# Effects of processing conditions on the quality of vacuum fried cassava chips (*Manihot esculenta* Crantz)

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ABSTRACT

Concern for the nutritional quality of chips is growing due to rising consumption, motivating research and development of new snack products that contribute to a lower calorie and fat intake in the diet while retaining their good flavor and facility of consumption. The objective of this study was to investigate the behavior of cassava chips, blanched or unblanched and processed under either atmospheric or vacuum frying conditions, in order to determine the influence of these treatments on mechanical and acoustic parameters, optical properties and oil absorption. Vacuum frying trials (17 kPa) were conducted at 120, 130 and 140 °C and compared with frying at atmospheric pressure (101.3 kPa) at 165 °C. Pre-blanching brings a considerable improvement in the color of the vacuum-treated samples and less oil absorption. Vacuum frying pre-blanched cassava chips may be an alternative to atmospheric frying since it improves the color of the samples, reduces the oil gain and maintains crispness. The treatment at 130 °C under vacuum conditions after pre-blanching achieved the best results.

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## 1. Introduction

Cassava *(Manihot esculenta* Crantz) is an extensively cultivated tuber crop and its consumption is considered part of the culture of many developing countries. Cassava is a staple food for millions of people in the tropical regions of Africa, Latin America and Asia (Nambisan, 2011). A major factor limiting the food value of cassava is the presence of cyanogenic glucosides (linamarin and lotaustralin), which liberate acetone cyanohydrin and hydrogen cyanide upon hydrolysis by the endogenous enzyme, linamarase (Conn, 1979). The presence of these toxic compounds in cassava and its food products is a cause of concern because of their possible effects on health. It is therefore necessary to eliminate/reduce their levels in tubers to a minimum in order to make cassava safe for consumption. Major research efforts to eliminate/reduce cyanoglucosides have focused on developing acyanogenic cassava varieties by breeding, controlling its metabolism, and processing to remove cyanogens. Many so-called "sweet" varieties have very low levels of cyanogenic glucosides and can be consumed safely after a thermal process. Traditional processing methods include boiling, blanching, drying, parboiling and drying, baking, steaming, frying and preparing flour. These processes result in cyanide losses ranging from 25% to 98% (Nambisan, 2011). To remove cyanogens from cassava, increase the value of this crop and open up new markets, new uses for cassava have been sought, once of which is fried cassava chips (Grizotto & De Menezes, 2002; Vitrac, Dufour, Trystram, & Raoult-Wack, 2002).

Numerous studies have revealed that excess consumption of fat, one of the main components of deep-fried food, is a key dietary contributor to coronary heart disease and perhaps to cancer of the breast, colon and prostate (Browner, Westenhouse, & Tice, 1991). In recent years, consumer preferences for low-fat and fat-free products have been the driving force behind the snack food industry's efforts to manufacture products with lower oil contents that still retain a desirable texture and flavor (Garayo & Moreira, 2002). Several processes have been developed to allow companies to manufacture reduced-fat products that possess the desired quality attributes of deep fat fried food whilst preserving their nutritional properties. These include alternative technologies such as extrusion, drying, and baking, which may be applied to raw food or to formulated products. Unfortunately, none of them has been as successful as expected because they are still unable to impart the desired quality attributes of deep fat fried food, such as flavor, texture, appearance, and mouthfeel (Dueik, Robert, & Bouchon,

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2010). For this purpose, vacuum frying may be an option for producing fruits, vegetables and other products with a low oil content and the desired texture and flavor characteristics. Vacuum frying is defined as the frying process that is carried out under pressures well below atmospheric levels, preferably below 50 Torr (6.65 kPa) (Nunes & Moreira, 2009). The lower pressure reduces the boiling points of both the oil and the moisture in the foods. Vacuum frying possess some advantages that include: (1) can reduce the oil content of the fried product, (2) can preserve the natural color and flavors of the product due to the low temperature and oxygen control during the process, (3) has fewer adverse effects on oil quality (Shyu, Hau, & Hwang, 1998), (4) decreased acrylamide content (Granda, Moreira, & Tichy, 2004), and (5) preservation of nutritional compounds (Da Silva & Moreira, 2008). Vacuum frying has been studied in various types of food, such as potato (Dueik & Bouchon, 2011; Garayo & Moreira, 2002), banana (Yamsaengsung, Ariyapuchai, & Prasertsit, 2011), jackfruit (Diamante, 2008), carrots (Dueik et al., 2010), pineapple (Pérez-Tinoco, Perez, Salgado-Cervantes, Reynes, & Vaillant, 2008) or vegetables chips (Da Silva & Moreira, 2008). However, no mention of using cassava to produce vacuum-fried chips for human consumption was found in the literature.

