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Mass transfer during the vacuum frying of Malanga slices (*Colocasiaesculenta*)

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***Abstract*—The objective of this research was to study the mass transfer during vacuum frying of Malanga slices (*Colocasiaesculenta*).Anexperimental design under 3 × 3factorial structure including two factors and four central points was employed. The factors were: Frying time (X_1) at 60, 80 and 300 s and Frying temperature(X_2) at 110, 130 and 150 °C for a total of 13 experimental units. The optimization process was made using the response surface methodology (RSM) and a second-order regression model was fitted. Finally, the moisture content and oil content was determined to be evaluated in a sensory analysis under a five-point hedonic scale. Malanga slices reached to loss 88.5 % moisture and to increase the oil absorption to 37.02% as the temperature and frying time increased. It can be due to during this process the matrix structure is modified and water flows with high ease of heating media, leaving empty spaces where the oil enters.**

Keyword-Diffusion coefficient, moisture, oil, sensory analysis

I. INTRODUCTION

Malanga (*Colocasiaesculenta*), also known as Taro, is a herbaceous plant of the family of Araceae, an edible root that represents an important source of calories in the regions of the world (4.2 to 4.4) Kcal g^{-1} dry matter and is favorably compared with other similar products such cassava (1.3 to 1.5) Kcalg^{-1} dry matter, eating in tropical areas of the world. Besides, it is starch-rich (21.1 to 26.2) % wet basis and has high contents of potassium and magnesium (2251 to 4143) mg*100 g^{-1} dry and (118 to 219) mg 100g^{-1} dry matter, respectively.

Because of the small sizes of its starch granules, Malanga is highly digestible, used in food preparation. In fact, it has been estimated there is a 30 % of losses during storage of this tuber, and this fraction could resolve hunger problems [1]. To minimize the losses of this tuber, it must be applied a food processing operation to carry from perishable to non-perishable foods. This food matrix has not received attention to improve its potential, which allows its widespread use; most existing studies on Malanga have focused on the characterization of the physicochemical, thermal and microstructural properties of flours, starches and pastes [2].

In Colombia is getting started to expand the Malanga consumption, but it is not presented a great demand still by consumers compared with other similar products. However, in other countries, it makes part of the daily diet of people due that is a good source of nutrients and minerals[3]. Like other starchy foods such as potatoes, cassava, plantains, yams; a viable and easy way to increase the Malanga consumption is through of development of fried products. Deep-fat frying is the most old and used to make delicious and crispy foods [4]. This unit operation consists in the immersion of food materials in heated edible oils above the boiling point of the water, producing the quality attributes desired such as color, taste, texture and mouthfeel. Nevertheless, this process is incompatible with recent trends of consumption (e.g healthier foods), which has motivated the research of strategies to decreasing of oil absorption [5], an alternative to reduce the final content of oil is through vacuum frying, which consist of decreasing the system pressure at lower levels, with purpose of reduce the boiling point of the water and remove moisture content more quickly and, in turn, low the frying temperature and time frying, favoring sensory and physicochemical properties of the product.

Aráuz&Ñurinda[6] evaluated the use of the Malanga as raw material for developing of a new product type snack; they found that the design of this agro-industrial productive process represents a developmental option, because it would provide an essential element in the diversification of the manufacturing industry. Ramírez*et al.,*[7]sensorially characterized Malanga chips through the quantitative descriptive analysis and a rapid profile test using trained and non-trained panelists, these authors reported good acceptance by part of the product. This kind of food is very consumed due to its sensory characteristics which are imparted by frying of it; these qualities are unique and granted by the other changes that are given during frying process where the oil quality direct influence on the product quality. Likewise, Gamboa*et al.,*[5] researched the effect of scalding on the oil absorption during the frying of Malanga chips, having into account the sample thickness, oil temperature and frying time; demonstrated that application of frying in short times and high temperatures decreased the oil absorption in the scalded and non-scalded samples. Besides, it was reported that oil absorption was high in the non-scalded chips Malanga chips, observing the inverse trend in the scalded chips. Therefore, the aim of this research was to study the mass transfer during vacuum frying of Malanga slices (*Colocasiaesculenta*).

