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Development of corn and flaxseed snacks with high-fibre content using response surface methodology (RSM)

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Abstract
With the increasing emphasis on health and well-being, nutrition aspects need to be incorporated as a dimension of product development. Thus, the production of a high-fibre content snack food from a mixture of corn and flaxseed flours was optimized by response surface methodology. The independent variables considered in this study were: feed moisture, process temperature and flaxseed flour addition, as they were found to significantly impact the resultant product. These variables were studied according to a rotatable composite design matrix (− 1.68, − 1, 0, 1, 1.68). Response variable was the expansion ratio since it has been highly correlated with acceptability. The optimum corn–flaxseed snack obtained presented a sevenfold increase in dietary fibre, almost 100% increase in protein content compared to the pure corn snack, and yielded an acceptability score of 6.93. This acceptability score was similar to those observed for corn snack brands in the market, indicating the potential commercial use of this new product, which can help to increase the daily consumption of dietary fibre.

Keywords: *extrusion, response surface methodology, corn and flaxseed snacks, expansion ratio*

Introduction

Food products design has hitherto focused on acceptability and cost reduction, while overlooking nutritive aspects (Poltronieri et al. 2000; Cardoso-Santiago et al. 2001; Jones and Jew 2007). This trend has recently changed following growing interest in the concept of 'functional foods' by both the food industry and the consumer (Oomah and Mazza 1998; Yanniotis et al. 2007). Functional foods are foodstuffs that have a beneficial effect on one or more target functions in the body, over and beyond adequate nutritional effects. They improve overall health and/or reduce the risks of disease and include whole, fortified, enriched or enhanced foods. This potentially beneficial effect on health must be gained by their regular consumption at the right amounts as part of a balanced diet (Rafter 2002; Roberfroid 2007). With this increasing emphasis on health and well-being, consumers are demanding taste, convenience and nutrition in food products, so nutrition needs to be incorporated as a dimension of product development (Ahmed 1999; Capriles et al. 2009).

One such functional food, and the focus on increasing research in recent years, is flaxseed. It is the richest vegetal source of omega-3 fatty acids (important for cardiovascular health), a good source of gums and mucilage [a kind of soluble fibre (SF) that helps lowering blood cholesterol and glycaemia] and insoluble fibre (IF) that promotes laxation. It is also the richest source of phenolic compounds known as lignans, phytoestrogens that have demonstrated anticarcinogenic properties (Nesbitt et al. 1997; Daun et al. 2003; Cotterchio et al. 2008; McCann et al. 2010; Chen et al. 2011). Moreover, flaxseed is high in protein (22–26%), and its amino acid profile resembles that of soy (Oomah and Mazza 1993).

Flaxseed is reported to contain about 27–37% dietary fibre (Daun et al. 2003; USDA 2009). Populations that consume more fibre have fewer chronic diseases.

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In addition, intake of fibre has beneficial effects on risk factors for several chronic diseases. Its consumption may lower blood pressure, improve serum lipid levels, reduce indicators of inflammation, increase stool weight and promote normal laxation. Dietary fibre may also offer some benefits in terms of weight loss and glycaemic control (De Vries and Rader 2006; Jones et al. 2006; ADA 2008).

Extrusion cooking is a well-established industrial technology employed in a number of food and feed applications. In addition to the usual benefits of heat processing, it improves digestibility of both starch and protein and destroys several anti-nutritional factors (Cheftel 1986; Camire et al. 1990). This process has also been suggested as a possible improver of fibre functionality (Artz et al. 1990).

The sensory quality and the acceptance of snack foods depend mainly on expansion ratio (ER) and texture parameters (Batistuti et al. 1991; Mendonça et al. 2000; Yanniotis et al. 2007). Systematic control of the extrusion variables involved in obtaining an expanded snack with higher flaxseed content is still lacking. Therefore, the aim of our work was to optimize the extrusion cooking process for the production of corn–flaxseed snacks in order to include the maximum possible amount of flaxseed into the corn matrix thereby introducing the health benefits of this seed, especially fibre, to this popular product.

Materials and methods

Materials

The flaxseed flour (dry basis: 9.5% moisture, 32.8% protein, 9.0% lipids, 16.4% SF and 41.3% IF) used was the byproduct obtained from partially defatted flaxseed, and it was provided by 'Indústria de óleos vegetais Pazze Ltda' (Panambi, Rio Grande do Sul State, Brazil). This milled product was stored at 5°C until extrusion. Degerminated corn grits (lipids < 1.0%) were bought from the local market and were stored at an ambient temperature before processing.

