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# Color kinetics and acrylamide formation in NaCl soaked potato chips

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**Abstract**

The objective of this work was to study the kinetics of color development in blanched and blanched-NaCl impregnated potato slices during frying by using the dynamic method and also to evaluate the effect of NaCl in reducing acrylamide formation in potato chips. The measurement of color was done by using an inexpensive computer vision technique which allowed quantifying in a more precise and representative way the color in $L^*a^*b^*$ units of complex surfaces such as those of potato slices during frying. The effect of potato slice soaking in NaCl was evaluated not only for color change but also for acrylamide formation. Prior to frying, potato slices (Desiree variety, diameter: 37 mm, width: 2.2 mm) were blanched in hot water at 85 °C for 3.5 min; these slices were considered as the control. Slices of the same dimensions were blanched as in the previous step, and soaked at 25 °C in a NaCl solution of 0.02 g/l 5 min at 200 rpm of agitation. These samples were considered as NaCl soaked potato chips.

Blanched and soaked slices were fried at 120, 140, 160 and 180 °C until reaching moisture contents of ~1.8% (total basis) for color evaluation. Acrylamide content was evaluated only in final samples fried from 120 °C to 160 °C. Color values in $L^*a^*b^*$ units were recorded at different sampling times during frying at the four mentioned temperatures using the total color change parameter ($\Delta E$). Experimental data of surface temperature, moisture content and color change in potato chips during frying were fitted to empirical relationships, with correlation coefficients greater than 90%. A first-order rate equation was used to model the kinetics of color change. In all cases, the Arrhenius activation energy decreases alongside with decreasing chip moisture content. Soaking in NaCl solution of potato slices before frying reduced dramatically acrylamide formation in potato chips in ~90% (average value) in comparison with control chips.


*Keywords:* Potato slices; Frying; Color; Kinetics; Soaking; NaCl; Acrylamide

## 1. Introduction

Deep-fat frying is one of the oldest processes of food preparation and consists basically of immersion of food pieces in hot oil. The high temperature causes evaporation of the water, which moves away from the food and through the surrounding oil. Oil is absorbed by the food, replacing some of the lost water (Oliveira, Pereira, & Oliveira, 1994). Potato chips have been popular salty snacks for 150 years and its retail sales in US are about $6 billion/year representing 33% of the total sales on this market (Clark, 2003; Garayo & Moreira, 2002).

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**Nomenclature**

| | |
|---|---|
| $a_i$ | regression coefficient in Eq. (3) |
| $a^*$ | redness chromatic parameter of the CIE Lab color scale |
| $b_i$ | regression coefficient in Eq. (5) |
| $b^*$ | yellowness chromatic parameter of the CIE Lab color scale |
| $E_a$ | activation energy (kJ/mol) |
| $k$ | first-order rate constant for color change (1/s) |
| $k_0$ | frequency factor (1/s) |
| $L^*$ | lightness parameter of the CIE Lab color scale |
| $m$ | moisture content (g water/g dry solid) |
| $n$ | regression coefficient in Eq. (4) |
| $N$ | number of data points used |
| $q$ | regression coefficient in Eq. (4) |
| $R$ | ideal gas constant (kJ/kmol K) |
| $t$ | time (s) |
| $T_s$ | surface temperature (°C, K) |

*Subscripts*

| | |
|---|---|
| 0 | initial |
| obs | observed values |
| pred | predicted values |
| max | maximum values |

Immersion frying has been defined as the immersion of a food product in an edible fat heated above the boiling point of water, and may therefore be considered a dehydration process (Hubbard & Farkas, 1999). These conditions lead to high heat transfer rates, rapid cooking, browning, texture and flavor development (Farkas, Singh, & Rumsey, 1996).

Color of potato chips is an extremely important criterion for the potato processing industry and it is strictly related to consumer perception (Scanlon, Roller, Mazza, & Pritchard, 1994). On the other hand, acrylamide has recently been reported as a critical compound for human health that is formed in potatoes during frying and that is highly related to the color of the chip (Mottram & Wedzicha, 2002; Pedreschi, Moyano, Kaack, & Granby, 2005; Pedreschi, Kaack, & Granby, 2006; Rosen & Hellenäs, 2002; Stadler et al., 2002). Fried potato color 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, 2003). 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, computer vision has 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 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). A pattern recognition approach was used for classification of potato chips processed under six different conditions and obtained good classification performance (Pedreschi, Mery, Mendoza, & Aguilera, 2004). 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.

