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Evaluation of microwave toasting of corn flakes

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Abstract
During flake production, corn undergoes processes of cooking, drying, tempering, laminating, and toasting. The toasting dictates the attributes of the finished product for the consumer acceptability. Traditionally corn flakes are toasted in high efficiency forced convection systems such as rotary or fluidized-bed ovens. The aim of the present work was to study microwave thin layer toasting of cooked flakes using a household oven. Flakes toasted in a fluidized-bed industrial oven were adopted as control. The effect of microwave power level and process time on the kinetics of dehydration and quality parameters such as bulk density, thickness, and sensorial attributes of flakes were investigated. Kinetics data were satisfactorily simulated by Peleg's equation as function of drying time. A relationship between moisture ratio, output energy, and microwave power was also derived from experimental tests. A significant reduction of processing time in comparison with the traditional method was observed by selecting a suitable level of microwave power.

Practical applications
This paper describes an innovative and novel method to obtain organoleptically acceptable corn flakes. The results demonstrated that microwave heating can be used to substitute the traditional drying systems used for flakes toasting, with the possibility of reaching a reduction of process time, depending on the accurate selection of process parameters.

1 | INTRODUCTION

Corn flakes are in the group of ready-to-eat breakfast cereals. These are processed cereals, which do not require any treatment before being consumed. Flakes are relatively shelf-stable, lightweight, and convenient to ship and store (Rooney, 1991). The industrial process for the production of rolled flakes from corn grits comprises the following steps: formulation, mixing, cooking, drying, cooling and tempering, flaking and toasting (Caldwell, Fast, & Faubion, 2000).

Certain attributes of breakfast cereals, mainly crispness, are critical for the acceptance of the product by the consumers (Roudaut, Dacremont, Vallès Pàmies, Colas, & Le Meste, 2002). Toasting is the last drying step to which the flakes are subjected and it is a key stage which dictates the attributes of the final product (Sumithra & Bhattacharya, 2008). Properly toasted flakes have the correct and desired color, texture and moisture content that assures the product conservation and quality. In contrast, an excessive toasting can provoke unpleasant bitter taste and dark color. Growing consumer demand for better quality products means that there is a continuing quest to improve the performance of existing drying technologies and to develop new ones.

Industrial scale toasting is carried out in rotary or fluidized-bed ovens where the flakes are suspended in hot air because it is difficult to toast them uniformly in a fixed position on flat bands. During convective heating four phases can be observed: heat-up, drying, expansion, and color and flavor development. Process variables (oven temperature, airflow rates, residence time) as well as initial moisture content of flakes are sensitive parameters which must be accurately controlled. Air temperature within 220–320 °C and high velocity air jets (2,100–3,350 m/min) are selected for rice and corn flakes to be toasted in fluidized-bed ovens which are suitably designed to provide a uniform air distribution inside the food chamber (Caldwell et al., 2000).

In the food industry, convection drying is the traditional method with hot air providing the necessary heat for water evaporation and moisture content reduction; however, it is a procedure with low thermal efficiency (30–40%) which can be improved up to 50–60% by air recirculation (Sabarez, 2016).

With the exception of methods that use electromagnetic energy; such as infrared, microwave, or radio frequency; the others provide heat on the surface of the material so that it must diffuse into the solid mainly by conduction.

Microwave heating of foods is an efficient method capable of generating energy inside the product through the interaction of radiation, mainly with water molecules. Due to volumetric heating, a short drying time, hygienic conditions, and energy saving can be obtained by microwave technique (Campañone, Bava, & Mascheroni, 2014; Meda, Orsat, & Raghavan, 2017; Sabarez, 2015). It is also known that the nonuniformity is a characteristic of microwave heating which negatively affects the process efficiency and the product quality. To correct this problem, several strategies have been proposed to control the microwave pattern (Campañone et al., 2014; Chandrasekaran, Ramanathan, & Basak, 2013; Horuz & Maskan, 2015; Kantrong, Tansakul, & Mittal, 2014; Koné, Druon, Gnimpieba, Delmotte, Duquenoy, & Laguerre, 2013; Li, Raghavan, & Orsat, 2010; Saengrayap, Tansakul, & Mittal, 2015) and simulation models of heat transfer have been developed to predict the temperature distribution inside the food chamber (Campañone and Zaritzky, 2005; Farag, Sobhy, Akyel, Jocelyn Doucet, & Chaouki 2012). Many microwave studies were performed using domestic devices or prototypes at minor scale (Al-Harahsheh, Al-Muhtaseb, & Magee, 2009; Horuz & Maskan, 2015; Kantrong et al., 2014; Saengrayap et al., 2015). Although these procedures are not scalable they are useful to select the operative range to obtain the desired attributes for the product. This knowledge is basic to further design of industrial ovens.

