Optimization and characterization of an extruded snack based on taro flour (*Colocasia esculenta* L.) enriched with mango pulp (*Mangifera indica* L.)

C. A. Pensamiento-Niño¹ · C. A. Gómez-Aldapa² · B. Hernández-Santos¹ ·
J. M. Juárez-Barrientos¹ · E. Herman-Lara¹ · C. E. Martínez-Sánchez¹ ·
J. G. Torruco-Uco¹ · J. Rodríguez-Miranda¹

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Abstract The aim of this study was to optimize and characterize an extruded snack made with taro flour and mango pulp. A central experimental design composed of the following three variables was used: mango pulp proportion (MPP = 0–10 g/100 g) in taro flour, feed moisture content (FMC = 16–30 g/100 g) and extrusion temperature (zone 4 of extruder) (T = 80–150 °C) using a single-screw extruder with a compression screw ratio of 3:1. Increasing FMC values decreased the torque, pressure, specific mechanical energy (SME), expansion index (EI), water solubility index and pH values and increased the residence time, bulk density (BD), hardness and total colour difference. Increasing T values led to a decrease in the torque, pressure, BD and hardness values, while increasing MPP values only caused a significant increase in the hardness values and β -carotene content and a decrease in the pressure value. The optimal extrusion conditions were T = 135.81 °C, FMC = 18.84 g/100 g and MPP = 7.97 g/100 g, with a desirability value of 0.772, to obtain a snack with EI = 1.52, BD = 0.66 g/cm³, hardness = 24.48 N, β -carotene content = 99.1 μ g/g and SME = 428.54 J/g. The mango pulp is an available and economical source of β -carotene for the enrichment of extruded expanded taro snacks.

Keywords β -Carotene · Expansion index · Mango · Taro

Abbreviations

BD	Bulk density (g/cm ³)
EI	Expansion index (–)
FMC	Feed moisture content (X_2) (g/100 g)
MPP	Mango pulp proportion (X_1) (g/100 g)
SME	Specific mechanical energy (J/g)
T	Extrusion temperature (X_3) (°C)
WAI	Water absorption index (g/g)
WSI	Water solubility index (%)
ΔE	Total colour difference (–)

Introduction

Currently, snack foods are being redesigned to increase their nutritional value by adding micro or macronutrients, phytochemical components, vitamins, and antioxidants, among other ingredients, to make the snack foods attractive to consumers by the nutraceutical properties of these compounds (Honi et al. 2018). The bioactive compounds typically found in small amounts in foods are currently added as ingredients in the development of new products not only for their bioactive potency but also for their colouring properties (Falfán-Cortés et al. 2014; Emin et al. 2012), in this sense, some research has been carried out to enrich snacks with antioxidant compounds such as β -carotene. Guzman-Tello and Cheftel (1990) reported a reduction from 73 to 38% of the initial synthetic trans- β -carotene content mixed with wheat flour when extruded at 125 and 200 °C, respectively. Falfán-Cortés et al. (2014) evaluated the effect of the addition of passion fruit pulp (0–7% (w/w)), extrusion temperature (80–140 °C) and feed moisture content (16–30% (w/w)) in a blend of corn starch,

✉ J. Rodríguez-Miranda
jesrodmir@gmail.com

¹ Tecnológico Nacional de México, Instituto Tecnológico de Tuxtepec, Av. Dr. Víctor Bravo Ahuja S/N., Col. 5 de Mayo, C.P. 68350 Tuxtepec, Oaxaca, Mexico

² Área Académica de Química, Ciudad del Conocimiento, ICBI-UAEH, Carr. Pachuca-Tulancingo Km 4.5, C.P. 42184 Mineral De La Reforma, Hidalgo, Mexico

