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Color development and acrylamide content of pre-dried potato chips

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Abstract

The objective of this work was to study the development of color formation in pre-dried potato slices during frying and acrylamide formation in the final potato chips. Color measurement was done by using an inexpensive computer vision technique which allowed quantifying representatively and precisely the color of complex surfaces such as those of potato chips in $L^*a^*b^*$ units from RGB images. Prior to frying, potato slices (Desirée variety, diameter: 37 mm, width: 2.2 mm) were blanched in hot water at 85 °C for 3.5 min. Unblanched slices were considered as the control. Slices of the same dimensions were blanched as in the previous step, and then air-dried until reaching a moisture content of 60% (wet basis). These samples were called pre-dried potato slices. Potato slices were fried at 120 °C, 140 °C, 160 °C and 180 °C until reaching moisture contents of ~1.8% (total basis) for color quantification. Acrylamide concentration was determined only in final chips fried at 120 °C, 150 °C and 180 °C and compared with that of two brands of commercial chips produced in Chile (Moms and Frito Lay). Color values in $L^*a^*b^*$ units were recorded at different sampling times during frying at the four mentioned temperatures using the total color difference parameter (ΔE). Pre-drying did not affect the color of potato chips considerably when compared against blanched chips; however when fried at 180 °C, pre-dried potato chips present 44%, 22%, 44% lower acrylamide content than that of the control, Moms and Frito Lay chips, respectively.

Keywords: Potato chips; Frying; Color; Pre-drying; Blanching; Acrylamide

1. Introduction

Potato chips have been a popular salty snack for 150 years whose consumption yearly in US is around 1.2 billion of pounds (Clark, 2003). Potato chips are thin potato slices that are dehydrated by deep fat frying to a moisture content of 0.02 kg/kg or less (Baumann & Escher, 1995). Potato chips have an oil content that ranges from 35% to 45% (wet basis) and gives the product a unique texture–flavor combination that makes them so desirable (Garayo & Moreira, 2002; Mellema, 2003). Dehydration in hot oil at temperatures between 160 °C and 180 °C is characterized by high drying rates that are critical for ensuring favorable structural and textural properties of the final product (Baumann & Escher, 1995).

Color development only begins when sufficient amount of drying has occurred in potato slices and depends also on the drying rate and the heat transfer coefficient during the different stages of frying. Color is visually considered one of the most important parameters in the definition of

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quality of fried potatoes (Scanlon, Roller, Mazza, & Pritchard, 1994) and is the result of the Maillard reaction that depends on the content of reducing sugars and amino acids or proteins at the surface, and the temperature and time of frying (Márquez & Añón, 1986).

Color of fried potatoes has been measured usually in units $L^*a^*b^*$ using either a colorimeter or specific data acquisition and image processing systems. $L^*a^*b^*$ is an international standard for color measurements, adopted by the Commission Internationale d'Eclairage (CIE) in 1976. L^* is the luminance or lightness component, which ranges from 0 to 100, and parameters a^* (from green to red) and b^* (from blue to yellow) are the two chromatic components, which range from −120 to 120 (Papadakis, Abdul-Malek, Kamdem, & Yam, 2000). In the $L^*a^*b^*$ space, the color perception is uniform which means that the Euclidean distance between two colors corresponds approximately to the color difference perceived by the human eye (Hunt, 1991).

Computer vision (CV) is a technology for acquiring and analyzing an image of a real scene by computers to obtain information or to control processes (Brosnan & Sun, 2004). Digital image processing is the core of CV with numerous algorithms and methods capable objectively of measuring and assessing the appearance quality of several agricultural products (Mery & Pedreschi, 2005). CV has been used in the food industry for quality evaluation, detection of defects, identification, grading and sorting of fruits and vegetables, meat and fish, bakery products and prepared goods, among others.

