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Evolution of mechanical and optical properties of French fries obtained by hot air-frying

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ABSTRACT

The aim of this study was to analyse the influence of frying technique (air-frying and deep oil-frying) and type of pre-treatment (freezing and blanching) on the evolution of mechanical and optical properties of French fries. The results showed that the chromatic parameters, a^* and b^*, experimented an increase regardless of the frying method. The increase in a^* was significantly higher in deep-oil frying as a result of Maillard's reactions. The texture analysis reported a first stage of initial softening related to starch gelatinization followed by a second stage where the maximum force increased due to the gradual formation of a crust, both stages being faster in deep-oil frying. Pre-frozen potatoes presented the highest value of maximum force parameter independent of the type of frying.

1. Introduction

Nowadays, fried products are very popular with people of all ages. Their preparation is easy, fast and economical. For these reasons, in recent decades, frying processes have been generalized not only in fast food establishments but also in restaurants, food industries (for example snacks), and homes, etc. Among all commonly fried products, French fries are the most important due to their high consumption and production (Garayo & Moreira, 2002).

The deep-oil frying process is one of the oldest techniques of preparing food, which is highly appreciated by consumers due to the taste. This process basically consists of an immersion of the product in hot vegetable oil, causing the egress of water and the ingress of oil, with the consequent changes in texture and colour properties. The product becomes crusty due to the loss of water and acquires a light brown colour due to Maillard's reactions consisting of high temperature reactions between reducing sugars (glucose and fructose) and amino acids such as asparagine.

The main disadvantage of the consumption of traditional French fries, and in general all deep-oil fried products, is related to their high levels of fat (around 35.3–44.5%) (Garayo & Moreira, 2002), since consumers are more and more concerned about health. It is known that a high fat diet is one of the major factors that causes an increase in the incidence of cardiovascular disease (Moreira & Barrufet, 1998; Ni & Datta, 1999). Because of this, much research has been aimed at the development of fried food products with reduced fat. Consequently, many studies on the mechanisms of fat absorption during frying have been carried out considering different pre-treatment and deep-oil frying conditions (Aguilera & Gloria-Hernández, 2000; Debnath, Rastogi, Krishna & Lokesh, 2009; Dueik, Robert, & Bouchon, 2010; Mai Tran, Dong Chen, & Southern, 2007). Air-frying is a new way to obtain fried products by means of an emulsion containing oil droplets in a hot air stream. The process takes place in a chamber in which the product is continuously in movement to promote the homogenous contact between the product and the external emulsion medium. In this way, the product is gradually dehydrated while the typical crust on fried products appears. Under air-frying conditions, the final product exhibits 80% lower oil content than traditional frying (Heredia, Castelló, & Andrés, 2010). However the lower oil content could affect several sensory aspects of the product such as crust formation, palatability, colour, brightness, etc. Therefore it is important to evaluate how the strategies focused on reducing the fat content of fried products influence sensory aspects.

There are several pre-treatments that can be applied to products before frying in order to improve the process or extend the shelf life of the raw material and provide enough supplies to food industry, restaurants or homes. Thus, potatoes or coated products can be fried when they are fresh or when they have been previously frozen (Mateos, 2003). This freezing pre-treatment allows the consumer to have the product ready to be fried avoiding the previous stages of pealing, cleaning, cutting, etc. Other common pre-treatments in potatoes sticks are blanching, air drying, microwave application,

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and osmotic treatment, among others (Krokida, Oreopoulou, Maroulis & Marinos-Kouris 2001a; Liu & Scanlon, 2007; Song, Zhang, & Mujumdar, 2007). These pre-treatments affect the final quality of the French fries, especially in terms of mechanical and optical properties and the amount of oil in the final product. Krokida, Oreopoulou, Maroulis, and Marinos-Kouris (2001b) observed that both blanching and air dehydration led to reduce oil absorption.

