OPTIMIZATION OF VACUUM FRYING CONDITIONS OF EGGPLANT (*Solanum melongena* L.) SLICES BY RESPONSE SURFACE METHODOLOGY

José D. Torres, Armando Alvis, Diofanor Acevedo, Piedad M. Montero and Diego F. Tirado

SUMMARY

Due to the global trend to consume low-fat products, efforts are being made to reduce oil uptake in fried products. In this paper, the effect of pretreatments and parameters of the vacuum frying process on quality attributes of purple creole eggplant slices is presented. A lab-scale vacuum fryer was used to perform vacuum frying at a maximum pressure of 30kPa. Numerical optimization was carried out using the response surface methodology (RSM) through a randomized Box-Behnken experimental design, with three factors: frying temperature (120, 130 and 140°C), frying time (120, 210, and 300s) and pretreatment (control, blanching and drying), which were established through preliminary tests. Moisture content and luminance (L) decreased with increasing temperature and frying time in all processed samples. Oil uptake, color change (ΔE) and breaking force increased significantly with the increase of these same factors. The highest desirability (0.73) was obtained in blanched samples treated at 130°C during 210s. The optimum values in responses were: moisture 64.77%, oil 3.89%, ΔE 16.67, luminosity 82.59, breaking force 0.96N, color 4.65, odor 4.06, taste 4.25 and greasiness 4.35. The correlation coefficients R^2 for the response variables indicated a good fit of the data to second-order regression models. Vacuum frying is an alternative to process eggplant slices with low-oil content and high acceptability.*

Introduction

Eggplant (*Solanum melongena* L.) is a horticultural species with high nutritional value, since it is rich in vitamins and phenolic compounds in the flesh, and anthocyanins in the peel, all with antioxidant properties (Aramendiz-Tatis *et al.,* 2010). Eggplant is one of the most abundantly grown vegetables in the Colombian Caribbean Region, especially in Cordoba, Sucre and Bolívar departments (Correa *et al.,* 2010). It can be consumed dried, cooked, as paste, pickled, and fried or combined with other culinary presentations (Lo Scalzo *et al.,* 2016).

Frying is one of the most popular and important methods of food processing around the globe (Tirado *et al.,* 2013; 2015). It can be defined as a special type of cooking by oil immersion at a temperature above the boiling point of water (Tirado *et al.,* 2012). During the process, foods experience starch gelatinization, protein denaturation and other changes in microstructure, physical and organoleptic properties (Pedreschi, 2012). During atmospheric frying, oil is submitted to high temperatures in the presence of water and air, which leads to the formation of a wide variety of compounds through hydrolytic, thermic and oxidative reactions (Dueik and Bouchon, 2011). The use of vacuum is an alternative to improve quality of products during deep fat frying (Garayo and Moreira, 2002). In the vacuum frying processes, foods are submerged into oil in a hermetic system where pressure is decreased below atmospheric levels. This makes it possible to reduce the boiling temperature of water, allowing the removal of water from the product at a higher rate (Mariscal and Bouchon, 2008).

Air absence during vacuum frying can inhibit lipid oxidation and darkening of fruits and vegetables (Shyu and Hwang, 2001; Shyu *et al.,* 2005). Therefore, dehydrated food produced by vacuum frying can exhibit a crunchy texture, suitable color and flavor, and appropriate nutrient retention (Da Silva and Moreira, 2008; Diamante *et al.,* 2012; Šumić *et al.*, 2016). Some authors suggest that evaporated water from

KEYWORDS / Moisture Loss / Oil Uptake / Optimization / Quality Attributes / *Solanum melongena* L. / Vacuum Frying /

Received: 01/26/2017. Modified: 09/27/2017. Accepted: 10/05/2017.

José D. Torres. Food Engineer, Universidad de Cartagena (Unicartagena), Colombia. M.Sc. Agro-Food Sciences, Universidad de Córdoba (Unicórdoba), Colombia. Ph.D. student in Engineering Sciences, Ponti-ficia Universidad Católica de Chile.

Armando Alvis. Food Engineer, Universidad INCCA de Colombia. Specialist in Educational Management, UNICÓRDOBA, Colombia. Ph.D. in Food Engineering, Universidad del Valle (Univalle), Colombia. Researcher, Unicórdoba, Colombia.

Diofanor Acevedo. Food Engineer and Pharmaceutical Chemist, Unicartagena, Colombia. Specialist in Food Science and Technology, Universidad Nacional de Colombia (UNAL), Colombia. Ph.D. In Food Engineering, Univalle, Colombia. Researcher, Unicartagena, Colombia.

Piedad M. Montero. Food Engineer, Universidad de la Salle, Colombia. Specialist in Food Science and Technology, UNAL, Colombia. M.Sc. In Food Science and Technology, Universidad de Zulia, Venezuela. Ph.D. in Sciences, Universidad Rafael Belloso Chacín, Venezuela. Researcher, Unicartagena, Colombia.

Diego F. Tirado. (Corresponding author). Food Engineer and M.Sc. in Environmental Engineering, Unicartagena, Colombia. Ph.D. student in Chemical Engineering, Universidad Complutense de Madrid, Spain. Researcher, Unicartagena, Colombia. Address: Grupo de Investigación Nutrición, Salud y Calidad (NUSCA), Unicartagena. Ave. del Consulado, calle 30 Nº 48-152. Campus Piedra de Bolívar. Cartagena, Colombia. e-mail: dtiradoa@unicartagena.edu.co

OPTIMIZACIÓN DE LAS CONDICIONES DE FRITURA AL VACÍO DE RODAJAS DE BERENJENA (*Solanum melongena* L.) UTILIZANDO LA METODOLOGÍA DE SUPERFICIE DE RESPUESTA

José D. Torres, Armando Alvis, Diofanor Acevedo, Piedad M. Montero y Diego F. Tirado

RESUMEN

Dada la tendencia mundial de consumir productos bajos en grasa se hacen esfuerzos para reducir la absorción de grasa en los productos sometidos a fritura. En este trabajo se presenta el efecto de pretratamientos y parámetros del proceso de fritura al vacío sobre los atributos de calidad de rodajas de berenjenas de la variedad criolla morada. Se utilizó una freidora a escala de laboratorio para llevar a cabo la fritura al vacío a presión máxima de 30kPa. Se realizó optimización numérica utilizando la metodología de superficie de respuesta (MSR) a través de un diseño experimental Box-Behnken aleatorizado, con tres factores: temperatura de fritura (120, 130 y 140ºC), tiempo de fritura (120, 210 y 300s) y pretratamiento (control, escaldado y secado), establecidos en ensayos preliminares. El contenido de humedad y luminosidad (L) disminuyeron con el aumento de temperatura y tiempo de fritura en todas las muestras procesadas. La absorción de aceite, cambio de color (ΔE) y fuerza de ruptura aumentaron significativamente con el incremento de estos factores. Se obtuvo la mayor deseabilidad (0,73) en muestras escaldadas tratadas a 130ºC durante 210s. Los valores óptimos en las respuestas fueron: humedad 64,77%; aceite 3,89%; ΔE 16,67; luminosidad 82,59; fuerza de ruptura 0,96N; color 4,65; olor 4,06; sabor 4,25; y grasosidad 4,35. Los coeficientes de correlación R^2 para las variables respuestas indicaron buen ajuste de los datos a los modelos de regresión de segundo orden. La fritura al vacío es una alternativa para procesar y obtener rodajas de berenjena con bajo contenido de aceite y alta aceptabilidad sensorial.*

