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ORIGINAL ARTICLE

Effect of different processing conditions to obtain expanded extruded based on cowpea

Efeito de diferentes condições de processamento na obtenção de extrusados expandidos à base de feijão-caupi

Izabel Cristina Veras Silva[1], Kaesel Jackson Damasceno-Silva[2], Jorge Minoru Hashimoto[2*], Carlos Wanderlei Piler de Carvalho[3], José Luis Ramirez Ascheri[3], Melicia Cintia Galdeano[3], Maurisrael de Moura Rocha[2]

[1]Universidade Federal do Piauí (UFPI), Departamento de Nutrição, Teresina/PI - Brasil
[2]Empresa Brasileira de Pesquisa Agropecuária (Embrapa Meio-Norte), Teresina/PI - Brasil
[3]Empresa Brasileira de Pesquisa Agropecuária (Embrapa Agroindústria de Alimentos), Rio de Janeiro/RJ - Brasil

***Corresponding Author:** Jorge Minoru Hashimoto, Empresa Brasileira de Pesquisa Agropecuária (Embrapa Meio-Norte), Avenida Duque de Caxias, 5650, Bairro Buenos Aires, CEP: 64008-780, Teresina/PI - Brasil, e-mail: jorge.hashimoto@embrapa.br

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Abstract

Cowpea is grown mainly in regions with a hot semi-arid climate, where other pulses do not develop satisfactorily. It is the 4th most produced pulse in the world, thus supplying the domestic and export markets. Following the trends of the food products market, a study was carried out to identify the best condition of the extrusion process, to transform these nutritious grains into quality expanded products and ready for consumption. The grains were decorticated and transformed into cotyledon flour. This flour was conditioned and the Evolum HT25 twin screw extruder feeder was adjusted to a rate of 7 kg h^{-1}. A Box-Behnken 2^3 design was used, considering the following variables and levels: extrusion temperature from 100 °C to 140 °C (in the 7th to 10th zone), screw speed (300 to 700 rpm) and conditioning moisture from 12% to 16%. The temperature affected linearly and negatively ($p \leq 0.05$) the sectional expansion index (2.65 to 7.64). The screw speed interfered linearly and positively ($p \leq 0.05$) in the longitudinal (1.12 to 9.32) and volumetric (4.91 to 24.15) expansion index, and negatively with the water absorption index (3.05 to 3.86 g g^{-1}). The screw speed (positive linear and negative quadratic), the moisture content (negative quadratic) and the interaction (positive) between the two interfered ($p \leq 0.05$) in the water solubility index (25.89% to 33.85%). The hardness value (1.24 to 2.83 N) was affected ($p \leq 0.05$) by screw speed (negative linear and positive quadratic), temperature (negative quadratic), moisture (positive quadratic), and interactions of moisture with temperature and screw speed. To obtain a hardness value close to that of commercial extrudates and high-water solubility, the maximum global desirability obtained was 0.81 for extrusion at 135.6 °C, 700 rpm and 12% moisture.

Keywords: *Vigna unguiculata*; Thermoplastic extrusion; Expansion; Solubility; Absorption; Hardness.

Resumo

O feijão-caupi é cultivado principalmente em regiões de clima semiárido quente, onde outras *pulses* não se desenvolvem satisfatoriamente. É a quarta *pulse* mais produzida no mundo, abastecendo o mercado interno e de exportação. Seguindo as tendências do mercado de produtos alimentícios, realizou-se o estudo para identificar a melhor condição do processo de extrusão, para transformar esses grãos nutritivos em produtos expandidos de qualidade e prontos para o consumo. Os grãos foram descorticados e transformados em farinha de cotilédones. Essa farinha foi condicionada e o alimentador da extrusora de dupla rosca Evolum HT25 foi ajustado para uma taxa de 7 kg h^{-1}. Um delineamento Box-Behnken 2^3 foi utilizado, contemplando as seguintes variáveis e níveis: umidade de condicionamento de 12% a 16%, temperatura de extrusão de 100 °C a 140 °C (da 7ª a 10ª zona) e velocidade das roscas de 300 a 700 rpm. A temperatura afetou linear e negativamente ($p \leq 0{,}05$) o índice de expansão seccional (2,65 a 7,64). A velocidade das roscas interferiu linear e positivamente ($p \leq 0{,}05$) nos índices de expansão longitudinal (1,12 a 9,32) e volumétrica (4,91 a 24,15), e negativamente no índice de absorção de água (3,05 a 3,86 g g^{-1}). A velocidade das roscas (linear positiva e quadrática negativa), o teor de umidade (quadrática negativa) e a interação (positiva) entre essas duas variáveis interferiram ($p \leq 0{,}05$) no índice de solubilidade em água (25,89% a 33,85%). O valor da dureza (1,24 a 2,83 N) foi afetado ($p \leq 0{,}05$) pela velocidade das roscas (linear negativo e quadrático positivo), pela temperatura (quadrático negativo) e pela umidade (quadrático positivo), e pelas interações negativas da umidade com a temperatura e a velocidade das roscas. Para obtenção de valor de dureza próximo aos de extrusados comerciais e alta solubilidade em água, a desejabilidade global máxima obtida foi de 0,81 para extrusão a 135,6 °C, 700 rpm e 12% de umidade.

Palavras-chave: *Vigna unguiculata*; Extrusão termoplástica; Expansão; Solubilidade; Absorção; Dureza.

Highlights

- Cowpea expanded extrudates showed characteristics similar to traditional flour extrudates
- The ranges of process variables used favored obtaining high quality expanded extrudates
- High global desirability was obtained for the characteristics evaluated in the extrudates

1 Introduction

Cowpea [*Vigna unguiculata* (L.) Walp.] is grown mainly in regions with a hot semi-arid climate, where other pulses do not develop satisfactorily (Freire Filho, 2011). It is the 4^{th} pulse and 2^{nd} bean species most produced in the world (7.2 million t.), supplying the domestic and export markets, as well as being surpassed by *Phaseolus vulgaris* (30.4 million t.), which accounted for 17.1% and 72.1% of bean production in 2018, respectively (Food and Agriculture Organization of the United Nations, 2020).