Another important aspect to bear in mind in French fries is the presence of acrylamide. This is a normal component generated in fried products as an intermediate of the Maillard's reactions due to a reaction between reducing sugars, the amino acid asparagine (Gökmen, Palazoglu, & Senyuva, 2006) and the intense heat treatment applied (Amrein, Schönbächler, Escher, & Amadò, 2004; Gökmen & Senyuva, 2006; Taubert, Harlfinger, Henkes, Berkels, & Schomig, 2004). At high levels it is considered to be toxic, being a possible carcinogen for humans (group 2A) by the International Agency of Research of Cancer (IARC, 1999). Pre-treating the potatoes by blanching with water at 90 °C seems to be the best way to reduce the amount of acrylamide in the final fried potato due to a release of reducing sugars (Haase, Matthaus, & Vosmann, 2003; Pedreschi, Moyano, Kaack, & Granby, 2005). Moreover, acrylamide formation seems to be related to the level of browning in the products according to different authors (Pedreschi et al., 2005; Pedreschi, Kaack, & Granby, 2006). They observed that there was a relationship between the amount of acrylamide and the increase in the colour coordinate a* (red-green variation) and consequently, this colour coordinate could be considered a good indicator of the acrylamide content.

For all the reasons explained, the aim of this work was to analyse the evolution of the mechanical and optical properties of French fries obtained by hot-air frying in comparison with those obtained by deep-oil frying. The effect of the application of a pre-treatment (freezing or blanching) was also analysed.

2. Materials and methods

2.1. Raw materials

Fresh potatoes (*Solanum tuberosum* L., Mona Lisa variety) were purchased from a local supplier in one batch. Potatoes were stored at 6 °C, and then acclimatized at 20 °C seven days before use. The potatoes were sorted, washed, peeled and cut into 0.009 m × 0.009 m × 0.03 m strips with a manual cutter. The frying process, either deep-oil or hot-air frying, was carried out on (i) control or unpretreated strips, (ii) strips blanched in hot water at 90 °C for 1 min, and (iii) commercial frozen pre-fried French fries (strips 0.009 m × 0.009 m × 0.03 m) with an initial fat content of 3%. The blanching step was carried out for 1 min in tap water in a stainless steel vessel kept at 90 °C in a thermostatically controlled water bath. The samples were directly immersed at a sample to solution ratio of 1/5 (w/w). After blanching, the samples were drained on a paper towel for 10 s before frying.

Refined seed oil with 0.2° acidity was used to fry the potatoes.

2.2. Methodology and equipment

Experiments were carried out at a fixed frying temperature of 180 °C in commercial deep oil-frying (model: FM 6720 Ideal 2000 Professional (Solac, Valencia, Spain) with a nominal power: 2000 W) and hot air-frying equipment (model: AH-9000 Actifry (Tefal, Valencia, Spain) with a nominal power: 1400 W). A product-to-oil ratio of 1:20 (w/v) and 1:0.003 (w/w) was used for deep-oil frying and hot-air frying experiments according to the specifications of the equipments, respectively. The frying time was selected based on a previous study of mass transfer phenomena of both techniques carried out by the same authors (Heredia et al., 2010). A constant frying temperature was confirmed by means of two PT-100 temperature sensors (model: TF101K) located at the top and the bottom of each fryer.

Three samples were removed from the frying equipment at 3 min intervals for hot air-frying experiments (total processing time: 30 min) and 2 min intervals (total processing time: 16 min) for deep-oil frying for analytical determinations.

2.3. Analytical determinations

Raw materials (unpretreated, blanched and frozen potatoes) were characterized, in triplicate, in terms of moisture and reducing sugars content. Moisture content (% wet basis) was determined gravimetrically by drying to constant weight in a vacuum oven at 60 °C (method 20.103 AOAC, 1980). Reducing sugars content (% wet basis) was determined according to Miller (1959). For reducing sugars, the 3,5-dinitrosalicylic acid spectrophotometric method was used by measuring the absorbance at 480 nm (Cañizares-Macías, Hernández, & Gómez-Ruiz, 2001) in a UV–visible spectrophotometer (V-630; Jasco Inc., Tokyo (Japan). Glucose was used as a standard.