OPTIMIZAÇÃO DAS CONDIÇÕES DE FRITURA A VÁCUO DE RODELAS DE BERINJELA (*Solanum melongena* L.) UTILIZANDO A METODOLOGIA DE SUPERFÍCIE DE RESPOSTA

José D. Torres, Armando Alvis, Diofanor Acevedo, Piedad M. Montero e Diego F. Tirado

RESUMO

Devido à tendência mundial em consumir produtos baixos em gordura, são realizados esforços para reduzir a absorção de gordura nos produtos submetidos a fritura. Neste trabalho se apresenta o efeito de pré-tratamentos e parâmetros do processo de fritura a vácuo sobre os atributos de qualidade de rodelas de berinjelas roxa. Utilizou-se uma fritadeira em escala de laboratório para realizar a fritura a vácuo na pressão máxima de 30kPa. Realizou-se optimização numérica utilizando a metodologia de superfície de resposta (MSR) através de um desenho experimental Box-Behnken aleatorizado, com três fatores: temperatura de fritura (120, 130 e 140°C), tempo de fritura (120, 210 e 300s) e pré-tratamento (controle, escaldado e secado), estabelecidos em ensaios preliminares. O conteúdo de umidade e luminosidade (L) diminuíram com o aumento de temperatura e tempo de fritura em todas as amostras processadas. A absorção de óleo, mudança de cor (ΔE) e força de ruptura aumentaram significativamente com o incremento de estes fatores. Obteve-se a maior desejabilidade (0,73) em amostras escaldadas tratadas a 130°C durante 210s. Os valores óptimos nas respostas foram: umidade 64,77%; óleo 3,89%; ΔE 16,67; luminosidade 82,59; força de ruptura 0,96N; cor 4,65; olor 4,06; sabor 4,25; e gordura 4,35. Os coeficientes de correlação R^2 para as variáveis respostas indicaram bom ajuste dos dados aos modelos de regressão de segunda ordem. A fritura a vácuo é uma alternativa para processar e obter rodelas de berinjelas com baixo conteúdo de óleo e alta aceitabilidade sensorial.*

food during deep frying is totally replaced by oil that is accumulated in the crust, which would be the way how absorption takes place but, so far, the mechanisms have not been fully clarified (Zhang *et al.,* 2016). An alternative to reduce surface oil uptake in vacuum-fried products is the use of pretreatments such as blanching, vacuum or microwave drying, osmotic dehydration, freezing and edible coatings, and post-treatments including hot air drying and centrifugation (Nunes and Moreira, 2009). Pedreschi (2012) claims that pretreatments are useful to improve and control oil uptake, obtaining suitable textures, promoting sugar lixiviation and air removal from tissues. It is important to have adequate information and methods for monitoring the process and to ensure the quality of products under vacuum frying. Numerical optimization by means of the response surface methodology (RSM) makes it possible to find appropriate conditions for food processing without increasing the cost of experiments. It also improves processes in which the desired responses are influenced by several independent variables (Esan *et al.,* 2015; Abtahi *et al.*, 2016; Yuksel and Kayacier, 2016).

So far, no vacuum frying process for eggplant has been reported in the literature, despite the importance of this type of research for the development of healthy low-oil content foods. This becomes of special interest since this vegetable is part of the gastronomic culture of the Colombian Caribbean Region. The main objective of this study was to optimize the vacuum frying conditions of pretreated eggplant slices by RSM.

Materials and methods

Sample preparation and storage conditions

Fresh eggplant (*S. melongena L.*), variety creole purple with yellow seeds, characterized in a previous work by Aramendiz-Tatis *et al.,* (2010) was used in this study. The fruits were purchased in the Central Market of Cartagena de Indias, Colombia, selected according to size uniformity and verifying that there were no diseases or external defects due to mishandling. The raw material was stored at 4ºC in a refrigerator until the next day. The initial moisture content of samples (86.54%) was measured by oven drying at 105ºC according to AOAC 930.15 (AOAC, 2005). Afterwards, eggplants were washed and cut in slices with diameters of 3.8cm ±0.2cm and thickness ~1.5 ±0.1cm using a Hobart® cylindrical cutter (model FP100-1B; Hallde Co., Sweden). Palm oil, purchased at a local supermarket the day before the experiments, was used in this research because of its resistance to oxidation during heating.

Pretreatment of eggplant slices

Control. The samples were not submitted to pretreatment prior to the vacuum frying process.

Blanching. Samples were submerged in a temperature controlled water bath (Tectron-Bio-20; Instrumentation Scientific Technologies), keeping the temperature at 90ºC for 2min. The electronic device was coupled to a pair of thermocouples (type J, stainless steel) of 0.25mm diameter to control water temperature and the center of eggplant slices (±0.05ºC). Before vacuum frying, water on the surface of the product was removed using absorbent paper.

Drying. It was carried out in a vacuum oven with a tray load of 1.75kg·m^{-2}. The samples were then submitted to a temperature of 60ºC with an air velocity of 1.8 ±0.11m·s^{-1}. Weight loss was periodically controlled until the slices achieved an average final moisture content of 0.7kg water/kg dry solid.

Vacuum frying. Frying of pretreated and control eggplant slices was performed using a Gastrovac® (International Cooking Concepts International, Spain) with dimensions of 40×26×46cm, with a maximum capacity of 10.5L and 220V. The equipment reached a maximum vacuum pressure of 30kPa. Water boils at 70ºC at this pressure. According to Mariscal and Bouchon (2008), 3 deltas were used to define temperatures of the frying process or 'equivalent thermal driving forces': ΔT_1= 50ºC, ΔT_2= 60ºC and ΔT_3= 70ºC. Therefore, the oil temperatures selected were 120, 130 and 140ºC. Frying times of 120, 210 and 300s were established from preliminary tests. The oil was initially heated to the established frying temperature, then eggplant slices were placed into the stainless-steel basket, the system was covered, and the vacuum pump was activated. The basket was submerged into the oil once the equipment had reached operating pressure. A 1:20 w/v ratio of product/oil was used. Once the frying time was reached, the basket was removed from the oil and the vacuum pump ran for an additional minute. Vacuum was then interrupted and the equipment stopped in order to remove the samples. The eggplant slices were drained in a metal net packing them in low density polyethylene bags for further analysis.