Cowpea beans have relevant amounts (db) of proteins (17.4% to 28.3%), low lipid content (1.0% to 1.6%), digestible carbohydrates (35.7% to 57.8%), including dietary fiber (19.5% to 35.6%) and minerals (3.3% to 4.6%), such as iron (6.0 to 8.1 mg 100 g^{-1}) and zinc (2.7 to 4.4 mg 100 g^{-1}) (Carvalho et al., 2012). Its inclusion in the diet has been associated with beneficial physiological effects such as improved lipid profile and antioxidant action (Kapravelou et al., 2015). However, they require a relatively long cooking time when preparing traditional dishes (Strauta & Muizniece-Brasava, 2016).

Grains can be decorticated and sensory food products prepared with Cowpea Cotyledon Flour (CCF) are more acceptable (Ngoma et al., 2018) and more nutritious (Wood & Malcolmson, 2011), and the lower insoluble fiber content will favor the physical expansion of dough, desirable in puffed products.

Social changes have caused changes in food consumption patterns (Ajita & Jha, 2017), increasing the demand for convenient foods, associated with nutrition and health aspects, therefore cowpea beans have attributes related to the last two aspects, needing to incorporate practicality for consumption, which if successfully obtained, they will be different from traditional carbohydrate and lipid-based ones (Strauta & Muizniece-Brasava, 2016).

Raw cowpea grains and flours contain anti-nutritional compounds, which are reduced or inactivated through traditional cooking. This process takes time to prepare, and does not exploit the potential for texture and flavor, and does not meet the practical requirements demanded by modern consumers such as read-to-eat and on-the-go. An efficient, versatile, continuous High Temperature and Short Time (HTST) process that inactivates enzymes, reduces microbial contamination and can transform raw materials into ready-to-eat expanded products is thermoplastic extrusion. A combination of pressure, heat and mechanical shear causes the food matrix to melt, followed by shaping in the matrix and immediate decompression at the extruder outlet, resulting in partial instantaneous evaporation of water and product expansion (Horvat & Schuchmann, 2013).

Low moisture contents, high process temperature and high screw rotation speeds decrease the strength and viscosity of the melt, favoring expansion (Horvat & Schuchmann, 2013), however, the occurrence of immediate retraction after maximum expansion may occur, if there is moisture condensation shortly thereafter, resulting in negative pressure inside the cells (Horvat & Schuchmann, 2013).

Koksel & Masatcioglu (2018) injected N_2 during the extrusion of pea flour in twin screw equipment, to compensate for the negative effect of the 24.1% of protein content. They found that the best condition was with moisture contents of 14% to 16% without N_2. Rathod & Annapure (2016) obtained a higher sensory acceptance score in the expanded extrudates when conditioning the lentil flour (23.86% of protein) with 14% of moisture, and extruding in a twin screw equipment at 180 °C and 250 rpm, thus indicating that it is possible to improve the expansion quality by adjusting the process conditions.

The twin-screw extruder has been preferred due to the greater consistency in the uniformity and quality of expanded products (Ajita & Jha, 2017). In addition to the versatility to accept a wide range of mass rheology, allowing processing with lower moisture contents and higher shear rates to obtain expanded products, without requiring additional drying, making obtaining the final product simpler, in a more compact and flexible processing plant (Miller, 1985).

However, most studies that processed whole Cowpea Bean Flour (WCF) by extrusion used single-screw equipment (Lira Filho, 2002; Marques, 2013; Batista et al., 2010; Jakkanwar et al., 2018). Strauta & Muizniece-Brasava (2016) used WCF in a twin-screw extruder, and Phillips et al. (1984) used CCF in a single-screw. Aiming to obtain products with a high level of expansion, the quality of the CCF extrudates processed in a twin-screw extruder was carried out, under conditions of high shear rate, using low moisture contents, at a high and wide range of screw speed rotation, and at conventional operating temperatures.

2 Material and methods

Figure 1 shows the graphic summary of the steps used to identify an optimized condition to obtain high physical quality expanded extrudates.

