A Kinetic Study of Furan Formation in Wheat Flour-Based Model Systems during Frying

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Abstract: Furan is a possible human carcinogen, which is formed in worldwide highly consumed fried starchy foods. In order to elucidate the mechanisms responsible for its occurrence in this food category and propose techniques for its mitigation, the kinetics of furan formation, oil absorption, lipid oxidation, and color change were studied in wheat flour-based model systems during frying at 160, 170, 180, and 190 °C up to 13 min and data were fitted to mathematical models. Additionally, an Arrhenius-type dependency with temperature was evaluated for all studied responses. More drastic frying conditions increased significantly ($P \le 0.05$) the furan content of fried samples. Furan formation followed a sigmoid trend with frying time only for frying temperature of 190 °C (RMS_{190°C}: 7.6%). At lower temperatures, furan generation did not reach the asymptotic concentration level. Color change, lipid oxidation, and oil absorption increased with frying temperature and followed asymptotic relationships with frying time. For all evaluated temperatures, color change (RMS: 4.4% to 12.5%) and polar compound generation (RMS: 2.6% to 7.4%) presented good fit to a first-order kinetic model. Oil absorption was successfully fit to a mass balance-based model (RMS: 10.0% to 19.8%). Under the experimental conditions studied, only color change (E_A: 15.47 kJ/mol), lipid oxidation (E_A: 6.67 kJ/mol), and oil absorption (E_A: 76.98 kJ/mol) presented good fit (RMS: 0.7% to 6.3%) to an Arrhenius-type equation. Based on our results, the keeping of frying temperature below 180 °C and the reduction of the frying time would contribute to reduce not only the final furan occurrence in fried foods but also their oil content.

Keywords: frying, furan formation, kinetics, processing parameters, starchy foods

Introduction

Even though the frying of starchy foods has many sensorial advantages because it adds taste, color, and texture, during this thermal process, some toxic compounds, such as acrylamide, hydroxymethylfurfural, and furan, are produced by reactions triggered at high temperature (Pedreschi and others 2005; Oral and others 2014; Mariotti and others 2015).

Acrylamide, a potential carcinogenic compound, is mainly formed through Maillard reaction (Mottram and others 2002) in starchy foods processed at high temperatures such as potato chips (Pedreschi and others 2005). On the other hand, both hydroxymethylfurfural (Morales and others 2001; Cais-Sokolinska and others 2004; Rada-Mendoza and others 2004; Murkovick and others 2007; Gökmen and others 2008; Gökmen and others 2007; Mesías-García and others 2010; Oral and others 2011) and furan (Crews and others 2007a; Crews and others 2009; EFSA 2010; Mesías-García and others 2010; Mariotti and others 2013) have been detected at different levels (1500 to 80 ng/g) in a broad range of thermally treated foods (for example, coffee, sweetened condensed milk, heat milk-based products, baby foods, tomato sauce, crackers, chips, and toasted breads) suggesting that different mechanisms and precursors can be responsible for its generation (EFSA 2010; Anese and others 2013; Mariotti and others 2015).

Since high levels of furan were detected in tomato sauces, fruit juices, and baby foods, most research has been focused to improve the understanding about its formation in these types of food matrixes (Mariotti and others 2013). Different furan quantification methodologies (Nyman and others 2008; Crews and others 2007a, b; Zoller and others 2007; Jestoi and others 2009; Kim and others 2010; Ruiz and others 2010;) have been developed to determine furan occurrence in foods. Considering the fact that furan is a volatile compound, the control of its analysis in food matrixes is a critical issue to determine the real amount of the toxicant in the sample (Kim and others 2010).

Multiple pathways are involved in furan formation in foods. The thermal degradation and rearrangement of sugars and amino acids (Owczarek-Fendor and others 2010a; Van Lancker and others 2010; Mariotti and others 2012), as well as the thermo-oxidation of polyunsaturated fatty acids (Owczarek-Fendor and others 2010b) and ascorbic acid (Owczarek-Fendor and others 2010a; Mariotti and others 2012), have been proposed as the mechanisms responsible for its generation in foods (Perez Locas and others 2004; Hasnip and others 2006; Crews and others 2007a; Van Lancker and others 2009; Vranova and Ciesarova 2009; Owczarek-Fendor and others 2011).