Blanching is a food preparation process in which the food is plunged into boiling water or steam. It is used to reduce enzyme activity. It is one of the most widely used methods to prevent browning (Liu-Ping, Min-Zhang, & Mujumdar, 2005; Shyu & Hwang, 2001; Shyu, Hau, & Hwang, 2005) and to leach soluble sugars (Krokida, Oreopoulou, Maroulis, & Marinos-Kouris, 2001). Xin, Zhang, Xu, Adhikari, and Sun (2015) reported that in potato chip processing, a blanching step before frying improves the color and texture and, in some cases, reduces the oil content by gelatinizing the surface starch. Troncoso, Pedreschi, and Zúñiga (2009) suggest that blanching and blanching combined with air drying significantly influence instrumental parameters such as color (L*,a*, b* and ΔE) and flavor, as well as the overall quality of the potato chips, but that the best flavor is obtained by vacuum frying the potato chips without pretreatment.

The objective of this study was to develop high-quality cassava chips using a blanching pretreatment and vacuum frying as the process treatments and to study changes in color, mechanical and acoustic parameters, oil content and moisture, in order to identify the potential of vacuum frying for producing novel cassava snacks that follow the new health trends.

## 2. Materials and methods

### 2.1. Sample preparation

Fresh cassava (*M. esculenta* Crantz) from Costa Rica was purchased from a local market in Valencia (Spain). It was verified that the pieces were whole, healthy (free of mold, rots or deterioration) and free of any strange odor. The whole cassavas were stored at room temperature prior to use. After peeling, the cassavas were cut into 1.5–1.8 mm thick slices with a slicer (Siemens MS70001, Siemens, Spain). The cassava slices were divided in two groups. One of them received a blanching pretreatment before being fried (B) and the other group was fried without pretreatment (UB).

### 2.2. Blanching treatment

Blanching was carried out in a thermostat-controlled water bath (Precisterm S-386, Selecta, Barcelona, Spain) at 70 °C for 10 min (Taiwo & Baik, 2007). After treatment, excess water on the product surface was removed by gently blotting with absorbent paper (Krokida et al., 2001).

### 2.3. Frying treatments

Two frying treatments, atmospheric frying and vacuum frying, were used. Sunflower oil (Hacendado, España S.A., Sevilla, Spain) was used for frying. The oil/cassava frying ratio was 20:1 g/g in all treatments. Atmospheric frying (AF) was carried out at an oil temperature of 165 °C, since this is within the range of temperatures normally used (between 150 °C and 180 °C) (Choe & Min, 2007). For the atmospheric frying experiments, a commercial deep fat fryer was used (Movilfrit, Barcelona, Spain). Vacuum frying was carried out at 17 kPa in a vacuum fryer (Gastrovac, International Cooking Concepts, Barcelona, Spain), at three oil temperatures (120, 130 and 140 °C). After frying and before vacuum rupture, the cassava chips were removed from the oil and centrifuged for 2 min to avoid oil impregnation (Da Silva & Moreira, 2008). The atmospheric and vacuum frying treatment times studied ranged from 1 to 10 min (at 1 min intervals). After frying, the cassava chips were cooled at room temperature, packed in polyethylene pouches (Cryovac® HT3050, Cryovac Sealed Air Corporation, Barcelona, Spain) and stored at 25 °C before analysis.

### 2.4. Proximate composition

The moisture content of the cassava chips was measured by drying in a vacuum oven at 70 °C at 10 kPa. Ground samples (5 g) were dried to a constant weight. The moisture content was calculated from the weight difference between the original and dried samples and expressed as dry base. Three samples were used for each time and temperature.

The total fat content of the dried cassava chip samples (5 g) was extracted with petroleum ether (BP 40–60 °C) for 4 h in a Soxtec System 2055 Tecator extracting unit (FOSS, Hillerød, Denmark) and gravimetrically determined. Three samples were used for each time and temperature.

### 2.5. Characteristics of the fried product

The weight loss was calculated as the percentage weight difference between the raw and fried samples relative to the weight of the raw cassava slices. Before weighing, the samples were dried with absorbent paper in order to remove the surface water from the fresh cassava slices and the surface oil from the fried ones. The samples were weighed with a Mettler Toledo model PB303-S analytical balance (Mettler Toledo GmbH, Greifensee, Switzerland). Three samples were used for each time and temperature.