II. MATERIALS AND METHODS

A. Raw material

Malanga from Riohacha city of the department of La Guajira was used for the experiment. Plate-shaped slices were cut into 2.5 × 2.5 × 0.3 cm and palm oil was used purchased at a local market.

B. Vacuum frying process of Malanga slices

Frying process was carried out in the Gastrovac^{TM} Vacuum Cooking and Impregnation System (International Cooking Concepts, Barcelona, Spain) with measures 40 × 26 × 46 cm, maximum capacity of 10.5 L and tension 220 V, developed at the Polytechnic University of Valencia. The pressure of study in the frying process was 30 KPa, where the boiling temperature of water was 70 °C. Temperature deltas of 40, 60 and 80 °C were used whereby the frying temperatures were 110, 130 and 150 °C with times of 60, 180 and 300 s. First, oil was heated at an established frying temperature, then the samples were placed in the frying basket, the cooking pot was closed and the vacuum pump was activated. When the equipment reached the desired study pressure, frying basket was lowered and immersed in the hot oil. After the frying time had elapsed, the basket was lifted, the pump was left on for one minute and then turned off, the vacuum was broken and the samples were removed from the equipment. Later, the chips were drained in a mesh basket[8].

C. Moisture and oil content analysis

The moisture of the samples was determined through drying in a conventional oven at 105 °C to constant weigh (AOAC 925.10)[9] . The oil content of the vacuum fried Malanga slices was determined by the petroleum ether extraction method established by AOAC 920.85[9].

D. Mass transfer coefficient

Diffusion as a predominant phenomenon for mass transfer was assumed having into account the steam migrates mainly through the entire slice. In this transfer phenomenon of the moisture was considered the fulfilment of the Fick's second law, where unidirectional diffusion throughout of the z axis and with constant diffusion coefficient are expressed through the Equation (1) [10].

$$J_a = D_{AB}(\partial^2 C_A/\partial^2 z^2) \quad (1)$$

This equation has been resolved for defining geometry cases[11]. In the essays, Malanga slices had parallelepiped shape; therefore, the geometry was assumed as a plate and considering the diffusion in an unstable state, we have the follow expression:

$$\frac{M_t - M_\infty}{M_t - M_\infty} = \frac{8}{\pi^2}\left(e^{-\left(\frac{\pi^2}{4}\right)\left(\frac{D_{at}}{L^2}\right)} + \frac{1}{9}e^{-9\left(\frac{\pi^2}{4}\right)\left(\frac{D_{at}}{L^2}\right)} + \frac{1}{25}e^{-25\left(\frac{\pi^2}{4}\right)\left(\frac{D_{at}}{L}\right)}\right) + \cdots \quad (2)$$

Disregarding the terms of higher order in Equation (2), assuming: $M_\infty = 0$ and regrouping the terms, this is simplified as Equation (3):

$$ln\left(\frac{\pi^2 M_t}{8M_0}\right) = \pi^2 D_{at}/4L^2 \quad (3)$$

Where M_t is the moisture content at time t, (kg H_2O kg^{-1} solids); M_o is the initial moisture content (kg H_2Okg^{-1} solids); t is the time (min); L is the thickness (m); D_a is the diffusion coefficient (m^2s^{-1}). For the determination of the diffusion coefficient (D_a) was used the Equation (3) of the graph $-\ln(\pi^2 M_t/8M_i)$vs$t = 0$. D_a is estimated of the slope of the three frying temperatures: (140, 160 and 180) °C.

E. Sensory Analysis

A five-point hedonic scale was used, where the panelists indicated their acceptance degree in the parameters: color, hardness and overall acceptance. The categories on the scale were since 5 – "I like very much" until 1- "I dislike very much". For sensory evaluation, a 30 person untrained panel was employed in an appropriate, ventilated room and with controlled conditions of temperature and humidity. Entire samples were provided to panelists of vacuum fried Malanga chips taking into account the previously treatments described in the experimental design.

F. Experimental design and statistical analysis

An experimental design under a 3 × 3factorial structure with two independent variables and three levels each. The factors were: frying time (X_1) at 60, 180 and 300 s and frying temperature (X_2) at 110, 130 and 150 °C. 13 experimental units were carried out including four central points per block (Table 1), following a random order. In order to find the best combinations between the levels of the factors, the optimization of the frying process was made using the response surface methodology (RSM) through the statistic software Statgraphics(Statgraphics Centurion Version 16.1.15, Chicago, EE. UU)[12]. Response variables Y_1= moisture content, Y_2 = oil content, Y_3 = sensory color, Y_4 = sensory hardness) were fitted to second-order model (Equation 1). Besides analysis of variance (ANOVA) were made expressing results with the arithmetic average and standard deviation.

