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Use of response surface methodology to compare vacuum and atmospheric deep-fat frying of papaya chips impregnated with blackberry juice

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ABSTRACT
Vacuum and atmospheric deep-frying were employed to obtain blackberry-based snacks using unripe papaya as matrix. Papaya slices were osmotically impregnated with blackberry juice and fried between 126°C and 154°C at atmospheric pressure and between 110°C and 127°C under vacuum conditions. A response surface methodology (RSM) was used to define which responses (water activity, moisture and oil content, L*, C*, H*, hardness and degree of liking (DOL)) were significantly related to frying parameters (time and temperature). Then a principal component analysis (PCA) was applied to choose which ones related to DOL. PCA demonstrated that hardness and hue were the main drivers of liking for atmospheric frying, while for vacuum frying they were color and oil content. A second RSM was calculated to choose optimal processing conditions. Optimum conditions were 6 min at 117°C in vacuum frying and 6 min at 130°C and 3 min at 150°C in atmospheric pressure.

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vacuum frying; atmospheric frying; response surface methodology; degree of liking

PALABRAS CLAVES
Fritura al vacío; fritura atmosférica; superficie de respuesta; agrado

Utilización de la metodología de superficie de respuesta para comparar la fritura por inmersión a presión atmosférica y al vacío de hojuelas de papaya impregnadas con jugo de mora

RESUMEN
Se obtuvo una hojuela de papaya verde, como matriz, aplicando una fritura por inmersión al vacío y otra a presión atmosférica. La papaya verde rebanada se impregnó osmóticamente con jugo de mora y se frió entre 126-154 °C a presión atmosférica y entre 110-127 °C a condiciones de vacío (24 kPa). Una metodología de superficie de respuesta se usó para definir cuál de las variables respuesta del producto (actividad de agua (Aw), contenido de humedad, contenido de aceite, color L*, C*, H*, dureza and agrado) se relacionaban significativamente con las variables estudiadas de fritura (tiempo y temperatura). Posteriormente un análisis de componentes principales se aplicó a los parámetros significativos para escoger los que se relacionaban con el agrado. La dureza y la tonalidad se relacionaron con agrado de la hojuela frita a presión atmosférica y el color y contenido de aceite para la fritura al vacío. Tomando en cuenta agrado, color, dureza y contenidos de humedad y grasa, una segunda superficie de respuesta se aplicó para escoger las condiciones óptimas de cada proceso, que fueron freír por 6 min a 117 °C al vacío y freír por 6 min a 130 °C y freír 3 min a 150 °C en fritura atmosférica.

1. Introduction

The global market for healthy snacks is steadily growing, enhanced by the increasing demand of consumers for convenience products with high nutritive and sensory qualities (Research and Markets, 2015). In industrial terms, meeting this demand requires the development of operations that minimize the adverse effects of processing. The methods used to process fruits should preserve their natural flavors and aromas, result in a good texture and, preferably, not involve preservatives. Alternative methods for fruit processing are currently required to meet these needs.

The production of fried fruit chips has been studied using vacuum-based processes with lower temperatures than those used in conventional frying (Fan, Zhang, Xiao, Sun, & Tao, 2005; Pérez-Tinoco, Pérez, Salgado-Cervantes, Reynes, & Vaillant, 2008; Da Silva & Moreira, 2008; Nunes & Moreira, 2009; Dueik, Robert, & Bouchon, 2010; Dueik & Bouchon, 2011; Diamante, Savage, & Vanhanen, 2012a., Xu & Kerr, 2012). Some researchers have investigated the effects of vacuum frying on the quality of fruit and vegetable snacks, such as potato chips (Garayo & Moreira, 2002; Granda, Moreira, & Tichy, 2004; Mir-Bel, Oria, & Salvador, 2009; Pandey & Moreira, 2012; Troncoso, Pedreschi, & Zúñiga, 2009; Yagua & Moreira, 2011), carrots (Dueik et al., 2010; Fan et al., 2005; Shyu, Hau, & Hwang, 2005), apple slices (Mariscal & Bouchon, 2008; Shyu & Hwang, 2001), sweet potatoes, green beans, blue potatoes (Da Silva & Moreira, 2008), mango chips (Da Silva & Moreira, 2008; Nunes & Moreira, 2009), kiwifruits (Diamante, Durand, Savage, & Vanhanen, 2010; Diamante, Presswood, Savage, & Vanhanen, 2011; Diamante et al., 2012a), apricot slices (Diamante, Savage, Vanhanen, & Ihns, 2012b), banana chips (Sothornvit, 2011; Yamsaengsung, Ariyapuchai, & Prasertsit, 2011); purple yams (Fang, Wu, Yü Ye, Liu, & Chen, 2011) and

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pineapple chips (Pérez-Tinoco et al., 2008). These novel snacks had significantly higher sensory and nutritional qualities compared with those of the atmospheric deep-fried products. Different studies have found that, compared with atmospheric frying, vacuum frying reduced the final fat content of carrot, potato and apple snacks (Dueik & Bouchon, 2011; Fan et al., 2005), as well as that of sweet potato chips and green beans (Da Silva & Moreira, 2008), and diminished the extent of acrylamide formation in potato chips by 94% (Granda et al., 2004). Moreover, the combination of an edible coating and an increased centrifugation speed after banana chips vacuum frying, maintained the good quality and low fat content of the final product (Sothornvit, 2011).