Quality analysis of vacuum-fried eggplant slices

Moisture and oil content. The average moisture and oil content of vacuum fried eggplant slices were calculated according to procedures 930.15 and 920.39 (AOAC, 2005), respectively. Measurements were carried out by triplicate and expressed on a dry basis.

Instrumental evaluation of color. Portions <5g of vacuum-fried eggplant slices were cut and used for this stage. A colorimeter CR-5 (Konica Minolta Sensing, USA), with illuminant D_{65} and a tone angle 10º was used under the CIEL*a*b* scale. Complete details of this procedure were described in a previous report (Torres *et al.,* 2017).

Breaking force. The vacuum-fried eggplant slices were submitted to breaking-force test. Slices were first weighted in an electronic balance machine (model Gr-200; A&D Co. Ltd., Japan) and then a texturometer (model TA.TX2i® plus; Stable Micro System Co. Ltd., UK) coupled with Texture Expert Exceed software version 2.64 was used. This equipment had a 50kg load cell and a velocity head of 5mm·s^{-2}. These values were selected from preliminary tests. Samples were placed on two parallel supports with a distance of 3cm between them. A third parallel axis made from the same support material was displaced vertically, exerting a stress until completely breaking the structure of the fried samples. Essays were carried out six times for each treatment, always on the central area in order to avoid variation in the results due to anatomic location (Da Silva and Moreira, 2008).

Sensory analysis

Panelists were encouraged to use a 5 point hedonic scale to rate their perception of the material according to color, odor, flavor and greasiness. The scale consisted of categories ranging from 'I like it very much' (5), going through neutral (3), until 'I do not like it at all' (1). In order to rate the samples, a panel of 30 tasters was used. Ages of the panelist group were 19 to 45 years and the group included 15 women and 15 men. Panelists cleaned their palates by deionized water prior to proceeding to the next sample. They were supplied with whole samples of pretreated and control vacuum-fried eggplant slices (Yuksel and Kayacier, 2016). Data was gathered in a spreadsheet and transformed into numerical values for further analysis.

Experimental design and statistical analysis

A randomized Box-Behnken experimental design with three independent variables was implemented. Each variable had three levels and three center points per block. The factors were set as frying temperature (X_1), frying time (X_2) and pretreatment (X_3). The commercial statistical software Statgraphics Centurión (versión 16.2.04; StatPoint Technologies Inc., EEUU) was used to perform the analysis. Levels of each variable were established from preliminary tests and coded as Table I shows. A total of 15 experimental runs were carried out to study the effect of these variables on the responses of Y_1: moisture loss (%), Y_2: oil uptake (%), Y_3: lightness (L*), Y_4: change of color (ΔE), Y_5: breaking force, Y_6: color, Y_7: odor, Y_8: flavor, and Y_9: greasiness. Regression equations were obtained by adjusting experimental data to second-level polynomial models by least squares. Statistical significance of each term in the regression equations was examined by ANOVA for each response. All the variables from the vacuum frying process were optimized using the RSM numerical method, based on the convenience concept to obtain the best slices of processed eggplants: *i*) minimization of moisture content, oil uptake, color change and breaking force and *ii*) maximization of lightness and sensory perceptions quality. Prediction models were used to generate surface plots. Results of each response variable were expressed as the mean and standard deviation, and were in turn compared using Tukey's HSD test with a level of significance of 5%. Eq. 1 represents the model used to analyze responses of the experimental design as a function of the three independent variables:

TABLE I
LEVELS OF VARIABLES USED IN THE BOX-BEHNKEN EXPERIMENTAL DESIGN

Variable	-1 (low)	0 (central)	1 (high)
Temperature (ºC) (X_1)	120	130	140
Time (s) (X_2)	120	210	180
Pretreatment (X_3)	Control	Blanching	Drying

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_{21}^2 + \varepsilon$$

where Y: response; β_0: intercept; X_1: temperature; X_2: time; X_3: pretreatment; β_1, β_2 and β_3: linear effect coefficients; β_{11}, β_{22}, β_{33}: quadratic effect coefficients; β_{12}, β_{13}, β_{23}: coefficients for the interaction of factors; and ε: random error.

Results and Discussion

Effect of vacuum-frying temperature and time on quality

Moisture loss. Figure 1 shows the behavior of the moisture content of the vacuum-fried eggplant slices at different experimental conditions (temperatures, times and pretreatments). It was found that moisture decreased with increasing frying temperature, which presented a significant effect ($p<0.05$), as frying time did. Figure 1a illustrates control samples behavior. As Figure 1a shows, dehydration was larger in the control samples, with values <10% at 140ºC and 300s, with statistically significant differences ($p<0.05$). No statistically significant differences were observed at temperature of 120ºC regarding moisture content in samples processed at 120 and 210s ($p>0.05$). However, slices evidenced a significant decrease in moisture at 300s. It should be noted that moisture was significantly reduced ($p<0.05$) in control samples after vacuum frying at 130 and 140ºC, regardless of frying time. A comparison with samples processed at 120ºC evidences that temperature is the most influential factor on water loss in the fried product. This phenomenon could be caused by the evaporation of free water from the product due to high temperatures, which promotes diffusion (Tirado *et al.,* 2013, 2015). It is also worth highlighting the fact that eggplant presents a much softer and less dense histological structure than other vegetables (Miraei-Ashtiani *et al.,* 2016). The soft texture of this structure might have influenced the final moisture content of the slices after being submitted to vacuum frying.

On the other hand, Figure 1b shows the moisture data for bleached eggplant slices at different experimental conditions. The final moisture content of these samples was found to be greater at 140ºC and 300s, compared to control samples. This indicated that blanching caused water retention in the sample in the form of residual moisture. Partial cooking of the product structure after bleaching may have caused such a phenomenon. A superficial crust could have formed and could have prevented excessive dehydration of samples.