A TA-XT2 texture analyzer (Stable Micro Systems Co Ltd, Godalming, UK) with version 4.0.13.0 of the Texture Expert data analysis program (2009) and a P/0.5S spherical probe measuring ½ inch in diameter (Stable Micro System) was used to determine the breaking force, area under the curve and number of peaks. The samples were placed on a HDP/CFS platform (Crisp Fracture Support Rig). The test parameters were: test speed 1 mm/s, activation force 5 g, distance of sound 3 mm. All the numerical results were expressed in grams. For the study of crispness, a surrounding sound detector fitted with a Bruel and Kjaer microphone (8 mm diameter) was used (Chen, Karlsson, & Povey, 2005; Varela, Chen, Fiszman, & Povey, 2006). The microphone was placed at a 45° angle at a distance of 4 cm from the center of the sample. The environmental acoustics and noise were filtered with a high-step filter (step size 1 kHz). The data acquisition rate was 500 points per second for both the force and the acoustic signals. All the tests were performed at room temperature in a laboratory with no special soundproof facilities. Twenty replications were performed for each kind of cassava chip. The force/displacement and sound pressure level (SPL)/

displacement curves were plotted simultaneously. From the force curve, the following parameters were extracted: area below the force curve (N·s), maximum force (N) and number of force peaks (drops in force higher than 0.049 N). From the sound curves, the number of sound peaks (drops in sound pressure level higher than 10 dB) and the sound pressure level (dB) (average of the ten highest peaks: SPLmax10) were calculated.

The surface color of the cassava chips was measured with a Minolta cm-3600-d spectrocolorimeter (Minolta, Osaka, Japan) using color data analysis software (SpectraMagic™ NX, Minolta, Osaka, Japan). The measurements were made using an SAV diaphragm (0.4–0.7 mm) with basic white and black plates, taking into account that the samples were translucent. Ten samples were used for each time and temperature.

## 2.6. Statistical analysis

Statistical analysis was executed using statistical package Statgraphics Centurion XVI ver. 16.2.04 (StatPoint Technologies Inc., Virginia, USA). One-way variance analysis was carried out in order to assess differences amongst fried sample measurements under specific conditions. Disparities between samples fried under different conditions were determined through confidence interval analysis using the Tukey test. Statistical significance was expressed at the $p < 0.05$ level.

## 3. Results and discussion

### 3.1. Blanching

The initial weight of the samples before blanching was $3.2 \pm 0.7$ g. After blanching, the average weight was $3.5 \pm 0.6$ g. Blanching brings a significant increase ($p < 0.05$) in weight (6.9%). This weight gain can be explained by the water absorption that occurs during blanching by immersion in hot water, which entails changes in product structure. According to Zivanovic and Buescher (2004), blanching disrupts hydrogen and other non-covalent bonds between cell wall polymers. Pectins from the cell wall and the middle lamella between adjacent cell walls are degraded and solubilized. This leads to a loss of adhesion between cells and loss of turgor which ultimately destroys the integrity of the membrane (Ma & Barrett., 2002; Xin et al., 2015), facilitating water exchange.

### 3.2. Weight loss during frying

Fig. 1 shows the effect of frying time and pretreatment on weight loss in vacuum- and atmospheric-fried cassava chips. The effect of pretreatment was significant ($p < 0.05$) for both vacuum- and atmospheric-fried samples during all stages of frying. At the end of the process (10 min), the weight loss of the blanched samples (B) (including all temperatures) was $57 \pm 2\%$ while that of the unblanched samples (UB) was $49 \pm 2\%$. Despite the weight gain due to the blanching process, the final weight of the samples was similar ($p \geq 0.05$): $1.7 \pm 0.4$ g for unblanched samples and $1.4 \pm 0.3$ for blanched samples. With regard to the effect of temperature, no differences ($p \geq 0.05$) were found between the treatments at the end of the process (10 min). The weight variation in the samples fried under atmospheric conditions (165 °C) was around $53 \pm 5\%$ with respect to their initial weight while that of the cassava chips fried under vacuum conditions was $54 \pm 5\%$ at 120 °C, $50 \pm 4\%$ at 130 °C and $55 \pm 3\%$ at 140 °C.