2.3.1. Mechanical properties

Texture determination of the potato strips was done at 50 °C, the optimum temperature for consumption, by a puncture test performed in a Texture Analyser TA.XTplus (Stable Micro System, Godalming, UK). The temperature of the samples was controlled by punching a PT-100 temperature sensor in additional samples not employed for textural determinations. Force vs. distance curves were generated in triplicate with the puncture test at different frying times. The assay was carried out until the samples were completely pierced. The punch diameter and the cross-head speed were 2 mm and 1 mm/s, respectively. The maximum force (Fmax), expressed in N, was obtained from the force vs. distance curves using the software Texture Expert (v 6.06) of the Texture Analyser. Fmax is defined as the force at which the punch penetrates the outer layer of the surface of the fried potato strips.

2.3.2. Optical properties

The colour analysis of potato strips was measured by means of a Minolta (CM-3600d) spectrocolorimeter with a 7 mm diameter lens. CIE-L*a*b* coordinates were obtained using D65 illuminant and 10° observer as a reference system. Coordinates in the CIE-L*a*b* colour space were obtained from the absorption spectrum between 380 and 770 nm.

The CIE-L*a*b* system is composed of: luminosity (L*), red-green variation (a*), yellow-blue variation (b*). Moreover, from coordinates a* and b* polar coordinates of chrome (C*) and hue (h*) were obtained by means of the following equations (1) and (2):

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{1}$$

$$h^* = \mathrm{arctg}\frac{a^*}{b^*} \tag{2}$$

Measurements were carried out on two of the four sides of each potato strip. No differences in the spectrum were found when black or white backgrounds were used to measure the colour of the samples, which confirmed the opacity of the samples. Once opacity confirmed, determinations were exclusively performed with black background. For each potato pre-treatment, type, and time of frying, three replicates were performed.

2.4. Statistical analyses

Statgraphics Centurion was used to perform the statistical analysis. Analysis of variance (simple ANOVA) was carried out to estimate the significanct difference between unpretreated, blanched and frozen potatoes in terms of moisture, total soluble solids, reducing sugars content and CIE-L*a*b* colour coordinates before frying.

3. Results and discussion

Colour and texture measurements could be a good way to control some parameters or characteristics of the products difficult to quantify by other procedures. Heat and mass transfers during frying cause physicochemical changes affecting the colour of fried products. Water loss and oil gain as a consequence of heat and mass transfers are responsible for colour, aroma and texture development. The gradual dehydration of the product implies the development of a crusty surface but also the apparition of a brown colour as a consequence of Maillard's reactions (Moyano, Ríoseco, & González, 2002). The high palatability of fried products is mainly due to the presence of oil. These phenomena are conditioned by process variables such as oil type and temperature, frying time, applied pre-treatments or the dimensions of the product (Krokida, Oreopoulou, Maroulis, & Marinos-Kouris, 2001c).

Table 1 shows the colour coordinates of the system CIE-L*a*b*, chrome (C*) and hue (h*) of raw, frozen and blanched potato strips at the beginning of the treatment as well as the composition of each kind of sample in terms of moisture (% wet basis) and reducing sugars (% wet basis). According to these results, the blanching pre-treatment mainly caused a luminosity loss and a decrease in the b* coordinate. This fact implied an increase in opacity along with a decrease in purity of colour and hue. On the other hand, frozen samples showed the highest luminosity value.