Finally, Figure 1c represents the moisture content in eggplant slices dried at 60ºC prior to vacuum frying. Moisture content in dried samples before the frying process (70.50%) was lower than control (86.54%) and blanched (89.50%) samples. However, dehydration was lowest, i.e., the slices had more final moisture content than the control samples at 140ºC and 300s. This was probably caused by the fact that thermal treatment contributed to a partial cooking on surface of the eggplant slices, allowing the formation of a barrier, which prevented water loss during the frying process. These results were similar to those obtained by Nunes and Moreira (2009), who reported that moisture loss during vacuum frying in pretreated mango chips caused contraction and volume loss; it also produced changes in texture, such as crunchiness and hardness, which in turn influence dehydration rates of processed food. On the other hand, Diamante *et al.* (2012) found that moisture content in gold kiwi fruit slices should be controlled in order to guarantee a suitable formation of crust during deep fat frying. Similarly, Oginni *et al.* (2015) reported that cassava-based snacks experienced vapor condensation within its pores after being vacuum-fried. The pressure difference between the surrounding material and the pore led to the oil uptake that was adhered to the surface. In the same way, Garayo and Moreira (2002) indicated that moisture loss in the vacuum frying of potato chips led to higher oil adherence in the surface of the chips. They also found that when the product reached its free water limit, a lower amount of oil was absorbed. It has been found that lower vacuum pressures produce higher drying rates during vacuum frying of pretreated vegetables slices. This could be attributed to the fact that by lowering pressures the boiling point of water is reduced and, therefore, water within the vegetables slices starts vaporizing in a faster way (Moreira *et al.,* 2009). Results from the present work agreed also with those reported by Shyu and Hwang (2001) regarding the vacuum frying of apple chips, by Shyu *et al.* (2005) in relation to vacuum-fried carrot chips and by Esan *et al.* (2015) regarding vacuum-fried yellow fleshed sweet potato (*Ipomoea batatas* L.)

Oil uptake. Figure 2 presents the results of oil uptake in pretreated eggplant slices and control samples. Oil content was

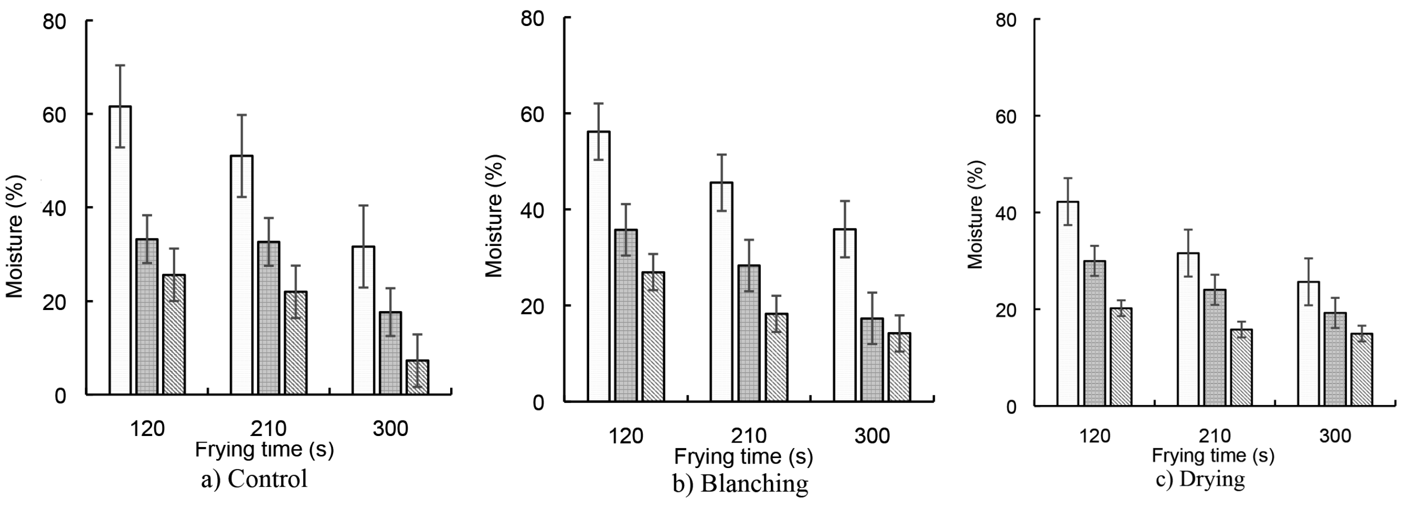

Figure 1. Effect of temperature and frying time on moisture loss of eggplant slices. □: 120ºC, ▒: 130ºC and ▧:140ºC. Means ±standard deviation of three replicates.

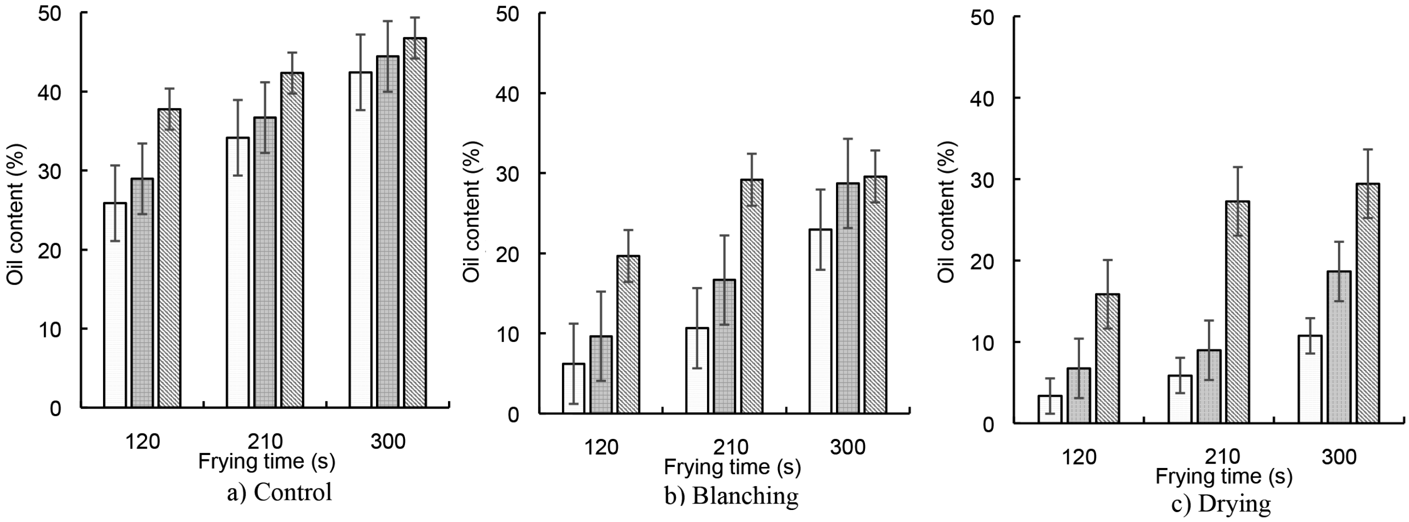

Figure 2. Effect of temperature and frying time on oil uptake during vacuum frying of eggplant slices. □: 120ºC, ▩: 130ºC and ▧:140ºC. Means ±standard deviation of three replicates.

found to be always higher with increasing temperatures and frying times ($p<0.05$). Final oil content in control samples was higher than in slices submitted to blanching and drying at all temperatures and frying times. This could have been caused by the high porosity of eggplant, and the greater availability of spaces in which free water was kept in the samples. This water was vaporized by the high temperature and then escaped allowing higher oil inlet. Blanched and dried slices exhibited lower oil absorption rate under all experimental conditions of time and temperature. In the case of drying, the low initial water content in samples could be responsible for this behavior. During bleaching at 90ºC for 2min, perhaps partial cooking was promoted in the eggplant structure, sealing the pores around the matrices, which in turn could have created a protective barrier that prevented excessive oil absorption. The oil uptake process within the eggplant slices was similar to those reported by Shyu and Hwang (2001) in apple chips, Reis *et al.* (2008) in potato sticks and Moreira *et al.* (2009) in apple chips and vacuum-fried potatoes.