Microwave processing has been extensively applied (alone or combined with convective, vacuum or infrared drying) for drying, heating, or sterilizing high moisture foodstuffs such as vegetables, fruits and meat products (Guo, Sun, Cheng, & Han, 2017). For low humidity foods, however, the applications are scarce and are limited to microwave or radio frequency assisted heating in the last stage of the baking process to dry biscuit without over-drying the outside surfaces (Caldwell et al., 2000).

High volumetric heating can cause high internal pressure inside the sample which results in boiling and bubbling of the sample (Chandrasekaran et al., 2013). As corn flake expansion is related to its crispness, it was expected that the use of microwave heating could result in an effective toasting of corn flakes. However, this procedure has not been explored yet.

Accordingly, the aim of this work was to evaluate the thin layer toasting of corn flakes by the use of a domestic microwave device. Thin layer model was adopted because it does not require turning the flakes up-side down to be toasted uniformly. The occurrence of uneven heating pattern, which is typical of microwave processing, was minimized using this method. Corn flakes toasted in a fluidized-bed industrial oven was set as control. The effects of microwave power and time on drying kinetics, bulk density, thickness, and organoleptic attributes of the final product were also investigated, with a view to expanding available information about them and even determining its potential application.

2 | MATERIALS AND METHODS

2.1 | Material

For the microwave tests, a sample of corn flakes (cooked and rolled but untoasted) with moisture content of 20.5 ± 0.1 g/100g (dry basis) was selected from the incoming stream to the toasting stage in the industrial processing plant. This material as well as the finished corn flakes (commercial toasted corn flakes) that were used as control, were provided by a local company for breakfast cereals (3 Arroyos SA, Pilar, Buenos Aires, Argentina). Moisture content was determined by official method AOAC 925.09 in an oven at 130 °C for 1 hr (Association of Official Analytical Chemists, 1995).

2.2 | Toasting of corn flakes

Toasting of the flakes was carried out in a domestic microwave oven Panasonic Piccolo model NN-S42CH (Panasonic Amazonia S/a, Industrial District, Manaus, Brazil) with a maximum output power of 1,000 W and 2,450 MHz, equipped with a rotating glass disk (300 mm) and a magnetron cooling fan. The digital controller of the furnace allows the user to select the operating variables: microwave power and time. The corn flake sample (20 g) was placed in the central position of the furnace chamber (282 mm × 486 mm × 359 mm), with a single layer of product being placed on a glass vessel.

Depending on processing conditions, the sample weight was recorded at 5 or 10 s intervals on a Mettler Toledo PB 3001-S (Mettler-Toledo AG, Greifensee, Switzerland) during microwave processing. After recording the weights, the samples were not further dried and new samples were placed instead to complete the next drying interval. This procedure was performed to avoid changes in the temperature and humidity of the product when removed from the microwave oven that could affect the analysis of the drying process. To address sample variation, kinetic tests were carried out in quadruplicate and moisture ratio (U/U_o) as function of process time was recorded. Three levels of output power (504, 672, and 840 W) and between 10 and 11 time levels comprised in the range 10–95 s were tested.

Industrial toasting was adopted as control. It was performed in a jet-zone fluidized-bed (Thermoglide2 Toaster–Baker Perkins, Agroexport Alimec SA, Buenos Aires, Argentina) where the corn flakes were subjected for 60 s to two successive jets with air currents of 180 °C (preheating) and 220 °C.

2.3 | Thickness and bulk density of corn flakes

Thickness was determined with a precision digital gauge (± 0.01 mm), measuring on the edge of the flakes. The average of 30 measurements and the standard deviation were reported as a function of processing time and microwave power level.

Bulk density was determined by weighing a fixed volume of flakes contained in a graduated cylinder of 0.5 L and the result was expressed in kg/m^3. A precision digital balance (± 0.1 g) Mettler Toledo PB 3001-S (Mettler-Toledo AG, Greifensee, Switzerland) was used and the experiments were performed in triplicate.