Green papaya fruit was chosen for this study because it has a neutral matrix (Mahattanatawee et al., 2006) that would favor impregnation with fruit juices. Blackberry fruits are an important source of anthocyanins and other polyphenolic compounds, such as ellagitannins, which have significant antioxidant activities (Acosta-Montoya et al., 2010; Fan-Chiang & Wrolstad, 2005). The bioactive compounds of Rubus fruits have been studied for their health benefits, such as their lipid-peroxidation protective capacity (Azofeifa, Quesada, & Pérez, 2011), antiproliferative and anticancer activities, and antihypertensive and anti-inflammatory effects (Cuevas-Rodríguez et al., 2010; Seeram, Adams, Zhang, Sand, & Heber, 2006), as well as their ability to improve motor and cognitive performance (Shukitt-Hale, Cheng, & Joseph, 2009). Due to these properties some authors have suggested that regular consumption of blackberries may protect against injuries caused by free radicals in the body (Reyes-Carmona, Yousef, Martinez-Peniche, & Lila, 2005; Wang & Lin, 2000).

In this investigation, a vacuum-frying process for the production of a healthy blackberry-flavored snack with high acceptability was studied. The effects of atmospheric and vacuum frying osmotically treated papaya slices were compared by physicochemical characteristics and degree of liking (DOL) of the chips.

2. Materials and methods

2.1 Raw material

Papaya fruit (*Carica papaya*, Costa Rican native variety 'criolla') was green-harvested in a commercial plantation located in the humid tropical province of Limón (300 meters above sea level), Costa Rica, Central America. The fruit was impregnated with blackberry juice. Palm olein oil (D'orofrit 5™, Grupo Numar, Costa Rica) was used to fry the fruit slices.

2.2 Process for the production of blackberry chips

Green papayas were washed, peeled and cut into 1.5 mm slices and, then, were blanched in boiling water containing $CaCl_2$ (1%, 5 min). The slices were impregnated with an osmotically active solution prepared using blackberry juice and sucrose with a final value of 50°Brix and a fruit:solution ratio of 1:6 (w/w). Final total soluble solids content of papaya slices was 40–42°Brix. Osmotic dehydration was conducted at 55°C for 60 min with constant magnetic agitation (40 rpm). After rinsing and draining the product (144–148 g) for 10 min, it was deep-fried using either a vacuum or an atmospheric process. A semi-continuous vacuum fryer manufactured in situ and described previously (Pérez-Tinoco et al., 2008) was used to apply a constant vacuum pressure of 24 ± 2 kPa. The frying time was controlled (±0.02 min), as was the temperature (±0.4°C). Atmospheric frying was performed using a 15-L stainless-steel batch fryer that was thermostatically controlled. The fryer basket was connected to a rotary system that was used to stir the oil (40 rpm). The fruit slices were placed into the frying oil using a 1:40 ratio of slices:oil. The samples were removed from the fryer and blotted using paper towels. They were packed in sealed glass jars containing nitrogen gas to prevent exposure to oxygen, and they were stored for a maximum of 2 days in the dark at room temperature before analysis. The response variables chosen to evaluate both frying processes were as follows: water activity (Aw), moisture content, oil content, color (L*, C*, H*), hardness and sensory DOL. The independent variables that were analyzed were the frying time (*t*) and the temperature (*T*), within the ranges determined by the experimental design.

2.3 Product quality attributes

Chemical analyses

The moisture content, oil content and total soluble solids of the products were measured using ground chips, following standard methods (AOAC, 1990).

Physical analyses

The water activity (Aw) was measured using an Aqua Lab CX-2 water activity meter (Decagon Devices Inc., Pullman, USA). The color was measured using a Hunter Lab D25 L-DP9000 colorimeter (2° standard observer angle and illuminant C; Novasys Group Pty Ltd., Ferntree Gully, Australia), using a white tile as the background. The fruit chips were ground to homogeneity using a laboratory mill and were placed in a Petri dish. The color measurement was repeated three times, and the results were expressed as tristimulus parameter (L*, a* and b*), hue angle ($H^* = \tan^{-1}(b^*/a^*)$) and chroma ($C^* = (a^{*2} + b^{*2})^{1/2}$) values.

Texture analysis

Hardness was assessed using a TA.XT Plus texture analyzer (Stable Micro Systems, Ltd, Godalming, UK). A flat-ended cylindrical probe (6.3 mm diameter) and a support with a flat base were mounted in the analyzer. A compression test was performed, and the peak force (N) at maximum compression, at a crosshead speed of 1 mm/s on the chip samples, was recorded. The measurements were repeated five times per sample lot of papaya chips, and the mean values were obtained.

Sensory analyses

The sensory evaluation of the papaya chips was performed using an 86-member consumer panel. A general DOL linear scale with scores ranging from 0 to 15 was applied, in which 0 was the most disliked attribute and 15 was the most liked attribute.