In the last years, some simple CV systems have been used to measure objectively the color of fried potatoes since they provide some obvious advantages over a conventional colorimeter, namely, the possibility analyzing the whole surface of the chip, and quantifying local characteristics such as brown spots and other defects. Color of potato chips has been measured using computerized video image processing by mean of gray level values (Scanlon et al., 1994). A computer-based video system was developed to quantify the color of potato chips in the $L^*a^*b^*$ color space (Segnini, Dejmek, & Öste, 1999). Marique, Kharoubi, Bauffe, and Ducatillon (2003) modeled the color classification of potato chips by image analysis and artificial neural networks obtaining correlation coefficients of 0.972 for training data and of 0.899 for validation data. A pattern recognition approach was used for classification of potato chips processed under six different conditions obtained good classification performance (Pedreschi, Mery, Mendoza, & Aguilera, 2004).

Reports of the presence of acrylamide in a range of fried and oven-cooked foods have caused worldwide concern because this compound has been classified as probably carcinogenic in humans (Rosen & Hellenäs, 2002; Tareke, Rydberg, Karlsson, Eriksson, & Tornqvist, 2002). In April 2002, Swedish researchers shocked the food safety world when they presented preliminary findings of acrylamide in some fried and baked foods, most notably potato chips and French fries, at levels of 30–2300 μm/kg (Pedreschi, Kaack, & Granby, 2004; Pedreschi, Kaack, & Granby, 2006). The data published so far indicate that a temperature >100 °C is required for acrylamide formation (Becalski, Lau, Lewis, & Seaman, 2003). Tareke et al. (2002) showed that acrylamide was formed by heating above 120 °C certain starch-based foods, such as potato chips, French fries, bread and processed cereals.

Acrylamide could be formed from food components during heat treatment as a result of the Maillard reaction between amino acids and reducing sugars (Mottram & Wedzicha, 2002; Stadler et al., 2002). Asparagine, a major amino acid in potatoes and cereals, is a crucial participant in the production of acrylamide by Maillard reaction at temperatures above 100 °C (Friedman, 2003). Since potato products are especially high in asparagine, it is now thought that this Maillard reaction is most likely responsible for the majority of the acrylamide found in potato chips and French fries. Both potato variety and field site had a noticeable influence upon acrylamide formation. In addition to food composition, other factors involved in acrylamide formation are the processing conditions (pretreatments, temperatures and times).

The blanching step previous to frying in potato chip production improves the color and texture, and could reduce in some cases the oil uptake by gelatinization of the surface starch (Califano & Calvelo, 1987). Drying of potatoes before frying using microwave, hot-air treatment and baking has resulted in a significant reduction in oil content of different products (Krokida, Oreopolou, Maroulis, & Marinos-Kouris, 2001; Moreira, Castell-Perez, & Barrufet, 1999; Moyano, Ríoseco, & Gonzaléz, 2002). Air dehydration leads to a lower moisture content which also reduces the oil absorption (Talburt, Weaver, Reeve, & Kueneman, 1987). The drying step that follows the blanching step reduces the amount of oil absorbed and improves the crispness of the potato chips (Pedreschi & Moyano, 2005a).

The objectives of this research were (i) to study color development in blanched and pre-dried potato chips at different oil temperatures using an inexpensive implemented CV system; (ii) to study the effect of blanching and pre-drying over the acrylamide content in potato chips fried at three oil temperatures.

2. Materials and methods

2.1. Materials

Potatoes (variety Desirée, ~23% of dry solids; 0.3% reducing sugars) and vegetable oil (Chef, COPRONA, Chile) were the raw materials. Potatoes stored at 8 °C and 95% of relative humidity were washed and peeled before cutting. Slices of thickness of 2.2 mm were cut from the pith of the parenchymatous region of potato tubers using an electric slicing machine (Berkel, model EAS65). A circular cutting mold was used to make circular slices with a diameter of 37 mm.

2.2. Pre-treatments

Slices were rinsed immediately after cutting for 1 min in distilled water to eliminate some starch adhering to the surface prior to frying. Blanched samples were prepared by heating raw slices in 5 l of hot water at 85 °C for 3.5 min (potato-to-water ratio ~0.005 w/w). Unblanched or raw slices were considered as the control. Pre-dried samples were prepared by placing some blotted blanched slices on a tray, arranged in a single layer and dried in a convection oven (Memmert, mod ULM 500) at a dry bulb temperature of 60 ± 1 °C and air velocity of 1 ± 0.1 m/s. The mass loss was monitored continuously until the slices reached a final moisture content of 60% (wet basis).