### 3.3. Moisture content

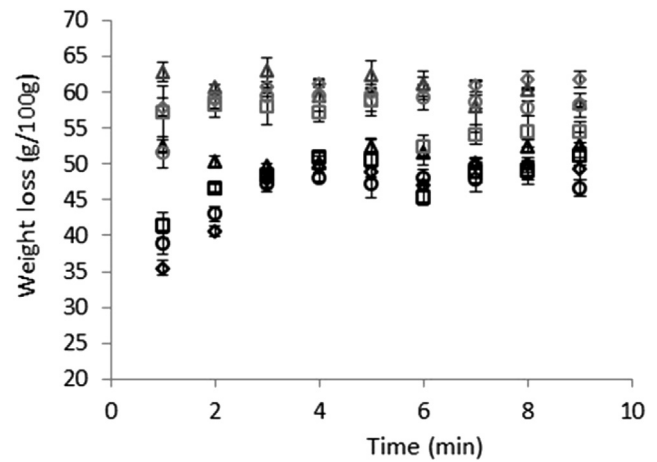Fig. 2 shows the moisture loss for each vacuum and atmospheric



**Fig. 1.** Weight loss (g/100 g) of cassava chips during the frying process. UB: unblanched samples (black); B: blanched samples (gray). ◇ 120 °C UB; □ 130 °C UB; △ 140 °C UB; ○ 165 °C UB; ◇ 120 °C B; □ 130 °C B; △ 140 °C B; ○ 165 °C B.

frying time and the effect of the pretreatment methods on the moisture content of the fried cassava chips. Their moisture content was found to be influenced by the blanching pretreatment. The loss of moisture during vacuum and atmospheric frying presented a classic drying profile. An initial rapid decrease in water content, mainly due to the loss of surface and unbound internal water, was followed by a gradually decreasing gradient due to crust formation. During frying, heat is transferred from the hot oil to the product surface by convection and from the product surface to the center by conduction. The water contained in the product moves from the inside of the chips to the outer zone leaving the product from the surface as vapor. Some of this vapor though, may remain trapped within the pores of the product due to restrictive intercellular diffusion. The vapor in this confined space will expand and become superheated, distorting the pore walls and contributing to total porosity (Kawas & Moreira, 2001; Moreira, Palau, & Sun, 1995). All the samples dried to the same final moisture content ($0.013 \pm 0.015$ g water/g dry solid). No differences in moisture ($p \geq 0.05$) between the treatments were found after 10 min of frying. When the moisture data (g water/g dry solid) were fitted to
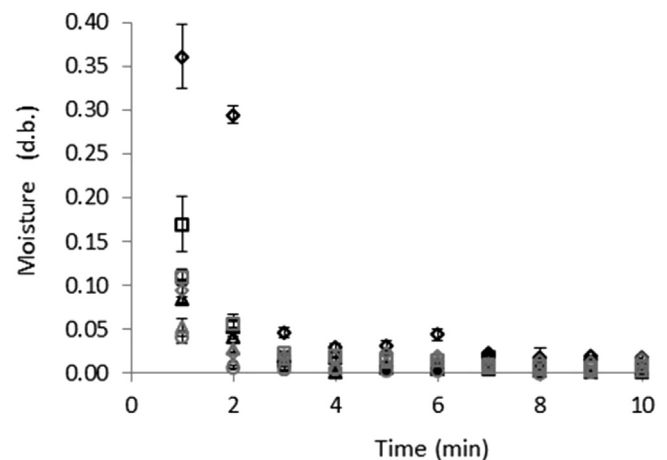


**Fig. 2.** Moisture loss (db) from cassava chips during the frying process. UB: unblanched samples (black); B: blanched samples (gray). ◇ 120 °C UB; □ 130 °C UB; △ 140 °C UB; ○ 165 °C UB; ◇ 120 °C B; □ 130 °C B; △ 140 °C B; ○ 165 °C B.

an empirical model as an exponential function of time, $X_w = a \cdot e^{-b \cdot t}$, (Baumann & Escher, 1995), they fitted this model accurately ($R^2 > 0.98$) and reflected the faster water loss in the atmospheric-fried samples (Table 1). The frying temperature significantly affected the rate of moisture loss and the time required to achieve the desired level of dehydration (Fig. 2) in the first stage of the frying process. During this stage, water loss increased (higher values of parameter "b") with temperature and blanching in the vacuum-frying treatments (Table 1). The treatments under a vacuum at 140 °C showed higher "b" values than those carried out at 165 °C under atmospheric pressure. The differences are thought to be associated mainly with micro-structural changes (Nunes & Moreira, 2009; Shyu et al., 2005; Taiwo & Baik, 2007). Samples fried under vacuum conditions are exposed to lower temperatures. As a result, micro-structural changes/damage are inhibited (this is one of the main advantages of vacuum technology). Also, during the initial depressurization step in vacuum frying, micro-structural surface changes may occur which may prevent water from escaping. The cassava slices fried under vacuum showed less bubbles and more uniform structure than those fried under traditional frying. Similar differences were found by Nunes and Moreira (2009) in vacuum fried mango chips. Furthermore, even though dehydration is mainly limited by heat transfer, diffusion may play a role (Dueik et al., 2010). Diffusion slows down at lower temperatures, a factor that may preclude moisture loss. Similar results were found by Mariscal and Bouchon (2008) when frying apple slices and by Dueik et al. (2010) with carrot crisps. After 5 min of frying there were no differences in the moisture content of the samples due to blanching/not blanching or to frying temperature ($p < 0.05$). At this point the mean moisture value was 0.025 ± 0.027 g water/g dry solid or 2.3 ± 2.4%. Other authors such as García-Armenta et al. (2016), in a study of the multifractal breakage pattern of tortilla chips, have associated a moisture content of around 1–4% with quality foodstuffs.