Table 1. Experimental units of the three-level factorial design

Experimental Units	Temperature (°C)	Time (s)
1	110	180
2	130	300
3	150	60
4	130	180
5	130	300
6	110	60
7	150	300
8	130	180
9	130	60
10	110	180
11	150	180
12	130	180
13	130	180

Second-order regression model was used to analyse the responses of the experimental design according to the independent variables that are schematized in the Equation (5):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{12} X_1 X_2 + \beta_{22} X_2^2 \quad (5)$$

Where β_0 is a constant or intercept, X_1 is frying temperature (°C); X_2 is frying time (s), β_1 and β_2 arecoefficients for linear effect of X_1 and X_2, respectively. B_{12} is the coefficient for interaction effect of X_1 and X_2. Finally, ε is the random error.

III. Results and Discussions

A. Moisture content

It was evidenced the moisture decreased when the frying time and temperature increased (Fig. 1). During the first 180 s of frying process, Malanga samples lost 88.5 % of the moisture content and at 300 s they lost 98.6 % of the same. Furthermore, it was observed dehydration is directly proportional to frying temperature and inversely to frying time. Since when the temperature increased in a given time, the moisture content in the product was lower. It is illustrated that the greatest loss of moisture occurs when the first 180 s run from 70% to 7.6%. After this time the rate of loss of moisture is lower. Likewise, the curves showed typical forms of drying curves and are similar to those reported by the immersion frying processes of other products[13]–[15].

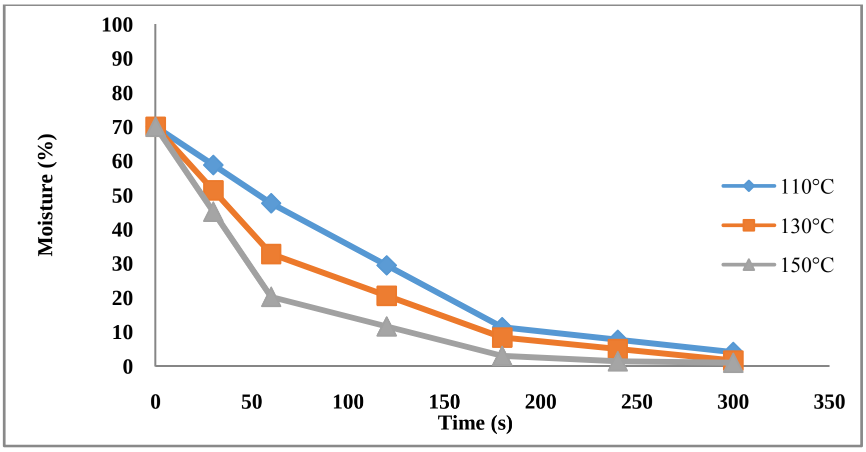

Fig. 1. Moisture content of Malanga slices

To calculate the diffusion coefficients of moisture, a dimensionless ratio of the percentage of moisture vs frying time was made during vacuum frying of Malanga slices. The slopes of the linear sections of these graphs were obtained through lineal regression analysis. In the Table 2 can be observed the diffusivity coefficient of water in the fried samples at 130 °C and 150 °C was higher than those fried at 110 °C due to exist a major mobility of the water molecules as the temperature increases; also when the oil content is high, diffusion coefficient enhance in the Malanga slices.

Alviset *al.*,[16] stated the rate of moisture loss is higher with the enhancing of the oil temperature, the same thing occurs with the effective diffusivity due to higher temperature is produced more porosity and consequently greater water diffusivity. These obtained values are into the range reported by Troncoso and Pedreschi (2009) [17] for water diffusion in the potato issue during vacuum frying (8.57×10^{-9} and 1.21×10^{-8} m^2s^{-1} for a temperature range between 120 °C and 140 °C). However, study data were lower to be obtained by Ahromrit y Nema (2010) [18], which found a diffusivity coefficient of 4.97×10^{-7} m^2s^{-1} in atmospheric frying of cylindrical Malanga Slices at frying temperature of 180 °C.