2.4 Experimental design and statistical analyses

Response surface methodology (RSM) was used to optimize the two frying processes. A central composite rotatable design (CCRD) with two variables, temperature (*T*) and time

(t), corresponding to the frying temperature and frying time, respectively, was utilized to assess the response patterns of the quality attributes. The average value of each quality attribute was taken as response Y, and the experimental data were subjected to multiple nonlinear regression analysis using JMP[TM] 5.1 statistical software (SAS Institute, Inc. NC, USA) and were fit using the following second-order polynomial equation:

$$Y = a_o + a_T T + a_t t + a_{TT} T^2 + a_{tt} t^2 + a_{Tt} Tt \qquad (1)$$

where a_o, a_T, a_t, a_{TT}, a_{tt} and a_{Tt} are the regression coefficients for intercept, linear, quadratic and interaction terms of the model and T and t are the independent variables, temperature and time.

The quality parameters chosen from the fit of the polynomial model equation were calculated using the same software. These parameters were the coefficient of determination (R^2) between the actual and the predicted response, the probability (P) that tested the absence of at least one significant regression factor in the model, and the probability (P-lof) that tested whether the lack of fit of the model was zero (F-test). The significance (p) of the regression coefficients of the model was evaluated using an analysis of variance.

Consumer clusters were identified using Ward's hierarchical clustering technique with Euclidian distances (Lee & Lee, 2008) using the statistics program SAS for Windows v 9.1 (SAS Institute, Cary, NC, USA). Cluster analysis provides consumers segments with homogeneous DOL within each clusters and different DOL between clusters.

Two RSM analyses were applied. The first one was carried out using multiple responses of nine quality attributes in order to determine the significant parameters for atmospheric and vacuum processes. Then, a principal component analysis (PCA) with those significant RSM quality parameters was applied to find which responses correlated with DOL, with the purpose of analyzing a second RSM using multiple responses of only those quality attributes that were related to consumer acceptance.

The PCA results were graphically represented, with each axis of the x and y coordinates corresponding to principal components 1 and 2 (PC 1 and PC 2). The vectors were the variables and the points corresponded to the samples. The alignment of vectors to each axis and their length explained the correlation with each component. The statistics program SAS for Windows v 9.1 (SAS Institute, Cary, NC, USA) was used.

Surface plots were made only for the second RSM to find optimal frying regions for both processes. The regions corresponding to the optimal DOL response were identified directly by visual examination of the contour plots of responses generated using Sigma Plot 10.0 graphing software (SYSTAT Software Inc., San Jose, CA, USA).

3. Results and discussion

The papaya chips impregnated with blackberry juice through osmotic dehydration were fried at atmospheric pressure and in vacuum, with different oil temperatures and time conditions that were set according to CCRD. For both frying processes, limits were selected for oil temperatures and frying times that would not burn the chips, thus providing an acceptable product for consumption.

Tables 1 and 2 present the central composite design for independent variables (frying temperature, °C, and frying time, min) and their responses (Aw, moisture, residual oil content, color (L*, C*, H*) and hardness) as well as sensory DOL. Aw was between 0.28 and 0.54 and humidity between 2.4% and 10.6% for atmospheric fried chips (Table 1) and Aw between 0.23 and 0.42, and humidity between 2% and 4.8% for vacuum fried chips (Table 2). Oil content was under 10% at atmospheric pressure but was higher in vacuum frying. Lightness changed slightly while hue and chroma were affected significantly by frying temperatures and times for both treatments, atmospheric and vacuum frying. High temperatures for longer times produced a yellowish color. Hardness varied between 0.7 and 17.5 N and between 4.4 and 9.2 N during atmospheric and vacuum frying, respectively. For sensory quality, consumers were grouped into clusters with similar DOL ratings by hierarchical cluster analysis, resulting in two consumer groups for atmospheric frying and for vacuum frying. For both frying processes,

Table 1. Central composite design for independent variables (temperature and time) and their responses for atmospheric-frying of papaya chips impregnated with blackberry juice.

Tabla 1. Diseño compuesto central para las variables independientes (temperatura y tiempo) y sus respuestas para la fritura atmosférica de chips de papaya impregnados con jugo de mora.