### 3.4. Oil content

The oil content of the fried cassava chips decreased with blanching (Fig. 3). Blanching cause expulsion of air between the cells (Xin et al., 2015), this reduction of air can reduce the porous space that can be occupied by oil during frying process. Other authors as Taiwo and Baik (2007) observed that the porosity of blanched and air dried samples of sweet potatoes were much lower than for the other pretreatments (osmotic dehydration and freezing). The mean oil content values were 0.036 ± 0.019 $g_{oil}/g_{dry\ matter}$ for the blanched samples (B) and 0.050 ± 0.034 $g_{oil}/g_{dry\ matter}$ for the unblanched samples (UB). When cassava slices are blanched, water is removed from their cells by diffusion. In addition, water will also be vaporized during vacuum frying and might leave behind pores in the cassava slices. Equally, vacuum treatment
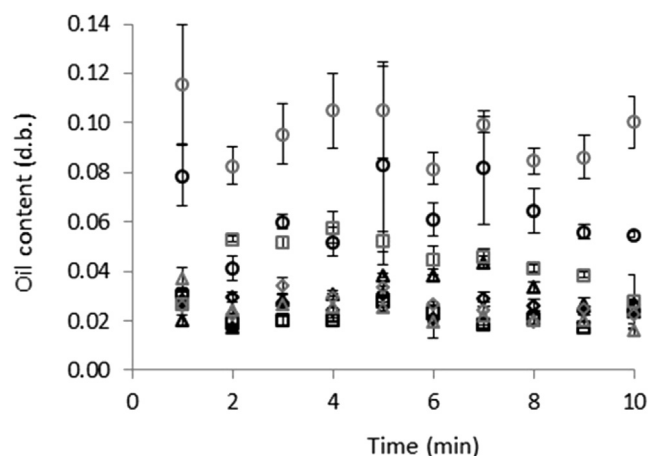


**Fig. 3.** Oil content of cassava chips (db) versus frying time in the different treatments. UB: unblanched samples (black); B: blanched samples (gray). ◇ 120 °C UB; ☐ 130 °C UB; △ 140 °C UB; ◯ 165 °C UB; ◇ 120 °C B; ☐ 130 °C B; △ 140 °C B; ◯ 165 °C B.

involves a significant reduction in oil content ($p < 0.05$). The mean oil content of the samples fried at atmospheric pressure (165 °C) was 0.085 ± 0.027, while the vacuum-fried samples showed lower oil content values: 0.027 ± 0.004 $g_{oil}/g_{dry\ matter}$ at 120 °C, 0.034 ± 0.014 $g_{oil}/g_{dry\ matter}$ at 130 °C and 0.027 ± 0.008 $g_{oil}/g_{dry\ matter}$ at 140 °C. The frying time was not significant for oil absorption ($p \geq 0.05$). Oil absorption is a complex mechanism which is still not clearly understood under vacuum conditions (Garayo & Moreira, 2002). Many factors contribute to making this a complex phenomenon. They include the initial product structure, the various exchanges between the product and the heating medium, product variations and oil properties, chemical reactions, food moisture content, the cooling phase, frying time, temperature, drainage time and pressurization time (Velasco, Marmesat, & Dobarganes, 2008). Several studies (Dana & Saguy, 2006; Moreira, Castell-Pérez, & Barrufet, 1999) have demonstrated that most of the oil does not penetrate the product during frying but during the cooling period, when the product is removed from the fryer and the product starts to cool, leading to water vapor condensation and a resulting decrease in internal pressure, whereupon oil adhering to the surface is sucked into the food due to a 'vacuum effect'. Therefore, oil uptake is a surface phenomenon involving the equilibrium between adhesion and drainage as the food is removed from the oil bath (Moreira & Barrufet, 1998; Moreira, Sun, & Chen, 1997). Mariscal and Bouchon (2008) concluded that permeability is of great importance because oil absorption is essentially a surface-related phenomenon resulting from the competition between drainage and suction into the porous crust once the food is removed from the oil bath and begins to cool. The present results indicate that blanching combined with vacuum frying can provide an alternative that reduces the oil content of cassava chips.