2.4 | Sensory evaluation

Toasted corn flakes were sensory evaluated by trained judges to establish overall acceptability. Standard recommendations (ISO, 2005) were adopted for sensory analysis. Each sample (30 corn flakes without anything added) was assessed according to a 3-point scale: (a) under toasted (rubbery texture, high translucence, and pale color); (b) properly

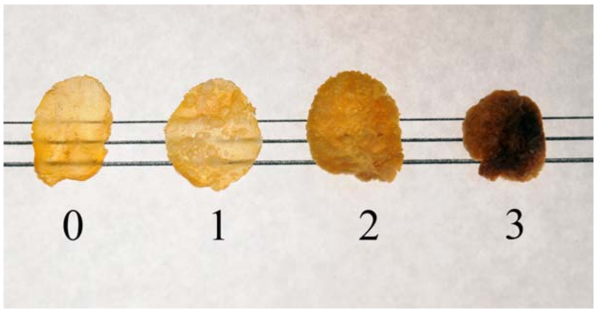

FIGURE 1 Three-point scale (Under toasted [1], Properly toasted [2], Over toasted [3]) used to test the effect of toasting on overall acceptability of corn flakes and the untoasted sample (0)

toasted (crisp texture, high opacity, golden color); (c) over toasted (crisp texture, high opacity, dark color). The scale points as well as the sample corresponding to the untoasted corn flake (0) are showed in Figure 1. From the images the differences in color and translucence can be clearly appreciated. Commercial sample of corn flakes (point 2 of the scale) was adopted as the product with the desired attributes. The assignation of each category was based on tasting and visual appreciation of translucence and color.

3 | RESULTS AND DISCUSSION

3.1 | Drying kinetics of corn flakes

Drying data in terms of moisture content ratio (U/U_0, dimensionless) as function of time is shown in Figure 2 at three selected values of microwave power. In contrast to air convection, the drying rate increased with increasing time as a result of dielectric heating caused by microwaves (Sabarez, Gallego-Juarez, & Riera, 2012). At the beginning a low drying rate was observed, due to necessary heat to reach the boiling point, followed by a faster drying stage. Jiang, Dang, Tan, Pan, and Wei (2017) and Al-Harahsheh et al. (2009) also found this typical curve-shape during microwave drying of pre-gelatinized potato starch and tomato pomace, respectively.

It can be appreciated that to reduce 50% of the initial moisture content 36, 50, and 60 s were used at 840, 672, and 504 W, respectively. Therefore, drying velocity significantly increased with increasing of microwave power.

Drying curves were successfully simulated ($R^2 > 0.88$) by

$$U = U_0 - \frac{t}{k_1 + k_2 t} \tag{1}$$

Which is the form of Peleg's equation (Peleg, 1988) to simulate a drying process. Where t is the drying time in seconds, U is the moisture content (g of water/g of dry matter) at time t, U_o is the initial moisture content (g of water/g of dry matter), k_1 and k_2 are the parameters of the model. Taking the limit for $t \rightarrow 0$ in the Equation 1 the inverse relationship between k_1 and the initial drying rate (V_i) is obtained:

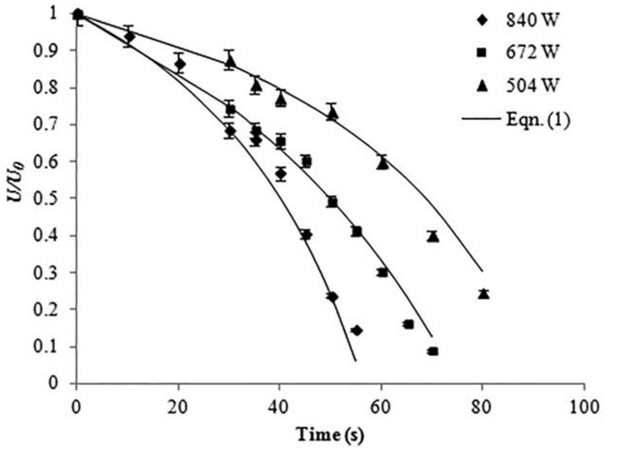

FIGURE 2 Experimental and predicted (Equation 1) values of moisture content ratio (U/U_0) as function of process time at different microwave output powers

$$V_i = 1/k_1 = \lim_{t \rightarrow 0} dU/dt \tag{2}$$

Table 1 shows the values of Peleg's parameters as function of microwave power together with the corresponding values of determination coefficient. Values of k_1 varied from 685 to 1,370 (s [g of water/g of dry matter]$^{-1}$) and k_2 varied from 4.8 to 10.1 (g of water/g of dry matter)$^{-1}$. Initial drying rate ($1/k_1$) increased asymptotically with growing microwave output power up to 1.46×10^{-3} (g of water/g of dry matter)/s at 840 W. Drying rates of similar magnitude although for others foodstuff were found in the literature. Al-Harahsheh et al. (2009) and Jiang et al. (2017) reported drying rates of tomato pomace and of pre-gelatinized starch of 0.83×10^{-3} and 0.42×10^{-3} (g of water/g of dry matter)/s using microwave powers of 800 and 543 W, respectively. The positive effect of microwave power on drying rate found in this work was also reported by the mentioned authors. In microwave treatments is usual to inform the level of output power and time applied or instead the value of output energy. The amount of absorbed energy is rarely reported, because it depends on several factors such as oven design, dielectric properties, size and shape of the product, and moisture content of the material, among others variables (Gaukel, Siebert, & Erle, 2017).

