sr}) are related to treatments in which the SME spent to extrude was lower. However, the opposite could also be observed. These values ranged between 0.30 and 1.09 N (Table 5). It could also be verified that corn flour and bean snacks produced with higher SME and reduced values of F_{sr} did not show significant differences from the commercial snack brand. Puncture force (F) reflects the force spent to penetrate, with a probe, the cell walls present on extrudates. The lesser the exerted force, the more easily ruptured the cells, resulting in a crispier product. Puncture force varied between 0.09 and 0.35 N (Table 5). The results for crispness work (W_c) ranged between 0.43 and 2.80 N Mm (Table 5). This property brings together information about F and N_{sr} values, and it is directly related to crispness of the extrudate material. It is noted once more that for treatments in which the SME spent to process the blend was lower, higher values of W_c were registered. Some authors have verified that the increase in moisture content of the mixture might cause reduction of expansion by consequent reduced formation of air bubbles and number of internal cells in the extrudates (Saeleaw et al., 2012). Therefore, this aspect can be related to the decrease of crispness of the material. Alternately, the decrease of water content increases specific mechanical energy favoring starch conversion and therefore degradation of molecular structure, resulting in a fragile structure with great fracturability (Roudaut, Dacremont, Pámies, Colas, & Meste, 2002).

3.5. *Optimum extrusion conditions*

To reach desirable characteristics for expanded extrudates, values (weights) of desirability (*di*) were established for each response variable. *di* values equal to 1 (one) were established for the independent variables SEI, LEI and VEI whereas values of *di* equal to 0 (zero) were established for the independent variables density and SME, as described by the following: SEI ($\geq$35), LEI ($\geq$2.5), VEI ($\geq$40), density ($\leq$0.2) and SME ($\leq$50). The values determined for each variable were established according to the correlation between IER and the other variables, and checked by applying linear regression. These values are desirable to obtain crispy snacks; however, as the optimization is punctual, it requires unique values of response variables for independent variables (screw speed, feed moisture content and bean content). The optimum extrusion conditions are shown in Table 6. Using 373 rpm screw speed with 15 g/100 g feed moisture content and 4.8 g/100 g bean content, it is possible to obtain products with SEI (32.30), LEI (2.30), VEI (73.20), SME (49.30 kJ/kg) and density (0.03 g/cm^3) with desirability value of 0.951404.

4. Conclusions

The extrusion processing variables of screw speed, feed moisture content and bean content significantly influenced the physical properties (SEI, VEI and density) of the extrudates, with the exception of SME and LEI. SEI increased with increasing screw speed, but a higher moisture and bean flour content resulted in decreasing SEI, as well as decreasing VEI. The increasing of moisture and bean flour increased the density of the extrudates. According to the texture analysis, some treatments with 30 and 45 g/100 g of bean content did not exhibit significant differences when

Table 5
Means[d] of the texture analysis of extrudates from blend of corn flour and carioca bean flour.

Run	N_{sr} (Mm^{-1})	F_{sr} (N)	F (N)	W_c (N Mm)
01	0.18bcde(0.03)	0.64abcd(0.02)	0.14ab(0.04)	0.83abc(0.35)
02	0.19cdef(0.02)	0.64abcd(0.02)	0.32e(0.04)	1.72d(0.18)
03	0.21efgh(0.04)	0.76abcd(0.04)	0.10a(0.02)	0.50a(0.16)
04	0.14abc(0.03)	0.79bcd(0.04)	0.19bc(0.04)	1.43bcd(0.58)
05	0.25h(0.03)	0.30a(0.01)	0.13ab(0.02)	0.51ab(0.10)
06	0.20cdef(0.04)	0.60abcd(0.02)	0.22cd(0.09)	1.25cd(0.89)
07	[a]	[a]	[a]	[a]
08	[a]	[a]	[a]	[a]
09	0.16abcd(0.02)	0.75cd(0.03)	0.28de(0.09)	1.81d(0.66)
10	0.12a(0.02)	1.09e(0.06)	0.30de(0.05)	2.63e(0.68)
11	0.13ab(0.02)	0.96de(0.04)	0.35e(0.04)	2.80e(0.53)
12	0.20efg(0.02)	1.02abc(0.01)	0.14ab(0.03)	0.67abc(0.16)
13	0.20efg(0.03)	0.46ab(0.01)	0.13ab(0.03)	0.64ab(0.16)
14	0.20defg(0.02)	0.40a(0.01)	0.12ab(0.02)	0.61ab(0.15)
15	0.18cdef(0.02)	0.42ab(0.01)	0.14ab(0.03)	0.79abc(0.20)
16	0.19cdefg(0.03)	0.54abcd(0.01)	0.17abc(0.05)	0.93abc(0.44)
17	0.23fgh(0.03)	0.44abc(0.01)	0.17abc(0.03)	0.78abc(0.19)
18	[a]	[a]	[a]	[a]
19	0.22fgh(0.03)	0.59abcd(0.02)	0.09a(0.02)	0.43a(0.11)
20	[a]	[a]	[a]	[a]
Commercial expanded snacks[e]	0.24gh(0.02)	0.38a(0.01)	0.12ab(0.01)	0.53ab(0.07)
L.S.D.[b]	0.04	0.04	0.08	0.71
CV[c] (%)	22.06	48.53	49.16	72.67