2.3. Frying conditions

Ten slices per sampling time were deep-fried in 5 l of hot oil contained in an electrical fryer (Beckers, Model F1-C, Italy) at each of the four temperatures (120 °C, 140 °C, 160 °C and 180 °C) and the three pre-treatments tested. Frying temperature was kept almost constant (±1 °C). Slices were fried at different time intervals until reach a final moisture content of ~1.8% (wet basis). Previously, the corresponding total frying times and the sampling intervals for each frying temperature were determined experimentally. The oil was preheated for 1 h prior to frying, and discarded after 6 h of use (Blumenthal, 1991).

For acrylamide study, 10 slices of control or blanched potato slices were fried for the minimum time required to reach a moisture content of ~1.8% (wet basis) at the following three oil temperatures: 120 °C, 150 °C and 180 °C.

All experiments were run in duplicate. Fried slices were drained after frying over a wire screen for 5 min and allowed to cool to room temperature before acrylamide or color analysis were done.

2.4. Analyses

2.4.1. Color quantification by computer vision

For studying the kinetics of color development during frying, a CV system previously implemented was used to measure the color of potato slices (Pedreschi et al., 2004). The general methodology that follows the mentioned CV system to convert RGB images into units $L^*a^*b^*$ is briefly described:

(i) *Image acquisition*: Images were captured using an image acquisition system for color digital camera similar to that developed by Papadakis et al. (2000), namely:
(a) Samples were illuminated using four fluorescent lamps (length of 60 cm) with a color temperature of 6500 K (Philips, Natural Daylight, 18 W) and a color rendering index (Ra) close to 95%. The four lamps were arranged as a square 35 cm above the sample and at an angle of 45° with the sample plane to give a uniform light intensity over the food sample.
(b) A Color Digital Camera (CDC) Power Shot G3 (Canon, Japan) was located vertically at a distance of 22.5 cm from the sample. The angle between the camera lens axis and the lighting sources was around 45°. Sample illuminators and the CDC were inside a wood box whose internal walls were painted black to avoid the light and reflection from the room. The white balance of the camera was set using a standardized gray color chart from Kodak.
(c) Images were captured with the mentioned CDC at its maximum resolution (2272 × 1704 pixels) and connected to the USB port of a Pentium IV, 1200 MHz computer. Canon Remote Capture Software (version 2.7.0) was used for acquiring the images directly in the computer in TIFF format without compression.

(ii) *Image preprocessing:* The digital images must be preprocessed to improve their quality before they are analyzed. Using digital filtering the noise of the image can be removed and the contrast can be enhanced. In addition, in this step the color image is converted to a gray-scale image, called the intensity image [I]. In order to reduce the computational time of processing the images were sub-sampled to 1136 × 852 pixels. A linear Gaussian low pass filter (Castleman, 1996) was applied in order to reduce the noise in the images.

(iii) *Segmentation:* The intensity image is used to identify disjoint regions of the image with the purpose of separating the part of interest from the background. This segmented image [S] is a binary image consisting only of black and white pixels, where '0' (black) and '1' (white) mean background and object, respectively. Image segmentation (to separate the true image of the potato chips from the background) was performed using a threshold combined with an edge detection technique based on the Laplacian-of-Gaussian filter (Castleman, 1996; Mery & Filbert, 2002). In our case, the region of interest within the image corresponds to the area where the potato chip is located and a robust algorithm for proper potato image segmentation was previously developed (Mery & Pedreschi, 2005).

(iv) *Conversion of RGB images into $L^*a^*b^*$ units*: This methodology was developed previously and is carefully detailed by León, Mery, Pedreschi, and León (in press). Five models for the conversion from RGB images to $L^*a^*b^*$ units were developed and tested: linear, quadratic, gamma, direct, and neural network. In the evaluation of the performance of those models, the neural network model stands out with an error of only 0.96%. So it was possible to find a $L^*a^*b^*$ color measuring system that is appropriate for an accurate, exacting and detailed characterization of a food item, thus improving quality control and providing a highly useful tool for the food industry based on a color digital camera.