Fig. 1 shows the evolution of L* during both types of frying with respect to the initial values (L^*_0). As can be observed, the type of frying affects this parameter differently. Deep-oil frying induced a greater luminosity loss in frozen samples and with more frying time, than unpretreated ones; while a null variation of this parameter was detected during hot air frying in unpretreated and frozen samples. In the blanched samples and those fried in hot air, the luminosity increased until 9 min of frying and then remained constant. The evolution of this parameter could be explained considering that luminosity depends on the amount of free water present on the surface favouring the reflexion of light (Hunt, 1980). In this way, the greater and faster surface dehydration during the initial stages of deep-oil frying (Heredia et al., 2010) implied a loss of luminosity in unpretreated and frozen samples. Moreover, deep-oil frying caused a darkening, reducing L* more than under hot air-frying conditions. By contrast, in blanched samples, L* initially increased during hot-air and in deep-oil frying as a consequence of the greater presence of liquid phase (water) during frying than other samples (Heredia et al., 2010).

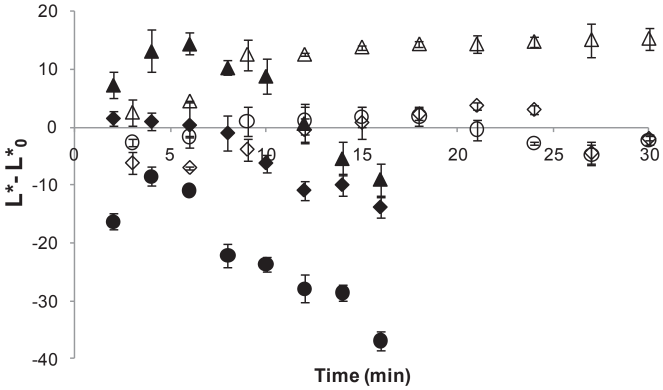

Fig. 1. Evolution of luminosity, with respect to initial value ($L^*-L^*_0$), versus time in unpretreated, blanched and frozen French fries fried subjected to deep-oil (◆, ▲ and ●, respectively) or air frying (◇, Δ and O, respectively) ($n = 3$).

Table 1
Moisture content, reducing sugars content (% wet basis) and CIE-L*a*b* coordinates of raw, frozen and blanched potato strips at the beginning of the frying process ($n = 3$).

	Raw	Blanched	Frozen
Moisture (%)	82.5 (0.2)%^{a}	83.1 (0.4)%^{a}	79.7 (0.5)%^{ab}
Reducing sugars (%)	0.07 (0.03)%^{a}	0.05 (0.02)%^{b}	0.09 (0.02) %^{a}
L*	61.9 (1.6)^{a}	52 (3)^{a}	71.90 (1.09)^{ab}
a*	−4.2 (0.8)^{a}	−3.79 (0.12)^{b}	−2.5 (0.5)^{b}
b*	14.5 (1.9)^{a}	4 (3)^{b}	10.4 (0.4)^{b}
h*	92 (3)^{a}	126 (3)^{b}	104 (3)^{b}
C*	14 (1.9)^{a}	5.9 (1.9)^{b}	9.9 (0.6)^{b}

Means with the same letter are not statistically different from each other at 95% confidence interval (p-value < 0.05).

Fig. 2 shows the evolution of coordinates a* and b* during frying. In general, frying produced an increase in both coordinates. With regards to coordinate a*, deep-oil frying caused a greater increase in the a* coordinate than hot-air frying especially in unpretreated samples. This phenomenon could suggest that air-frying decreases acrylamide generation, a carcinogenic compound directly related to the increase of a* (Gökmen & Senyuva, 2006), compared to deep-oil frying conditions. The measurement of the parameter a* is used to determine the optimal frying point of fried products. In general, high values of a* are not desirable, which means that positive values are not recommendable since they would indicate an orange tonality as a consequence of non enzymatic browning (the product will be too fried). Values between 0 and −5 of the a* coordinate and values of the b* coordinate higher than 10 are generally considered an optimal tonality for French fries (Krokida et al., 2001c).