Further, researches above have demonstrated that the liquid water diffusivity in the food is depending on the oil temperature [19], this could be due that at high temperatures the drying rates increase, since the moisture is lost of the food material by water vaporization to the water at the interface of the crust/core and the subsequent flow of steam through the crust to the surroundings[20].

On the other hand, the obtained average values for D_{eff} in the study ofAlvis*et al.*, (2015) in fried sweet potatoes (*Ipomoea Batatas Lam*), at the respective temperatures of 150, 170 and 190 °C, the diffusion coefficients were (9.19×10^{-7}, 10^{-7} x 10^{-7} and 13.9×10^{-7}) m^2s^{-1} for uncoated samples and (9.52×10^{-7}, 12.3×10^{-7} and 15.3×10^{-7}) m^2s^{-1} for coated samples, being higher than those performed in this study.

Table 2. Moisture diffusivity coefficient in vacuum frying of Malanga

Temperature (°C)	Coefficient (D_{eff}) (m^2/s)
110	8,93649E-09
130	1,10338E-08
150	1,36783E-08

According to Troncoso and Pedreschi (2009) the type of frying (atmospheric or vacuum) affects the water diffusivity of the product, so it is not valid the direct comparison between the values of diffusivity reported in other studies, since vacuum frying could generate an important hydrodynamic gradient that could significantly affect the microstructure of the product, and consequently its physicochemical and transport properties[17]. Also, structural factors (eg, contraction and porosity) not considered by diffusivity models could affect the water diffusivity of the product during frying [21].

B. Oil absorption

It was observed that was an increase in the oil absorption as the frying time and temperature increased (Fig. 2). Also, it can be observed that Malanga samples absorbed about 37.02% of oil after frying, this is because during this process the structural matrix is modified and the water flows more easily towards the heating medium, leaving empty spaces where the oil enters; however, water loss and oil absorption are considered asynchronous phenomena.

The effect of the frying conditions on the oil absorption indicated that the oil content was significantly affected for the temperature and time of the process ($p<0.05$). The highest increase in oil content coincides with the time when a large amount of moisture is lost from the Malanga slices, showing that there is a relationship between the oil content of the Malanga slices and the loss of moisture of the same, this agrees with the results found byShyu*et al.*, [22] when studying the effects of pre-treatments and vacuum frying conditions on the quality of carrot chips. The researchers found that by increasing the temperature and frying time, the moisture content of the chips fell while the oil content increased. These same results were obtained by other authors[5], [23].

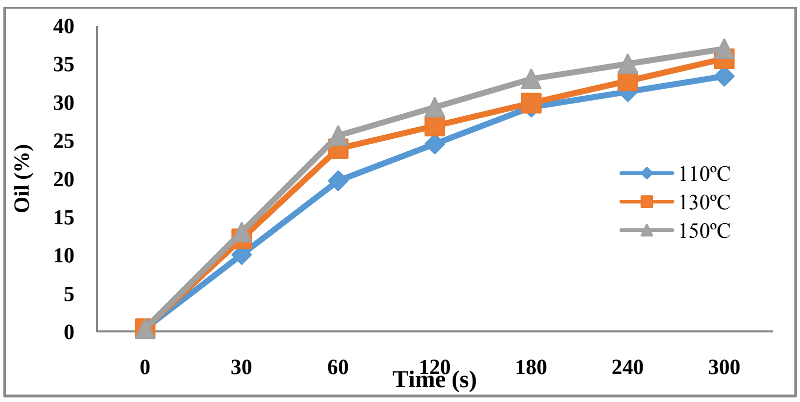

Fig. 2. Experimental values for oil absorption of fried Malanga slices at different temperatures as a function of time.