In order to study the kinetics of deteriorative reactions the dynamic method was proposed (Mizrahi, 2000). This method uses the continuous change in moisture content and temperature to evaluate the kinetics of deterioration in moisture-sensitive products and it can be applied to cases where the reaction has known rate order and is dependent on water content and temperature. This method requires moisture, food temperature and a deteriorative index as a function time. At temperatures up to 60 °C, browning is normally a zero-order reaction. Since deep-fat frying process usually has a very short period with a surface temperature lower than 60 °C, a first-order kinetic analysis for browning during frying is expected. Moyano, Ríoseco, and Gonzaléz (2002) studied the kinetics of crust browning during deep-fat frying of potato strips by using the dynamic method and considering a first-order rate equation. Márquez and Añón (1986) used a first-order reaction approach to study the color development in fried potatoes. Ateba and Mittal (1994) calculated first-order kinetic parameters for browning during the frying of meat balls. Krokida, Oreopolou, Maroulis, and Marinos-Kouris (2001) assumed that the color parameters $L^*$, $a^*$ and $b^*$ followed a first-order kinetics to determine the rate of color changes during frying of potato strips. Pedreschi et al. (2005) assumed that the color parameter $a^*$ followed a first-order kinetics to determine the rate of color changes during frying of potato and find a good correlation between the acrylamide content of the chips and their color.

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. Since color development is a surface phenomena, the surface potato slice temperature, $T_s$, should be considered. $T_s$ may be greater than the central temperature, depending on the potato thickness and also the coloring rate is moisture dependent (Moyano et al., 2002). Then, the Arrhenius relationship should be written as follows:

$$\ln k(m) = \ln k_0(m) + \frac{E_a(m)}{RT_s} \tag{1}$$

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. 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.

Mottram and Wedzicha (2002) showed how acrylamide could be formed from food components during heat treatment as a result of the Maillard reaction between amino acids and reducing sugars. 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 (pre-treatments, temperatures and times).

The blanching step previous to frying in potato chip processing improves the color and texture, and could reduce in some cases the oil uptake by gelatinization of the surface starch (Califano & Calvelo, 1987). Blanching could reduce the content of glucose and asparagine in potato slices by leaching these compounds into hot water leading to significant lower acrylamide formation than in unblanched potato chips (Pedreschi, Kaack, & Granby, 2004). Haase, Matthäus, and Vosmann (2003) reported that a reduction of the sugar content by blanching could reduce the acrylamide concentration by about 60% according to the raw material (potato variety and field site) and the production process variables (e.g. blanching conditions and frying temperature). Soaking of potato strips in 3%, 5% and 7% NaCl solutions previous to frying reduced significantly the oil absorption and increased texture parameters in the final French fries (Bunger, Moyano, & Rioseco, 2003).

The objective of this work was to (i) study the browning kinetics during deep-fat frying of blanched and soaked potato slices in NaCl by using the dynamic method; (ii) determine acrylamide formation in potato chips processed under different conditions; (iii) evaluate the effect of NaCl immersion over the color and final acrylamide content of potato chips.

## 2. Materials and methods

### 2.1. Materials

Potatoes (variety Desiree, ~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 (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). Blanched slices were considered as the control (i). Blanched slices were soaked in a 0.002 g/l NaCl solution at 25 °C for 5 min at 200 rpm of agitation. These samples were called salt soaked slices (ii).

### 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, 140, 160 and 180 °C) and pre-treatments tested for color evaluation. 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 pre-heated for 1 h prior to frying, and discarded after 6 h of use (Blumenthal, 1991).

Temperature was measured in the frying oil and near the surface of selected potato slices using a data acquisition system, comprising a data-logger (Omega, OM-300, New Zealand) and a personal computer. The thermocouple was imbedded 0.5 mm below the surface of the chip. Temperatures were recorded at 1 s intervals. Temperature measured near the surface of potato slices was called surface temperature $T_s$.

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, 140 and 160 °C. Fried chips were drained after frying over a wire screen for 5 min and allowed to cool to room temperature before acrylamide and color analysis were done.

All experiments were run in duplicate.

### 2.4. Analysis

Moisture content of potato chips was measured by drying the samples in a convection oven until constant weight at 105 °C. The oil content was determined when required by a simple and rapid method that consists in an initial extraction with a mixture of 1:2:0.8 (v/v/v) in chloroform, methanol, and water. Then, this mixture is adjusted to 2:2:1.8 (v/v/v) to continue the oil extraction. In this way, the chloroform layer contains the purified oil (Bligh & Dyer, 1959).