reporting that at a passion fruit pulp concentration of 1.42% and barrel temperature of 127 °C and $\approx$ 27% of feed moisture content were the best conditions to preserve the β -carotene in extruded products (0.007 mg/100 g of dry base (db) and the highest expansion index (1.8)). The β -carotene retained during the extrusion process are attributable to the raw material (source of β -carotene), the type of extruder and the extrusion conditions, with thermal degradation being the main factor contributing to the losses of β -carotene during extrusion (Falfán-Cortés et al. (2014). Extrusion cooking is a high-temperature short-time process in which food materials are plasticized and cooked by a combination of temperature, pressure and mechanical shear, resulting in molecular transformation and chemical reactions. This technology uses a continuous process with high productivity, significant retention of nutritional quality, and natural colour and flavour of food (Navarro-Cortez et al. 2016). This method presents multiple advantages, the main advantage being that the ingredients undergo a series of transformations, which would ordinarily be carried out in several unit operations (mixing, shearing, cooking, drying and texturing), in a single fast and efficient step (Rodríguez-Miranda et al. 2011b). Therefore, this method is important for the production of snacks with higher nutritional content and the use of non-conventional and perishable raw materials to give an added value, as in the case of taro and magician and with the above decrease the losses after harvest. Taro (*Colocasia esculenta* (L.) Schott) is a tuber with edible starch belonging to the Araceae family. Taro cultivation in developing countries has become important in recent years due to the high fibre content (0.6–0.8 g/100 g); protein content (2–6 g/100 g); and mucilage, vitamin, phosphorus, calcium and starch content (70–80 g/100 g db) of taro (Rodríguez-Miranda et al. 2011a). In contrast, mango (*Mangifera indica* L.) is a fruit that belongs to the Anacardiaceae family, and the edible part of fruit is between 60 and 75% of the whole fruit. Mango has high carotenoid content when mature and is a good source of provitamin A (Liu et al. 2013). The major component of mango is water, which is present at 84%. The sugar content varies from 10 to 20%, and the protein content is 0.5%. The predominant acid is citric acid, although malic, succinic, uronic, tartaric and oxalic acids are also found in smaller amounts (Ribeiro et al. 2007). Therefore, the aim of the study was to optimize the process to develop an extruded snack based on taro flour (*Colocasia esculenta* L.) enriched with mango pulp (*Mangifera indica* L.) prepared using a single screw extruder and to evaluate the effect of extrusion temperature, feed moisture content and the proportion of mango pulp in taro flour on some process parameters, physical, functional properties and β -carotene content of the extruded snacks.

Materials and methods

Raw materials

Taro (*Colocasia esculenta* L.) and mango of the Manila variety (*Mangifera indica* L.) were purchased at the local market in the city of San Juan Bautista Tuxtepec, Oaxaca, Mexico. The taro was washed, peeled and cut into 0.5 cm thick slices and then dried at 65 °C for 25 h (Rodríguez-Miranda et al. 2011a). The dried slices were ground and sieved until a particle size of 0.59 mm (# 30 mesh) was obtained. Mango pulp was obtained according to the procedure described by Falfán-Cortés et al. (2014). The mango was peeled, pulped, and crushed and then centrifuged at $1027 \times g$ for 10 min at 15 °C (Hettich D-78532 1706-01 centrifuge, Model Rotina 380R, Germany). The precipitate (pulp) was blended with taro flour in different concentrations according to the experimental design (Fig. 1, Table 1). The samples were placed in Ziploc® bags and stored at 4 °C until use. The chemical compositions (% db) of the taro flour and mango pulp were: 6.12 and 4.33 protein, 0.25 and 0.33 lipids, 1.82 and 8.83 fibre, 3.09 and 9.19 ash, 88.72 and 77.32 carbohydrates, as well as a β -carotene content of 68.45 and 108.85 $\mu\text{g/g}$, respectively.

β -carotene content

The β -carotene content was determined in a Spectrophotometer (Cary 60 UV–VIS MY11510011, ©Agilent Technologies, Inc., USA.) according to the procedure described by Ying et al. (2015) in raw materials and extruded products. Four millilitres of dimethylsulfoxide (DMSO) were added to 80 mg of sample in a water bath at 75 °C, and the mixture was stirred at 150 rpm for 50 min. Subsequently, the mixture was cooled to 25 °C, and 4 mL of butyl-hydroxy-toluene (BHT) at 0.1% (w/v) in hexane (C_6H_{14}) was added, and the mixture was vortexed for 10 s and left to stand for 30 min. Two to three drops of pure ethanol were added to precipitate any protein present in the hexane phase. The hexane layer was recovered and placed in a 10 mL beaker; 0.5 g of anhydrous sodium sulfate was added (Na_2SO_4 anhydride); and finally, the absorbance of the recovered hexane was analysed at a wavelength of 450 nm.

Colour and pH

The colour of the extruded products was determined by using a Hunter Laboratory tristimulus colorimeter (UltraScan® VIS, Hunter Laboratory, Model USVIS1347, Hunter Associates Laboratory, Inc., Reston, Virginia, USA). The values L^* , a^* and b^* were obtained and used to

Fig. 1 General schematic diagram of obtaining and evaluating extruded snacks based on taro flour enriched with mango pulp

calculate the total colour difference (ΔE). The pH was measured in a dispersion of 1 g of flour in 10 mL of distilled water at 25 °C.