2.4.2. Acrylamide determination

Acrylamide analysis, acrylamide (2-propene amide) [CAS No. 79-06-1] (>99.5%) was obtained from Sigma–Aldrich (St. Louis, MO, USA). Labelled *d*3-acrylamide (>98%) was from Polymer Source Inc. (Dorval, Québec, Canada). The SPE columns were Isolute Multimode 300 mg from International Sorbent Technology (Hengoed, Mid Glamorgan, UK). Mini uniprep Teflon filter vials 500 μl, filter pore size 0.45 μm, Whatman Int. Ltd (Kent, UK). The water used was MilliQ water (Millipore Corp., Bedford, MA, USA). The acetonitrile was of HPLC grade from Rathburn Chemicals (Walkerburn, Scotland). Formic acid for the eluent (0.1% in water) was from Merck (Darmstadt, Germany). All stock solutions of acrylamide and *d*3-acrylamide (1000 and 10 $\mu g\, ml^{-1}$) as well as calibration standards (2–30 $ng\, l^{-1}$) were prepared in water and kept at −18 °C until use.

Homogenised potato (4.00 g) were extracted with 40.0 ml MilliQ water by an Ultra-turrax mixer (Janke & Kunkel, Staufen, Germany) (after the addition of 200 μl *d*3-acrylamide 10 μg/ml as internal standard). Each analytical batch included 1–2 spiked samples for recovery measurements. The samples were centrifuged for 10 min at 3500 rpm (Hereaus Sepatech Megafuge 3.0 R (Osterode, Germany)). The clean up was made on 300 mg Isolute Multimode SPE columns (IST), using an ASPEC TM XLi automatic SPE clean up system (Gilson Inc., Middleton, WI, US). The SPE columns were conditioned with acetonitrile (1 ml) and water (2*2 ml). The first 500 μl was discharged and the following 400 μl of sample was collected in Mini uniprep Teflon filter HPLC vials.

A HP1100 HPLC system (Agilent Technologies, Palo Alto, CA, USA) was used for acrylamide separation on a Hypercarb column, 5 μm, 50 mm*2.1 mm (ThermoHypersil, Cheshire,UK) www.thermohypersil.co.uk after a guard column (Phenomenex SecurityGuardTM, C18 ODS, 4 mm × 2.0 mm, Cheshire, UK). The sample (10 μl) was injected and eluted with 0.1% formic acid in water at a flow of 250 $\mu l\, min^{-1}$. The MS/MS detection was performed on a Quattro Ultima triple quadrupole instrument with masslynx software (Micromass Ltd., Manchester, UK). The electrospray was operated in the positive ion mode, and the capillary was set to 3.0 kV, the cone voltage was 31 V, and the collision energy 10 eV. The source temperature was set at 120 °C and the desolvation temperature at 400 °C. Nitrogen was used as nebulizer gas (flow 500 $l\, h^{-1}$) and desolvation gas (flow 150 $l\, h^{-1}$), and argon was used as collision gas at a pressure of 2.3×10^{-3} mbar. The multiple reaction monitoring (MRM) mode of the degradation patterns *m*/*z* 72 → 55 (acrylamide) and *m*/*z* 75 → 58 (*d*3-acrylamide) were used for quantification. Acrylamide analyses were done in a laboratory accredited for acrylamide analysis in foods by The Danish Accreditation Body.

2.5. Color development during frying

The kinetics of color formation of potato slices during frying at four different oil temperatures was followed by the parameter total color difference (ΔE) which was calculated in the following way: $\Delta E = ((L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2)^{1/2}$. The $L^*a^*b^*$ values correspond to the values of potatoes slices fried at different frying times and the values of $L_0^*a_0^*b_0^*$ corresponds to potato slices without frying (time zero). Experimental data of chip color changes ΔE was fit to the following empirical relationship:

$$\Delta E = b_1 + b_2 \exp\left(\frac{-t}{b_3}\right) \tag{1}$$

where t is the frying time, and b_1, b_2 and b_3 are regression coefficients.