Acrylamide analysis, acrylamide (2-propene amide) [CAS No. 79-06-1] (>99.5%) was obtained from Sigma-Aldrich (St. Louis, MO, USA). Labelled d3-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 acetonitril 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 *d3*-acrylamide (1000 and 10 µg 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) was extracted with 40.0 ml MilliQ water by an Ultra-turrax mixer (Janke & Kunkel, Staufen, Germany) (after addition of 200 µl d3-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 3.0R (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). Ten microliters was injected and eluted with 0.1% formic acid in water at a flow of 250 µl 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 e$^{-3}$ mbar. The multiple reaction monitoring (MRM) mode of the degradation patterns $m/z$ 72 → 55 (acrylamide) and $m/z$ 75 → 58 (d3-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. Measuring color by computer vision

For studying the kinetics of color evolution of potato slices fried at different oil temperatures, a computer vision system (CVS) was implemented to measure representatively and accurately the color (Pedreschi et al., 2004). The general methodology to convert RGB images into $L^*a^*b^*$ units is described in detail by Leon, Mery, Pedreschi, and Leon (in press). A brief description of each step follows:

(i) *Image acquisition:* A digital image of the object is captured and stored in the computer. When acquiring images it is important to consider the effect of illumination intensity and the specimen's orientation relative to the illumination source since the gray level of the pixels is determined not only by the physical features of the surface but also by these two parameters (Peleg, 1993; Chantler, 1995). Typically, a color digital camera provides three digital images, namely, red [R], green [G] and blue [B] digital images. The follow steps were considered for image acquisition:
  (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. Color standards were photographed and analyzed periodically to ensure that the lighting system and the CDC were working properly.

(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 pre-processing:* 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 grayscale 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) *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 and implemented (Mery & Pedreschi, 2005).

(iv) *Conversion from RGB images into $L^*a^*b^*$ units*: This methodology was developed previously and is carefully detailed by Leon et al. (in press). Five models for the conversion fro RGB to $L^*a^*b^*$ units were developed and tested: linear, quadratic, gamma, direct, and neural network. In the evaluation of the performance of these models, the neural network model stands out with an error of only 0.96%, so this model was only used. 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.

### 2.6. Dynamic method

Total color change was calculated by the total color difference parameter $\Delta E = ((L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2)^{1/2}$. The procedure to obtain color kinetic parameters by the dynamic method was as follows: for a given moisture content, and for each frying temperature, the time to reach that moisture and the corresponding $T_s$ were obtained. Thus, at a given moisture content and their respective $T_s$ and reaction time, it is possible to determine the rate of color change and its specific reaction rate, $k$, from data of color chip ($\Delta E^*$) vs. time. For a given moisture content, at each frying temperature, different values for $T_s$ and $k$ are obtained, making possible to draw an Arrhenius plot ($\ln k$ vs. $1/T_s$) to determine the activation energy $E_a$ and the frequency factor $k_0$. The root mean square deviation (RMS) of the predicted from experimental color change data was evaluated:

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\Delta E^*_{\mathrm{obs}} - \Delta E^*_{\mathrm{pred}}}{\Delta E^*_{\mathrm{obs}}}\right)^2} \tag{2}$$

## 3. Results and discussion

### 3.1. Kinetics of color change

In industry the most common frying temperature for potato products is 180 °C. In this study we select two low frying temperatures (120 and 140 °C) and two high or commercial (160 and 180 °C) in order to evaluate the effect of the oil temperature over browning development and acrylamide formation in potato chips. Two pre-treatments were studied: blanching (control) and blanching-soaking in NaCl.

Temperatures near the surface of potato chips are restricted to values slightly above the boiling point of water but, as frying proceeds and the surface becomes drier, the surface temperature $T_s$ approaches the oil temperature. Fig. 1 shows $T_s$ as an example for the frying temperatures of 120 and 180 °C, for control and NaCl soaked potato slices during frying. Temperature profiles for both control and blanched potato slices were very similar at any of the two frying oil temperatures tested since they have similar surface and internal microstructure.