Regarding the pre-treatment effect, different results were observed depending on the type of frying. In deep-oil frying, unpretreated and blanched samples showed a higher increase in the a* parameter than frozen samples. However, differences as a function of pre-treatment during hot air-frying were minimized (overlap of the standard deviation in most of the times analysed), though the unpretreated ones exhibited the lowest increase in a*. This could be associated with the differences in terms of the individual heat transfer coefficient, being lower for hot-air frying. In deep-oil frying, conduction within the food material is the rate-controlling heat transfer mechanism; whereas in hot-air frying an external rate-control takes place. Therefore, the difference between the initial temperature of the samples is more important in deep-oil frying than in hot-air frying. The lower temperature of frozen samples in comparison to the others determines the kinetics of Maillard's reactions, resulting in a lower increase in a*.

Changes in coordinate b* are not as remarkable as those in coordinate a* considering the type of frying, although again deep-oil fried samples showed higher differences in the increment in b* than hot-air fried ones. Pre-treatment also affected the parameter b* in a different way according to the type of frying. The higher the value of coordinate b*, the greater the yellowness, and this colour is desirable in fried products. Greater yellowness was obtained for unpretreated samples obtained by deep-oil frying followed by the frozen samples and then by the blanched ones. In hot-air frying, differences were lower and samples showed the opposite behaviour.

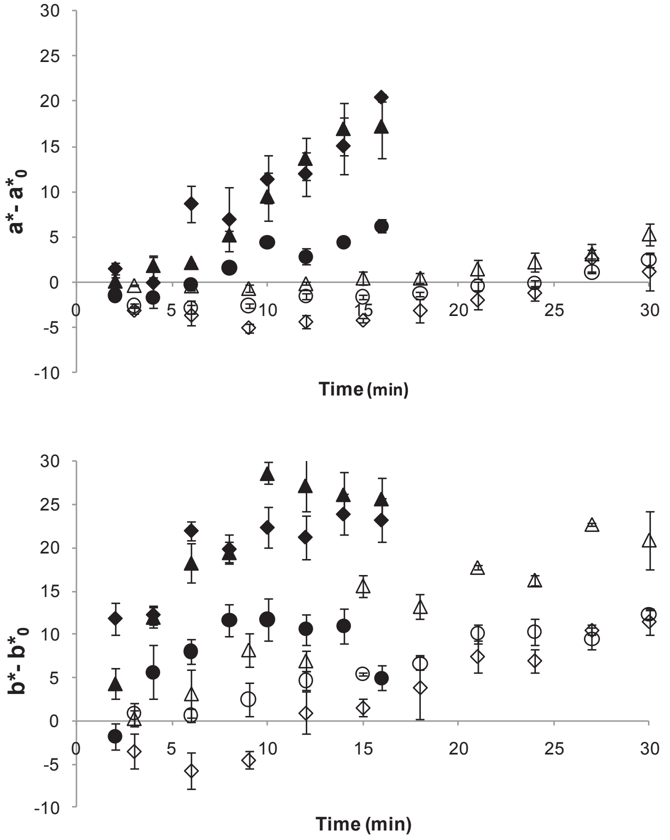

Fig. 2. Evolution of chromatic parameters a* and b*, with respect to initial value (a*−a$^*_0$; b*−b$^*_0$), versus time in unpretreated (control), blanched and frozen French fries fried subjected to deep-oil (◆, ▲ and ●, respectively) or air frying (◇, Δ and O, respectively) ($n = 3$).