Methods

Radial ER. This was calculated by dividing the average cross-sectional area of extrudate (obtained with calipers) by the cross-sectional area of the extruder die. Values reported were averages of 15 measurements for each treatment.

Extrusion and sample preparation. A laboratory single screw extruder (model RXPQ Labor 24 INBRAMAQ, Brazil) with a length-to-diameter ratio of 10:1 was employed. The barrel was divided into three independent electrically heated zones cooled by water. Conditions during extrusion were fixed at: 236 rpm screw rotation, 4:1 screw compression ratio and 3.5 mm die diameter. The processing temperature of the extruder was kept constant in zone 1 (feed area) at 30°C and at 70°C in zone 2. The temperature of zone 3 (the nearest zone from the die) varied with experimental design. Feed rate was 270 g min^{-1}.

Experimental design. The effects of three independent extrusion parameters (variables), moisture content (x_1), temperature (x_2) and flaxseed flour content (x_3) on the ER were investigated. Initial experiments at feed moistures of 11–28% (d.s.b.), central section temperature of 76–140°C and flaxseed flour addition

Table 1. Specification matrix of the second-order design: x_1, moisture (% d.s.b.); x_2, temperature (°C)* and x_3, flaxseed adition (%).

	Coded variables				
Design point*	x_1 [$(x_1 - 15)/4$]	Actual coded values	x_2 [$(x_2 - 110)/20$]	Actual coded values	x_3 [$(x_3 - 25)/5$]
1	−1	−0.92	−1	−1	−1
2	−1	−0.52	1	0.70	1
3	1	1.14	−1	−0.75	1
4	1	0.91	1	1	−1
5	0	0	0	0.4	0
6	0	0	0	0	0
7	−1	−0.92	−1	−1	1
8	−1	−0.92	1	0.70	−1
9	1	0.91	−1	−1	−1
10	1	1.14	1	1.30	1
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	1.68	1.93	0	0	0
15	−1.68	−1.20	0	0.25	0
16	0	0	1.68	1.40	0
17	0	0	−1.68	−1.68	0
18	0	0	0	0.20	1.68
19	0	0	0	0	−1.68

* Does not correspond to order of processing; d.s.b., dry solids basis.

Table 2. Independent and response variables of flaxseed–corn snacks.

Assay*	x_1 (% M, d.s.b.)	x_2 (T, °C)	x_3 (%, F)	Y_1 (ER)
1	11	90	20	2.85 (0.20)
2	11	130	30	1.52 (0.08)
3	19	90	30	3.02 (0.16)
4	19	130	20	3.10 (0.11)
5	15	110	25	3.11 (0.33)
6	15	110	25	3.23 (0.37)
7	11	90	30	†
8	11	130	20	1.43 (0.06)
9	19	90	20	2.73 (0.17)
10	19	130	30	2.38 (0.16)
11	15	110	25	2.62 (0.22)
12	15	110	25	3.01 (0.21)
13	15	110	25	2.17 (0.15)
14	21.7	110	25	2.24 (0.12)
15	8.3	110	25	1.52 (0.07)
16	15	143.6	25	1.77 (0.13)
17	15	76.4	25	3.64 (0.27)
18	15	110	31.7	2.52 (0.12)
19	15	110	18.3	3.98 (0.23)

* Does not correspond to order of processing; † Extruder stopped. No response obtained and assay was excluded from regression analysis. d.s.b., dry solids basis; M, moisture; T, temperature; F, flaxseed.

of 11–28% showed that good expansion could be obtained at 90–130°C, 15% moisture and 15–25% flaxseed addition. Based on these preliminary experimental data, a randomly assigned five-level design (−1.68, −1, 0, 1, 1.68; Box and Draper 1987) was employed (Table I). Results were fitted to a second-order polynomial

$$y = b_0 + b_1x_1 + b_2x_2 + \cdots + b_nx_n + b_{11}x_1^2 + b_{22}x_2^2 + \cdots b_{nn}x_n^2 + b_{1n}x_1x_2x_n + E,$$

where y is the dependent variable (ER or shear strength), $b_0, b_1, \ldots, b_n$ are the constants, x_1 is the feed moisture, x_2 the temperature of the third zone of the barrel, x_3 the flaxseed flour addition, E the experimental error with normal distribution, mean zero and variance ∂^2.