Moisture loss during frying at 120 and 180 °C showed a classical drying profile, which was confirmed in Fig. 2. From the point of view of heat and water transfer, the behavior of control and NaCl soaked potato slices was quite similar. Blanching could cause partial starch gelatinization originating a different microstructure with respect to raw tissue; no significant difference in water migration and $T_s$ patterns was observed between control and NaCl soaked slices. Blanching has been reported as a pre-treatment that could improve the color and texture of the chips

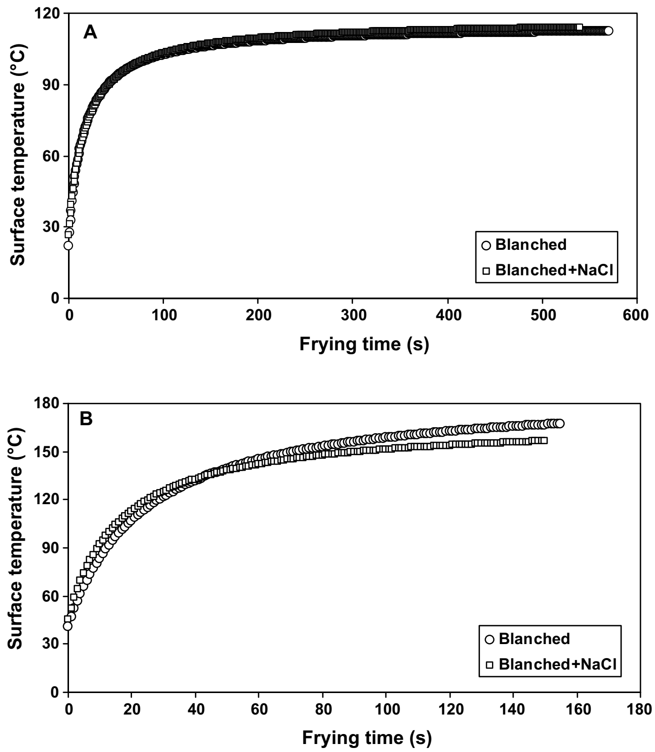


Fig. 1. Surface temperature of control and NaCl soaked potato slices during frying at 120 °C (A) and 180 °C (B).

and reduce their oil uptake (Califano & Calvelo, 1987). On the other hand, NaCl soaking has been reported as a pre-treatment which reduce oil uptake and improve the texture in French fries (Bunger et al., 2003).

Fried potato color is the result of Maillard, non-enzymatic browning reactions that depends on the reducing sugar content on the slice surface, and the temperature and frying period (Márquez & Añón, 1986). Low reducing sugar contents are required to minimize color development during frying (Mottur, 1989). Color changes in the potato slices during frying were followed by $\Delta E$, since this color parameter showed clear changes during frying. Potato slices tend to get darker as frying proceeds (as a result of surface non-enzymatic browning reactions) as indicating by the progressive increasing of $\Delta E$ values with frying time (Fig. 3A and B). RMS values of $\Delta E$ were $\leqslant 10\%$ for all the studied cases. The higher the frying temperature the darker the potato chips get since non-enzymatic browning reactions are highly temperature dependant (Fig. 3A). Soaking in NaCl lead to potato chips lighter in color than those of the control after frying at 120, 140, 160 and 180 °C (Fig. 3B). In agreement with our results, Santis, Mendoza, Moyano, Pedreschi, and Dejmek (in press) found that soaking potato slices in NaCl solutions before frying causes paler potato chips.

Experimental data of surface temperature $T_s$, moisture content of potato slices $m$, and chip color changes $\Delta E$ were fit to the following empirical relationships:

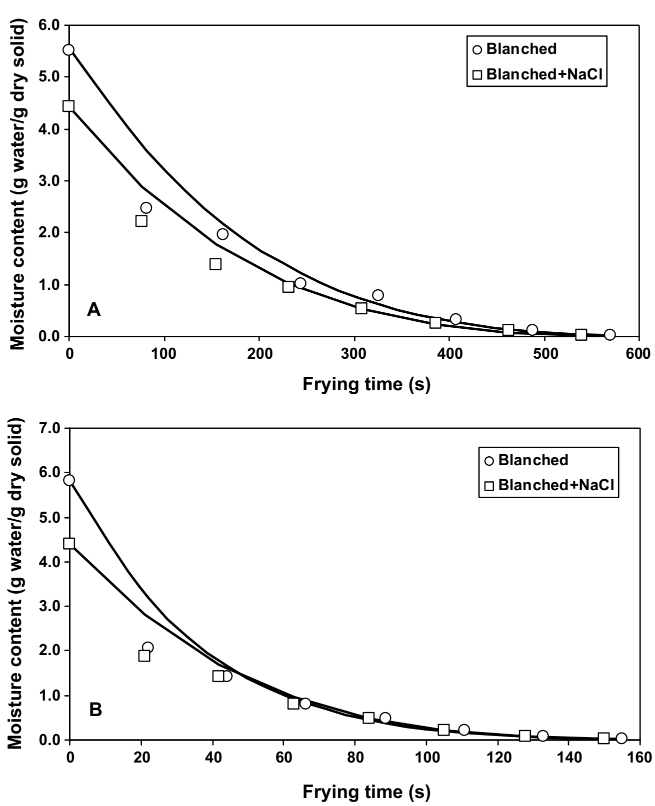


Fig. 2. Moisture loss of control and NaCl soaked potato slices during frying at 120 °C (A) and 180 °C (B).