In this sense, to know the kinetics of furan formation in foods could be considered a useful tool for designing thermal processes which control the level of furan content in the final product. However, to date, there is very little information on this subject. Only recently, Palmers and others (2015) reported that the rates of furan formation in orange and mango juices were clearly matrix dependent, which could be attributed to the differences in juice composition, such as sugars and ascorbic acid content. Likewise, studies about the kinetics of furan formation in tomato paste and

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pulp during heating revealed that ascorbic acid oxidation is the critical step in furan formation reaction mechanism during heating of tomato pulp (Gül Akıllıoğlu and others 2015). On the other hand, Huang and others (2015) studied the furan formation in pasteurized soy sauce. These authors obtained thermodynamic parameters that can be used to predict furan formation in this food during pasteurization.

Previous paragraphs clearly show that current research has been focused in foods with similar physical characteristics. Moreover, the processing evaluated for all the cases was the same, which means liquid products heated under similar ranges of temperatures. In this sense, to extrapolate these results to other food structures, such as solid foods, could generate erroneous conclusions considering the fact that furan formation is highly influenced not only by the matrix but also by the heating method (Mariotti and others 2013).

To the best of our knowledge, research on kinetic of furan formation in other food matrixes, such as starchy fried foods, has not yet been carried out. A better understanding about the effect of processing conditions over furan generation in starchy fried foods is necessary to develop effective mitigation technologies, which allow the reduction of furan occurrence in this worldwide highly consumed food category. In order to that, we studied the furan formation in a fried wheat flour-based model system. The kinetics of furan formation, color change, lipid oxidation, and oil absorption were determined and modeled with the aim to improve our understanding of furan occurrence in this food category.

Materials and Methods

Materials

Dough formulation was prepared with the following ingredients: wheat flour (La Selecta, Chile, moisture content of 15% in wet basis) and HPLC grade water. For frying experiments, sunflower oil (Camilo Ferrón, Chile) was used as the heating medium.

For furan quantification, the following reagents were used: furan (Dr. Ehrenstorfer Co. Augsburg, Germany), d_4 -furan (100 µg mL⁻¹, Dr. Ehrenstorfer Co.), methanol (HPLC grade, Rathburn, Walkerburn, Scotland); sodium chloride (> 99%, Merck, Darmstadt, Germany). Working standards of furan and d_4 -furan (1.5 µg mL⁻¹) were prepared with 10 mL of HPLC grade water and 150 µL of standard solution of furan and d_4 -furan.

To determine the absorbed oil content of fried samples, chloroform (HPLC grade, Merck) and methanol (HPLC grade, Rathburn) were used. Regarding to polar compounds determination, petroleum ether (b.p. 40 to 60 °C, HPLC grade) and diethyl ether (HPLC grade) were provided by Merck.

Methodology

Wheat flour dough preparation. Dough formulation was prepared based on the criteria that all the samples should have the same moisture content of $40 \pm 0.6\%$ wet base (wb) before being fried (Mariotti and others 2012). The samples were prepared using a food mixer (5K5SS, Kitchen aid, MI, U.S.A.). Water was added according to the protocol described by Gazmuri and Bouchon (2009). Approximately, a batch of 300 g of dough was prepared for each experiment, immediately before frying. The resultant dough was then wrapped in a plastic bag and left for 1 h at room temperature (20 °C). Then, the dough was knead to ensure homogeneity, laminated using a dough roller (LSB516 Doyon, Canada), and cut into 40 mm dia circles. The exact thickness of

the resultant dough slices ranged from 2.0 to 2.3 mm (Mariotti and others 2012).

Frying conditions. The wheat flour dough circle slices were fried at all the possible combinations of the following selected time-temperature conditions: 7 times (1.5, 3, 5, 7, 9, 11, and 13 min) and 4 oil temperatures (160, 170, 180, and 190 °C). The samples were fried in a 20 L capacity deep-fryer (Chacón, Chile). In order to avoid hidden effects, treatments were randomized and performed in triplicate. The fryer was filled with 15 L of oil that was preheated for 2 h prior to frying (Blumenthal 1991), and oil was discarded after 90 min of frying time. Sample-to-oil mass ratio was maintained as low as possible in order to keep a constant temperature of frying. Throughout the frying process, 10 slices of 3.70 ± 0.03 g were placed in a basket and held in position with a wire grid to prevent them from floating. The fried samples were drained over a wire screen for 5 min (Moyano and Pedreschi 2006).

After that, fried samples were refrigerated for 30 min. Then, chemical and image analyses were carried out simultaneously.