Extrusion process

Extrusion was conducted in a single-screw laboratory extruder (Extruder 19/25DN, Model 832005.007, Brabender® GmbH & Co. KG, Germany) with a length of 428 mm, diameter of 19 mm, compression ratio of 3:1. A 3 mm circular exit die was used. The extruder had four heating zones (Zone 1 = 40 °C, Zone 2 = 60 °C, Zone 3 = 80 °C and Zone 4 = 80–150 °C). Before extruding, the formulations were blended (Fig. 1), and the moisture content of each was adjusted from 16 to 30 g/100 g according to the experimental design (Table 1).

Variables of the extrusion process

Residence time and torque

The residence time and torque was measured according to procedures described by Rodríguez-Miranda et al. (2012a).

Specific mechanical energy (SME)

The SME (J/g), defined, as the total mechanical energy input required obtaining 1 g of extruded product, was calculated as described by Rodríguez-Miranda et al. (2012a).

Characterization of extruded products

Expansion index (EI) and bulk density (BD)

The EI was calculated in 20 samples with a Vernier caliper (Vernier, Science Purchase, 0604CAL6, USA), dividing the diameter of the extruded products by the internal diameter of the exit orifice of the extruder (Rodríguez-Miranda et al. 2014a). The BD was determined as described by Navarro-Cortez et al. (2016).

Table 1 Experimental data of extruded snack for response surface analysis

Run	Extrusion process variables				Responses										
	MPP (g/100 g) (X ₁)	FMC (g/100 g) (X ₂)	T (°C) (X ₃)	RT (g/ min)	To (Nm/ s)	P (N/ cm ²)	SME (J/ g)	EI (–)	BD (g/ cm ³)	WAI (g/ g)	WSI (%)	H (N)	pH	β-C (μg/ g)	ΔE
1	2 (–1)	19 (–1)	94 (–1)	37.01	27.13	1740	460.67	1.13	1.46	6.35	10.77	3.40	6.27	64.28	32.89
2	8 (1)	19 (–1)	94 (–1)	36.32	32.93	1193	569.79	1.10	1.33	6.34	10.41	94.08	6.25	49.73	33.39
3	2 (–1)	19 (–1)	136 (1)	37.15	18.10	1041	306.10	1.26	0.84	6.10	14.09	16.14	6.25	78.27	33.47
4	8 (1)	19 (–1)	136 (1)	37.74	15.87	600.5	264.16	1.47	0.70	5.83	15.89	8.47	6.20	109.98	34.53
5	2 (–1)	27 (1)	94 (–1)	44.17	23.20	510	330.04	1.01	1.26	5.36	10.58	65.44	6.14	62.59	35.02
6	8 (1)	27 (1)	94 (–1)	43.21	14.33	426.8	208.44	0.92	1.35	5.24	13.23	36.85	6.16	30.27	33.16
7	2 (–1)	27 (1)	136 (1)	43.44	10.77	250.3	155.74	1.47	0.91	5.75	9.56	20.69	6.14	102.05	33.18
8	8 (1)	27 (1)	136 (1)	42.13	11.70	241.5	174.51	1.35	0.96	6.34	12.51	95.73	6.11	138.15	36.19
9	0 (–1.682)	23 (0)	115 (0)	41.12	31.77	808.1	485.45	1.03	1.34	5.51	8.97	67.65	6.23	49.91	33.81
10	10 (1.682)	23 (0)	115 (0)	33.14	25.23	575.9	478.45	1.05	1.30	5.28	11.46	77.16	6.19	142.50	36.89
11	5 (0)	23 (0)	80 (–1.682)	32.80	28.10	1408	538.31	1.12	1.39	6.24	10.09	96.54	6.30	115.59	32.24
12	5 (0)	23 (0)	150 (1.682)	34.03	18.07	255.3	333.55	1.65	0.74	6.84	11.88	1.13	6.27	52.55	32.09
13	5 (0)	16 (–1.682)	115 (0)	33.92	47.80	1435	885.37	1.63	0.69	5.68	24.14	0.80	6.22	6.26	31.09
14	5 (0)	30 (1.682)	115 (0)	41.95	16.83	390.2	252.15	1.01	1.31	5.20	11.72	3.51	5.92	6.78	38.50
15	5 (0)	23 (0)	115 (0)	37.54	23.50	673.2	393.34	1.02	1.39	6.74	11.99	3.20	6.15	38.40	34.00
16	5 (0)	23 (0)	115 (0)	35.12	20.83	617.3	372.66	1.02	1.38	5.57	9.60	3.52	6.19	35.38	36.16
17	5 (0)	23 (0)	115 (0)	35.06	23.67	583.1	424.14	1.03	1.39	6.58	15.98	3.45	6.23	38.42	37.08
18	5 (0)	23 (0)	115 (0)	35.01	21.23	601.5	381.08	1.05	1.37	5.51	14.27	3.40	6.24	39.28	35.21
19	5 (0)	23 (0)	115 (0)	34.94	15.93	591.1	286.53	1.02	1.43	5.60	11.28	3.27	6.11	38.43	37.10
20	5 (0)	23 (0)	115 (0)	34.23	22.97	559.3	421.53	1.02	1.40	5.93	13.47	3.22	6.21	38.61	37.39