Finally, Shyu *et al.,* (2005) observed that oil content in carrot chips increased with temperature and frying time. They indicated that oil uptake was significantly related to the final moisture content. However, this conclusion does not match the results obtained by Zhang *et al.,* (2016), who studied the potato frying process and reported that the final moisture content exerted no statistically significant effect on oil uptake. The present study provided new, convincing information that aims to clarify the existing relation between initial moisture and oil uptake during the frying process. So far, this relation has not been completely elucidated and it represents the basis for introducing a specific pre-drying strategy into the frying processes of the food industry.

Color parameters. Figure 3 shows the effect of temperature and time on lightness (L*) changes in vacuum-fried eggplant slices. On the CIEL*a*b scale, Lightness represents a numerical parameter that indicates clarity at values close to 100º and darkness when values tend to 0º. This scale is used as an indicator of how color reactions develop in processed foods. In this work, it was found that all samples and pretreatments involving high temperatures and long times showed a significant decrease in L* ($p<0.05$). At the same temperatures and frying times, the lowest levels of L* were observed in dried samples, followed by control slices and then those that experienced blanching. Eggplant slices fried at 140ºC for 300s under all treatments exhibited the lowest L* values. These results indicate that non-enzymatic darkening reactions took place at a higher rate when the process time and temperature was increased, regardless of whether or not pretreatment is applied.

On the other hand, Figure 4 illustrates color changes (ΔE) experienced by control and pretreated eggplant slices. The most notorious ΔE were observed in both control and dried samples fried at 140ºC during 300s. Slices subjected to blanching showed a lower variation of ΔE, which was statistically significant ($p<0.05$), especially for slices processed during 120s at 120ºC. Results obtained with respect to ΔE in control slices and vacuum pretreated slices agreed with those reported by Garayo and Moreira (2002) and Esan *et al.* (2015). These authors indicated that development of color during vacuum frying takes place after the product has experienced a proper drying process. On the other hand, Dueik and Bouchon (2011) found that time and temperature are the factors with the greatest influence on ΔE. This phenomenon is caused by Maillard reactions, which depend on the content of reducing sugars and amino acids or proteins on the surface. Shyu *et al.* (2005) observed that ΔE of carrot chips increased with increasing

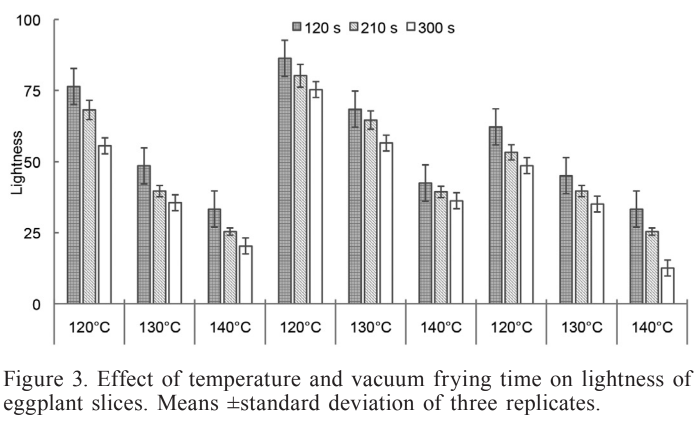

Figure 3. Effect of temperature and vacuum frying time on lightness of eggplant slices. Means ±standard deviation of three replicates.

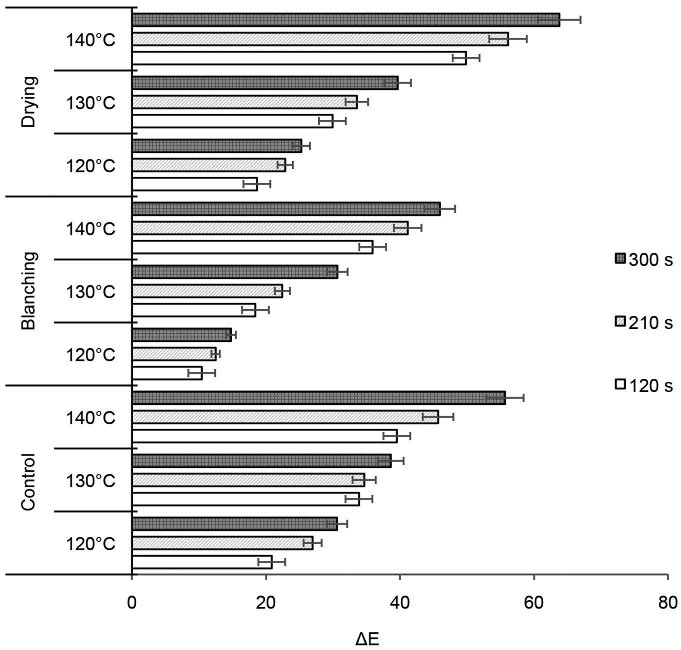

Figure 4. Effect of temperature and vacuum frying time on color changes of eggplant slices. Means ±standard deviation of three replicates.

TABLE II
EFFECT OF TEMPERATURE AND VACUUM FRYING TIMES ON BREAKING FORCE OF SLICES EGGPLANT

Time (s)	120ºC	130ºC	140ºC
Control			
120	0.96 ±0.07 a	1.73 ±0.36 c	1.85 ±0.22 c
210	1.29 ±0.12 b	1.77 ±0.17 c	2.07 ±0.18 c
300	1.47 ±0.21 b	1.88 ±0.23 c	2.19 ±0.15 c
Blanching			
120	1.01 ±0.17 a	1.43 ±0.12 b	1.85 ±0.14 c
210	1.55 ±0.13 b	1.71 ±0.09 c	1.87 ±0.11 c
300	1.88 ±0.16 c	1.92 ±0.25 c	1.96 ±0.06 c
Drying			
120	1.24 ±0.08 b	1.39 ±0.02 b	1.91 ±0.03 c
210	1.42 ±0.05 b	1.64 ±0.19 c	2.26 ±0.11 c
300	1.76 ±0.14 c	1.94 ±0.27 c	2.43 ±0.07 c

Data indicate the mean ±standard deviation of the six replicates. Different letters in the same column indicate statistically significant differences ($p \leq 0.05$), according to Tukey's HSD test.

temperature (between 70 and 110ºC) and frying times (between 300 and 1800s). Variation of these parameters became evident at 100ºC. This was attributed to the instability of carotenoids above 100ºC.

