EFFECT OF MICROWAVE FRYING ON ACRYLAMIDE GENERATION, MASS TRANSFER, COLOR AND TEXTURE IN FRENCH FRIES

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Abstract The objective of this work was to evaluate the effect of microwave power on acrylamide generation, as well as moisture and oil fluxes and quality attributes of microwave-fried potatoes. Concretely, 25 g of strips potatoes, in 250 mL of fresh oil (at room temperature), were subjected to three different microwave powers (315, 430 and 600 W) in a conventional microwave oven. Microwave frying resulted in an acrylamide reduction ranged from 37 to 83% compared to deep-oil frying. Microwave-fried French fries presented lower moisture and higher fat content than deep-oil fried potatoes. Concretely, microwave-fried potatoes presented values of moisture and texture more similar to potato chips than French fries, nonetheless with lower fat levels (less than 20 g/100 g wb) and acrylamide content (lower than 100 µg/kg wb) at the reference time. This study presents an alternative way of frying to address the production of healthier potato chips.

Keywords Microwave frying; French fries; acrylamide; mass flows; food quality

Introduction

Frying is one of the most popular technologies employed in household cooking and industrial transformation of raw foods because of the specific organoleptic properties of fried products, highly valued by consumers, and very difficult to achieve with other cooking methods. Specially, fried potatoes represent a high volume of consumption around the World. Nevertheless, in recent decades, fried products have lost popularity due to their high fat content. Furthermore, it is also increasing concern about acrylamide intake, a potentially carcinogenic compound found in high amounts in different food commonly consumed, both fried and baked products (Tareke et al. 2002). This fact led to health authorities and the food industry to encourage the search for strategies and technologies that lead healthier products production, with the aim of reducing both fat and acrylamide contents in fried products. Among the different strategies for decreasing the acrylamide content in fried foods, it should be noted the application of treatments prior to frying, as blanching. Other studied alternatives involve the use of different frying technologies such as vacuum frying (Granda and Moreira 2005) or air-frying (Andrés et al. 2013; Sansano et al. 2015) to produce fried products with both low fat and acrylamide contents.

With regard to microwaves technology, it has mainly been applied before conventional deep-oil frying of French fries or chicken nuggets (Adedeji et al. 2009; Belgin Erdoğdu et al. 2007). The mass and energy transfer phenomena in microwave heating differ from conventional techniques, due to the nature of microwave heating that generates a temperature gradient from inside to the surface (Datta 2001). The interaction of microwave with polar water molecules of the interior of the product absorbs wave energy and produces a quick heating. This heat creates a sharp mass transfer due to the internal pressure of steam water which produces a quick drying without overheating the product surface (Datta 1990; Parikh and Takhar 2016). Thus, microwave frying seems to offer an improvement in efficiency and economy as well as a reduction of temperature and time of the process. Several studies are based on a hybrid system that combines microwave and conventional heating (Schiffmann 2017), and others are carried out under microwave conditions; but in those cases, oil medium is heated over the frying temperature prior to frying. In these instances, acrylamide content was substantially reduced in potato strips (Sahin et al. 2007) and coating of nuggets (Barutcu et al. 2009) compared to deep-fat frying, as well as oil uptake and frying time (Oztop et al. 2007). Nevertheless, the impact of microwaves technology on acrylamide generation as well as on the mass transfer phenomena and color and texture development during frying without previous heating of frying oil have not been studied yet. Therefore, our study consisted of the use of fresh oil and fresh potatoes from the beginning, in order to understand the overall process that potatoes and oil experience during microwave heating and frying. From the previous knowledge about the different potato and oil dielectric properties (Tang et al. 2002), and consequently different heating rates at microwave exposure, the experiments were carried out without pre-heating of oil medium, to know the different behavior of both matrix during the heating process.

Hence, the aim of this study was to evaluate the effect of microwave power (315, 430 and 600 W) on acrylamide generation, compositional changes (in terms of moisture and fat contents), texture and color development in microwave fried potatoes. It was stablished a single process that, in a unit operation, it could be combined a previous potato cooking and, when oil is heated, a frying step.