Frying temperature[a] (°C)	Frying time[a] (min)	Aw	Moisture content (g/kg)	Oil content[b] (g/kg)	Color L*	Color C*	Color H*	Hardness (N)	Cluster 1[c] (n = 45)	Cluster 2[c] (n = 44)
125.9 (−√2)	4.5 (0)	0.45	88	46.6	30.4	35.4	18.5	0.9	10.28	5.36
130.0 (−1)	3.0 (−1)	0.54	106	43.9	30.1	28.9	18.1	0.7	9.37	5.30
130.0 (−1)	6.0 (+1)	0.37	47	71.8	41.3	30.5	18.7	3.2	10.23	5.06
140.0 (0)	2.4 (−√2)	0.35	61	55.4	35.0	32.3	17.1	4.4	9.62	4.21
140.0 (0)	4.5 (0)	0.31	31	52.3	39.7	31.5	19.2	17.2	9.30	6.72
140.0 (0)	4.5 (0)	0.30	41	60.7	39.9	31.0	19.4	17.5	9.38	6.80
140.0 (0)	4.5 (0)	0.30	4	62.4	41.6	31.0	20.0	13.5	9.66	6.59
140.0 (0)	4.5 (0)	0.31	41	58.1	41.0	27.9	21.3	16.3	9.70	6.85
140.0 (0)	6.6 (+√2)	0.32	36	67.3	43.8	26.1	43.3	10.0	10.59	8.03
150.0 (+1)	3.0 (−1)	0.30	29	58.0	40.4	26.3	21.7	4.8	10.72	9.88
150.0 (+1)	6.0 (+1)	0.31	30	85.0	39.7	26.5	56.3	4.3	10.34	8.00
154.1 (+√2)	4.5 (0)	0.28	24	93.2	39.2	25.7	55.7	3.9	10.48	7.90

[a]Coded value of each factor is given in parentheses.
[b]Dry matter.
[c]Mean DOL of consumer segments (clusters).

[a]Valor codificado de cada factor está entre paréntesis
[b]d.m.: materia seca
[c]Promedio DOL (grado de aceptación) de los segmentos de consumidor (conglomerados)

Table 2. Central composite design for independent variables (temperature and time) and their responses for vacuum-frying of papaya chips impregnated with blackberry juice.

Tabla 2. Diseño compuesto central para las variables independientes (temperatura y tiempo) y sus respuestas para la fritura al vacío de chips de papaya impregnados con jugo de mora.

Frying temperature[a] (°C)	Frying time[a] (min)	Aw	Moisture content (g/kg)	Oil content[b] (g/kg)	Color L*	Color C*	Color H*	Hardness (N)	Cluster 1[c] (n = 54)	Cluster 2[c] (n = 32)
110.5 (−√2)	6.0 (0)	0.35	48	155.8	36.5	39.0	17.3	4.4	10.14	5.64
113.0 (−1)	5.0 (1)	0.42	45	153.1	35.8	31.7	18.0	4.4	9.40	5.91
113.0 (−1)	7.0 (+1)	0.36	47	154.3	42.9	30.6	23.4	8.2	10.30	7.48
119.0 (0)	4.6 (−√2)	0.34	27	130.6	33.8	26.9	27.4	6.4	10.11	8.11
119.0 (0)	6.0 (0)	0.28	23	114.1	38.6	28.9	26.5	5.8	10.78	8.10
119.0 (0)	6.0 (0)	0.30	27	112.8	37.1	26.7	28.9	5.9	11.73	7.23
119.0 (0)	6.0 (0)	0.29	29	92.3	38.5	27.6	32.6	5.0	10.46	7.14
119.0 (0)	6.0 (0)	0.31	29	100.3	38.1	28.3	24.7	7.6	10.53	7.38
119.0 (0)	7.4(+√2)	0.26	27	135.3	42.3	25.6	52.7	6.6	7.23	3.66
125.0 (+1)	5.0 (−1)	0.23	22	104.3	39.9	28.4	39.2	5.4	9,18	6.06
125.0 (+1)	7.0 (+1)	0.24	21	138.3	38.2	28.4	58.1	9.2	4.97	3.30
127.0 (+√2)	6.0 (0)	0.27	20	116.7	33.9	23.5	50.9	5.6	6.48	4.22

[a]Coded value of each factor is given in parentheses.
[b]Dry matter.
[c]Mean DOL of consumer segments (clusters).

[a]Valor codificado de cada factor está entre paréntesis
[b]d.m.: materia seca
[c]Promedio DOL (grado de aceptación) de los segmentos de consumidor (conglomerados)

consumers in cluster 1 rated acceptability higher than consumers in cluster 2.

Independent and dependent variables (Tables 1 and 2) were analyzed to get the regression equation, to predict the responses under a specific range, and the analysis of variance of independent variables, to find the significant coefficients of the model (linear, quadratic and interactions) and lack of fit (Tables 3 and 4).

RSM for atmospheric frying (Table 3) showed that Aw, moisture and oil content, L*and H* color parameters, hardness and cluster 1 (45 consumers) had statistical significance through a polynomial model (P < 0.05 and P-lof >0.14). Only the mean DOL responses of one cluster (with 54 individuals), Aw, moisture and oil content and L* and H* color parameters for vacuum frying (Table 4) could be related with statistical significance through a polynomial model (P < 0.05 and P-lof >0.32).

The optimum conditions were not selected using surface plots since significant response variables were still too many to be analyzed by multiple responses. Rossi (2001) recommend a data reduction technique such as PCA. Also, taking into account that the study purpose was to produce a healthy fried fruit snack with high consumer acceptance, the remaining variables to be used in a further response surface analysis should be related with consumer acceptance.