MPP mango pulp proportion, FMC feed moisture content, T temperature, RT residence time, To torque, P pressure, SME specific mechanical energy, EI expansion index, BD bulk density, WAI water absorption index, WSI water solubility index, H hardness, β-C β-carotene content, ΔE total color difference

Functional properties

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

These indexes were determined according to the methodology described by Rodríguez-Miranda et al. (2012a).

Hardness

The maximum fracture strength in compression (Rodríguez-Miranda et al. 2014b) of the extrudates was determined on a TA-XT2 texture analyser (Texture Technologies Corp. Scarsdale, NY/Stable Micro Systems, Haslemere, Surrey, UK) using a Warner–Bratzler cutting blade with a test speed of 5 mm/s. The hardness was determined in Newton (N). Fifteen repetitions were performed per treatment.

Experimental design and data analysis

Central experiments were designed (Table 1) with three independent variables by using a commercial statistical package (Design-Expert 7.0.0 Statease Inc., Minneapolis, MN, USA). The independent variables were as follows: mango pulp proportion (MPP = 0–10 g/100 g), feed moisture content (FMC = 16–30 g/100 g) and extrusion temperature (zone 4 of extruder) (T = 80–150 °C). The limits established for the independent variable MPP were defined by preliminary tests. The levels higher than 10 g/100 g of MPP can hinder the expansion of the product during extrusion, resulting in a more compact and hard product, unwanted for the consumer. The feed volume (20 g/min) and screw speed (100 rpm) were kept constant. The experimental data were evaluated using the response surface methodology (RSM) to investigate the effect of the extrusion process (FMC and T) and the MPP on the response variables. The statistical significance of the terms of regression was examined by analysis of variance (ANOVA) for each response.

Process optimization

The objective in the optimization process was to find the process conditions and proportion of mango pulp with the maximum content of β -carotene, greater expansion as well as lower energy expenditure in development of a snack enriched in β -carotene based on taro flour. Numerical optimization was carried out by superposition of the different response surfaces based on the maxima and minima observed, i.e., maximum EI, minimum BD, minimum hardness, maximum β -carotene content, minimum SME and residence time, torque, pressure, WAI, WSI, pH and

ΔE within range, established in the Design Expert 7.0 program (State-Ease Inc., Minneapolis, MN, USA) as optimal values. To predict the dependent variables at the optimum value, the complete models were considered in desirability function.

Results and discussion

Effect of mango pulp proportion (MPP), feed moisture content (FMC) and extrusion temperature (T) on extrudates

Regression coefficients

Table 2 shows the regression coefficients for all the responses analysed. The MPP (X_1) has significant linear effect ($p < 0.05$) on pressure, hardness and β -carotene content and a quadratic effect (X_1^2) on hardness and β -carotene content. On the other hand, the FMC (X_2) exhibits a significant linear effect ($p < 0.05$) on residence time, torque, pressure, hardness, SME, EI, BD, WSI, pH and ΔE and quadratic effect (X_2^2) on residence time, pressure, EI, BD, WSI and pH, while T (X_3) has a significant linear effect ($p < 0.05$) on torque, pressure, EI, BD and hardness and a quadratic effect (X_3^2) on pressure, hardness, EI, BD, pH, ΔE and β -carotene content. The X_1X_2 and X_2X_3 interactions have significant effects ($p < 0.05$) on pressure and hardness, and the X_1X_3 interaction has a significant effect ($p < 0.05$) on β -carotene content. The quadratic regression model adjusted to the experimental data show that the model is accurate for the evaluated responses ($p < 0.05$), with the exception of the WAI ($p > 0.05$). The models had an $R^2 > 0.653$.