Materials and methods

Raw Material

Fresh potatoes (*Solanum tuberosum*, Agria variety) were purchased from a local supplier (*Patatas Aguilar, Ribaroja, Spain*) and stored at 8ºC (used within 5 days of purchase). Corn and sunflower seed refined oil (Sovena, Brenes, Spain) was used in all frying runs.

Experimental Methodology

A household microwave oven (GW72N Samsung Electronics) was used in this study. The microwave power applied in each power level was determined by IMPI 2-L test (Buffler 1993) as 315, 430 and 600 W. Before experiments, potatoes were dipped for 24 hours in water at room temperature to balance the moisture profile (85 ± 2% of moisture content) and cut into strips (0.01m x 0.01m x 0.05m) with a commercial cutter (Taurus kitchen line, New Wulmstorf, Germany). Samples were fried every minute from 1 to 10 min, 1 to 8 min, and 1 to 6 min at 315, 430 and 600 W, respectively. The final frying times (10, 8 and 6 min) were chosen based on a preliminary study, where frying above the highest time of each power, produced excessive dried-out and burnt samples. Each frying run was conducted as follows: 250 mL of fresh oil (without pre-heating) were placed in a Pyrex beaker and 5 potato strips (25 g ± 1.5 g) were immersed in it to conduct a frying run at a specified time and power. All runs were done renewing the oil after each frying time. As control, conventional deep-oil frying was performed in a commercial deep-fat fryer of 2 L of capacity (model: FM 6720 Ideal 2000 Professional, Solac), previously heated at 180 ± 2 ºC. Samples were fried for a total frying time of 8 min and sampling was done in 1-min interval. After both frying techniques, the excess oil on the surface of the samples was removed with dry tissue paper for 20 seconds. All experiments (microwave and conventional frying) were carried out with a constant ratio potato:oil of 1:10 (w/v).

Oil and potato temperatures were registered during the full process of both frying techniques using temperature sensors (Thermometer model HIBOK 14, sensor type K, sensitivity 39 $\mu V \cdot °C^{-1}$, accuracy ± 0.1). The temperature was registered immediately after each frying time and power level evaluated. Two temperature sensors were placed at the center (4-6 mm deep) of two different potatoes, and two thermocouples registered oil temperature.

Analytical Determinations

Moisture and oil net fluxes

Water content was analyzed by vacuum drying at 60 ºC until constant weight was achieved and total oil content was determined by solvent extraction using the Soxhlet method with petroleum ether (AACC 1995). Net changes of components (ΔM_t^i) (concretely, oil (ΔM_t^{oil}) and water (ΔM_t^{w})) during frying were obtained according to equation (1):

$$\Delta M_t^i = \frac{(M_t \times x_t^i)-(M_0 \times x_0^i)}{M_0} \qquad (1)$$

where M_0 is the total mass of the sample at initial time (g), M_t is the total mass at time *t* (g), x_0^i is the mass fraction of component (water or oil) at initial time (g/total g) and x_t^i is the mass fraction of component (water or oil) at time t (g/total g). Superscript *i* is "oil" or "w" for oil and water component, respectively.

Mechanical and optical properties

The formation of external crust at the reference frying time was evaluated, on 5 samples by time, by subjecting the sample to a cutting test at 45-50 ºC using a Texture Analyser (mod. TA-XT Plus Aname, Spain) equipped with a 50 kg load cell and a Warner Bratzler knife blade. The crosshead speed was 1 mm/s. From the force-deformation curve, the maximum shear force F_{max} (N) necessary to cut one strip of potato was recorded.

The determination of the optical properties of French fries at the reference frying time was carried out using a spectrocolorimeter (MINOLTA, mod. CM-3600d, Japan). The color space coordinates *CIEL*a*b** were obtained from the absorption spectrum between 380 and 770 nm by reflectance with the reference system: D65 illuminant and 10° observer, and a 7 mm lens. Measurements were made on 5 potato strips and on two sides. Total color change (ΔE) was calculated from equation *(2)*, using raw potatoes color coordinates as reference (L_0, a_0, b_0).

$$\Delta E = [(L^*-L_0)^2 + (a^*-a_0)^2 + (b^*-b_0)^2]^{1/2} \quad (2)$$

Acrylamide determination

The determination of acrylamide content was carried out by means of dispersive solid phase extraction (QuEChERS) according to Sansano et al. (2015) but using $^{13}C_3$-acrylamide as internal standard.