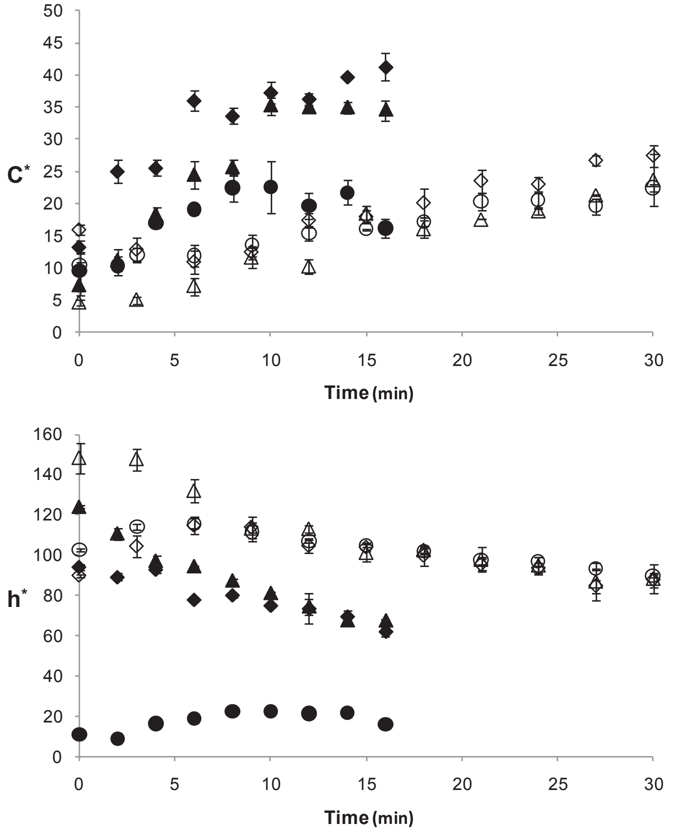

Fig. 3. Evolution of chrome (C*) and hue (h*) versus time in unpretreated (control), blanched and frozen French fries fried subjected to deep-oil (◆, ▲ and ●, respectively) or air frying (◇, Δ and O, respectively) ($n = 3$).

The difference between colour coordinates in both frying methods is even higher when values are compared after 16 min of frying, maximum frying time in deep-oil frying. At this frying time, the increase in a* for hot-air frying is negative and close to zero. This fact corroborates the lowest speed of physicochemical changes associated with mass and heat transfer in hot air-frying in comparison with traditional frying (Heredia et al., 2010). Greater energy input to the potato strip will result in faster drying. It is known that low moisture content favours Maillard's reactions (increase of a* and darkness of the samples) and consequently the formation of acrylamide (Gökmen et al., 2006).

In summary, deep-oil frying tends to increase the darkness of the samples in comparison to hot-air frying, especially in frozen samples. In fact, frozen samples showed a whiter colour before frying as a consequence of freezing. In contrast, hot-air frying implied an increase in luminosity or a null change despite requiring the longest treatment time.

Fig. 3 shows the evolution of chrome (C*) and hue (h*) of the French fries as a function of frying time and pre-treatment for both frying methods. It can be observed that deep-oil fried samples showed higher C* than hot-air fried ones, and the influence of the pre-treatment was only significant in deep-oil frying. Concretely, frozen potatoes showed lower values of C* than the others. With regards to hue (h*), the type of frying did not greatly affect h* values. However, it should be noted that frozen samples showed the lowest value of h* for deep-oil frying.

As has been mentioned before, high values of coordinate a*, and consequently high values of h*, could be related to high acrylamide generation as a consequence of browning (Becalski, Lau, Lewis, & Seaman, 2003; Haase et al., 2003; Pedreschi et al., 2006). These results suggest that hot air frying could be a healthier frying method as it slows down the kinetics of acrylamide formation and reduces the oil intake in the final product. However, to confirm this it would be necessary to determine the acrylamide content in the different studied conditions.

The texture of fried products is mainly characterised by the formation of a surface crust. This is also the parameter which is most appreciated by consumers. This crusty texture is a consequence of changes in the external layers of the product at a cellular level. These physicochemical changes include the physical damage caused by cutting the product, the formation of a rough layer with a release of intracellular material, starch gelatinization, protein denaturalization, water evaporation, expansion, tissue browning and finally oil ingress (Bouchon, Hollins, Pearson, Pyle, & Tobin, 2001).