Process variables

The residence time values varied from 32.80 to 44.17 g/min (Table 1). Figure 2a shows that the residence time was significantly influenced ($p < 0.05$) by the FMC. It is observed that the increase in FMC causes an increase in the residence time; high residence time values were observed when the FMC values ranged from 27 to 30 g/100 g, while at low FMC values (16–23 g/100 g), the residence time value decreased. This phenomenon occurs because the FMC causes a decrease in the viscosity of the mixture, having an effect similar to that of high lipid levels in the system (Rodríguez-Miranda et al. 2012a).

The torque value varies from 10.77 to 47.80 Nm (Table 1). Figure 2b shows that at low FMC (16–23 g/100 g) and low T (80–115 °C) values, the torque value increases, and increasing the FMC (18–27 g/100 g) and T (94–135 °C) value reduces the torque value. The decrease

Table 2 Coefficients estimated by multiple linear regression of the physicochemical characterization of extruded snacks using taro flour and mango pulp blends

Coefficients	Response											
	RT	To	P	SME	EI	BD	WAI	WSI	H	pH	β-C	ΔE
Intercepto	35.190*	21.650*	605.961*	386.142*	1.060*	1.396*	5.983*	12.794*	3.423	6.186*	37.414*	36.160*
Linear												
X ₁	− 1.157	− 1.124	− 108.184*	− 3.472	0.000	− 0.014	− 0.014	0.822	10.503*	− 0.011	12.936*	0.578
X ₂	2.798*	− 6.305*	− 352.163*	− 131.576*	− 0.093*	0.087*	− 0.200	− 1.917*	8.087*	− 0.068*	2.320*	1.152*
X ₃	0.134	− 4.250*	− 269.828*	− 74.162	0.165*	− 0.226*	0.128	0.737	− 14.097*	− 0.012	8.461	0.194
Quadratic												
X ₁ ²	1.470	0.603	16.680	− 4.827	− 0.017	− 0.027	− 0.183	− 1.097	24.363*	0.008	23.914	− 0.287
X ₂ ²	1.755*	1.952	88.367*	25.865	0.083*	− 0.142*	− 0.164	1.629*	− 2.417	− 0.040*	− 7.794	0.481
X ₃ ²	0.158	− 1.312	66.954*	− 21.097	0.107*	− 0.120*	0.224	− 0.825	14.166*	0.034*	19.622*	− 1.411*
Interactions												
X ₁ X ₂	− 0.271	− 1.438	111.938*	− 21.252	− 0.048	0.050	0.093	0.521	− 11.117*	0.008	− 1.672	− 0.051
X ₁ X ₃	0.116	0.221	22.612	− 1.337	0.025	− 0.006	0.057	0.309	0.001	− 0.010	14.336*	0.679
X ₂ X ₃	− 0.423	1.379	105.813*	31.497	0.049	0.064	0.283	− 1.318	8.315*	0.001	9.139	− 0.068
R ²	0.730	0.674	0.964	0.660	0.855	0.929	0.653	0.722	0.684	0.869	0.656	0.711
P of F (model)	0.0506	0.0024	< 0.0001	0.0017	0.0350	0.001	0.1324	0.0571	0.0699	0.0022	0.1163	0.0671
Lack of Fit	0.0116	0.0289	0.0057	0.0222	0.1106	0.004	0.9590	0.3852	< 0.0001	0.8444	< 0.0001	0.2953

*Bold numbers indicate estimates of significant parameters ($p < 0.05$) X_1 mango pulp proportion, X_2 feed moisture content, X_3 temperature, RT residence time, To torque, P pressure, SME specific mechanical energy, EI expansion index, BD bulk density, WAI water absorption index, WSI water solubility index, H hardness, β -C β -carotene content, ΔE total color difference

Fig. 2 Response surface plots of process variables **a** residence time, **b** torque, **c** pressure, and **d** specific mechanical energy (SME)

in the T_o values with the increase in the FMC value could be due to the unavailability of water for gelatinization of the starch, which results in a decrease in the apparent viscosity; the decrease in the torque value can be attributed to the reduction of friction in the extruder as a result of the increase in the FMC value, which minimizes the difficulty of processing the mixtures. In general, the torque value tends to decrease with increasing T values due to a decrease in viscosity (Kannadhasan et al. 2009).