2.6. Statistical analysis

Analysis of variance was carried out when require using Statgraphic Statistical Package (Statistical Graphics Corporation, Version 4, Rockville, USA) including multiple range tests ($P > 0.5$) for separation of least square means.

3. Results and discussion

3.1. Kinetics of color change

There were selected two low frying temperatures (120 °C and 140 °C) and two high (160 °C and 180 °C) in order to evaluate the effect of the oil temperature over browning development in potato slices during frying. For acrylamide analysis, we use three oil temperatures to fry potato chips (120 °C, 150 °C and 180 °C). Three pre-treatments were studied: (i) unblanched or raw potato (control); (ii) blanched; (ii) blanched-dried (pre-dried potato chips).

The CV system implemented to measure the color in $L^*a^*b^*$ units in potato chips has the advantage to allow quantifying the average color values over the entire heterogeneous surface of potato chips making the measurements more representative. Luminosity (L^*) diminish with frying time for pre-dried potato samples since some parts of slice surface tend to get darker as a result of non-enzymatic browning during frying (Fig. 1). The same trend was found for control and blanched samples (results not shown). The luminosity of potato slices decreases more as the frying temperature increases as expected. Similar trend for L^* has been found for frying of potato strips and potato slices (Bunger, Moyano, & Rioseco, 2003; Segnini et al., 1999). However, some authors have reported that the lightness of potato strips increases during the early stages of the frying, while it remains almost constant afterwards (Krokida et al., 2001). The potato variety used for frying will have a strong effect over the color parameters of the potato slices during frying. The chromatic parameter a^* of pre-dried potato slices increases considerably during frying due to browning reactions that takes place during frying; the higher the frying temperature the faster the slices tend to get red (Fig. 2). These results are coincident with those found by other authors for frying of potato slices of other potato varieties such as Panda, Saturna and Bintje

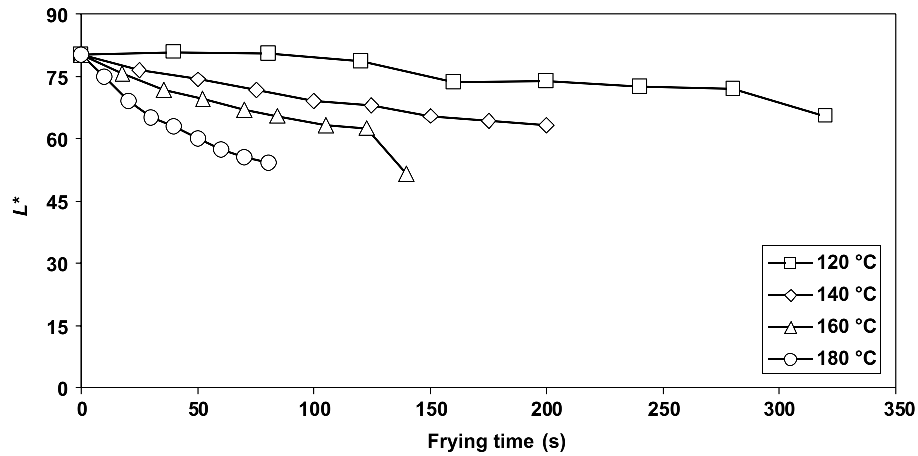

Fig. 1. Change in L^* parameter with frying time for pre-dried potato slices.