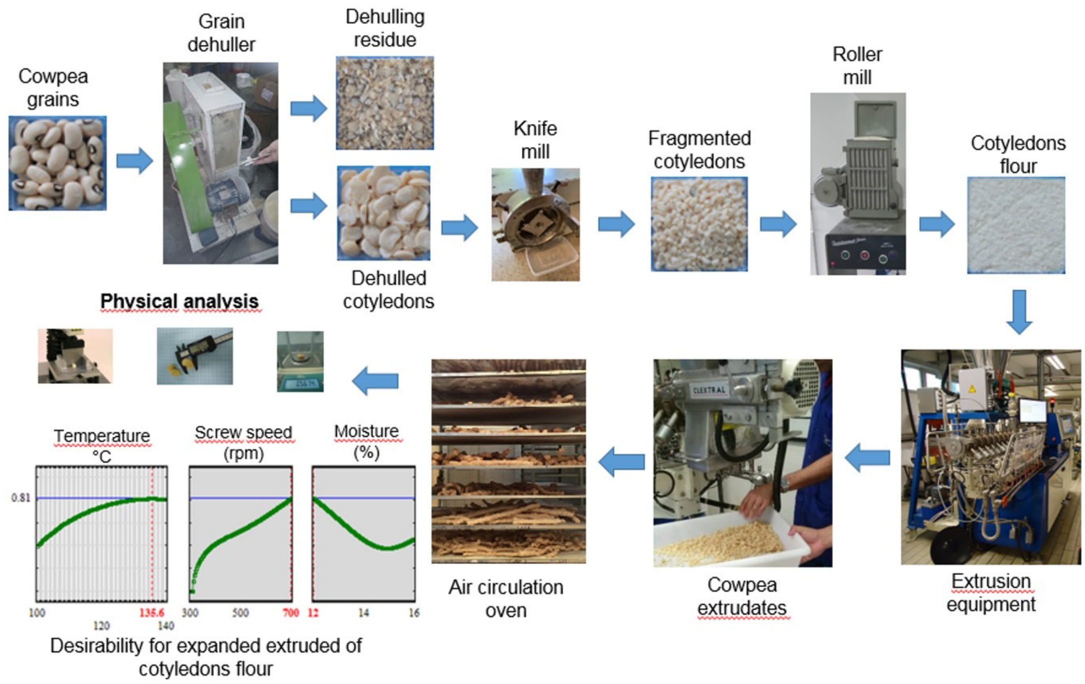

Figure 1. Graphical summary of the process of obtaining expanded extrudates from cowpea cotyledon flour with desirable physical characteristics.

2.1 Raw material

Cowpea beans of cultivar BRS Tumucumaque were mechanically decorticated by friction and abrasion (MB-1, Máquinas Suzuki S/A, Santa Cruz do Rio Pardo, Brazil). The cotyledons were fragmented in a knife mill (Renard Indústria e Comércio Ltda., Model MFC-180-75-01 01 No. 5753, São Paulo, Brazil) with a 3 mm diameter opening screen attached to the outlet and transformed into CCF in roller mill (Brabender OHG, Senior Quadrumat Model, Duisburg, North Rhine-Westphalia, Germany).

2.2 Chemical composition and particle size

The following were determined according to the official methodologies of the Association of Official Analytical Chemists (2012): moisture (925.45b), proteins (960.52), lipids (930.39), ash (923.03), dietary fiber (985.29) and carbohydrates by difference. The mean particle diameter was determined according to the method described by Henderson & Perry (1976). All determinations were performed in triplicate.

2.3 Extrusion process

The CCF was processed in the co-rotating, intermeshing twin-screw extruder Evolum HT25 (Clextral, Firminy, France), with a screw diameter of 25 mm, length:diameter ratio of 40:1, ten temperature zones (the temperatures of zones 1, 2, 3, 4, 5 and 6 were maintained at 30, 30, 60, 90, 100 and 100 °C, respectively, the others were adjusted according to the experimental design), a feed rate of 7 kg h^{-1} and a die of four holes with a diameter of 3.8 mm.

2.4 Experimental design

A Box-Behnken design was used with three independent variables, 2 levels (2^3) and central points: temperature (100, 120 and 140 ºC), moisture (12%, 14% and 16%); and screw speed (300, 500 and 700 rpm), as shown in Table 1. The tests were performed in decreasing order of extrusion temperature. The choice of these parameters and the respective intervals were defined based on preliminary studies and literature data. After extrusion, the snacks were dried in an air circulation oven (60 °C for 4 h), cooled and packaged in polyethylene containers.

Table 1. Levels expressed in coded and real values of experimental conditions of Box-Behnken experimental design 23 of the cowpea cotyledon flour (CCF) extrusion process and their experimental responses.

Trial	Encoded values (real values)			SEI	LEI	VEI	WSI (%)	WAI (g g^{-1})	Hardness (N)
	x_1 (°C)	x_2 (rpm)	x_3 (%)						
1	-1 (100)	-1 (300)	0 (14)	5.38 ± 0.47	1.50 ± 0.13	8.06 ± 1.10	28.91 ± 0.70	3.75 ± 0.16	2.04 ± 0.47
2	1 (140)	-1 (300)	0 (14)	3.90 ± 0.81	1.89 ± 0.17	7.39 ± 1.81	23.90 ± 0.63	3.86 ± 0.32	1.59 ± 0.50
3	-1 (100)	1 (700)	0 (14)	5.85 ± 0.82	3.66 ± 0.43	21.50 ± 4.41	32.24 ± 0.74	3.47 ± 0.38	1.27 ± 0.28
4	1 (140)	1 (700)	0 (14)	2.65 ± 0.46	9.32 ± 2.43	24.15 ± 5.31	33.85 ± 0.36	3.34 ± 0.24	1.46 ± 0.49
5	-1 (100)	0 (500)	-1 (12)	7.64 ± 1.20	2.42 ± 0.22	18.38 ± 2.39	31.67 ± 1.68	3.76 ± 0.23	1.27 ± 0.31
6	1 (140	0 (500)	-1 (12)	4.64 ± 0.81	1.99 ± 0.26	9.17 ± 1.58	30.55 ± 0.39	3.50 ± 0.19	1.86 ± 0.78
7	-1 (100)	0 (500)	1 (16)	4.64 ± 1.18	1.34 ± 0.12	6.21 ± 1.78	30.18 ± 0.71	3.55 ± 0.36	2.08 ± 0.40
8	1 (140)	0 (500)	1 (16)	4.34 ± 0.48	2.59 ± 0.43	11.25 ± 2.28	30.77 ± 1.77	3.48 ± 0.28	1.32 ± 0.57
9	0 (120)	-1 (300)	-1 (12)	4.61 ± 0.43	1.66 ± 0.13	7.66 ± 0.92	25.89 ± 0.21	3.70 ± 0.24	2.44 ± 0.59
10	0 (120)	1 (700)	-1 (12)	4.68 ± 0.70	3.23 ± 0.24	14.98 ± 1.22	30.97 ± 0.74	3.05 ± 0.18	2.40 ± 0.27
11	0 (120)	-1 (300)	1 (16)	4.39 ± 0.45	1.12 ± 0.06	4.91 ± 0.52	26.60 ± 0.26	3.82 ± 0.11	2.83 ± 0.56
12	0 (120)	1 (700)	1 (16)	3.50 ± 0.69	2.30 ± 0.36	7.93 ± 1.20	30.74 ± 0.85	3.05 ± 0.10	1.98 ± 0.44
13	0 (120)	0 (500)	0 (14)	5.08 ± 0.56	1.98 ± 0.14	10.07 ± 1.32	32.53 ± 0.66	3.16 ± 0.68	1.61 ± 0.53
14	0 (120)	0 (500)	0 (14)	4.10 ± 0.65	4.35 ± 0.88	17.75 ± 4.31	32.45 ± 0.35	3.59 ± 0.12	1.24 ± 0.14
15	0 (120)	0 (500)	0 (14)	6.77 ± 0.53	3.07 ± 0.28	20.77 ± 2.16	32.17 ± 0.13	3.57 ± 0.10	1.50 ± 0.42