The pressure value obtained was 241.5–1740 N/cm² (Table 1). Figure 2c shows that the pressure value increases with decreasing MPP and FMC values. The increase in the T value during the process causes a decrease in the pressure value, and this effect can be attributed to the decrease in the viscosity of the molten mixture caused by the increase in the T value. The highest-pressure values

were at $MPP = 0$ –7.6 g/100 g, $FMC = 16$ –23 g/100 g and at $T = 80$ –135 °C. The increase in the T value with increasing FMC values affects the viscosity of the mass throughout the extruder, which leads to a decrease in the die pressure. Kaur et al. (2000) have reported that increasing temperatures decrease the viscosity of the materials. The interaction of FMC- T increases the pressure, because with the increase of the FMC it causes an excessive viscosity of the molten material that leads to a low torque of the motor, while the increase of the T increases the pressure of the saturated vapors exceeds the melting pressure towards the exit of the extruder. In the other hand, in the interaction of MPP-FMC, the increase in MPP increases the concentration of sugars in the blend, Fan et al. (1996) reported that sugars reduced the expansion of the section of corn extrudates, monosaccharide's have a more

pronounced effect than disaccharides. This result in a softer matrix that collapses under the high vapor pressure during expansion, reducing the final degree of expansion, accordingly there is a higher pressure exerted during the extrusion process.

SME values ranged between 155.74 and 885.37 J/g (Table 1). SME during extrusion plays a direct role in the macromolecular transformations and in the interactions among the different components in the materials. The macromolecular transformations can be the conversion of starch or changes in the structure of the protein that, consequently, determine the rheological properties of the materials (Aguilar-Palazuelos et al. 2012). Figure 2d shows that when the FMC value decreases the SME value increases; this effect was observed at MPP values of 0–7.6 g/100 g and FMC values of 16–23 g/100 g, while at MPP values of 2–7.6 g/100 g and FMC values of 18–30 g/100 g, the lowest values of the SME were observed. The viscosity of the food increases when the FMC value decreases, and therefore, the SME value increases (Rodríguez-Miranda et al. 2012a). It was also observed that upon increasing the T value, the SME value decreases. High temperatures are associated with a decrease in the viscosity of the melt within the extruder, which in turn reduces the input of energy to the extruder. Upon increasing the FMC value, the viscosity decreases, which eventually leads to an SME minimum (Rodríguez-Miranda et al. 2012a).

Extrudate properties

Expansion index (EI) and bulk density (BD)

EI of the extruded products ranged from 0.92 to 1.65 (Table 1). Increasing the FMC value decreased the EI value, and increasing the T value favoured the expansion of the snacks. This phenomenon can be attributed to the fact that expansion occurs at high temperatures and low moisture content, causing transitions, phase transformations and structural changes in the biopolymers, leading to the formation of air bubbles inside the starch and retaining the air bubbles after the exit of the material (Moraru and Kokini 2003). Korkerd et al. (2016), mention that beyond the critical temperature of extrusion there is a decrease in the EI, which depends on the type of starch and moisture content, which could be the result of increased dextrinization, excessive softening and possible structural degradation of starch, in which with stands the high vapour pressure and collapse. Figure 3a shows that at MPP values of 2–8 g/100 g and T values of 115–150 °C, an increase in the EI value was obtained. This increase in the EI value with an increase in the T value and decrease in the FMC value has also been reported by other authors (Falfán-Cortés et al. 2014; Ruiz-Armenta et al. 2018). The increase

in FMC can reduce the elasticity of the mass by plasticizing the melt and, therefore, reduces gelatinization, decreases expansion and increases density (Korkerd et al. 2016). Paraman et al. (2013), mention that moisture content of feed higher than 28% significantly decreases the expansion and increased the hardness of the crispy proteins, as well as the density of the product increases, this drunk to an inadequate denaturation of the proteins.