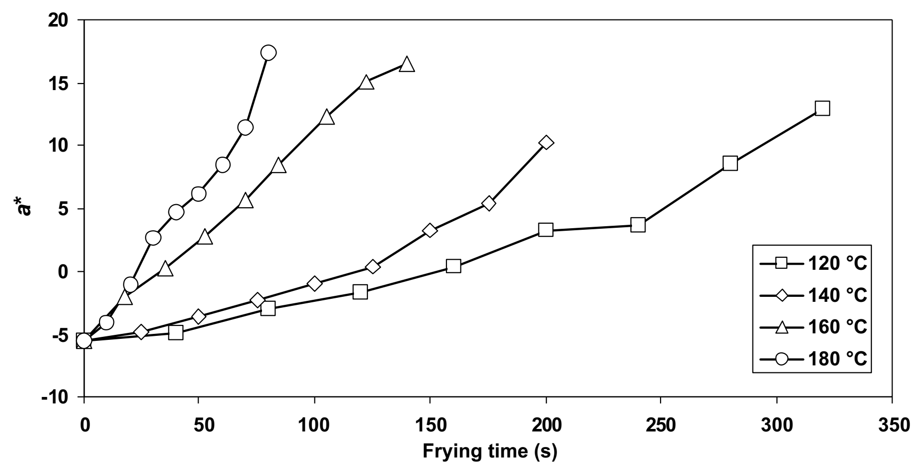

Fig. 2. Change in a^* parameter with frying time for pre-dried potato slices.

(Pedreschi et al., 2004; Segnini et al., 1999). Finally, the chromatic color component b^* increases with frying time and as with the other chromatic component their values tend to increase faster as the frying temperature increases (Fig. 3). These results suggest that the yellowness of potato slices increases during frying and are coincident with those obtained by other authors (Krokida et al., 2001; Segnini et al., 1999). $L^*a^*b^*$ color components showed very similar

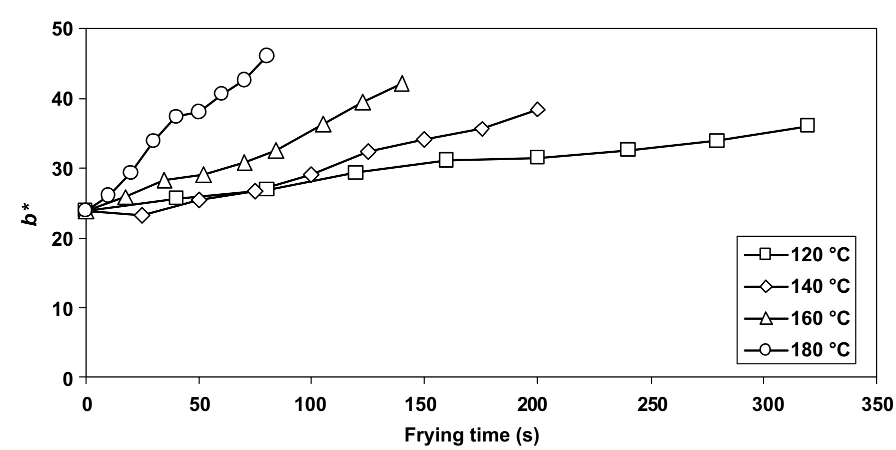

Fig. 3. Change in b^* parameter with frying time for pre-dried potato slices.