A PCA of chips fried at atmospheric pressure (Figure 1(a)) showed that cluster 1 mean DOL was largely explained by lower hardness, higher oil content and hue (H*). Higher hue values had a positive influence on cluster 1 consumers DOL since corresponding vectors took the same direction (high correlation). Higher frying times and temperatures (samples 9–12) positively influenced DOL, which was not an expected outcome. Meanwhile, the higher water content of chips

Table 3. Analysis of variance and regression coefficients for intercept, linear, quadratic and interaction terms of the model for quality attributes of atmospheric fried chips.

Tabla 3. Análisis de variancia y coeficientes de regresión para los términos lineales, cuadráticos e interacción del modelo para los atributos de calidad de las hojuelas fritas a presión atmosférica.

Regression coefficients/Sources	Aw	Moisture content (g/kg)	Oil content[a] (g/kg)	Color L*	Color C*	Color H*	Hardness (N)	Cluster 1 DOL	Cluster 2 DOL
a_0	0.305 ***	38.39 ***	58.39 ***	40.529 ***	30.378 ***	20.3 ***	16.782 ***	9.514 *	−13.976
a_T	−0.095 ***	−32.83 ***	15.92 ***	3.736 ***	−4.042	16.55 ***	1.661	0.322	0.139
a_t	−0.035	−16.37 **	12.64	4.051 **	−3.731	12.733 ***	1.742	0.321 *	0.272
a_{TT}	0.075 **	18.04 **	11.80	−5.33 **	−1.489	14.252 **	−15.07 ***	0.82 *	0.001
a_{tt}	0.045	10.47	3.20	−0.744	1.321	7.729	−10.281 **	0.552 *	−0.061
a_{Tt}	0.088 **	29.64 **	−0.44	−5.973 **	0.495	16.78 **	−1.482	−0.61	−0.027
R^2	**0.935**	**0.981**	**0.82**	**0.972**	0.65	**0.97**	**0.97**	**0.862**	0.639
p	**<0.01**	**<0.01**	**0.05**	**<0.01**	0.179	**<0.01**	**<0.01**	**<0.02**	0.193
P-lof > F	**0.14**	**0.56**	**0.182**	**0.38**	0.052	**0.22**	**0.27**	**0.244**	0.0004

[a]Dry matter.
Significance levels: *** p < 0.0001; ** p < 0.001; * P < 0.05; P-lof > F: lack of fit of the model.
Boldface values mean statistical significance.

[a]d.m.: materia seca
Niveles de significancia: ***: P < 0.0001; **: P < 0.001; *: P < 0.05; P-*lof*> F: falta de ajuste del modelo
Los valores en negrita indicar significación estadística.

Table 4. Analysis of variance and regression coefficients for intercept, linear, quadratic and interaction terms of the model for quality attributes of vacuum fried chips.

Tabla 4. Análisis de variancia y coeficientes de regresión para los términos lineales, cuadráticos e interacción del modelo para los atributos de calidad de las hojuelas fritas al vacío.

Regression coefficients/Sources	Aw	Moisture content (g/kg)	Oil content[a] (g/kg)	Color L*	Color C*	Color H*	Hardness (N)	Cluster 1 DOL	Cluster 2 DOL
a_0	0.295 ***	27.37 ***	104.87 ***	38.085 ***	27.87 ***	28.155 ***	−9.199	10.751 ***	7.463 ***
$a_{T°}$	−0.056 *	−11.06 ***	−15.03	7.487 **	−3.435 **	12.914 ***	0.078	−1.341 ***	−0.754 *
a_t	−0.023	0.15	5.22	1.038	−0.352	7.515 ***	0.995	−0.921 ***	−0.935 *
$a_{T°T°}$	0.007	4.13 **	16.42	2.250	1.963	2.371	−0.007	−1.227 ***	−1.198 *
a_{tt}	0.005	0.69	14.76	−0.364	−0.557	5.353 **	0.494	−1.048 ***	−0.719 *
$a_{T°t}$	0.009	−0.82	8.21	0.414	0.252	3.365	−6.09e-17	−1.278	−1.083
R^2	**0.806**	**0.949**	**0.915**	**0.862**	0.766	**0.965**	0.4901	**0.989**	0.858
p	**<0.05**	**<0.01**	**<0.01**	**<0.01**	0.063	**<0.01**	0.4263	**<0.001**	<0.05
P-lof> F	**0.316**	**0.461**	**0.766**	**0.613**	0.031	**0.478**	0.239	**0.851**	0.074

[a]Dry matter.
Significance levels: *** $P < 0.0001$; ** $P < 0.001$; * $P < 0.05$; *P*–lof > *F*: lack of fit of the model
Boldface values mean statistical significance.

[a]d.m.: materia seca.
Niveles de significancia: ***: $p < 0.0001$; **: $P < 0.001$; *: $P < 0.05$; *P-lof*> F: falta de ajuste del modelo
Los valores en negrita indicar significación estadística.

prepared using atmospheric frying appeared to negatively affect DOL, since chips became softer and chewy, according to consumers' comments. On the other hand, consumers rejected chips when they were too hard. Optimal hardness was around 3.9–10 N, and resulted from lower moisture and Aw and higher oil content (Table 1). Lightness vector was aligned with PC 1 while DOL vector was aligned with PC 2 showing no effect. In the atmospheric process, hardness appears to be the most important quality attribute for acceptance, with color being relegated to a second level.