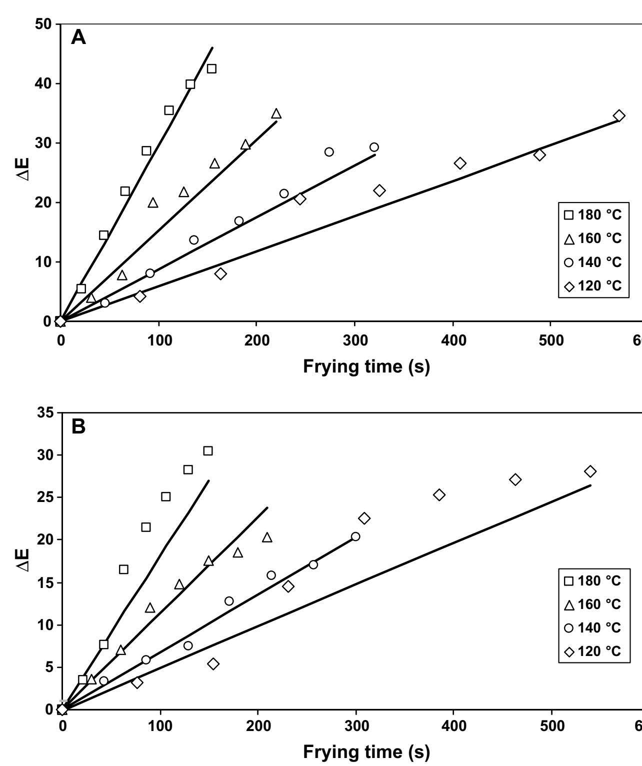


Fig. 3. Kinetics of color change in potato slices during frying followed by parameter $\Delta E$ for: (A) control potato slices fried at 120, 140, 160 and 180 °C; (B) NaCl soaked potato slices fried at 120, 140, 160 and 180 °C.

$$T_s = \frac{(a_1 + a_2 t)}{(1 + a_3 t)} \tag{3}$$

$$m = \left(m_0^{(1-n)} - (1-n)qt\right)^{1/(1-n)} \tag{4}$$

$$\Delta E = b_1 + b_2 \exp\left(\frac{-t}{b_3}\right) \tag{5}$$

In the case of moisture content, Eq. (4) was obtained by assuming that the drying rate was given by $dm/dt = -qm^n$. Moyano et al. (2002) find $n$ values ranging from 1.31 to 2.08, with correlations coefficients higher than 99% for potato strips fried at 160, 170 and 180 °C. Recently, Pedreschi et al. (2005) find $n$ values ranging from 0.65 to 0.83, and in all cases the correlation coefficient values were higher than 98% for potato slices fried at 120, 150 and 180 °C. In this work, $n$ was an adjustable parameter and in all cases the correlation coefficient values were higher than 95%.

From Eq. (5) the rate of color change was calculated as:

$$\frac{d\Delta E}{dt} = -\frac{b_2}{b_3} \exp\left(\frac{-t}{b_3}\right) \tag{6}$$

In order to obtain the specific reaction rate of color change $k$, the approach used by Ateba and Mittal (1994) was employed. They calculated the rate of crust color change by using a first-order kinetics:

$$\frac{d\Delta E}{dt} = k(\Delta E_{max} - \Delta E) \tag{7}$$

where $\Delta E_{max}$ is the maximum total color change which was determined experimentally for each treatment and for each frying temperature. In all cases the maximum value was reached at around 70 min of frying. In this way $k$ is given by:

$$k = \frac{-b_2 \exp(-t/b_3)}{b_3(\Delta E_{max} - \Delta E)} \tag{8}$$

Following the procedure explained above, $k$ values were obtained for selected moisture contents and Arrhenius plots for control and NaCl soaked fried potato slices were drawn (Fig. 4A and B). Table 1 shows activation energies $E_a$ for the surface color change as a function of the moisture content of the chips. $E_a$ diminishes as the moisture content of the chips decreases for both samples; and, for the same moisture content, $E_a$ of blanched slices was higher than that of NaCl soaked samples. $E_a$ values for high moisture content are in the order to those reported for non-enzymatic browning, while for lower moisture contents they get closer to those reported for diffusion control (Gekas, 1992; Saguy & Karel, 1980; Taoukis & Labuza, 1996). At first sight, this suggests a possible shift in color development rate control from a chemical step to a diffusional one. A similar situation was found for color change in French fries (Moyano et al., 2002), but a statistical analysis carried out for the data of enthalpy of activation against entropy of activation showed that only one mechanism for browning reaction was present (Moyano & Zúñiga, 2004).