x_1 = Extrusion temperature (°C), x_2 = Screw speed (rpm), x_3 = Flour moisture (%), SEI = Sectional expansion index, LEI = Longitudinal expansion index, VEI = Volumetric expansion index, WSI = Water solubility index (%), WAI = Water absorption index (g g^{-1}).

2.5 Determination of physical properties

The Sectional Expansion Index (SEI), Longitudinal Expansion Index (LEI) and Volumetric Expansion Index (VEI) were calculated according to the methodology described by Alvarez-Martinez et al. (1988). Hardness (N) was determined in 10 replicates of 2 cm long extrudates in the TA-XT2i texture analyzer (Stable Micro Systems, London, England), using XTRAD software, with the platform (HDP/90) and broken with a rectangular 12.0 x 7 cm Warner Bratzler steel knife (HDP/WBR) accessories.

2.6 Water Solubility Index (WSI) and Water Absorption Index (WAI)

WSI and WAI values were performed according to the methods described by Anderson et al. (1969), in triplicate. The WAI was obtained by dividing the weight of the gel by the weight of the ground sample and expressed in g of gel g^{-1} of the sample. Petri dishes with supernatant were placed in an oven at 105 °C for approximately 15 hours, cooled and weighed (dehydrated soluble residue). The WSI was obtained by dividing the dehydrated soluble residue by the sample weight, and the value expressed as a percentage.

2.7 Cross-section images by scanner

The extrudates were cut transversely into 12 mm segments. The cross-section was placed on the scanner glass (HP Scanjet G2710). The image capture area was standardized at 30 x 30 mm, 300 dpi, in order to allow better visualization and comparisons of the cellular structure between treatments.

2.8 Statistical analysis

Data were submitted to multiple regression analysis using the Statistics program (StatSoft, Version 10, OK, USA). The second order polynomial model was selected to predict the region of the optimal point of the responses, being expressed according to the general equation (Equation 1):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12}x_1x_2 + \beta_{13}x_1x_3 + \beta_{23}x_2x_3 \quad (1)$$

Where *y* represents the response variable, β_0, β_1, β_2, and β_3 are estimators of linear parameters, β_{11}, β_{22}, and β_{33} are the quadratic terms and β_{12}, β_{13}, and β_{23}, the model interaction term. The independent variables x_1, x_2, and x_3, are the coding for temperature, screw speed, and moisture, respectively. The significant experimental models ($p \leq 0.05$) were submitted to analysis of global desirability, in an equity condition, adopting values of "s" and "t" equal to 1, to identify the process condition that favors the desirable characteristics.

3 Results and discussion

3.1 Chemical composition and particle size of CCF

The content (db) of protein and soluble dietary fiber was higher in CCF compared to WCF, being respectively: 25.28 ± 0.08 and 24.89 ± 0.58% of proteins; 1.36 ± 1.01 and soluble dietary fiber; 1.68 ± 0.02 and 2.07 ± 0.10% of lipids; 3.02 ± 0.04 and 3.23 ± 0.01% of ash; 9.91 ± 0.89 and 12.26 ± 0.78% of insoluble dietary fiber. The tegument represents about 6% of the grain weight and contains a high content of insoluble fiber, minerals and little protein, explaining the protein increase and reduction of other components, nutritionally the CCF is better than the WCF, and the CCF does not have hilum fragments, usually dark in color, which results in extruded with dark spots. The mean geometric diameter of the CCF particles was 265.90 µm. This value is within the corn meal particle size range (180 to 710 µm) evaluated by Carvalho et al. (2010) in a twin screw extruder. They obtained greater expansion when using flours of greater particle size range, and greater WAI in flour of smaller particle size range, thus, the ideal particle size range will depend on the characteristics that you want to obtain in the extrudate.

3.2 Sectional Expansion Index (SEI)

The SEI was significantly affected only by the negative linear effect of temperature (Table 2), the coefficient of determination value was relatively high ($R^2 = 0.80$) and the lack of adjustment was not significant ($p = 0.20$), preventing to define the mathematical model. This may have occurred due to the combination of independent variables used, mainly due to the low and narrow variation in moisture content, narrow temperature variation and wide variation in the screw rotation speed. Analyzing the data in Table 1, the negative effect of temperature on the SEI value can be observed, which ranged from 2.65 to 7.64. According to Gui et al. (2012), the LEI value is inversely proportional to the SEI, this was observed, but with a low negative correlation ($r = -0.37$; $p \leq 0.05$) and positive with VEI ($r = 0.24$; $p \leq 0.05$) (Table 3).

Table 2. Values of coefficients estimated by multiple linear regression for SEI, LEI, VEI, WSI, WAI and hardness of extrudates.