Statistical analysis

The influence of the microwave frying at 315, 430 and 600 W, at the reference frying time, compared to the deep-oil frying on the water and oil content, color and texture was analyzed using Statgraphics Centurion XVI. Analysis of variance (ANOVA) was evaluated for each parameter by a one-way analysis with a significance level of 95%.

Results

The evolution of oil and potato temperatures along microwave and deep-oil frying is shown in Figure 1. During the conventional frying, the product quickly reached the boiling temperature of water (100 °C) and it kept constant along frying. Regarding the oil medium, it experimented a slightly decrease from 180 ºC to 160 ºC because of mass transfer of water, in vapor state, from the product to the external medium. However, during microwave frying without pre-heating of oil medium, the electromagnetic field promotes a faster heating of the water of the raw potato (polar molecules) of the product than the oil (non-polar molecules) (Venkatesh and Raghavan 2004). This effect is due to the dielectric properties of both substances. Raw potato has at 2450 Hz a higher loss factor (ε'') than oil (15.7 vs 0.14) (Tang et al. 2002), what means that the microwave energy tends to mainly dissipate in the potato generating heat (De los Reyes et al. 2007). Therefore, the product temperature was much higher than the oil one at the beginning of microwave frying; while from 3 min, the higher the microwave power the faster the kinetic of oil heating. The increment of water molecules presence in the oil medium as long as frying progresses modifies the dielectric properties of the medium and potatoes, promoting the oil heating rather than potatoes cooking (Lizhi et al. 2008). Thus, temperature of oil was closed to 160 ºC at 430 and 600 W at the end of frying.

The heat transfer phenomena occur coupled with mass transfer ones. To this regard, net changes of water loss (ΔM^{w}_{t}) and oil uptake (ΔM^{oil}_{t}) under conventional and microwave-frying conditions are shown in Figure 2. In general, microwave frying increased both net fluxes of water loss (ΔM^{w}_{t}) and oil uptake (ΔM^{oil}_{t}) compared to the fluxes achieved under deep-oil frying. At the beginning of microwave frying (until minute 4), when oil temperature is lower to 100 ºC, the condensation of the water on the surface of the product rather than the evaporation occurs, giving as a result lower water loss than under deep-oil frying conditions. Nevertheless, from 4 minutes of microwave frying, the application of microwave promoted water pumping from the inner part of the potato to the surface, and further vaporization. Parikh & Takhar, (2016) showed that during microwave frying, an increase of temperature and the internal pressure were faster than conventional frying. This fact was attributed to the internal vapor pressure caused by the volumetric heating in the presence of microwaves, that also favoured the moisture escape. Concurrently, the volumetric heating that results in microwave frying seems to create structural channels through the potato tissue, which favors the oil uptake to a greater extent than in deep-oil frying. This fact took place at low and medium microwave power levels: 315 and 430 W, showing higher oil uptake than under deep-oil frying conditions. Pedreschi & Moyano (2005) reported that longer times and lower temperatures increased the oil intake, as happens at low–medium microwave power levels. In contrast to the highest power (600W), as every household microwave oven, lower power levels are provided by pulsed microwaves (in this study at 315 and 430 W). When magnetron stops, there is not electromagnetic energy input, so the flux of water toward the surface slows down and oil uptake takes place. This effect would explain why at 315 and 430 W, samples gained a higher amount of oil than at 600 W.

The effect of microwave frying on acrylamide generation seemed to be greatly dependent on the frying technique (Table 1). Thus, deep-oil fried potatoes presented higher acrylamide content (µg/kg) than microwave-fried potatoes excepting at the end of frying in which an exponential increase took place under microwave frying. Concretely, the exponential increase occurred from 7, 6 and 4 min of frying at 315, 430 and 600 W, respectively coinciding with a moisture content of 0.15-0.20 g water/g potato in all cases. It is therefore necessary to control the water content, since, at these moisture levels, the protection of the water flow gets lost and acrylamide content increases considerably. It is reported that remaining wet the product surface highly limits the acrylamide formation in fried or baked products (Ahrné et al. 2007; Bråthen and Knutsen 2005). On the other hand, the flux of water, in vapor state, occurring from the surface of the product to the external oil during frying, could sweep along part of the generated acrylamide, very instable and volatile compound, as well as its precursors (Amrein et al. 2006). This volatilization phenomenon is enhanced when microwave power is applied owing to the volumetric heating and the greater flux of water (Belgin Erdoğdu et al. 2007). This mechanism of degradation and/or volatilization of acrylamide could be observed at 4, 5 and 6 min of microwave frying at 430 W and 315 W, and under conventional frying, respectively; and it has been also reported in model systems (Biedermann et al. 2002; Taubert et al. 2004).