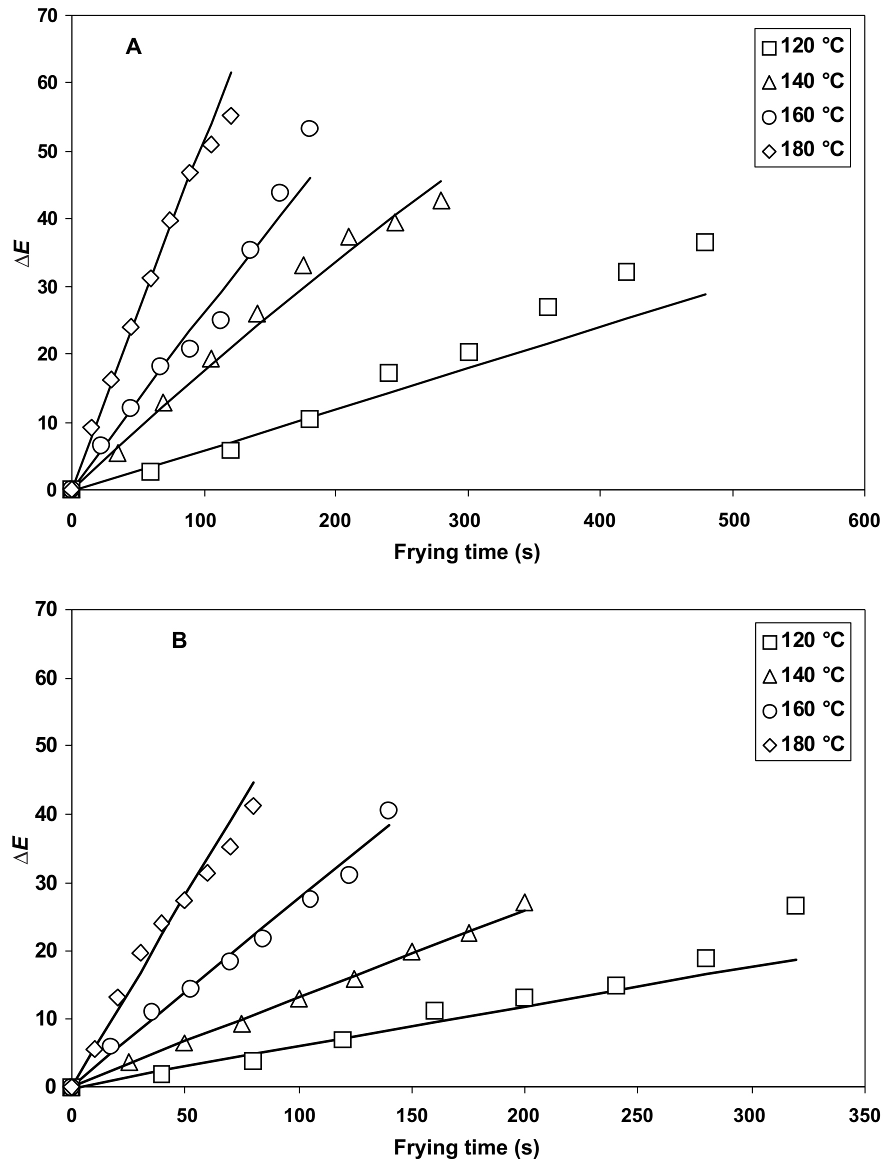

Fig. 4. Kinetics of color change in potato slices during frying followed by parameter ΔE for (A) control potato slices fried at 120 °C, 140 °C, 160 °C and 180 °C; (B) Pre-dried potato slices fried at 120 °C, 140 °C, 160 °C and 180 °C. Symbols: experimental data; solid lines: Eq. (1).

trend for the frying of control and blanched potato slices to those obtained for pre-dried potato slices fried at the same oil temperatures (results not shown).

Low reducing sugar and asparagine contents are required to minimize color development during frying of potatoes (Mottur, 1989; Pedreschi et al., 2004). Fried potato color is the result of Maillard, non-enzymatic browning reactions that depends on the superficial reducing sugar content, and the temperature and frying period (Márquez & Añón, 1986). Color changes in the potato slices during frying were followed by ΔE, since this color parameter showed notorious changes during frying. Eq. (1) fit experimental ΔE data properly in all the studied cases. Potato slices tend to get darker as frying proceeds (as a result of surface non-enzymatic browning reactions) as indicating by the progressive linear increasing of ΔE values with frying time (Fig. 4A and B). The higher the frying temperature the darker the potato chips get since non-enzymatic browning reactions are highly temperature

Table 1
Color difference values of potato chips (~1.8% moisture content wet basis) fried at 120 °C, 140 °C, 160 °C and 180 °C

Treatments	ΔE			
	120 °C	140 °C	160 °C	180 °C
Unblanched	36.65^{a}	42.55^{a}	53.38^{a}	55.27^{a}
Blanched	19.34^{b}	23.67^{b}	43.73^{b}	45.33^{b}
Pre-dried	26.52^{b}	27.16^{b}	40.47^{b}	41.23^{b}

Means in one column followed by the same superscript are not different at $P > 0.5$.