### 3.5. Color

Color is considered the most representative indicator of quality in a chip. It is affected by the chemical composition of the raw material and determines processing capability (Lisinska & Leszczynski, 1989). A golden color is a characteristic and very significant attribute of fried products and is decisive in determining consumer acceptance (Krokida et al., 2001). Table 2 shows the instrumental parameters of color (L*, a* and b*) according to the pretreatment and frying conditions of samples fried for 5 min. The blanching pretreatment significantly ($p < 0.05$) affected the

**Table 1**
Kinetic parameters from empirical model as an exponential function of time, $Xw = ae^{bt}$, (Baumann & Escher, 1995) of blanched cassava chips (B) or unblanched (UB) fried under vacuum conditions (120, 130, and 140 °C) and atmospheric conditions (165 °C). SEE: standard error of estimate.

| Temperature (°C) | Treatment | a | b | $R^2$ | SEE |
|---|---|---|---|---|---|
| 120 | UB | 1.76 | 1.34 | 0.988 | 0.071 |
| | B | 1.76 | 2.91 | 0.997 | 0.038 |
| 130 | UB | 1.76 | 2.29 | 0.997 | 0.038 |
| | B | 1.76 | 2.71 | 0.997 | 0.039 |
| 140 | UB | 1.76 | 2.99 | 0.997 | 0.040 |
| | B | 1.76 | 3.47 | 0.997 | 0.041 |
| 165 | UB | 1.76 | 2.77 | 0.998 | 0.033 |
| | B | 1.76 | 3.73 | 0.997 | 0.041 |

**Table 2**
CIE L*a*b* values of blanched cassava chips (B) and unblanched (UB), fried under vacuum conditions (120, 130 and 140 °C) and atmospheric conditions (165 °C). Lightness (L*), green-red chromaticity (a*), blue-yellow chromaticity (b*) (Medium values of ten replicates).

| Temperature (°C) | Treatment | L* | a* | b* |
|---|---|---|---|---|
| 120 | UB | 53 (2)[1,a] | −0.9 (0.9)[1,a] | 17 (3)[1,a] |
| | B | 57 (2)[2,a] | −1.4 (0.2)[2,a] | 8 (2)[2,a] |
| 130 | UB | 50 (2)[1,a] | 3.0 (1.1)[1,a] | 25 (2)[1,ab] |
| | B | 60 (2)[2,a] | −1.4 (0.1)[2,a] | 9 (1)[2,ab] |
| 140 | UB | 47 (2)[1,a] | 8.7 (1.3)[1,b] | 31 (1)[1,b] |
| | B | 57 (3)[2,a] | −1.4 (0.2)[2,b] | 10 (2)[1,b] |
| 165 | UB | 51 (8)[1,a] | 7.6 (5.5)[1,b] | 28 (2)[1,c] |
| | B | 58 (7)[2,a] | 2.1 (3.2)[2,b] | 23 (6)[1,c] |

Note: superscript characters indicate the effect of blanching (numbers) and temperature (letters). Values in the same column for each treatment with the same letter or number are not statistically different according to the Tukey test (p < 0.05).

instrumental parameters of color. Blanching increased L* and diminished a* and b*, providing samples with less browning and a more golden-yellow color in comparison with unblanched samples. L* is a critical parameter in the frying industry and is usually used as a quality control factor, therefore its adequate control is of great importance. Blanching is a common method of avoiding browning before frying under vacuum (Liu-Ping et al., 2005; Shyu et al., 2005; Shyu & Hwang, 2001) or atmospheric conditions. Blanching helps to leach soluble sugars (Krokida et al., 2001), and heating samples to a temperature above the gelatinization point of starch allows a decrease in the reducing sugars involved in the Maillard reaction.

Vacuum frying had a significant effect on the instrumental parameters of color (Table 2). Vacuum frying significantly (p < 0.05) reduced the a* and b* values. Cassava chips fried under a vacuum had similar L* values to those of the slices fried under atmospheric conditions. As mentioned before, in connection with the effect of the blanching pretreatment, higher a* and b* values indicate a "darker" color (in web version), which is desirable in these products (Fig. 4). The redness (a*) values increased significantly (p < 0.05) with frying temperature (Table 2). Baik and Mittal (2003), Pedreschi, Hernández, Figueroa, and Moyano (2005) and Ngadi, Li, and Oluka (2007) also reported that redness increased gradually with traditional frying time, finding that the higher the frying temperature, the darker the resulting potato slices. This suggests that the Maillard reaction was limited by temperature and not by the pressure conditions. Analysis of variance showed that temperature had a significant effect (p < 0.05) on the yellowness (b*) of cassava chips. The high vacuum-frying temperature (140 °C) decreased L*. The color coordinates show that the cassava chips which were vacuum fried at 140 °C were "darker" than those fried at 120 °C or 130 °C. Several studies have shown that during frying under atmospheric or vacuum conditions, higher temperatures increase the extent of browning (Garayo & Moreira, 2002; Krokida et al., 2001; Pedreschi et al., 2005; Shyu & Hwang, 2001; Shyu et al., 2005; Troncoso et al., 2009), supporting the results observed in the