Finally, a reference time was stablished for each microwave power as well as for deep-oil frying to compare their results in terms of water and oil contents, texture, color (ΔE) and acrylamide ~~content~~ reduction (%). The reference time was stablished from the overall quality attributes of the final French fries obtained by microwave and deep-oil frying.

Table 2 shows the results for each of these parameters at 8, 6, 4 and 7 minutes for 315, 430, 600 W and deep-oil frying, respectively. The statistical analysis of the variance showed significant differences in water and oil contents, between microwave frying and deep-oil frying. The use of microwave produced samples with a lower water content and a higher oil content compared to deep-oil frying (0.14 ± 0.04 vs 0.05 ± 0.01 g/g w.b). Microwave fried samples were harder and crisper than conventional ones, mainly because of the significant water loss in microwave frying. Higher color variation was observed at 430 and 600 W, because a* and b* coordinates notably increased along frying. However, microwave frying significantly reduced the concentration of acrylamide (from 37 to 83 %) in the final product, especially when the higher power level was used.

Conclusion

Microwave-fried samples exhibited a reduction of acrylamide content, obtaining lower amount of acrylamide when increasing the applied power. This effect can be attributed to three factors: the reduction of the frying times; a decrease in the temperature and: especially to the protector effect of the steam flow from the center of the samples (dragging both the acrylamide formed and its precursors). The application of microwaves intensified the phenomena of water transport and thus, the speed of dehydration, which results in a considerable reduction of the frying time required in deep-oil frying to reach the same levels of moisture. The final microwaved French fries exhibited lower water content and resulted in a superficial texture comparable to potato chips rather than French fries. As a result of this study, microwave frying can be an alternative to deep-oil frying for obtaining potato chips with less acrylamide and fat contents.

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Table 1. Mean values (and standard deviation) of acrylamide content (μg/kg) at the different frying times and power levels.

Time (min)	315 W	430 W	600 W	Deep-oil frying
1	46 (6)	44 (2)	23 (10)	21 (5)
2	41 (13)	45 (4)	25 (5)	63 (5)
3	53 (7)	63 (4)	29 (2)	87 (8)
4	50 (12)	65 (11)	30 (5)	106 (5)
5	63 (7)	65 (4)	46 (4)	157 (17)
6	58 (4)	90 (2)	172 (19)	158 (4)
7	52 (4)	167 (4)	-	138 (12)
8	60 (7)	337 (54)	-	231 (20)
9	94 (31)	-	-	-
10	182 (40)	-	-	-

Table 2. Mean values (and standard deviation) of the analyzed parameters at the different reference times.

Parameter	**315 W (8 min)**	**430 W (6 min)**	**600 W (4 min)**	**Deep-oil frying (7 min)**
Water content (g/g w.b)	0.13 (0.03)^{b}	0.19 (0.04)^{c}	0.15 (0.04)^{bc}	0.67 (0.05)^{a}
Oil content (g/g w.b)	0.19 (0.01)^{b}	0.12 (0.02)^{c}	0.10 (0.03)^{c}	0.05 (0.01)^{a}
F_{max} (N)	45 (16)^{b}	59 (15)^{b}	44 (13)^{b}	18 (4)^{a}
ΔE	16 (3)^{a}	20 (2)^{b}	25 (3)^{c}	16 (5)^{a}
Reduction of acrylamide (%)	59 (5)	38 (1)	79 (4)	-