A lower oil absorption was observed in comparison with the study reported by Paz *et al.,*[5], which fried Malanga chips at atmospheric pressure at temperatures of 180 °C and 200 °C, and times of 1 min and 3 min, obtaining a maximum and minimum value of oil absorption of 71.45% and 26.04% respectively; this could be due to the different thicknesses of the sample, the geometric figure and the high temperatures used. These authors also reported significant differences in the amount of oil absorbed during Malanga frying in both bleached and non-bleached samples ($p <0.01$). For unbleached chips, greater oil absorption was obtained with thicker chips, however an inverse trend in oil absorption was obtained in the bleached chips, which can be explained by a higher moisture gain of the thinner chips, due to its greater surface/volume or structural changes in tissue softening. Diaz *et al.,*[24] reported an increase in fat gain in fried plantain using temperatures from 110 °C to 150 °C but observed the opposite trend in the range of 150 ° C to 190 ° C. Vitrac*et al.,* [25] reported that lowering the oil temperature from 160 °C to 140 °C resulted in a lower oil content in cassava chips for the same frying time.

Nevertheless, oil absorption is a surface-related phenomenon involving the balance between oil adhesion and drainage [26], and the greater amount of oil can be absorbed when the Malanga slices are removed from the oil bath and begin to refrigerate. In this way, Troncoso*et al.,* [17] stated that the higher oil absorption in the vacuum frying occurs in the pressurizing step that proceeds after the product is removed from the oil and remains inside the container.

The pressure in the pores increases rapidly, causing the oil adhering to the surface to continuously penetrate the interior of the food until the pressure in the pores equals the atmospheric pressure. However, Garayo and Moreira [27] stated that at low pressure the air is introduced faster than the oil within the pore space, because the density of the air decreases with the pressure and obstructs the passage of the latter towards the product inside.

C. Sensory analysis

In Table 3, it is observed that the color acceptability values progressively increased with augmented the time and the temperature of frying, no significant color changes were found during the first frying times (60 s to 180 s temperatures of 110 ° C and 130 ºC, respectively), with the highest values being found at 150 ºC and 180 s at 300 s.

These results agree with those obtained by Shyi-Liung and Hwang [28] who reported a greater color variation by increasing the time and temperature during vacuum frying of apple chips. Color changes in the food surface can be caused by caramelization and/or Maillard reaction, responsible for golden or brown tones in fried foods, resulting from the reaction between reducing sugars and amino acids at elevated temperatures [29]. On the other hand, the sensorial hardness was significantly affected by the temperature and the time of the process. During the first 180 s at 110 °C and 130 °C the fried Malanga samples were a good acceptance by panelists, the lowest rating was reached after 300 s at all temperatures.

These results agree with the results obtained by Shyu and Hwang [22] and Paz-Gamboa*et al.*, [5] who reported that the hardness decreased when the frying time and temperature increased, indicating an augment in the crunchiness of the product, during frying of carrot chips and breaded shrimp, respectively.

Table 3. Color changes of the Malanga slices at different times and temperatures

		Time		
		60 s	**180 s**	**300 s**
Temperature	110 ºC			
	130 ºC			
	150 ºC			

D. Regression coefficients

The values of the regression coefficients indicate that the variables were adjusted appropriately to the regression model shown in Equation 5. The optimum conditions of the process were obtained when the temperature and the time of fry reached values of 150 ºC and 174.01 s respectively, achieving a desirability of 0.7061.

Table 4. Coefficients of regression model developed

Coefficients	**Oil**	**Moisture**	**Color (sensory)**	**Hardness (sensory)**
β_0	10,1943	149,883	19,8035	2,57191
β_1	0,11109	-0,7064	-0,00362	-0,01238
β_2	-0,02686	-0,6993	-0,32651	0,07474
β_{11}	-0,00007	0,00068	0,00002	0,00001
β_{12}	-0,00024	0,00252	0,00003	-0,000010
β_{22}	0,00069	-0,00030	0,00140	-0,000418
R^2	0,979896	0,985042	0,83150	0,965664

IV. CONCLUSIONS

It was possible to establish that the dehydration is directly proportional to the temperature and inversely proportional to the frying time. Since when the temperature increases in a given time, the moisture content in the product has decreased. On the other hand, the water diffusivity coefficient in the fried samples at 130 °C and 150 °C was higher than the frying at 110 °C because there is a greater mobility of the water molecules as the temperature increases. In addition, it was demonstrated Malanga samples absorbed about 37.02% of oil after frying; so that during this process the structural matrix is modified and the water flows more easily into the heating medium, leaving empty spaces where the oil enters.It is expected that this contribution will persuade small and medium-sized companies that use as raw material the Malanga to make low-fat and good acceptability fried products.

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