The order of processing was chosen by randomizing feed moisture levels at increasing levels of temperature. Operation started from the lowest temperature and operation continued without stopping between samples. Multiple regression, analysis of variance (ANOVA) and graphics were carried out using the statistical package program Origin (6.0 – Microcal Software Inc., MA, USA) and Chemomatrix (Instituto de Química, Universidade Estadual de Campinas, Brazil, available online at http://www.chemomatrix.unicamp.br). Comparison of mean values was performed by one-way ANOVA, with significance defined at the $p < 0.05$ level, using Origin 6.0.

The flavouring solution contained 10% canola oil, 4% barbecue powder flavouring and 2% salt and was applied externally to the snacks in a coating pan (Erweka, Heusenstamm, Germany) by spraying the solution over the snacks, mixing and drying.

Proximate composition was carried out according to AOAC (1990): desiccation at 105°C, for moisture; calcination at 550°C, for ash; micro-Kjeldhal for protein ($N \times 5.75$) and defatting in Soxhlet apparatus with petroleum ether for total lipids. The total starch content was determined in accordance with Goñi et al. (1997) and glucose was quantified using glucose oxidase, peroxidase and 2,2′-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assays (Bergmeyer and Bernet 1974). The starch content was calculated as glucose $\times 0.9$. Dietary fibre was estimated according to the enzymatic gravimetric method developed by Prosky et al. (1988). Each value was the average of three determinations.

Sensory evaluation. Forty-one untrained panellists, recruited among staff and graduate students of Faculdade de Saúde Pública, Universidade de São Paulo, Brazil, tested the snacks. Aproximately, 5 g were placed in a plastic pack coded with three-digit random numbers. Consumers were asked to assess one set of the sample flavoured with barbecue for the attributes: colour, taste, crunchiness and general acceptability using a structured nine-point hedonic scale: 1, extreme dislike; 5, neither like nor dislike and 9, extreme like (Peryam and Pilgrim 1957). Consumers evaluated the samples at room temperature in individual booths and under fluorescent light to minimize the influence of colour in acceptance (Stone and Sidel 1985).

Results and discussion

Adjusting moisture content of the material before extrusion was time-consuming and prone to error. To minimize inaccuracy, moisture content was checked one time, and the actual values were codified at the matrix for regression analysis (Table I). Temperature readings, checked at the control panel of the extruder, were also used to calculate the codified values that were employed in the regression matrix (Table I).

Results for the ER of extrudates and their regression coefficients are presented in Tables II and III.

Table 3. Regression coefficients, R^2 adjusted and probability values for dependent variable.

Regression coefficient	Constant b_0	Linear x_1	Linear x_2	Linear x_3	Quadratic x_1^2	Quadratic x_2^2	Quadratic x_3^2	Interaction x_1x_2	Interaction x_1x_3	Interaction x_2x_3	R^2 (adjusted)
ER, Y_1	2.882*	0.534*	−0.590*	−0.196	−0.464*	−0.145	0.121	0.543*	0.058	−0.271	0.840

* Regression coefficients showed a significant relationship ($p < 0.5$).

Table 4. ANOVA for the regression of the second-degree polynomial for the response: ER.

Source	Sum of squares	Degrees of freedom	*F* value
Regression	7.614	9	4.624
Residues	1.463	8	
Lack of fit	0.812	5	0.748
Pure error	0.651	3	
Total	9.077	17	

Note: $R^2 = 0.928$; R^2 adjusted $= 0.840$.

The assay n° 7 (moisture 11%, temperature 90°C and flaxseed addition 30%) halted the process and caused the extruder to stop because the extreme conditions of strain overloaded the equipment capacity, and led to no response. Therefore, this assay was excluded from the matrix for regression analysis. Table IV shows that the procedure of codifying actual values to the matrix better detected the pure error sum square of the process. These values were consistently higher than when the predicted variable values were employed. Results indicated that linear effects of both moisture and temperature, the second-order effect of moisture and the moisture–temperature interactions were all significant. However, the flaxseed flour addition effect was not significant. The regression was significant and showed no lack of fit ($p < 0.05$) and the resultant polynomial for ER is

$$y = 2.88 + 0.53x_1 - 0.59x_2 - 0.46x_1^2 + 0.54x_1x_2.$$

The response surface for this variable is presented in Figure 1. A region of maximum response can be seen from these plots and the partial derivatives of the ER with respect to moisture, and temperature indicated that the conditions of processing for maximum expansion were 19% moisture and 123°C. In accordance with the model, the combination of independent variables that resulted in the maximum ER of extrudates was run in an independent experiment to show the applicability of the model.