present study. Consequently, combining a blanching pretreatment with vacuum frying at a moderate temperature could be a good way to improve the color of cassava chips.

### 3.6. Texture and sound

Recent methods have simultaneously measured both the compression force and the sound pressure when a solid food is being fractured (Castro-Prada, Luyten, Lichtendonk, Hamer, & Van Vliet, 2007; Chaunier, Courcoux, Della Valle, & Lourdin, 2005; Chen et al., 2005; Salvador, Varela, Sanz, & Fiszman, 2009). These methods are more objective, in that they avoid dependence on panelists. Chen et al. (2005) showed that the occurrence of acoustic events and force drops almost correspond. Representative profiles of the force and the simultaneously recorded sound during probe displacement in the cassava chips are shown in Fig. 5. The force-—displacement curves present a jagged appearance with several fracture events, typical of crispy food (Chen et al., 2005; Salvador et al., 2009; Taniwaki & Kohyama, 2012; Taniwaki, Sakurai, & Kato, 2010; Varela et al., 2006; Vincent, 1998). In order to compare the behavior of the different cassava chips objectively, specific parameters were extracted from the force and sound curves. The parameters evaluated were: 1) the area under the force versus displacement curve; 2) the number of total force peaks, which are an index of the jaggedness of the curve; 3) the maximum force peak, which is related to the hardness of the product; 4) the number of total sound peaks; and 5) the sound pressure level (average of the ten highest peaks, SPLmax10). Table 3 shows the force and sound curve parameter values for samples fried for 5 min. Blanching brought an increase in area and a reduction in the maximum force peaks (p < 0.05) but had no effect on the rest of the parameters measured (p ≥ 0.05). Vacuum frying increased the number of force peaks (p < 0.05) (Table 3). In the vacuum-fried samples, a rise in temperature brought a decrease in the area under the force versus displacement curve and in the maximum force values. With respect to the sound parameters, the samples fried under vacuum conditions at 130 °C and 140 °C showed high numbers of sound peaks (p < 0.05). The sound pressure level (SPLmax10) ranged between 95.04 dB and 98.48 for all treatments. The highest SPLs were found in the samples fried at 130 °C under vacuum conditions and in those fried at 165 °C under atmospheric conditions.

In general, sensory crispness is positively related to the number of fracture and acoustic events, to SPLmax10, and to the area below the force curve (Salvador et al., 2009). In addition, a certain degree of sensory hardness is necessary for the perception of crispness. On the other hand, normally a low number of force and acoustic events is taken as an index of low crispness (Salvador et al., 2009). The increase in temperature in vacuum-fried samples brings a reduction of the area under the force curve. Segnini, Dejmek, and Öste (1999a, 1999b) and Pedreschi, Segnini, and Dejmek (2004) used the maximum breaking force as an indication of crispness. A high
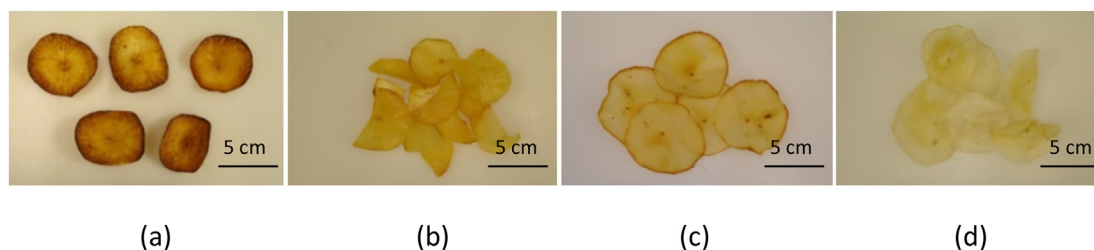


(a)  (b)  (c)  (d)