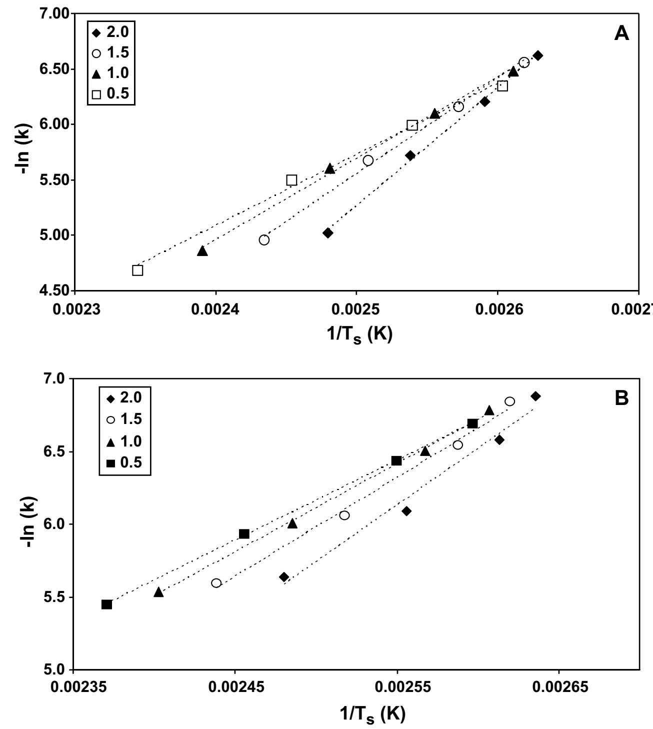


Fig. 4. Arrhenius color change plot for selected moisture contents of (A) control and (B) blanched fried potato slices.

Table 1
Activation energies of color change during frying of control and NaCl soaked fried potato slices at selected moisture contents

| $m$ (g water/g dry solid) | Control $E_a$ (kJ/mol) | NaCl soaked $E_a$ (kJ/mol) |
|---|---|---|
| 3.0 | 176.596 | 96.641 |
| 2.5 | 116.878 | 78.037 |
| 2.0 | 88.287 | 64.859 |
| 1.8 | 80.692 | 61.001 |
| 1.5 | 71.684 | 56.259 |
| 1.3 | 66.834 | 53.627 |
| 1.0 | 60.807 | 50.257 |

### 3.2. Acrylamide in potato chips

Low frying temperatures (e.g. 120 °C) and NaCl soaking treatment NaCl before frying decreased drastically the acrylamide content in potato chips (Fig. 5). NaCl soaking treatment reduced the acrylamide content in potato chips by 97%, 92% and 82% at the frying temperatures of 120, 140 and 160 °C, respectively. The mechanism by which NaCl soaking diminish acrylamide formation is not clearly understood and has not been reported in the literature yet. Since NaCl soaking reduces considerably the level of browning improving the potato chip color, it could be that the reduction mechanism in the case should be strictly associated with the Maillard reaction (Mottram & Wedzicha, 2002; Stadler et al., 2002). Data published so far indicate

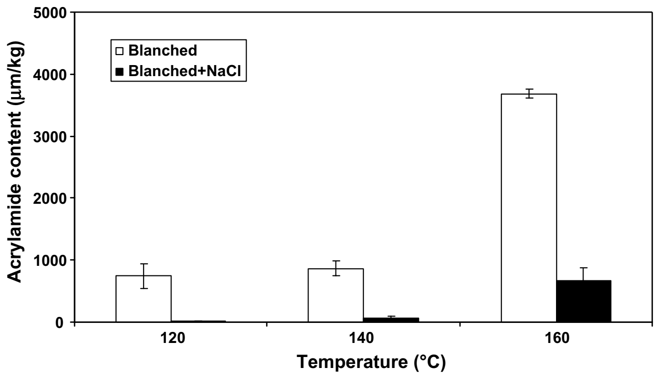


Fig. 5. Acrylamide content for control and NaCl soaked potato chips fried at 120, 140 and 160 °C.

that a temperature >100 °C is required for acrylamide formation (Becalski et al., 2003). In this work, acrylamide formation increased considerably in control and NaCl soaked samples (5 and 31 times, respectively) when the frying temperature was increased from 120 to 160 °C.