To estimate the incident microwave power a calorimetric method was applied. Distilled water (20 g) was placed in the microwave chamber instead of sample of corn flakes and the increase in water

TABLE 1 Effect of microwave output power on parameters of Peleg's model: initial drying rate (V_i) and constants of the model (k_1 and k_2)

Microwave power (W)	k_1 s (g water/g dm)$^{-1}$	k_2 (g water/g d. m.)$^{-1}$	V_i (g water/g dm)/s	R^2
840	685.02	7.25	1.46×10^{-3}	0.8831
672	729.22	4.82	1.37×10^{-3}	0.9752
504	1370.00	10.11	0.73×10^{-3}	0.9094

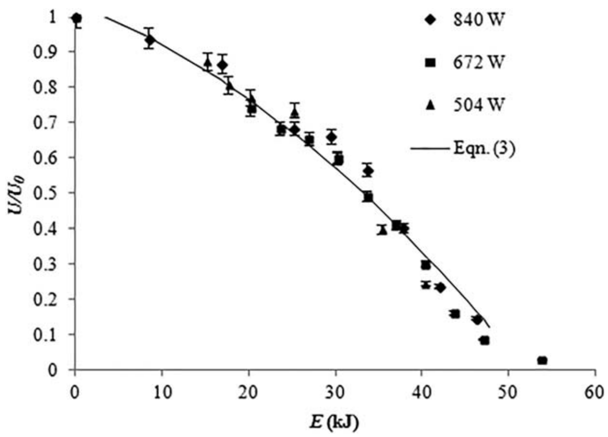

FIGURE 3 Moisture content ratio (U/U_0)–energy (E) relationship at different levels of microwave output power

temperature was recorded as function of time for each level of microwave output power. Tests were performed for an output power of 840 W (10–55 s), 672 W (30–80 s), and 504 W (30–95 s). The incident power was in average 40% of output power in accordance to the thermal efficiency reported by Arballo et al. (2012) for domestic microwave ovens.

In Figure 3, moisture content ratio (dimensionless) "versus" output energy (E, kJ) was represented. Output energy was calculated as the product of output microwave power (P, kW) and process time. Due to energy equivalences between different combinations of power–time, the results obtained from different values of microwave power converged on the same curve. The relationship was satisfactorily fitted ($R^2 = 0.96$) by means of the following mathematical expression:

$$\frac{U}{U_0} = 1 - \frac{E}{140.22P - 1.48E} \quad (3)$$

It can be appreciated in the figure that moisture content decreases quickly from initial to final content as delivered energy increases due to the high rate of heat transfer in microwave heating.

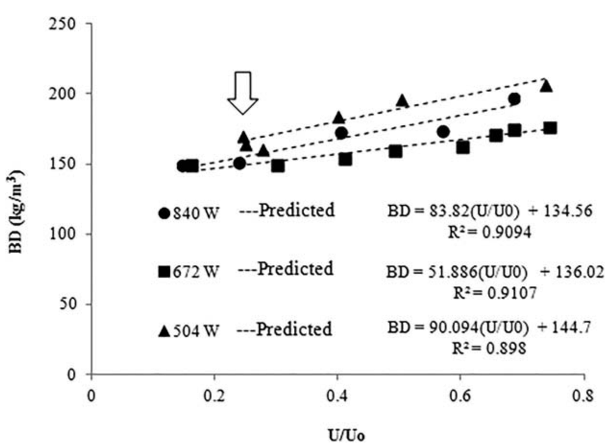

FIGURE 4 Experimental and predicted (—, linear regression) values of bulk density (BD) as function of moisture content ratio (U/U_0) at different microwave output powers

3.2 | Changes of flakes attributes during toasting

Bulk density is a key parameter in the flake industry, due to its relationship with corn flake appearance and size as well as its strong incidence on the required package volume.