Fig. 4 shows the evolution of maximum force (N) during deep-oil and hot-air frying. This variable permits study not only of the softening of the vegetable tissue during the first minutes of the process, but also the development of the crust over time (Bourne, 2002). As can be observed, in general, samples showed an initial stage of softening or firmness loss from the maximum value of firmness registered at time zero, followed by a second stage where maximum force tended to increase as the surface crust appeared. However, it should be noted that the kind of frying affected the first stage of softening. In deep-oil frying a sharp decrease of the maximum force was produced in the first 2 min, which is related to a fast gelatinization of surface starch, characteristic of deep-oil frying, along with the partial denaturalization of proteins (Bouchon et al., 2001); while in hot-air frying the firmness loss took

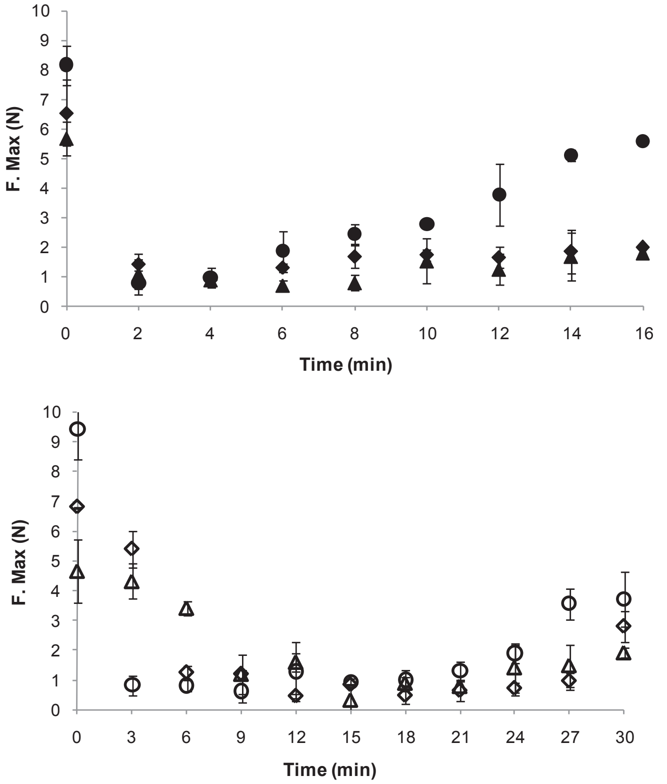

Fig. 4. Evolution of the Maximum Force (N) versus time in unpretreated (control), blanched and frozen French fries fried subjected to deep-oil (◆, ▲ and ●, respectively) or air frying (◇, Δ and O, respectively) ($n = 3$).

place in a more gradual way, reaching a minimum value between 15 and 21 min depending on the pre-treatment applied. Another difference is that crust formation started to appear earlier in the deep-oil fried potatoes (from 2 min on), due to the high evaporation rate, than in the hot-air fried ones (from 18 min on). It is important to point out that the transition from the first stage (softening) to the second one (crust formation) takes place when the minimum force value is achieved. In a study carried out by Heredia et al. (2010) in which mass transfer phenomena, in terms of compositional changes and water and oil fluxes, were studied, it was reported that all samples presented a similar moisture content (60–62%) at 2 and 18 min of deep-oil frying and hot-air frying, respectively. Therefore, it could be possible to associate this moisture content with the beginning of crust formation.

With regards to the influence of the applied pre-treatment in both types of frying it was observed that frozen potatoes had greater firmness at the end of the process. The higher consistency of their crust could be due to the fat coating, since they are pre-fried with an initial fat content of 3% according to the manufacturer. Unpretreated and blanched French fries showed a similar tendency in mechanical behaviour, although blanched potatoes tend to have a less crunchy surface.

4. Conclusions

The kinetics of mechanical and optical changes were strongly dependent on the frying method, being faster in deep-oil frying. Hot-air frying caused the lowest increase in the a* coordinate, which suggests that this new kind of frying could considerably reduce the amount of acrylamide in French fries. Regarding texture, results show that it is possible to obtain French fries with similar textural features even if hot-air frying slows down the kinetics of mechanical changes compared to deep-oil frying.

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