^{abc} Different letters indicate differences between homogenous groups

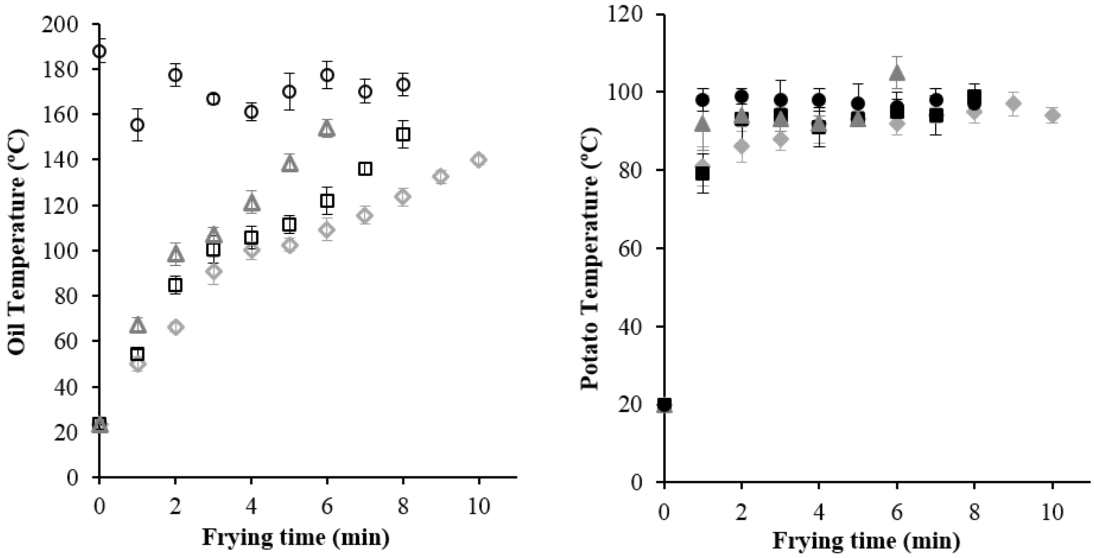

Fig. 1. Evolution of oil (left) and potato (right) temperatures with frying time under conventional (•) and microwave frying at 315 W (♦), 430 W (■), 600 W (▲). Empty icons correspond to respective oil temperature.

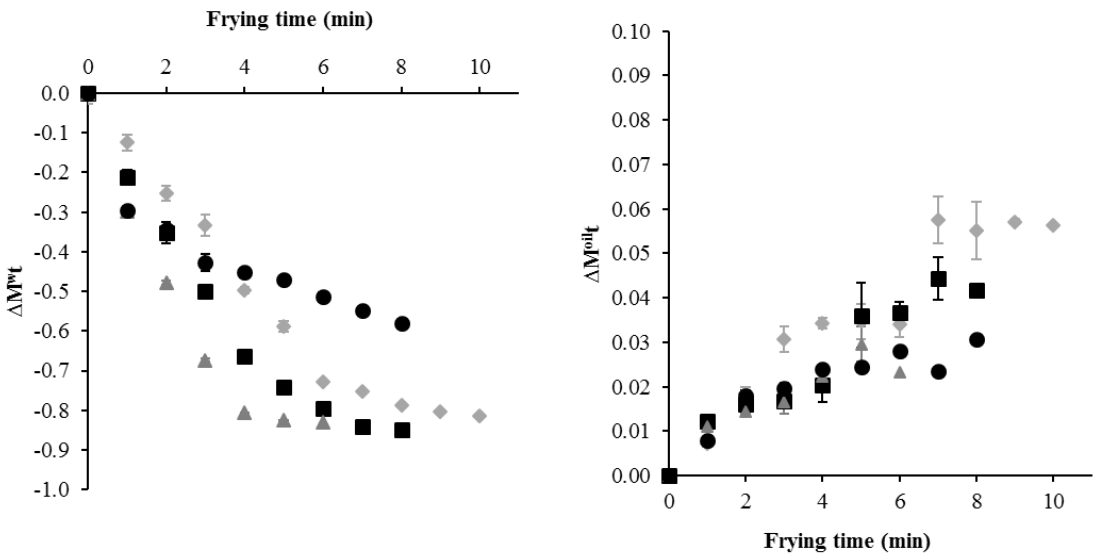

Fig. 2. Evolution of water loss ($\Delta M^{w}{}_{t}$) and oil gain ($\Delta M^{oil}{}_{t}$) (n=5) of French Fries with frying time under conventional (•) and microwave frying at 315 W (♦), 430 W (■), 600 W (▲).

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