## 4. Conclusions

The color changes of control and NaCl soaked potato slices during frying followed a first-order kinetics. The dynamic method was used to calculate the activation energies of the reactions as a function of potato moisture content. In this way, instead of getting a unique mean value for $E_a$, a more realistic picture of the non-enzymatic browning extent during frying was obtained. The $E_a$ values allowed determining a possible mechanism change for the color reaction during frying. The first-order kinetics permitted to predict well the potato slice color changes during frying. NaCl soaking lead to a significant reduction of acrylamide formation in potato chips after frying at any of the oil temperatures tested. For both control and NaCl soaked potato chips, acrylamide formation decreased drastically as the frying temperature decreased from 160 to 120 °C. Soaking of potato slices before frying improve not only their color (less browning) after frying but also reduce dramatically the amount of acrylamide formation in the range of temperatures tested.

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## References

Ateba, P., & Mittal, G. S. (1994). Dynamics of crust formation and kinetics of quality changes during frying of meatballs. *Journal of Food Science, 59*, 1275–1278, 1290.

Becalski, A., Lau, B. P., Lewis, D., & Seaman, S. W. (2003). Acrylamide in foods: occurrence, sources, and modeling. *Journal of Agricultural and Food Chemistry, 51*, 802–808.

Bligh, E. G., & Dyer, W. A. (1959). A rapid method of total lipid extraction and purification. *Canadian Journal of Biochemistry and Physiology, 37*, 911–917.

Blumenthal, M. M. (1991). A new look at the chemistry and physics of deep fat frying. *Food Technology, 45*(2), 68–71, 94.

Brosnan, T., & Sun, D. W. (2003). Improving quality inspection of food products by computer vision – a review. *Journal of Food Engineering, 61*, 3–16.

Bunger, A., Moyano, P. C., & Rioseco, V. (2003). NaCl soaking treatment for improving the quality of French-fried potatoes. *Food Research International, 36*, 161–166.

Califano, A. N., & Calvelo, A. (1987). Adjustment of surface concentration of reducing sugars before frying of potato strips. *Journal of Food Processing and Preservation, 12*, 1–9.

Chantler, M. (1995). Why illuminant direction is fundamental to texture analysis. *IEE Procedures Visual Image Signal Process, 142*, 199–206.

Clark, J. P. (2003). Happy birthday, potato chip! And other snack developments. *Food Technology, 57*(5), 89–92.

Castleman, K. (1996). *Digital image processing*. Englewood Cliffs, New Jersey: Prentice Hall, 667 p.

Farkas, B. E., Singh, R. P., & Rumsey, T. R. (1996). Modeling heat and mass transfer in immersion frying, I. Model development. *Journal of Food Engineering, 29*, 211–226.

Friedman, M. (2003). Chemistry, biochemistry, and safety of acrylamide. A review. *Journal of Agricultural and Food Chemistry, 51*, 4504–4526.

Garayo, J., & Moreira, R. (2002). Vacuum frying of potato chips. *Journal of Food Engineering, 55*, 181–191.

Gekas, G. (1992). *Transport phenomena of foods and biological materials*. Boca Raton: CRC Press.

Haase, N. U., Matthäus, B., & Vosmann, K. (2003). Minimierungsansätze zur Acrylamid-Bildung in pflanzlichen Lebensmitteln-aufgezeigt am Beispiel von Kartoffelchips. *Deutsche Lebensmittel-Rundschau, 99*, 87–90.

Hubbard, L. J., & Farkas, B. E. (1999). A method for determining the convective heat transfer coefficient during immersion frying. *Journal of Food Process Engineering, 22*, 201–214.

Hunt, R. W. G. (1991). *Measuring colour* (2nd ed.). Ellis Horwood, Ltd., 313 p.

Krokida, M. K., Oreopolou, V., Maroulis, Z. B., & Marinos-Kouris, D. (2001). Colour changes during deep far frying. *Journal of Food Engineering, 48*, 219–225.

Leon, K., Mery, D., Pedreschi, F., & Leon, J. (in press). Color measurements in $L^*a^*b^*$ units from RGB digital images. *Food Research International*.