**Fig. 4.** Cassava chips atmospherically fried at 165 °C for 5 min, unblanched (a) and blanched (b); cassava chips vacuum fried at 130 °C for 5 min, unblanched (c) and blanched (d).
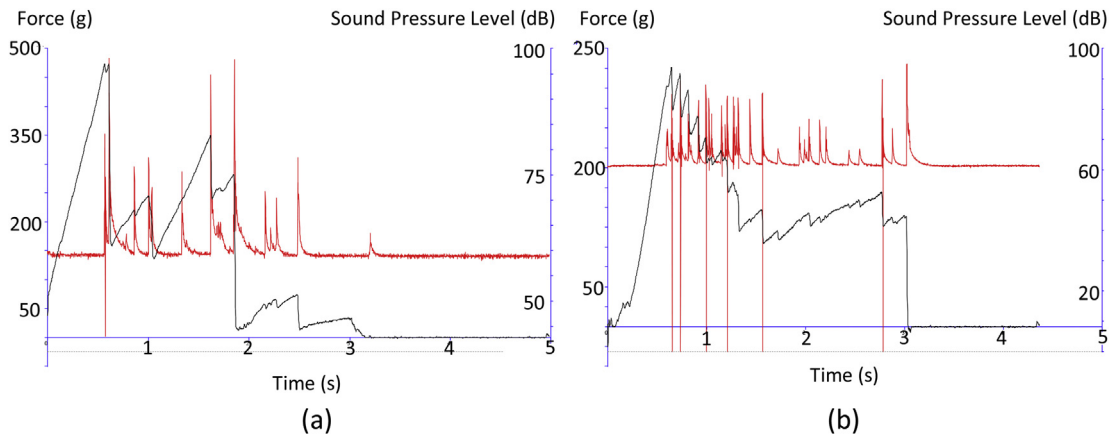
**Fig. 5.** Force (black line) and Sound Pressure Level (SPL, red line) versus probe displacement for unblanched cassava chips fried at 165 °C-for 5 min (a), and blanched cassava chips fried at 130 °C-for 5 min. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 3**
Parameters obtained for force and sound curves of cassava chips after frying time of 5 min. Area under the force versus displacement curve; Number of total force peaks; Maximum force peak; Number of total sound peaks; Sound pressure level (average of the ten higher peaks, SPLmax10). UB: unblanched samples; B: blanched samples (Medium values of twenty replicates).

| Temperature (°C) | Treatment | Area (N s) | Number of force peaks | Force max. (N) | Number of sound peaks | SPLmax10 (dB) |
|---|---|---|---|---|---|---|
| 120 | UB | 5.0 (4.0)[1,a] | 12 (6)[1,a] | 8.8 (4.8)[1,a] | 13 (7)[1,a] | 96 (7)[1,ab] |
|  | B | 5.8 (2.9)[2,a] | 12 (5)[1,a] | 6.8 (2.5)[2,a] | 17 (8)[1,a] | 97 (5)[1,ab] |
| 130 | UB | 3.9 (1.5)[1,b] | 12 (4)[1,a] | 4.5 (1.1)[1,bc] | 23 (7)[1,b] | 98 (4)[1,b] |
|  | B | 4.7 (0.9)[2,b] | 11 (5)[1,a] | 3.3 (1.0)[2,bc] | 18 (9)[1,b] | 97 (4)[1,b] |
| 140 | UB | 2.8 (1.1)[1,c] | 12 (5)[1,a] | 3.4 (1.3)[1,c] | 17 (8)[1,b] | 96 (5)[1,a] |
|  | B | 3.3 (1.1)[2,c] | 11 (4)[1,a] | 2.5 (0.7)[2,c] | 18 (7)[1,b] | 95 (3)[1,a] |
| 165 | UB | 3.2 (1.3)[1,bc] | 7 (3)[1,b] | 4.7 (0.9)[1,b] | 13 (4)[1,a] | 97 (3)[1,ab] |
|  | B | 4.3 (2.6)[2,bc] | 10 (4)[1,b] | 4.8 (1.6)[2,b] | 14 (6)[1,a] | 97 (3)[1,ab] |

Note: superscript characters indicate the effect of blanching (numbers) and temperature (letters). Values in the same column for each treatment with the same letter or number are not statistically different according to the Tukey test (p < 0.05).

number of force and sound peaks have been associated with high sensory crispness (Chen et al., 2005; Varela et al., 2006). In cassava chips, samples fried at 130 °C under vacuum conditions seem to present a good combination of force and sound parameters that can be related to samples with an adequate crispness profile.

## 4. Conclusions

The blanching pretreatment brings a considerable improvement in the color of the vacuum-fried samples and less oil absorption. Vacuum frying blanched cassava chips may be an alternative to atmospheric frying since it improves the color of the samples, reduces their oil gain and maintains their crispness. Frying at 130 °C under vacuum conditions following blanching was the treatment that gave the best results.

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