Coefficients	SEI	LEI	VEI	WSI	WAI	Hardness
β_0	5.32	3.13	16.20	32.38	3.44	1.45
β_1	-1.00 *	0.86 ns	-0.27 ns	-0.49 ns	-0.05 ns	-0.05 ns
β_2	-0.20 ns	1.54*	5.07 *	2.81 *	-0.28 *	-0.22 *
β_3	-0.59 ns	-0.24 ns	-2.49 ns	-0.10 ns	-0.01 ns	0.03 ns
β_{11}	0.07 ns	0.48 ns	0.73 ns	-0.21 ns	0.16 ns	-0.32 *
β_{22}	-0.95 ns	0.47 ns	-1.65 ns	-2.45 *	0.00 ns	0.46 *
β_{33}	-0.08 ns	-1.53 ns	-5.67 ns	-1.38 *	-0.03 ns	0.50 *
β_{12}	-0.43 ns	1.32 ns	0.83 ns	1.65 *	-0.06 ns	0.16 ns
β_{13}	0.67 ns	0.42 ns	3.56 ns	0.43 ns	0.05 ns	-0.34 *
β_{23}	-0.24 ns	-0.10 ns	-1.08 ns	-0.23 ns	-0.03 ns	-0.20 *
F	2.21	2.02	2.15	16.36 *	2.17	21.40 *
p (model)	0.20	0.23	0.21	0.003 *	0.204	0.002 *
R^2	0.80	0.78	0.79	0.967	0.796	0.97
Lack of Fit	0.94	0.32	0.68	0.03*	0.75	0.94
MS Pure error	1.817	1.402	30.382	0.035	0.059	0.036
CV (%)	19.31	55.22	37.78	7.31	2.79	5.64

SEI = Sectional expansion index, LEI = Longitudinal expansion index, VEI = Volumetric expansion index, WSI = Water solubility index, WAI = Water absorption index. β_0 is a constant; β_1, β_2 and β_3 are the linear coefficients of temperature, screw speed and moisture, respectively; β_{11}, β_{22} and β_{33} are the quadratic coefficients; β_{12}, β_{13} and β_{32} are the interactions coefficients. *Significative (≤ 0.05). nsNot significative, F = F-test = Mean square regression/Mean square residual, MS = Mean square, CV = Coefficient of variation.

Table 3. Correlation coefficients between physical characteristics of CCF extrudates.

	SEI	LEI	VEI	WSI	WAI	Hardness
SEI	1	-0.37 ns	0.24 ns	0.16 ns	0.29 ns	-0.23 ns
LEI		1	0.78 *	0.58 *	-0.30 ns	-0.44 ns
VEI			1	0.71 *	-0.19 ns	-0.65 *
WSI				1	-0.58 *	-0.55 *
WAI					1	0.02
Hardness						1

SEI = Sectional expansion index, LEI = Longitudinal expansion index, VEI = Volumetric expansion index, WSI = Water solubility index, WAI = Water absorption index; *Significative (≤ 0.05). nsNot significative.

Lira Filho (2002) and Jakkanwar et al. (2018) extruding WCF in a single screw also found negative effects of temperature on the SEI, but Marques (2013) obtained a positive correlation. Bepary et al. (2019) also found negative effects of temperature when using ricebean (*Vigna umbellata* (Thunb.) Ohwi & H. Ohashi) flour and a twin screw extruder. Carmo et al. (2019) processing a formulation containing 60% of pea and 40% of oat in a twin-screw extruder found a negative effect of temperature on lower moisture contents.

Process conditions that increase the shear rate, such as low moisture content, process temperature close to 100 °C and high screw rotation speeds decrease the melt viscosity and strength, favoring the expansion of the extrudate bubbles soon after the output of the matrix (Horvat & Schuchmann, 2013). However, probably the negative effect of the temperature with the SEI value is associated with the retraction after the maximum expansion of the extrudate. Because, according to Horvat & Schuchmann (2013), if there is moisture condensation inside the extrudate still in a rubbery state, soon after leaving the matrix, retraction may occur until it reaches a temperature of 45 °C above the glass transition temperature (Tg). For corn grits, the Tg is between 55 °C and 70 °C (Liu et al., 2009). At higher process temperatures, the greater the vulnerability to shrinkage will be. Arhaliass et al. (2003) pointed out that shrinkage changes with the conditions of the extrusion process, and can obtain a shrinkage of 0 to 60% when working with a moisture content of 18.4%.

3.3 Longitudinal Expansion Index (LEI)

The LEI was indirectly calculated by making a mass balance in the extruder and an assumption for the density of the molten mass in the die (Kumar et al., 2007), but it could also be determined through the ratio between the exit velocity of the extruded material after expansion and its velocity in the die hole (Alvarez-Martinez et al., 1988).

The LEI value ranged from 1.12 to 9.32 (Table 1), it was not possible to define the mathematical model due to the lack of significance ($p = 0.23$). However, the values were positively influenced by the linear effect of the speed of screw rotation (Table 2), as the speed increased, there was an increase in the LEI, similar results were presented by Fontoura et al. (2019) and Kumar et al. (2007).

Alvarez-Martinez et al. (1988) did not find any deep rupture in the molecular structure of amylopectin, and obtained greater radial expansion when there was greater shear of the melt in the matrix associated with the elastic properties of amylopectin. Under these conditions, the molten material stores energy and when leaving the matrix it expands in the radial direction. As the moisture contents used were lower (12 to 16%) and rotation speeds were much higher, more ruptures in the molecular structure probably occurred at higher rotations, favoring longitudinal expansion. High screw speeds also shorten residence time (Lee & McCarthy, 1996), which prevents a large accumulation of energy in the molten material. It can be seen in Table 3 that there was a significant positive correlation between LEI and WSI ($r = 0.58$, $p \leq 0.05$), indicating that when the LEI was higher, there was greater degradation of molecular structures.

3.4 Volumetric Expansion Index (VEI)

The VEI value was determined by multiplying SEI and LEI (Alvarez-Martinez et al., 1988). The same considerations about the model significance and lack of adjustment for SEI were applied to VEI. The VEI ranged from 4.91 to 24.15 (Table 1), and was positively affected by the linear effect of the screw rotation speed (Table 2), showing a good positive correlation with the LEI values (r = 0.78, $p \leq 0.05$) (Table 3). The VEI also showed a good negative correlation with hardness (r = -0.65, $p \leq 0.05$) and positive with WSI (r = 0.71, $p \leq 0.05$). These values were much higher than the VEI of 0.62 to 1.8 obtained by Carmo et al. (2019) using a screw speed of 200 rpm and at similar temperatures and moisture.