Marique, T., Kharoubi, P., Bauffe, P., & Ducatillon, C. (2003). Modelling of fried potato chips color classification using image analysis and artificial neural network. *Journal of Food Science, 68*, 2263–2266.

Márquez, G., & Añón, M. C. (1986). Influence of reducing sugars and amino acids in the color development of fried potatoes. *Journal of Food Science, 51*, 157–160.

Mery, D., & Filbert, D., (2002). Classification of potential defects in automated inspection of aluminium castings using statistical pattern recognition. In: *Proc 8th Euro conf non-destructive testing (ECNDT 2002)*, June 17–21, Barcelona, 14 p.

Mery, D., & Pedreschi, F. (2005). Segmentation of color food images using a robust algorithm. *Journal of Food Engineering, 66*, 353–360.

Mizrahi, S. (2000). Accelerated shelf-life tests. In D. Kilcast & P. Subramaniam (Eds.), *The stability and shelf life of food*. Cambridge: Woodhead Publishing Limited.

Mottram, D. S., & Wedzicha, B. L. (2002). Acrylamide is formed in the Maillard reaction. *Nature, 419*, 448–449.

Mottur, G. P. (1989). A scientific look at potato chips – the original savory snack. *Cereal Foods World, 34*, 620–626.

Moyano, P. C., Ríoseco, V. K., & Gonzaléz, P. A. (2002). Kinetics of crust color changes during deep-fat frying of impregnated French fries. *Journal of Food Engineering, 54*, 249–255.

Moyano, P. C., & Zúñiga, R. N. (2004). Enthalpy-entropy compensation for browning of potato strips during deep-fat frying. *Journal of Food Engineering, 63*, 57–62.

Oliveira, J. C., Pereira, P. M., & Oliveira, F. A. (1994). The role of transport phenomena. In R. P. Singh & F. A. Oliveira (Eds.), *Minimal processing of foods and process optimization*. Boca Raton, USA: CRC Press.

Papadakis, S. E., Abdul-Malek, S., Kamdem, R. E., & Yam, K. L. (2000). A versatile and inexpensive technique for measuring color of foods. *Food Technology, 54*(12), 48–51.

Pedreschi, F., Kaack, K., & Granby, K. (2004). Reduction of acrylamide formation in fried potato slices. *Lebensmittel-Wissenschaft und-Technologie, 37*, 679–685.

Pedreschi, F., Kaack, K., & Granby, K. (2006). Acrylamide content and color development in fried potato strips. *Food Research International, 39*, 40–46.

Pedreschi, F., Mery, D., Mendoza, F., & Aguilera, J. M. (2004). Classification of potato chips using pattern recognition. *Journal of Food Science, 69*, 264–270.

Pedreschi, F., Moyano, P. C., Kaack, K., & Granby, K. (2005). Color changes and acrylamide formation in fried potato slices. *Food Research International, 38*, 1–9.

Peleg, M. (1993). Fractals and foods. *Critical Review Food Science & Nutrition, 33*, 149–165.

Rosen, J., & Hellenäs, K. E. (2002). Analysis of acrylamide in cooked foods by liquid chromatography tandem mass spectrometry. *Analyst, 127*, 880–882.

Saguy, I., & Karel, M. (1980). Modeling of quality deterioration during food processing and storage. *Food Technology, 24*(2), 78–85.

Santis, N., Mendoza, F., Moyano, P. C., Pedreschi, F., & Dejmek, P. (in press). Soaking in a NaCl solution produce paler potato chips. *Lebensmittel-Wissenschaft und-Technologie*.

Scanlon, M. G., Roller, R., Mazza, G., & Pritchard, M. K. (1994). Computerized video image analysis to quantify colour of potato chips. *American Potato Journal, 71*, 717–733.

Segnini, S., Dejmek, P., & Öste, R. (1999). A low cost video technique for color measurement of potato chips. *Lebensmittel-Wissenschaft und-Technologie, 32*, 216–222.

Stadler, R. H., Blank, I., Varga, N., Robert, F., Hau, J., Guy, A., et al. (2002). Acrylamide from Maillard reaction products. *Nature, 419*, 449–450.

Taoukis, P., & Labuza, T. P. (1996). Summary: integrative concepts. In O. W. Fennema (Ed.), *Food chemistry* (3rd ed.). New York: Marcel Dekker.

Tareke, E., Rydberg, P., Karlsson, P., Eriksson, S., & Tornqvist, M. (2002). Analysis of acrylamide, a carcinogen formed in heated foodstuffs. *Journal of Agricultural and Food Chemistry, 50*, 4998–5006.