Breaking force. Table II includes the variations of breaking force (N) in the vacuum-fried eggplant slices. It was observed that control, blanched and dried samples exhibited a significant increase in the response of breaking force ($p<0.05$) at high values of time and temperature. Such phenomenon could have been caused by a large formation of crust due to microstructural changes in the tissues of fried products (Garcia-Segovia *et al.*, 2016). Also, these changes in hardness are attributed to dehydration (Oginni *et al.*, 2015).

The texture resulting after the vacuum frying process is a consequence of changes experienced by food composition (Dueik and Bouchon, 2011). Proteins and carbohydrates were mainly modified due to the heat transferred to the sample (Esan *et al.,* 2015; Zhang *et al.,* 2016). This caused the formation of a crust, which provided crunchiness in the product (Pedreschi, 2012). Šumić *et al.* (2016) reported that the evaporation process of water molecules causes a volume reduction by dehydration of the microstructure and increases structural porosity. Numerous holes, clefts and cracks appear at the crust matrix, and they are responsible of the higher surface hardness of the product. Garayo and Moreira (2002) and Da Silva and Moreira (2008) observed that vacuum-fried potato chips presented higher contraction than atmospherically fried potato. This seems to indicate that the crust is easily formed at atmospheric pressure, and it prevents the achievement of higher contraction levels in potato slices.

The determination of the breaking force represents a measure of how crunchy a chip is. Low values of breaking force indicate a high level of this texture attribute. In their research, Shyu and Hwang (2001) and Shuy *et al.* (2005) observed that by increasing the oil temperature, lower values of breaking force were obtained. The same happened when increasing vacuum level. This tendency was not evidenced in the results obtained in the current study. In fact, the values of breaking force showed a statistically significant increase ($p<0.05$) with increasing time and temperature. This was attributed to changes experienced by the product, such as partial cooking of structure and a high moisture loss. Harder, crunchier eggplant slices were obtained at the end of the process thanks to this set of conditions. The obtained results are consistent with those observed by Dueik *et al.* (2010) when they studied texture changes in carrot chips. They reported an initial softening, which was followed by a final hardening as a product of the progressive development of a dehydrated crust. At the beginning of the frying process, texture could become softer due to the combined effects of loss of cell integrity, free diffusion of cell content in the tissue and reduction of cell adhesion. Once a certain amount of time had passed, food would increase its hardness due to the dehydration of external cells and formation of a crust. A final stage of optimization was performed to the processing conditions in order to establish the best physical and sensory responses of vacuum-fried eggplant slices.

Numerical optimization of the vacuum frying of eggplant slices

Table III presents the averages obtained for the response variables in the experimental design: moisture loss, oil content, lightness, color change, breaking force and sensory perception (color, odor, flavor and greasiness) after the vacuum frying process of eggplant slices. On the other hand, Table IV shows the regression coefficients obtained for each second-order polynomial to which the experimental data was adjusted. Their respective coefficients of determination (R^2) are also shown, as calculated by analysis of variance. R^2 ranged from 0.75 for ΔE to 0.99 for the breaking force. The statistical analysis indicated that regression models were adequate to explain the data. These models are of a predictive type and can be used to foretell responses according to different changes in factors levels.

The moisture content of eggplant slices was significantly affected by temperature (X_1), followed by pretreatment (X_3) and frying time (X_2). This indicated that temperature changes and previous treatments were the main factors, which need to be controlled during vacuum frying eggplant slices, since the product experiences dehydration at a high rate. The estimated effects of the model also indicated that the quadratic interactions of temperature-time (X_1 and X_2) and

TABLE III
CONDITIONS USED FOR THE BOX-BEHNKEN EXPERIMENTAL DESIGN PERFORMED ON VACUUM FRYING PROCESS AND RESPONSE VARIABLES

Run	Temp	Time	Pre-treatment	Moisture (%)	Oil (%)	Lightness	ΔE	Breaking force (N)	Color	Odor	Flavor	Greasiness
1	-1	-1	0	66.19	32.62	87.39	19.41	1.01	4.98	4.15	4.51	4.26
2	1	-1	0	23.96	15.29	42.49	21.92	1.85	4.82	4.02	4.38	4.09
3	-1	1	0	35.89	22.95	67.37	18.77	1.88	4.76	4.34	4.78	4.15
4	1	1	0	24.79	17.61	44.37	24.93	1.96	4.75	4.29	4.14	3.99
5	-1	0	-1	68.02	36.59	82.19	12.96	1.29	3.78	4.83	3.95	3.22
6	1	0	-1	21.96	27.77	39.45	27.68	2.17	3.63	4.72	3.74	3.06
7	-1	0	1	31.59	15.88	73.28	18.87	1.42	3.29	3.28	3.33	4.46
8	1	0	1	19.79	17.28	46.45	26.12	2.26	2.92	3.03	4.04	4.32
9	0	-1	-1	33.24	25.86	50.54	15.87	1.73	3.45	4.29	3.72	3.11
10	0	1	-1	31.63	28.95	53.55	16.61	1.68	3.15	4.61	3.61	3.35
11	0	-1	1	29.98	15.86	71.08	15.91	1.39	2.08	3.28	3.33	4.69
12	0	1	1	22.23	10.75	70.12	25.65	1.84	2.58	2.86	3.27	4.58
13	0	0	0	54.33	12.27	86.23	13.45	0.19	4.54	3.98	4.78	3.83
14	0	0	0	52.02	16.66	74.65	21.65	1.71	4.48	4.09	4.63	4.21
15	0	0	0	41.19	14.22	56.56	21.15	1.49	4.26	3.76	4.06	4.12