3.5 Water Solubility Index (WSI)

According to Jakkanwar et al. (2018) and Ajita & Jha (2017) the WSI is used as an indicator of the degradation of biomolecules (starches, proteins, sugars, fibers, etc.), thus being measured by the number of water-soluble components recovered after extrusion.

For the conditions of the extrusion process applied to CCF, the WSI value ranged from 23.90% to 33.85%, it was significantly affected by the positive linear and negative quadratic effects of the screw rotation speed (Table 2) (Figure 2a). Moisture content was also significantly affected by the negative quadratic effect, and there was a positive interaction between temperature and screw speed (Table 2).

The model was significant (p = 0.003) with a high value of R^2 = 0.97, but the lack of adjustment was also significant (Table 2), and this is not desirable. This was because the averages of the central points were very close (Table 1), and consequently the pure error value was very low, in this situation the significance tests for lack of fit should be considered irrelevant (Warner & Nelsen, 1996), and the model can be considered predictive.

Increases in WSI values have been observed when there are increases in screw speed, causing an increase in the shear rate, potentiated by low moisture contents (Jakkanwar et al., 2018; Sharma et al., 2017). The values presented were higher than those of the cited works, indicating that the processing conditions were severe for the macromolecules.

3.6 Water Absorption Index (WAI)

The WAI is an indirect measure of the degree of cooking that results in the ability of the flour, mostly made up of starch, to absorb water almost instantly, a characteristic that depends on the ingredient used and the process parameters (Sharma et al., 2017).

For the conditions of the extrusion process applied to CCF, the WAI values ranged from 3.05 to 3.86 g g^{-1}, only the negative linear effect of the screw rotation speed significantly affected the WAI value (Table 3), but it was not possible to define the mathematical model due to the lack of significance (p = 0.20).

The negative value of the coefficient (Table 2) indicates that the increase in the screws speed significantly reduced the value of WAI of extruded CCF flours. Sharma et al. (2017) reported when extruding a mixture of rice (70%) and mung bean (30%) flours that high screws speed had severe effects on the biopolymers, leading to structural breakage of the molecules, decreasing the ability to bind water, and this effect was also observed in WCF (Jakkanwar et al., 2018). In the opposite condition of low screws speed, a greater proportion of undamaged polymer chains and greater availability of hydrophilic groups with the ability to bind water have been found, increasing the value of the WAI (Jin et al., 1994).

3.7 Hardness

In expanded extrudates, the texture is a critical sensory attribute and determines the sensory quality of the product, playing an important role in acceptability (Anton & Luciano, 2007). The applied test simulates a bite as if the incisor teeth were aligned; representing a blade, cutting perpendicularly to the longitudinal axis of the extrudate until complete breakage, and the peak force obtained is the measure of the cutting force, indicative of the product's hardness. This is one of the parameters of mechanical characteristics, defined as the force required to achieve a given deformation, or the force required to break the extrudate (Bepary et al., 2019).

The products must also not be too hard to the point of being difficult to bite and chew, or very fragile, which breaks easily during packing and transport.

Hardness ranged from 1.24 to 2.83 N (Table 1), and was affected by screw rotation speed (negative linear and positive quadratic effect), temperature (negative quadratic effect), moisture (positive quadratic effect), and the two interactions with moisture having negative effects (Table 2 and Figure 2b). The model was significant, explaining 97% of the variation and the lack of adjustment was not significant (Table 2). The values correlated negatively and significantly ($p \leq 0.05$) with VEI (r = -0.65) and WSI (r = -0.55) (Table 3).

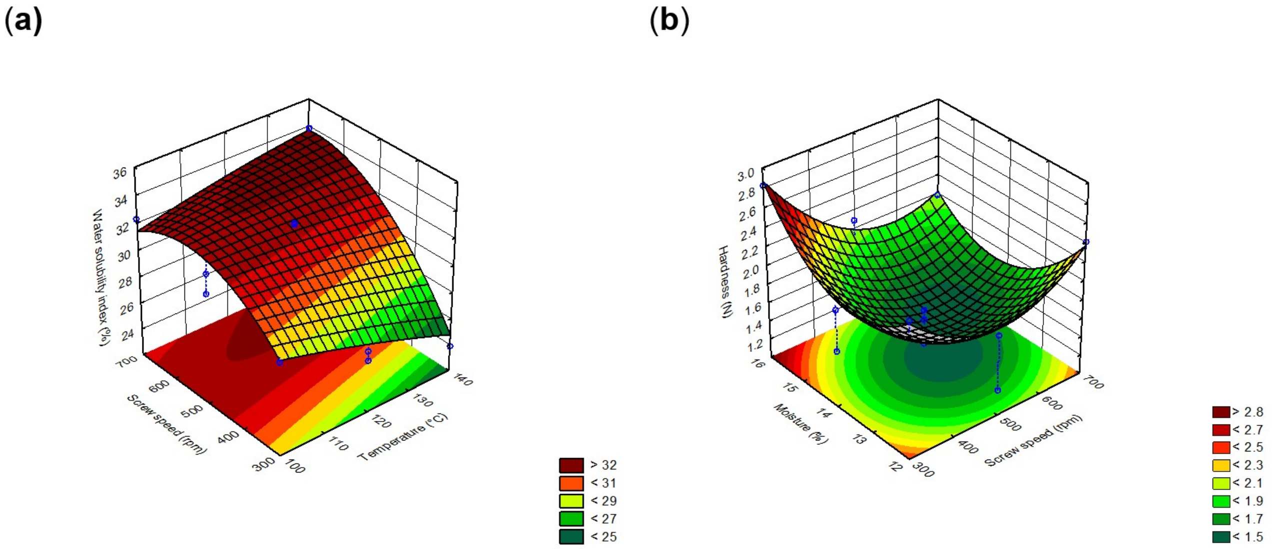

Figure 2. Effect extrusion process on water solubility index with moisture maintained at 14% (a) and hardness with temperature maintained at 120 °C (b).