BD is considered as an index of the extent of puffing and ranged from 0.69–1.46 (g/cm³) (Table 1). Figure 3b shows that at high FMC values and low T values, BD increased. However, when the FMC and T value were 16–27 g/100 g and 115–150 °C respectively, the BD value decreased. This decrease was a consequence of the expansion of the extrudes. Some authors have reported that the expansion of extruded products depends on the degree of starch gelatinization, the amount of starch and the processing conditions (Rodríguez-Miranda et al. 2014b). At comparatively higher temperatures melt viscosity get reduced hence bubble walls become too thin to contain the vapour pressure, resulting in more bubble fracture, thus increasing rate of collapse and overall expansion decreased, increasing the BD (Borah et al. 2016). The BD value of the snacks is an indirect measure of the EI, since the BD value has a negative correlation with the expansion (Navarro-Cortez et al. 2016).

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

WAI values ranged between 5.20 and 6.84 g/g (Table 1). WAI is associated with the amount of water absorbed by the starch granules after swelling and can be used as an index of the degree of gelatinization of the starch. (Rodríguez-Miranda et al. 2011b). Moreover, the WAI is associated with the hydrophilic balance of the proteins present in the mixture, which changes based on the degree of denaturation of the proteins, whereby the extrusion process modifies the solubility index of the proteins (Rodríguez-Miranda et al. 2012a). The variables (MPP, T and FMC) did not show significant effect ($p > 0.05$) on WAI.

WSI oscillated between 8.97 and 24.14% (Table 1). Figure 3c shows that at low FMC values (18–27 g/100 g) and high T values (94–150 °C), the WSI increased, which may be because, under these processing conditions, a greater amount of gelatinized material causes greater solubilization. Solubility is used in the extrusion process as an indicator of the degradation of molecular components such as starch, fibres and proteins (Seth and Rajamanickam 2012). WSI indicates the total degradation of starch granules. The increase in solubility of the extruded products is attributed to the dispersion of amylose and amylopectin

Fig. 3 Response surface plots of process variables **a** expansion index (EI), **b** bulk density (BD), **c** water solubility index (WSI), **d** hardness, **e** pH, **f** β -carotene content and **g** total color difference

molecules followed by gelatinization when the processing conditions are mild and to the formation of low-molecular-weight components under harsh conditions (Colonna et al. 1984). The relatively low FMC and T resulted in low mass shear with the consequent lower macromolecular degradation. The higher the dextrinization, attributed to higher and degradation of the starch to small more soluble particles, which increases the WSI (Carvalho et al. 2013).

Hardness

The hardness of the extruded products ranged from 0.80 to 96.54 N (Table 1). Notably, the lowest value of hardness was obtained at MPP = 5 g/100 g, FMC = 23 g/100 g and T = 150 °C. Figure 3d shows that the increase in the FMC and MPP values directly affected the increase in the hardness values of the extruded products; the same behaviour was reported by Liu et al. (2013). Low hardness values of the extrudates were obtained at low MPP (5–7.97 g/100 g) and FMC (16–23 g/100 g) values. Ruiz-Armenta et al. (2018) reported that at higher extrusion temperatures, greater expansion is obtained, and the hardness of the extrudates is reduced. Moraru and Kokini (2003) reported that with high values of EI and low values of texture, extruded products are generated at high temperatures, leading to several events, such as the structural transformation of biopolymers; phase transition and nucleation; and swelling, growth and collapse of air bubbles. The negative effect of the MPP-FMC interaction is due to the fact that the increase in MPP decreases the starch content present in the mixture and by increasing the FMC that provides the motive power for the expansion is affected, therefore the expansion decreases and porosity probably due to excessive softening by excess water thereby decreasing the hardness of the final product (Moraru and Kokini 2003). While the interaction FMC-T increased the hardness of the final product, because the increase of the FMC and increase of T allow the raw material to undergo a glass transition during the extrusion process and thus facilitates the deformation of the matrix and its expansion, however there is a temperature range where the expansion reaches a maximum, and this optimum temperature depends on the type of starch, and if not reaching that temperature, the excess water increases the final product stiffness and hardness (Moraru and Kokini 2003).

pH

The pH values of the extrudates ranged between 5.92 and 6.30 (Table 1). Figure 3e shows that increasing FMC and T values decreased the pH values of the extruded products, which may be because the increase in the FMC and T values during the extrusion process helps release some organic acids (e.g., fatty acids) present, leading to low pH values (more acidic) of the samples (Navarro-Cortez et al. 2016). Bowen et al. (2006) reported that the presence of free fatty acids may cause changes in the pH of the system and result in hydrolysis of the starch. Sriburi and Hill (2000) reported an increase in pH in extruded products, with initial values between 1 to 6.5 increasing to 2.15 and 6.63, respectively.