The PCA analysis for vacuum fried chips (Figure 1(b)) indicates that the vector for the consumer cluster 1 DOL was aligned with the axis of principal component 2 (PC 2), as was the oil content vector, showing that consumer DOL was higher for the lowest oil content chips (negative correlation). The hue vector ran in the opposite direction and was aligned with the first principal component, demonstrating a negative correlation with DOL and that consumers liked lower hue values, bright purple color.

The chip samples were separated along principal component 1 (PC 1) according to frying temperature and time. At higher frying temperatures, product hue value increased, while moisture and Aw decreased.

As opposed to atmospheric frying, and although oil content is generally higher in vacuum fried chips, oil content was the most influential parameter for DOL. Also, contrary to atmospheric frying, the vacuum process did not produce chips with large variations in hardness and in all cases hardness was acceptable. Consequently, in the case of vacuum fried chips, consumers were mainly attracted by low oil content and a low hue corresponding to a brighter purple color. Lightness (L*) did not show major contributions (Table 2 and Figure 1(b)), although it did correlate significantly according to the ANOVA (Table 4). According to Mariscal and Bouchon (2008) L* is a critical color parameter in the frying industry and high L* values are associated with the occurrence of non-enzymatic browning reactions. High temperatures (over 100°C) combined with low Aw actually enhance non-enzymatic browning, as shown by Jiménez et al. (2012) for the same blackberry anthocyanins as those used in our study. Nonetheless, L* is not a critical parameter for vacuum frying, as it is for traditional industrial frying.

The oil content of vacuum fried chips (92.3 to 155.8 g/kg) was in all cases higher than in conventionally fried chips (<93.2 g/kg) (Tables 1 and 2) and it seems that this is not a limiting quality parameter for vacuum frying. Oil content in vacuum-fried chips was similar to that reported by Troncoso et al. (2009) for potato chips, by Da Silva and Moreira (2008) for potato and mango chips, and by Troncoso and Pedreschi (2009) for pre-treated potato chips. Higher oil content in vacuum fried chips can be explained by capillary absorption favored when the vacuum was broken to restore the system to atmospheric pressure while the product cooled in the receiver flask. Researchers have found that the volume of oil absorbed by the product is inversely proportional to the depressurization velocity (Mir-Bel et al., 2009). During depressurization, the gas pressure in pores of the product is much lower than that at its surface, causing oil penetration. The problem of oil absorption during vacuum-frying might be reduced by including a centrifugation step immediately after frying and before vacuum break and by using edible coatings (Sothornvit, 2011). Nonetheless, in the typical market for snacks, chips with less than 20% oil content are considered 'low-fat' products. In fact, the papaya blackberry-based chips contained less oil than that observed by Shyu and Hwang (2001) in vacuum fried apple chips produced at 100°C and 20 min (16.9% fat content). This difference could be explained by product microstructure, because the final oil content of snacks is highly correlated with the initial porosity of the food material used (Dueik, Moreno, & Bouchon, 2012).

In order to choose optimal atmospheric frying parameters, a new RSM (Figure 2) was run using only the parameters that explained DOL (Figure 1(a)) in the PCA. Multiple response surface methodology provided a second-order polynomial model. RSM for atmospheric frying did not show an optimal DOL value, since the stationary point is a saddle. There are two regions where DOL remained higher. It