[a] SEI values above 10. Snacks very hard to puncture by probe.

[b] Least significant difference.

[c] Coefficient of variation.

[d] Means (standard deviation). Means with different letters in the same column are significant at $p < 0.05$ by Tukey's test. N_{sr} = frequency of ruptures; F_{sr} = average specific force of ruptures; F = average compression force and W_c = crispness work.

[e] Commercial snack brand made only with corn (available at Brazilian markets), the same conditions for texture analysis were used.

Table 6
Results of optimization by desirability function for the extrudates with corn and carioca bean.

Independent variables		Response variables	
Screw speed (rpm)	373.0	SEI	32.30
Feed moisture (g/100 g)	15.0	LEI	2.30
Bean content (g/100 g)	4.8	VEI	73.20
		SME (kJ/kg)	49.30
		Density (g/cm^3)	0.03

SEI: Sectional expansion index; **LEI**: Longitudinal expansion index; **VEI**: Volumetric expansion index.

compared with commercial snack brands. However, when combined with high moisture content (≥19 g/100 g) and lower screw speed (≤333 rpm), the results were not satisfactory. The optimum extrusion processing needs to be studied with attention to the intended type of product and physical properties desired. The findings of this study demonstrate the feasibility of developing value-added products from corn and carioca bean by extrusion processing.

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References

Alvarez-Martinez, L., Koundury, K. P., & Harper, J. M. (1988). A general model for expansion of extruded products. *Journal of Food Science, 53*(2), 609–615.

Anton, A. A., Fulcher, R. G., & Artnfield, S. D. (2009). Physical and nutritional impact of fortification of corn–starch based extruded snacks with common bean (*Phaseolus vulgaris* L.) flour: effects of bean addition and extrusion cooking. *Food Chemistry, 113*, 989–996.

AOAC. (2000). *Official methods of analysis*. Washington, DC, USA: Association of Official Analytical Chemists.

ASAE Standards. (1995). *Methods for determining and expressing fineness of feed materials by sieving method S319.2*. St. Joseph, Michigan. USA: ASAE.

Bassinello, P. Z., Freitas, D. G. C., Ascheri, J. L. R., Takeiti, C. Y., Carvalho, R. N., Koakuzu, S. N., et al. (2011). Characterization of cookies formulated with rice and black bean extruded flours. In , *Procedia Food Science: Vol. 1. International Congress on Engineering and Food, 11th, 2011, Atenas* (pp. 1645–1652). Amsterdam: Elsevier.

Berrios, J. J. (2006). *Extrusion cooking of legumes: Dry beans flours*. In *Encyclopedia of agricultural, food and biological engineering* (Vol. 1) (pp. 1–8).

Berrios, J. J., Camara, M., Torija, M. E., & Alonso, M. (2002). The effect of extrusion processing and sodium bicarbonate addition on the carbohydrate composition of black bean flours. *Journal of Food Processing and Preservation, 26*(2), 113–128.

Berrios, J. J., Morales, P., Camara, M., & Sanchez-Mata, M. C. (2010). Carbohydrate composition of raw and extruded pulse flours. *Food Research International, 43*, 531–536.

Berrios, J. J., Wood, D. F., Whitehand, L., & Pan, J. (2004). Sodium bicarbonate and the microstructure, expansion and color of extruded black beans. *Journal of Food Processing and Preservation, 28*(5), 321–335.

Bouvier, J. M., Bonneville, R., & Goullieux, A. (1997). Instrumental methods for the measurement of extrudate crispness. *Agro Food Industry Hi-Tech, 8*, 16–19.