TABLE IV
ADJUSTED REGRESSION COEFFICIENTS

Coefficients	Moisture (%)	Oil (%)	Lightness	ΔE	Breaking force (N)	Color	Odor	Flavor	Greasiness
β0	494.06	664.52	-599.17	406.96	50.02	84.14	43.36	23.84	-5.05
β1	-1.17	-12.39	13.18	-6.48	9.79	-1.29	-0.63	-0.34	0.12
β2	-1.03	0.56	-0.57	-0.15	1.54x10^{-2}	-5.08x10^{-3}	3.82x10^{-4}	2.62x10^{-2}	-4.66x10^{-3}
β3	-136.53	4.17	-22.55	20.88	-1.43	5.92	0.97	0.24	1.76
β11	2.0x10^{-2}	6.04x10^{-2}	-6.52x10^{-2}	2.73x10^{-2}	3.35x10^{-3}	4.95x10^{-3}	2.38x10^{-3}	1.22x10^{-3}	-4.92x10^{-4}
β12	1.02x10^{-2}	-5.05x10^{-3}	6.08x10^{-3}	1.01x10^{-3}	-2.11x10^{-2}	4.16x10^{-5}	2.22x10^{-5}	-1.41x10^{-3}	2.77x10^{-6}
β13	1.31	-7.01x10^{-2}	0.39	-0.18	-1.03x10^{-3}	-5.52x10^{-3}	-3.53x10^{-3}	2.32x10^{-2}	5.41x10^{-4}
β22	-1.51x10^{-2}	6.23x10^{-4}	-6.84x10^{-4}	-2.42x10^{-5}	2.59x10^{-5}	-1.16x10^{-5}	3.18x10^{-6}	-1.97x10^{-4}	1.46x10^{-5}
β23	1.72x10^{-2}	-2.27x10^{-2}	-1.12x10^{-2}	0.025	1.38x10^{-3}	2.22x10^{-3}	-2.05x10^{-3}	1.38x10^{-4}	-9.72x10^{-3}
β33	-10.55	1.58	-5.61	-4.51x10^{-2}	0.32	-1.51	-0.21	-0.85	-0.24
R^2	0.87	0.82	0.79	0.75	0.99	0.98	0.96	0.86	0.97

temperature-pretreatment (X_1 and X_3) were highly significant for moisture ($p<0.05$). R^2 of the quadratic polynomial was 0.87, indicating a suitable adjustment of the experimental data. This model was appropriate for describing the behavior of water loss within eggplant slices. Oil content of vacuum-fried eggplant slices was significantly affected by both linear and quadratic interactions of temperature (X_1, X_{12}; $p<0.05$). It was also observed that quadratic time (X_{22}) exerted a highly significant effect, which indicated that an increase in frying time affected oil uptake. A R^2 of 0.82 was obtained, indicating that the implemented model successfully described behavior of oil uptake in vacuum-fried slices.

Lightness and color changes were significantly affected by temperature and pretreatment (X_1 and X_3) in both linear and quadratic interactions. Temperature-time interaction exerted a highly significant effect on the change of color in the pretreated and control slices. This suggested that eggplant tended to rapidly change color during deep fat frying. It is therefore necessary to implement an adequate control of time and temperature conditions, in order to avoid unwanted sensory changes in the product. The obtained determination R^2 was 0.79 for lightness and 0.75 for ΔE. Acceptable levels of correlation can thus be achieved when describing the behavior of these responses. Breaking force was significantly affected by both linear and quadratic correlations of temperature (X_1, X_{12}), which indicated that eggplant slices require higher values of strength to be broken after losing large amounts of water. A R^2 of 0.99 revealed a suitable adjustment of the experimental data to the second-order regression model. Therefore, changes of breaking force that are experienced by the product can be properly described by using the obtained regression. Changes in sensory properties such as color, odor, flavor and greasiness were generally highly influenced by temperature and pretreatments (X_1 and X_3). The best conditions were obtained at 130ºC and a blanching pretreatment. R^2 were 0.98, 0.96, 0.86 and 0.97, respectively. This showed that data gathered from the sensory panel successfully adjusted to the quadratic model. The process of multiple-response numerical optimization yielded a maximum convenience score of 0.73 for the following set of experimental factors: frying temperature (130ºC), frying time (210s) and blanching. Optimum values of the minimized responses were obtained at moisture of 64.77%, oil content of 3.89%), ΔE of 16.67, and breaking force of 0.96N. On the other hand, the maximized responses were lightness (82.59), color (4.65), odor (4.06), flavor (4.25) and greasiness (4.35).

Finally, Figure 5 shows the behavior of response surfaces for eggplant slices submitted to blanching during the optimization of vacuum frying. Results of frying optimization of eggplant are similar to those reported by Akinpelu *et al.* (2014), who based on the convenience found frying conditions of 133ºC and 6min for banana chips. On the other hand, Esan *et al.* (2015) found optimal conditions for frying at 108ºC and 9min, with maximum convenience of 0.61. Similarly, Abtahi *et al.* (2016) found conditions to be 153.46ºC and 1.03min. In general, most of the work relating to the optimization of vacuum frying processes focuses on deciding

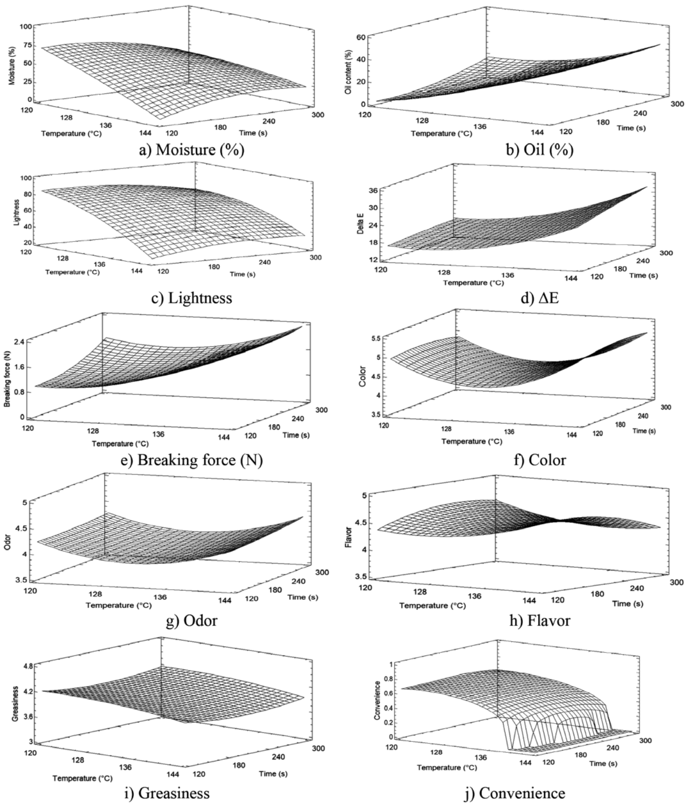

Figure 5. Response surface plots by vacuum frying optimization of blanched eggplant slices: (a) moisture (%), (b) oil (%), (c) lightness, (d) ΔE, (e) breaking force, (f) color, (g) odor, (h) flavor, (i) greasiness, and (j) convenience.

on conditions that allow the development of products with good physical characteristics and high acceptability.

Conclusions

Results of the optimization procedure indicated that moisture content and lightness levels of eggplant slices experienced a significant decrease by increasing temperature (X_1) and frying time (X_2) during vacuum frying. These responses were also affected ($p<0.05$) by the pretreatment factor (X_3). On the other hand, oil content, color change and breaking force increased significantly with increasing factors. Linear and quadratic interactions of temperature had the highest influence. A lower oil uptake and moisture loss was observed in blanched and dried eggplant slices under all experimental conditions of time and temperature compared to control samples. Pretreatments exerted a significant effect on sensory quality, change of color and breaking force of the vacuum-fried eggplant slices. The combination of factors levels that produced the best vacuum-fried eggplant slices were: frying temperature (130ºC), frying time (210s) and blanching pretreatment. Vacuum frying combined with pretreatments represents an alternative to produce fried purple creole eggplant slices with low oil uptake, suitable physical features and sensory acceptability. The same approach could be applied to different vegetable food with similar characteristics.