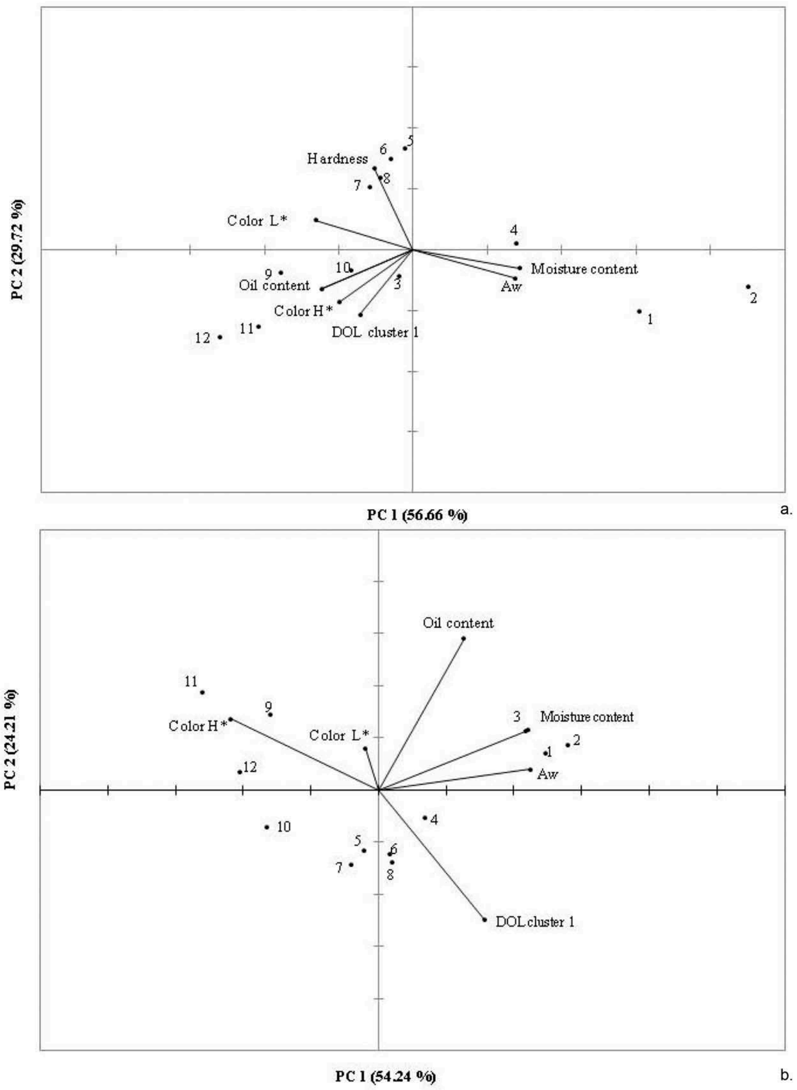

Figure 1. Principal component analysis (PCA) results for the atmospheric and vacuum fried impregnated blackberry chips. (a): Atmospheric fried papaya blackberry chip samples:1: 125.9°C, 4.5 min; 2: 130°C, 3 min; 3: 130°C, 6 min; 4: 140°C, 2.4 min; 5, 6,7and 8: central point at 140°C, 4.5 min; 9: 140°C, 6.6 min; 10: 150°C, 3 min; 11: 150°C, 6 min; 12: 154.1°C, 4.5 min. (b): vacuum fried papaya blackberry chip samples:1: 110.5°C, 6 min; 2: 113°C, 5 min; 3: 113°C, 7 min; 4: 119°C, 4 min; 5, 6, 7 and 8: central point at 119°C, 6 min; 9: 119°C, 7.4 min;10: 125°C, 5 min; 11: 125°C, 7 min; 12: 127°C, 6 min.

Figura 1. Análisis de componentes principales (PCA) para hojuelas de papaya impregnadas con mora fritas a presión atmosférica y al vacío. (a): Muestras de hojuelas de papaya con mora fritas a presión atmosférica:1: 125.9 °C, 4.5 min; 2: 130 °C, 3 min; 3: 130 °C, 6 min; 4: 140 °C, 2.4 min; 5, 6,7and 8: punto central 140 °C, 4.5 min; 9: 140°C, 6.6 min; 10: 150 °C, 3 min; 11: 150 °C, 6 min; 12: 154.1 °C, 4.5 min (b): Muestras de hojuelas de papaya con mora fritas al vacío:1: 110.5 °C, 6 min; 2: 113 °C, 5 min; 3: 113 °C, 7 min; 4: 119°C, 4 min; 5, 6, 7 and 8: punto central 119 °C, 6 min; 9: 119 °C, 7.4 min;10: 125 °C, 5 min; 11: 125 °C, 7 min; 12: 127 °C, 6 min.

can be observed that DOL increased at 150°C for 3 min and at 130°C for 6 min. Hardness lower than 15 N, oil content lower than 90 g/kg and a reddish purple color (H* < 60) corresponded to 130°C and 6 min and to 150°C and 3 min (Figure 2).

The vacuum frying parameters of oil content, Aw, moisture content, H* and DOL were chosen from the PCA (Figure 1(b)). Multiple response surface methodology provided a second order polynomial model. The RSM stationary point for vacuum frying was a maximum value. For vacuum frying, DOL reached an optimum value between 114°C and 119°C, and 5.4 and 6.4 min, where contour color was lighter (Figure 3). As stated by Moreira (2014), vacuum fried products show higher retention of nutritional quality (phytochemicals) and enhanced color (less oxidation). On the other hand, in vacuum fried products, attribute hardness was acceptable for all samples and was not a discriminating factor for consumers. Nonetheless, additional factors must be taken into account, such as Aw and moisture content, in order to ensure sufficient shelf life. Therefore, optimum vacuum frying conditions must be at 117°C and 6 min where DOL was still a maximum. These conditions are similar to those defined by Da Silva and Moreira (2008) for mango snacks (121°C and 6 min), as well as those reported by Pérez-Tinoco et al. (2008) for pineapple chips (112°C and 6.9 min).

Table 5 shows calculated quality parameters for each frying process at optimal conditions. Atmospheric fried chips may have higher moisture and lower oil content than vacuum fried chips. Hardness was low for both processes.