In studies that evaluated the hardness of extruded WCF, Lira Filho (2002) using the same analytical methodology, obtained high values (10.53 to 58.18 N), which were affected by linear and quadratic effects of temperature. Jakkanwar et al. (2018) evaluating the same process parameters, reported that moisture positively affected and screws speed negatively affected hardness values. Strauta & Muizniece-Brasava (2016) found harder extrudates as well as higher moisture content. Bepary et al. (2019) using the same analytical procedure, and the same independent extrusion variables, but in different ranges, obtained ricebean whole flour extrudates with hardness from 9.61 to 27.95 N, with positive effects of rotation speed and moisture, and negative for temperature.

Using commercial cylindrical extrudates and the same probe model, Paula & Conti-Silva (2014) obtained hardness, called by them fracturability, from 12.6 to 19.9 N, these values were about 10 times higher than those obtained with the extrudates of CCF.

3.8 Extruded cross section images

Differences in cross-section (size, shape and irregularities), color and cells (shape, distribution and size) are visible in Figure 3. According to Miller (1985), low levels of moisture in extrusion reduce the uniformity and circularity of the products.

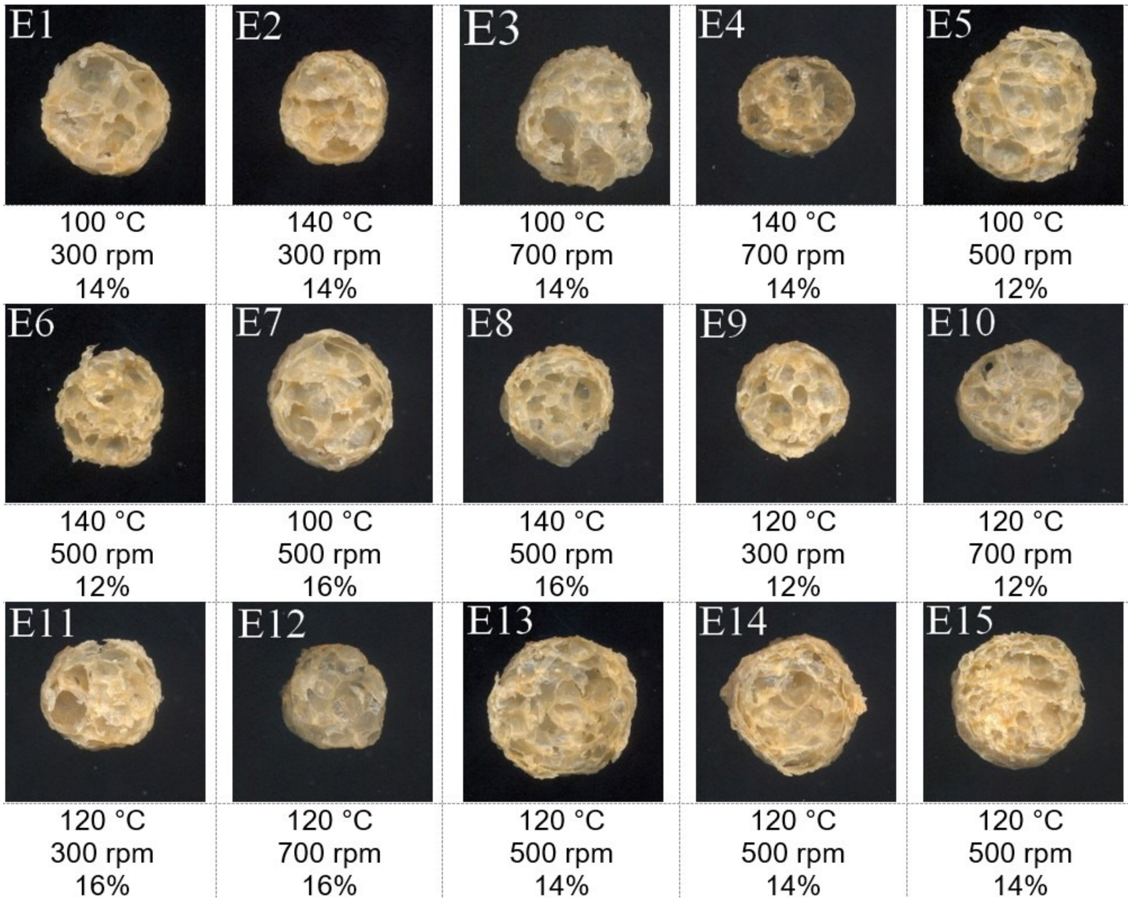

Figure 3. Cross section of cowpea cotyledon flour extrudates obtained under different temperature conditions (100 to 140 °C), screw speed (300 to 700 rpm) and moisture (12 to 16%).

E5, E6, E9 and E10 corresponding to the extrudates of treatments 5, 6, 9 and 10, which were processed with the lowest moisture content, it is observed in image E5 the loss of circularity and relatively large cells, and lower hardness value (Table 1). At E6 the cells are irregular and have a smaller cross section, and a darker color, indicating walls of the denser cell structure, revealing a higher hardness value than E5 (Table 1), however, all the other attributes evaluated in E5 were higher in relation to E6, especially for VEI, which was twice as high (Table 1). The higher temperature of the E6 (140 °C) resulted in a more compact structure, probably due to the longer time for shrinkage, as to reduce from 140 °C to below the temperature of the rubbery state, more time is needed.