Carvalho, C. W. P., Takeiti, C. Y., Onwulata, C. I., & Pordesimo, L. O. (2010). Relative effect of particle size on the physical properties of corn meal extrudates: effect of particle size on the extrusion of corn meal. *Journal of Food Engineering, 98*, 103–109.

Chillo, S., Civica, V., Ianetti, M., Mastromatteo, M., Suriano, N., & Del Nobile, M. A. (2010). *Journal of Food Engineering, 100*, 329–335.

Companhia Nacional de Abastecimento (CONAB). *Acompanhamento da safra brasileira: 2009–2010*. <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/969898a66ca1ceede424d5853d3f8543.pdf> Accessed 20.07.10.

Derringer, G. C., & Suich, R. (1980). Simultaneous optimization of several responses variables. *Journal of Quality Technology, 12*(4), 214–219.

Ding, Q., Ainsworth, P., Tucker, G., & Marson, H. (2006). The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. *Journal of Food Engineering, 73*, 142–148.

Fan, J. T., Mitchell, J. R., & Blanshard, J. M. V. (1996). The effect of sugars on the extrusion of corn: the role of the glass transition in determining product density and shape. *International Journal of Food Science and Technology, 31*, 55–65.

Giménez, M. A., González, R. J., Wagner, J., Torres, R., Lobo, M. O., & Samman, N. C. (2012). Effect of extrusion conditions on physicochemical and sensorial properties of corn-broad beans (*Vicia faba*) spaghetti type pasta. *Food Chemistry*. http://dx.doi.org/10.1016/j.foodchem.2012.08.068.

Gomes, J. C., Silva, C. O., Costa, N. M. B., & Pirozi, M. R. (2006). Desenvolvimento e caracterização de farinhas de feijão. *Revista Ceres, 53*, 548–558.

Meng, X., Threinen, D., Hansen, M., & Driedger, D. (2010). Effects of extrusion conditions on system parameters and physical properties of a chickpea flour-based snack. *Food Research International, 43*, 650–658.

Mesa, N. J. E., Alavi, S., Singh, N., Shi, Y., Dogan, H., & Sang, Y. (2009). Soy protein-fortified expanded extrudates: baseline study using normal corn starch. *Journal of Food Engineering, 90*, 262–270.

Nyombaire, G., Siddiq, M., & Dolan, K. D. (2011). Physico-chemical and sensory quality of extruded light red kidney bean (*Phaseolus vulgaris*, L.) porridge. *LWT – Food Science and Technology, 44*, 1597–1602.

Pérez, A. A., Drago, S. R., Carrara, C. R., De Greef, D. M., Torres, R. L., & González, R. J. (2008). Extrusion cooking of a corn grits/soybean mixture: factors affecting expanded product characteristics and flour dispersion viscosity. *Journal of Food Engineering, 87*, 333–340.

Rampersad, R., Badrie, N., & Comissiong, E. (2003). Physico-chemical and sensory characteristics of flavoured snacks from extruded cassava/pigeon pea flour. *Journal of Food Science, 68*, 363–367.

Reyes-Moreno, C., Milán-Carrilo, J., Gutiérrez-Dorado, R., Paredes-López, O., Cuevas-Rodríguez, E. O., & Garzón-Tiznado, J. A. (2003). Instant flour from quality protein corn (*Zea mays* L.). Optimization of extrusion process. *LWT – Food Science and Technology, 36*, 685–695.

Roudaut, G., Dacremont, C., Pámies, B. V., Colas, B., & Meste, M. (2002). Crispness: a critical review on sensory and material science approaches. *Trends in Food Science and Technology, 13*, 217–227.

Ruiz-Ruiz, J., Martínez-Ayala, A., Drago, S., González, R., Betancur-Ancona, D., & Chel-Guerrero, L. (2008). Extrusion of a hard-to-cook bean (*Phaseolus vulgaris* L.) and quality protein corn (*Zea mays* L.) flour blend. *LWT – Food Science and Technology, 41*, 1799–1807.

Saeleaw, M., Dürrschmid, K., & Schleining, G. (2012). The effect of extrusion conditions on mechanical-sound and sensory evaluation of rye expanded snack. *Journal of Food Engineering, 110*, 532–540.

Siddiq, M., Kelkar, S., Harte, J. B., Dolan, K. D., & Nyombaire, G. (2013). Functional properties of flour from low-temperature extruded navy and pinto beans (*Phaseolus vulgaris*, L.). *LWT – Food Science and Technology, 50*, 215–219.