4. Conclusions

Unripe papaya fruit appears to be a suitable base for impregnation with blackberry juice, allowing the production of healthy fruit snacks by employing vacuum or atmospheric

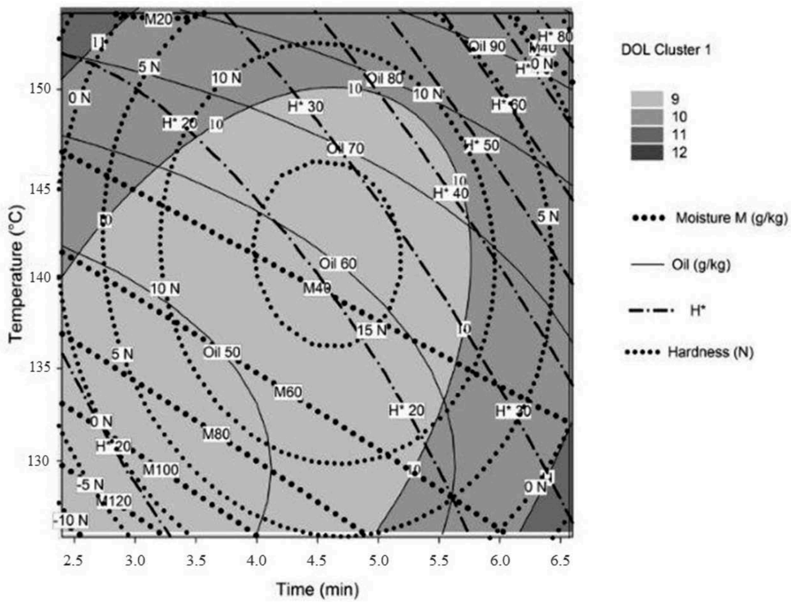

Figure 2. Contour plots of the multiple responses values for the atmospheric fried chips.

Figura 2. Gráficos de contorno con los valores de respuesta múltiple para las hojuelas fritas a presión atmosférica.

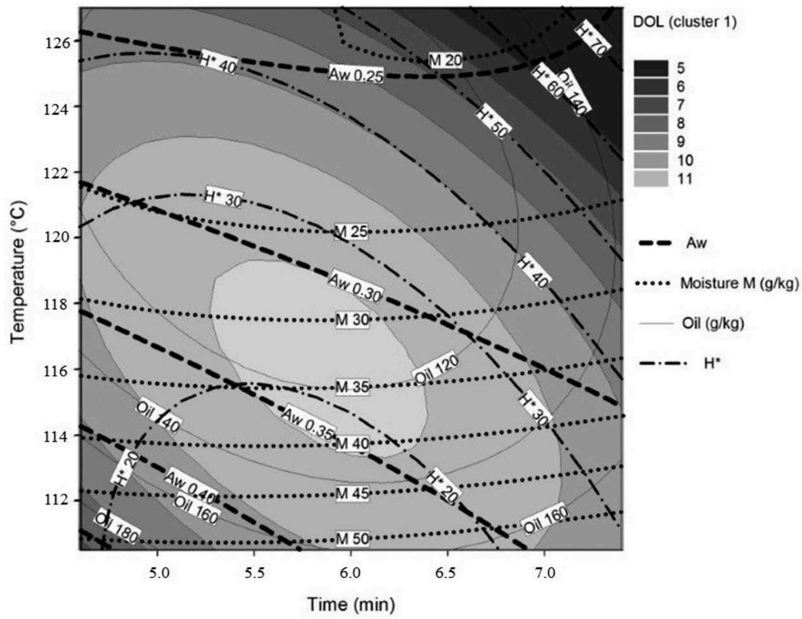

Figure 3. Contour plots of the multiple responses values for the vacuum fried chips.

Figura 3. Gráficos de contorno con los valores de respuesta múltiple para las hojuelas fritas al vacío.

Table 5. Quality comparison of chips fried with atmospheric deep-fat frying and under vacuum, at their respective optimum conditions.

Tabla 5. Comparación de la calidad de las hojuelas fritas por fritura de inmersión atmosférica y al vacío con respecto a sus condiciones óptimas respectivas.

	Calculated responses		
	Atmospheric frying		Vacuum-frying
	130°C/6 min	150°C/3 min	117°C/6 min
Aw	0.37	0.29	0.32
Moisture content (g/kg)	47.00	43.00	31.00
Oil content (g/kg)	71.80	73.00	120.00
Color L*	41.30	40.80	36.90
Color C*	30.50	27.00	28.80
Color H*	18.70	43.00	23.00
Hardness (N)	3.20	7.79	6.00

frying processes. Vacuum frying was effective for producing papaya chips with low moisture content and water activity values, thus generating a product stable at room temperature. The product had an intense purple color attractive to consumers, as shown in the DOL study. The data obtained in the PCA was essential for calculation of the optimal region for the response surface contour plots. Conventional frying at atmospheric pressure also resulted in a product with good quality characteristics and low oil content, probably because it was coupled with an osmotic dehydration step. The highest atmospheric frying temperature in this study was not as high temperatures traditionally used in this process (over 180°C), thus generating a higher quality chip in this case.

Although vacuum frying is an optimal method for producing fruit chips with preserved nutritional characteristics, the inclusion of a post-frying centrifugation step is recommended to prevent absorption of oil by the product.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Notes on contributors

Lea Wexler collected the test data and drafted the manuscript. Ana M. Perez, Elba Cubero-Castillo and Fabrice Vaillant designed the study, interpreted the results and reviewed the manuscript.

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