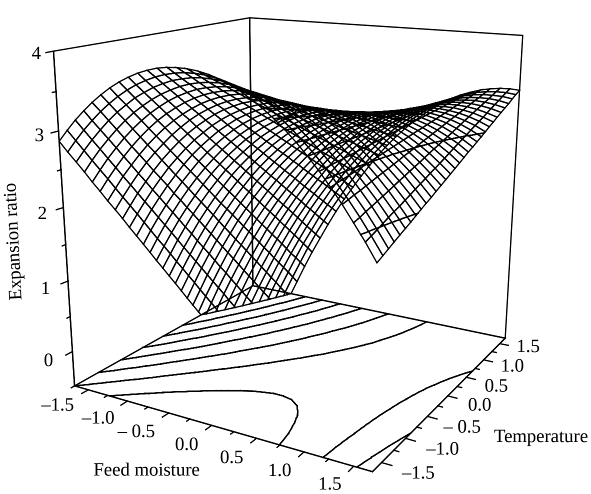

Figure 1. Radial ER as a function of feed moisture and extrusion temperature ($y = 2.88 + 0.53x_1 - 0.59x_2 - 0.46x_{12} + 0.54x_1x_2$).

The results are displayed in Table V. Response surface methodology (RSM) allowed the flaxseed inclusion to the corn matrix up to 30%, higher than the maximum values of 15% and 20% reported by previous studies (Ahmed 1999; Wu et al. 2007).

The influence of extrusion-cooking conditions on several product characteristics has been extensively modelled and studied. The individual role of the major variables of extrusion and their interrelationships on the expansion of corn starches and cereals were found to be moisture content, extruder barrel temperature, screw speed and die-nozzle length-to-diameter ratio (Mercier and Feillet 1975; Faubion and Hoseney 1982; Gomes and Aguilera 1984; Chinnaswamy and Hanna 1988). Irrespective of the type of flour, linear effects of the moisture content on expansion of extruded starchy materials are the rule for cereal extrusion (Arêas 1992). In this paper, with the flaxseed addition, a fibre and protein-rich material, quadratic moisture effect and interactions between moisture and temperature were also observed, besides the linear effect of temperature.

Volumetric expansion of extruded starch-based materials (occurring as either radial or longitudinal) is a consequence of extensive flash-off of internal moisture and flow properties of molten mass and depends on the degree of gelatinization, which is determined by processing conditions and raw material composition (Chinnaswamy and Hanna 1988; Arêas 1992; Mendonça et al. 2000). Considering corn starch alone, the moisture content usually reported for maximum expansion is 13–14% (Gomes and Aguilera 1984; Chinnaswamy and Hanna 1988). Water is well known as a plasticizer of the amorphous regions of starch granules and, in addition, it reorganizes the hydrogen bonds between itself and the associated starch chains (Harper 1981; Yanniotis et al. 2007).

The higher the protein and fibre contents of the formulations, the more viscous was the resulting dough. Therefore, more mechanical energy is dissipated in the extrusion process of these materials resulting in higher back pressures at the die, hampering radial expansion at the exit (Harper 1981). The fibre component has the capacity to hydrate itself and, consequently, to compete for water and restrict availability of this plasticizer thereby impairing the gelatinization process (Yanniotis et al. 2007). The characteristic composition of the feed material used in this paper may explain the higher moisture (19%) content observed for the maximum expansion of

Table 5. Optimum conditions for flaxseed–corn snacks and ER: predicted and experimental results.

Extrusion conditions for maximum expansion	ER determined*	Predicted by the model
19% *M*, 123°C, 25% flaxseed	3.93 (0.08)	3.10
19% *M*, 123°C, 30% flaxseed	3.75 (0.10)	3.10

* Values expressed as mean (standard deviation), $n = 15$; M, moisture.