ACKNOWLEDGEMENTS

Authors thank to the Administrative Department of Science, Technology and Innovation of Colombia (COLCIENCIAS) for financial support to the Research Group Nutrición, Salud y Calidad Alimentaria (NUSCA) through the project 110766441899 (Nº 664 of 2014).

REFERENCES

Abtahi MS, Hosseini H, Fadavi A, Mirzaei H, Rahbari M (2016) The optimization of the deep-fat frying process of coated zucchini pieces by response surface methodology. *J. Culin. Sci. Techn. 14*: 176-189.

Akinpelu OR, Idowu MA, Sobukola OP, Henshaw F, Sanni SA, Bodunde G, Munoz L (2014) Optimization of processing conditions for vacuum frying of high quality fried plantain chips using response surface methodology (RSM). *Food Sci. Biotechnol. 23*: 1121-1128.

AOAC (2005) *Official Methods of Analysis of AOAC International.* 17th ed. Association of Official Analytical Chemists. Maryland, USA.

Aramendiz-Tatis H, Espitia M, Cardona C (2010) Análisis de sendero en berenjena (*Solanum melongena* L.). *UDCA Actual. Divulg. Cient. 13*: 115-123.

Correa E, Araméndiz H, Azeredo L, Pombo C, Cardona C (2010) Tipificación de comercializadores de berenjena en zonas productoras del Caribe colombiano. *Temas Agrarios 15*: 1-10.

Da Silva PF, Moreira RG (2008) Vacuum frying of high-quality fruit and vegetable-based snacks. *LWT-Food Sci. Techn. 41*: 1758-1767.

Diamante LM, Savage GP, Vanhanen L (2012) Optimisation of vacuum frying of gold kiwi fruit slices: application of response surface methodology. *Int. J. Food Sci. Technol. 47*: 518-524.

Dueik V, Bouchon P (2011) Development of healthy low-fat snacks: Understanding the mechanisms of quality changes during atmospheric and vacuum frying. *Food Rev. Int. 27*: 408-432.

Dueik V, Robert P, Bouchon P (2010) Vacuum frying reduces oil uptake and improves the quality parameters of carrot crisps. *Food Chem. 119*: 1143-1149.

Esan TA, Sobukola OP, Sanni LO, Bakare HA, Munoz L (2015) Process optimization by response surface methodology and quality attributes of vacuum fried yellow fleshed sweetpotato (*Ipomoea batatas* L.) chips. *Food Bioprod. Proc. 95*: 27-37.

Garayo J, Moreira R (2002) Vacuum Frying of Potato Chips. *J. Food Eng. 55*: 181-191.

Garcia-Segovia P, Urbano-Ramos AM, Fiszman S, Martínez-Monzó J (2016) Effects of processing conditions on the quality of vacuum fried cassava chips (*Manihot esculenta* Crantz). LWT-Food Sci. Techn. 69: 515-521.

Lo Scalzo R, Fibiani M, Francese G, D'Alessandro A, Rotino GL, Conte P (2016) Cooking influence on physico-chemical fruit characteristics of eggplant (*Solanum melongena* L.). *Food Chem. 194*: 835-842.

Mariscal M, Bouchon P (2008) Comparison between atmospheric and vacuum frying of apple slices. *Food Chem. 107*: 1561-1569.

Miraei Ashtiani SH, Golzarian MR, Baradaran Motie J, Emadi B, Nikoo Jamal N, Mohammadinezhad H (2016) Effect of loading position and storage duration on the textural properties of eggplant. *Int. J. Food Prop. 19*: 814-825.

Moreira R, Da Silva P, Gomes C (2009) The effect of a de-oiling mechanism on the production of high quality vacuum fried potato chips. *J. Food Eng. 92*: 297-304.

Nunes Y, Moreira R (2009) Effect of osmotic dehydration and vacuum frying parameters to produce high-quality mango chips. *J. Food Sci. 74*: 355-362.

Oginni OC, Sobukola OP, Henshaw FO, Afolabi WAO, Munoz L (2015) Effect of starch gelatinization and vacuum frying conditions on structure development and associated quality attributes of cassava-gluten based snack. *Food Struct. 3*: 12-20.

Pedreschi F (2012) Frying of potatoes: Physical, chemical, and microstructural changes. *Dry. Technol. 30*: 707-725.

Reis FR, Masson ML, Waszczynskyj N (2008) Influence of a blanching pretreatment on color, oil uptake and water activity of potato sticks, and its optimization. *J. Food Proc. Eng. 31:* 833-852.

Shyu SL, Hau LB, Hwan LS (2005) Effects of processing conditions on the quality of vacuum-fried carrot chips. *J. Sci. Food Agri. 85*: 1903-1908.

Shyu SL, Hwang LC (2001) Effects of processing conditions on the quality of vacuum fried apple chips. *Food Res. Int. 34*: 133-142.

Šumić Z, Vakula A, Tepić A, Čakarević J, Vitas J, Pavlić B (2016) Modeling and optimization of red currants vacuum drying process by response surface methodology (RSM). *Food Chem. 203*: 465-475.

Tirado DF, Acevedo D, Guzmán LE (2012) Freído por inmersión de los alimentos. *Reciteia 12*: 69-82.

Tirado DF, Acevedo D, Guzmán LE (2013) Coeficientes convectivos de transferencia de calor durante el freído de láminas de tilapia (*Oreochromis niloticus*). *Inf. Tecnol. 24*(6): 41-46.

Tirado DF, Acevedo D, Montero PM (2015) Transferencia de calor y materia durante el proceso de freído de alimentos: tilapia (*Oreochromis niloticus*) y fruta de pan (*Artocarpus communis*). *Inf. Tecnol. 26*: 85-94.

Torres JD, Acevedo D, Montero PM (2017) Effects of vacuum frying on the attributes of quality of Arepa con Huevo. *Inf. Tecnol. 28*: 99-108.

Yuksel F, Kayacier A (2016) Utilization of stale bread in fried wheat chips: Response surface methodology study for the characterization of textural, morphologic, sensory, some physicochemical and chemical properties of wheat chips. *LWT-Food Sci. Technol. 67*: 89-98.

Zhang T, Li J, Ding Z, Fan L (2016) Effects of Initial Moisture Content on the Oil Absorption Behavior of Potato Chips During Frying Process. *Food Bioproc. Technol. 9*: 331-340.