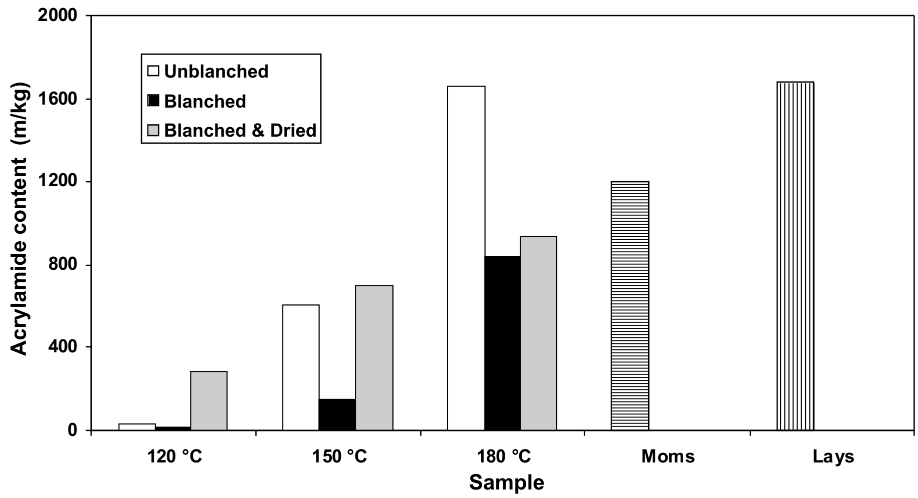

Fig. 5. Acrylamide concentration for control, blanched and pre-dried potato chips fried at 120 °C, 150 °C and 180 °C, and for two brands of commercial chips (Moms and Frito Lays).

dependant. Pre-drying of potato slices lead to paler potato slices than those of the control after frying at 120 °C, 140 °C, 160 °C and 180 °C. However, the differences in color (ΔE) are not significant ($P > 0.5$) between the frying of blanched and pre-dried potato chips (Table 1). For the blanching treatment used in this research (85 °C, 3.5 min), it has been demonstrated that the blanched potato slices when fried absorbed considerable more oil than control chips (Pedreschi & Moyano, 2005b). On the other hand, blanched-dried slices (pre-dried slices) absorbed less oil and developed crispier textures than control and only blanched slices during frying (Pedreschi & Moyano, 2005a).

3.2. Acrylamide formation in potato chips

Different samples were fried for different times to reach in the minimal time at each temperature a moisture content of ~1.8%. Previous experiments were done to determine the minimal time the reach this moisture content. Low oil temperatures (e.g. 120 °C) and blanching treatment before frying decreased drastically the acrylamide content in potato chips (Fig. 5). Blanching treatment reduced the acrylamide content in potato chips in 68%, 75% and 49% at the frying temperatures of 120 °C, 150 °C and 180 °C, respectively. The mechanism by which blanching diminish acrylamide formation is due to the leaching of reducing sugars and asparagine during the immersion of the slices in hot water. Data published so far indicate that a temperature >100 °C is required for acrylamide formation (Becalski et al., 2003). Acrylamide formation increased considerably in control, pre-dried and blanched slices when the frying temperature was increased from 120 °C to 180 °C. Pre-drying has a complex effect over the acrylamide formation in potato chips. At the low frying temperature of 120 °C it generates considerably more acrylamide formation than blanching and control. At intermediate frying temperatures such as 150 °C, pre-drying almost did not alter the formation of acrylamide of the control potato chips. However, at high and commonly used frying temperatures such as 180 °C, pre-drying diminished in 44% the acrylamide formation in control potato chips and generates almost the same amount of acrylamide as in blanched potato chips. However, pre-drying generates chips with lower oil content and crispier than only blanched chips (Pedreschi & Moyano, 2005a). Besides, when fried at 180 °C, pre-dried potato chips present 22% and 44% lower acrylamide content than that Moms and Frito Lay commercial chips, respectively. Additional research is needed to determine the mechanism and the influence of pre-drying of potato slices in acrylamide formation in potato chips fried at different temperatures.

4. Conclusions

Pre-drying improved the color and diminished the acrylamide formation of the control potato chips. Blanching reduced acrylamide formation drastically during frying at the three temperatures tested. Acrylamide formation increased considerably with frying temperature; the more drastic increase took place in control potato chips. At 180 °C, pre-dried potato chips presented acrylamide content much lower than those of control and commercial chips, and similar to those of only blanched potato chips.

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