Between the E9 and E10, the difference in the process was the extremes of screws speed, 300 and 700 rpm, respectively. The SEI values for both were similar (Table 1); however, it is observed that E9 has a denser structure, due to darker coloration and thicker cell walls. E10 has thinner cell walls, lighter color, as a result of greater longitudinal expansion, its LEI was 3.23, almost twice as much as E9 (1.66) (Table 1), similarly were the VEI values (14.98 and 7.66, respectively) (Table 1). Although E9 seems to be more compact due to its dark color, the hardness values were very close, probably offset by the values of WSI and WAI, which presented a greater discrepancy in the values (Table 1).

E7, E8, E11 and E12 were obtained by extruding CCF with 16% of moisture. At this moisture content, the SEI of E7 was visually (Figure 3) and in absolute value greater than E8 (Table 1). However, the LEI was almost double for E8, and consequently, VEI was also almost double of E7, and WSI and WAI values were closer (Table 1), the hardness value was influenced by the LEI value, then the smaller the value, the more compact and darker the extrudate will be, resulting in a higher hardness value (Table 1).

Between E11 and E12, the higher screws speed for E12 resulted in a less compact extrudate, visible by the lighter coloration and thinner structure of the cell walls compared to E11 (Figure 3), and with a lower value of SEI, WAI and hardness, and higher value for LEI, VEI, WSI, all were different from E11 (Table 1).

For 14% of moisture content (E1, E2, E3, E4, E13, E14 and E15), comparing E1, E2, E3 and E4, the lower rotation speed in E1 and E2 resulted in darker extrudates, mainly due to the LEI and, consequently, by positive correlation (Table 3). The lower VEI value, there was less molecular structure degradation due to the lower WSI and higher WAI values, resulting in harder extrudates (Table 1). High screws speed in E3 and E4 resulted in higher LEI values, and due to a significant positive correlation (Table 3), WSI and VEI values were also high. As WSI and hardness presented a negative correlation (Table 3), E3 and E4 presented lower values of hardness (Table 1).

The extrudates from treatments 13, 14 and 15 (E13, E14 and E15) were processed under the same conditions (repeats of the central point), according to the images in Figure 3, the coloration, internal distribution of cells, size of the cross section were very similar, the values for WSI and hardness were also very close (Table 1).

3.9 Global desirability

Using the mathematical models for hardness and WSI, and considering that for the range of values of the independents' variables, it is desirable to obtain extrudates that do not break easily during filling and transport, with values close to those of commercial extrudates (Paula & Conti-Silva, 2014). The extrudates must also have high WSI values so that they solubilize inside the mouth during chewing. Under these conditions, the maximum value of global desirability obtained by simulation was 0.81, provided by the process conditions of 135.6 °C, screw speed of 700 rpm and 12% of moisture (Figure 4). This condition predicts a product with superior quality for hardness (2.51 N) and for WSI (32.14%), a value close to those observed experimentally, obtained in the region of the central point (Table 1).

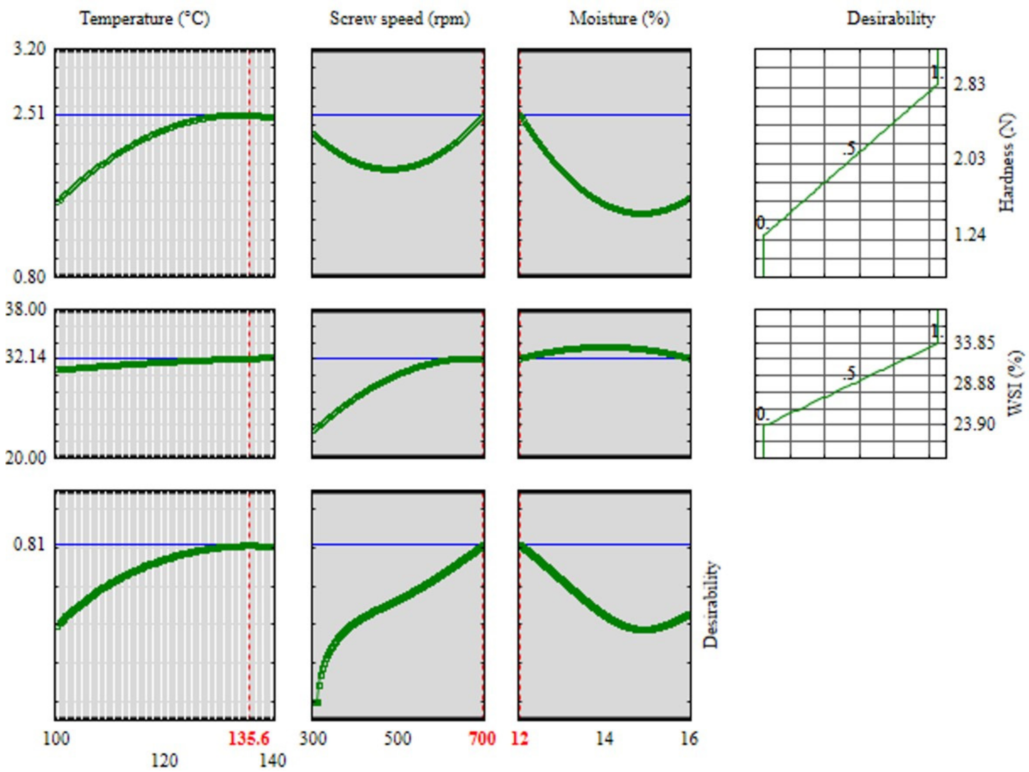

Figure 4. Profiles for predicted values and desirability for expanded extruded of CCF.

4 Conclusion

For the range of values used for the three variables, all of them interfered with the quality of the extrudates. By simulation, the maximum value for the overall desirability was 0.81. for the condition of lower moisture content, maximum rotation speed and temperature of 135.6 °C, which will provide high expansion rates, hardness values for extrudates close to those of commercial products and with high solubility values. The correlations between these characteristics were favorable for obtaining quality expanded extrudates. The images of the cross-section of the extrudates were important in assisting in the interpretation of the effects of the variables.

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