Table 6. Proximate composition (g/100 g) of unflavoured corn–flaxseed snacks and unflavoured corn snacks (dry basis).*

	Corn and flaxseed snacks	Corn snacks
Moisture	6.41 (0.10)[a]	7.00 (0.40)[a]
Protein	14.69 (0.60)[a]	7.45 (0.80)b
Lipids	0.22 (0.09)[a]	0.22 (0.02)[a]
Ash	1.70 (0.04)[a]	0.28 (0.04)[b]
Starch	66.5 (5.59)[a]	89.66 (0.34)[b]
SF	4.60 (1.71)[a]	0.66 (0.11)[b]
IF	9.78 (0.23)[a]	1.43 (0.31)[b]
Dietary fibre (FAT)†	14.38	2.09

*Values expressed as mean (standard deviation), $n = 3$, mean values in the same row not sharing the same letter differ significantly ($p < 0.05$); †Obtained by summing SF and IF.

corn–flaxseed snack versus values for corn starch alone. Previous studies involving the extrusion of fibre-rich materials have frequently shown the significant effect of fibre addition. This effect is typically linear, with lower expansion at higher fibre levels (Lue et al. 1991; Mendonça et al. 2000; Onwulata et al. 2001; Yanniotis et al. 2007). In this paper, this behaviour was not noted, the flaxseed linear effect was not significant, in the range studied. The effect of its addition on the ER was probably not significant because the major component in this case (70% of corn, considering the optimum point) is a starch-based material. Artz et al. (1990) determined the effect of screw speed (200–500 rpm), temperature (90–150°C) and pH (3–11) on the ER of extrudates prepared from a blend of corn fibre and corn starch. Statistical analysis of their results indicated that none of the variables had a significant effect on ER or shear strength. In spite of the increasing popularity of fibres in extruded products, many gaps in knowledge remain especially with regard to the mechanisms governing extrudate expansion of composite raw materials (Yanniotis et al. 2007).

The increase in the fibre content of extruded food results in premature rupture of gas cells thus reducing the overall expansion, which may affect the appearance, texture and acceptability of the product (Mendonça et al. 2000; Yanniotis et al. 2007; Capriles et al. 2009). In this paper, optimization enabled incorporation of a high-fibre content (30% of flaxseed flour) while maintaining the crunchiness expected for this product. The addition of flaxseed promoted an almost 100% increase in protein and seven times more fibre compared to a snack made with corn alone (see Table VI). Recommended dietary reference intakes, based on epidemiological studies, are 14 g of dietary fibre per 1000 kcal. This amount would provide protection against cardiovascular disease. Thus, a portion of 30 g of this product (the usual portion in the market) provides 15% of the adequate fibre intake for adults with a 2000 kcal diet (IOM 2002). Usual intake of dietary fibre in the USA is only 15 g/day (ADA 2008). In Brazil (Secretaria de Vigilância Sanitária, Ministério da Saúde, Brasil 1998), according to present regulations, it is possible to use the claim 'high-fibre content' when the product contains more than 6 g of total dietary fibre per 100 g of product. Since the corn and flax snack has 14.7% of fibre, it can be labelled 'high fibre' and might help increase the consumption of dietary fibre in the daily diet.

Table 7. Acceptability of corn–flaxseed snacks with barbecue flavouring.

Atributes	Scores*
Crunchiness	7.44 (1.28)
Colour	4.46 (2.13)
Taste	7.32 (1.69)
General acceptability	6.93 (1.34)

*Structured nine-point hedonic scale: 1, extremely dislike; 5, neither like nor dislike and 9, extremely like. Values expressed as mean (standard deviation).

Table VII shows the sensory evaluation of snacks with added barbecue flavouring. The data evidence that among the evaluated attributes, colour was rejected because the majority of panellists (75.6%) assigned grades of between 1 and 5, giving a mean score for this parameter, which fell below the acceptance limit. The reduction in sensory scores for colour would not be a major drawback for the production of these snacks because this dark snack could be coated with an appropriate seasoning that matches its colour, such as meat flavourings (Ahmed 1999).

Other attributes (crunchiness, flavour and overall acceptability) were accepted with averages greater than or close to 7. According to Capriles et al. (2007), the overall acceptability for commercialized corn snacks flavoured with bacon, prepared with 22% hydrogenated vegetable fat as the flavouring fixative agent is 7.5 ± 1.0, close to scores obtained in this study. Therefore, the corn–flaxseed snacks developed in this paper have the potential to be marketed.

Conclusions

This study demonstrated the effects of the extrusion process variables on the characteristics of a flaxseed–corn-based snack. Moisture and temperature had a significant effect on the ER but it was not noted with flaxseed, in the range studied. RSM allowed the flaxseed inclusion into the corn base up to 30%, a very high value compared to levels described in other studies. The partial derivatives model determined the point of maximum expansion that was subsequently confirmed experimentally. The snack made with the inclusion of flaxseed flour into the corn matrix presented a sevenfold increase in dietary fibre, an almost 100% increase in protein content and yielded a similar overall acceptability score (6.93 ± 1.34) to commercial corn snacks.

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