Figure 4 shows the changes of bulk density (BD) as function of moisture content ratio during processing up to reach the optimum level of crispness (indicated by an arrow) at moisture content of 4.8% (dry basis) or moisture content ratio of 0.24 (dimensionless). The average value of bulk density at this point was 154 ± 3 kg/m^3, which resulted equivalent to that of control sample (160 ± 6 kg/m^3) obtained by industrial manufacture.

An average reduction of 17.3% in the bulk density at the optimum point respect to initial value of bulk density was found considering all the power levels tested. The relationship between bulk density and moisture content ratio (dimensionless) at fix level of microwave power was successfully modelled ($R^2 > 0.89$) using linear equation as it can be appreciated in Figure 4. Such regression analysis could be performed by selecting moisture content ratio within 0.74–0.24 (dimensionless).

At the beginning of toasting step, the corn flakes are subjected to shrinkage (mainly a thickness reduction) due to the initial water loss. As toasting progresses, the surface of flakes changes due to the appearance of air bubbles generating an increase of the thickness. Despite the heterogeneous morphology of flakes, the coefficient of variation for thickness measurements did not exceed 8%. Thickness of corn flakes as function of process time at each value of microwave power is presented in Table 2. It can be appreciated that thickness grows up 2.4

TABLE 2 Thickness and overall acceptability (OA) of corn flakes as function of process time and microwave output power

	Microwave power					
	840 W		672 W		504 W	
Time (s)	OA	Thickness (mm)	OA	Thickness (mm)	OA	Thickness (mm)
0	1	0.68 ± 0.03	1	0.68 ± 0.03	1	0.68 ± 0.03
10	1	0.59 ± 0.02	–	–	–	–
20	1	0.76 ± 0.03	–	–	–	–
30	1	1.02 ± 0.05	1	0.57 ± 0.03	1	0.47 ± 0.01
35	1	1.24 ± 0.07	1	0.73 ± 0.03	1	0.49 ± 0.02
40	1	1.48 ± 0.08	1	0.83 ± 0.06	1	0.49 ± 0.03
45	1	1.35 ± 0.06	1	0.81 ± 0.04	–	
50	**2**	1.58 ± 0.11	1	0.94 ± 0.05	1	0.57 ± 0.02
55	3	1.42 ± 0.08	1	1.00 ± 0.06	–	–
60	–	–	1	1.16 ± 0.08	1	1.03 ± 0.06
65	–	–	**2**	1.39 ± 0.07	–	–
70	–	–	**2**	1.39 ± 0.08	1	1.21 ± 0.07
80	–	–	3	1.31 ± 0.07	1	1.22 ± 0.07
90	–	–	–	–	**2**	1.66 ± 0.09
95	–	–	–	–	3	1.60 ± 0.08

(-) not measured, Under toasted (1), Properly toasted (2), Over toasted (3). Values in bold are cases in which the optimal product was obtained.

times at optimum crispness point from the initial value (2.2 times in average considering all the power tested).

However, thickness at optimum crispness point was dependent on microwave power and the differences between them were significant. Therefore, thickness is not a convenient parameter to set the quality of the product.

Conversely, as toasting progresses the translucence of corn flakes decreases, their opacity increases while they gain crispness (Figure 1). Such changes could be easily followed by visual inspection during the sensory analysis.

Optimum crispness was obtained at 2–7% (dry basis) of moisture content; such condition was reached in 50 s (840 W), 65 s (672 W), or 90 s (504 W) depending on selected power level. It must be noted that microwave processing time at 672 W resulted equivalent to that of control. However, microwave toasting at 840 W resulted in 17% reduction in the processing time in comparison to that of control where the corn flakes are toasted using a fluidized-bed oven. Moreover, toasting time could be further reduced with an additional increment in the microwave output power.

4 | CONCLUSIONS

Toasting of corn flakes was performed by microwave heating instead of traditional forced convection method. Drying kinetics of corn flakes can be successfully simulated by means of Peleg's equation. Organoleptic characteristics of corn flakes toasted by microwave heating were similar to the standard adopted by the manufacture industry.

Optimum point in terms of sensory attributes occurred at fixed value of moisture content ratio (0.24) regardless of the applied power. It was corroborated that the use of bulk density is suitable criteria to accept or refuse the product which can be easily implemented.

The results suggest that microwave toasting could be a good alternative to traditional convection toasting by selecting a combination of convenient times and microwave power output. Moreover, a significant reduction of process time could be achieved by microwave method with equivalent results in terms of final moisture content and product attributes. However, further studies are needed before industrial scaling of this method. They should be focused on strategies to control the microwave power density to overcome the nonuniform heating and to avoid hot spots responsible for the deterioration of the product quality.

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