β -carotene content

The β -carotene content ranged from 6.26 to 142.50 μ g/g (Table 1), and the highest β -carotene content was found at MPP 10 g/100 g, FMC 23 g/100 g and T 115 °C (Table 1). Figure 3f shows that increasing MPP and T values helped in the retention and final preservation of the β -carotene content in the product. The highest β -carotene content in the products was obtained at high MPP values and high extrusion T values, because the mango pulp is high β -carotene content (108.85 μ g/g). On the other hand, the T value did not have a significant effect ($p > 0.05$) on this variable, and the conservation of this component can possibly be attributed to the presence of a protein-carbohydrate matrix that protects this bioactive component during the extrusion process (Basto et al. 2016). An additional aspect to consider is that extrusion is a short-time cooking process, so it is possible that there was not enough time to cause effective damage to low molecular weight compounds; however, the heating and shearing could have ruptured the cell wall, which may have helped to release more carotenoids, such as β -carotene (Rojas-Garbanzo et al. 2011), therefore the interaction of MPP-T helps the release of the β -carotene contained in the blend. The results are consistent with those reported by other authors (Basto et al. 2016; Falfán-Cortés et al. 2014).

Total colour difference (ΔE)

There are many reactions that occur during extrusion cooking that affect colour (Falfán-Cortés et al. 2014). The ΔE value of the products varied from 31.09 to 38.50 (Table 2), with the highest ΔE value observed at MPP 5 g/100 g, FMC 30 g/100 g and T 115 °C (Table 2). Figure 3g shows that increasing FMC values increased the ΔE value, while at high T values, the ΔE value decreased. The increase in the T value during the extrusion process leads to

Table 3 Optimum values of extrusion process parameters and responses for extruded snack

Process parameters	Importance	Target	Experimental value		Optimum value	Desirability
			Min	Max		
MPP (g/100 g)	3	Range	0	10	7.9	0.772
FMC (g/100 g)	3	Range	16	30	18.84	
T (°C)	3	Range	80	150	135.81	
Responses					Predicted values	
Residence time (g/min)	3	Range	32.80	44.17	35.56	
Torque (Nm)	3	Range	10.77	47.80	23.40	
Pressure (N/cm ²)	3	Range	241.5	1740	567.8	
SME (J/g)	4	Minimize	155.74	885.37	428.54	
EI	5	Maximize	0.92	1.65	1.52	
BD (g/cm ³)	5	Minimize	0.69	1.46	0.66	
WAI (g/g)	3	Range	5.20	6.84	5.85	
WSI (%)	3	Range	8.97	24.14	17.08	
Hardness (N)	5	Minimize	0.80	96.54	24.48	
pH	3	Range	5.92	6.30	6.21	
β-carotene content (μg/g)	5	Maximize	6.26	142.50	99.10	
ΔE	3	Range	31.09	38.50	34.39	

MPP mango pulp proportion, FMC feed moisture content, T temperature, SME specific mechanical energy, EI expansion index, BD bulk density, WAI water absorption index, WSI water solubility index, ΔE total color difference

products with less luminosity and tends to darken the products. It is known that the reduction of sugars and proteins (amino acids) in food can occur at high processing temperatures and can promote non-enzymatic browning (Maillard reaction), which results in the darkening of the final product (Navarro-Cortez et al. 2016).

Optimization

Numerical optimization by superposition of the different response surfaces was used to determine the optimal level of the three independent variables based on the concept of convenience and desirability. In Table 3, we can observe the importance assigned to each of the response variables as well as the intervals determined. At these conditions predicted values were: T = 135.81 °C, FMC = 18.84 g/100 g and MPP = 7.97 g/100 g with a desirability value of 0.772, to obtain a product with the following characteristics: EI = 1.52, BD = 0.66 g/cm³, hardness = 24.48 N, β-carotene content = 99.1 μg/g and SME = 428.54 J/g.

Conclusion

Taro flour enriched with mango pulp could be used to produce snacks. Increasing the moisture content in the feed decreased the torque, pressure, specific mechanical energy, expansion index, water solubility index and pH and

increased the residence time, apparent density, hardness and total colour difference. Increasing the temperature led to a decrease in torque, pressure, bulk density and hardness, while an increase in the proportion of mango pulp caused a significant increase in the hardness and β-carotene content and a decrease in pressure. Therefore, mango pulp is an available and economical source of β-carotene for the enrichment of extruded expanded taro snacks.

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