Solid content determination. To determine the solid content of wheat flour, it was placed in a Petri dish, dried in a forced air oven at 105 °C to constant weight, and cooled in a desiccator (A.O.A.C. 1995).

For fried products, the solid content was determined in extracted, oil-free samples. The solid content of samples was used to calculate their furan concentration, oil content, polar content, and moisture content on a defatted dry weight basis (ddb) (Mariotti and others 2012).

Oil content measurement. Total oil content of fried wheat flour-based model systems was determined gravimetrically by Bligh and Dyer extraction (A.O.A.C. 1995).

Polar compounds determination. The content of polar compounds present in the absorbed oil of fried wheat flour-based model systems was determined by adsorption chromatography, using chromatographic glass columns packaged with silica gel (particle size: 0.063 to 0.200 mm; adjusted to a water content of 5% w/w) according to the International Union of Pure and Applied Chemistry official methodology (A.O.A.C. 1995).

Furan quantification. Furan was quantified in fried samples according to the methodology described by Mariotti and others (2012). Pulverized fried samples (0.5 g) were weighed into headspace vials and diluted with 5 M NaCl solution. After adding the internal standard (d_4 -furan), the vials were sealed. Automated headspace sampling followed by gas chromatography/mass spectrometry (GC/MS) analysis was used to detect furan and d_4 -furan in the scan mode. The furan analyses were performed on a GC-MS (Agilent Technologies, Model 7890A/7050, Santa Clara, Calif., U.S.A.) equipped with a static headspace autosampler (Agilent Technologies, Model CTC Combi PAL). A capillary column HP-PLOT/Q, 30 m \times 0.32 mm ID \times 0.20 μ m film (Agilent Technologies) was used with He (99.995% purity) as carrier gas at the flow-rate of 1 mL min⁻¹. The column temperature was programmed as follows: 50 °C holding 1 min to 180 °C at 10 °C min⁻¹. The total analysis time was 14 min. The injector port was kept at 200 °C and 1 µL sample was injected in split mode (4:1). The MS source temperature was 230 °C and the MS quad temperature was 150 °C. The mass spectrometer was operated in electron ionization mode. Furan was detected using single ion monitoring of the fragments m/z 68 and m/z 39. The internal standard d_4 -furan was detected by monitoring the m/z 72 and m/z 42. The headspace operating conditions were as follows: incubation temperature: 60 °C; incubation time: 20 min; syringe temperature: 70 °C; agitator speed: 50 °C, fill speed: 500 mL s⁻¹; pull-up delay: 500 ms; injection speed: 500 μ L s⁻¹; injection volume: 1 mL; preinjection delay: 500 ms; postinjection delay: 500 ms; and flush hours: 60 s. Furan was quantified by using a standard addition curve, where the concentration of furan in the fortified test portions was plotted compared with the furan/*d*₄-furan response factors. The calibration curve was constructed using 7 vials of which: 4 vials were fortified with furan, as follows: 2 vials at ca. half of the expected concentration of furan in the sample, one vial at ca. twice of the expected concentration of furan in the sample (FDA 2004; Zoller and others 2007).

Color development determination. The color development of fried samples was determined using a computer vision system according to the methodology described by Pedreschi and others (2007b). This methodology allows to convert RGB images into CIE L*a*b* units. The steps involved to accomplish this purpose are: (i) image acquisition in which a digital image of the sample is captured and stored in the computer; (ii) image preprocessing in which the quality of digital images is improved before they are analyzed; (iii) image segmentation of the true image of fried starchy samples from the background, and (iv) conversion from RGB images into L*a*b* units.

Changes in color were expressed as the total color difference (ΔE) , which was calculated in the following way:

$$\Delta E = \left(\left(L_0^* - L^* \right)^2 + \left(a_0^* - a^* \right)^2 + \left(b_0^* - b^* \right)^2 \right)^{0.5}$$
(1)

where L^* , a^* , b^{*} , and L_0^* , a_0^* , b_0^* indicate the values of lightness, redness, and yellowness at different frying times and at time zero, respectively.

Kinetics analysis. The overall effect of the frying temperature over furan generation, color development (evaluated as total color change), polar compounds generation, and oil uptake was described using a modification of the Gompertz equation for furan formation, a first-order kinetic model for total color change (ΔE) and polar compounds and a model based on mass balance for oil absorption.

Furan formation was described by Eq. (1) (Van Boekel 2008):

$$F = F_{eq} \exp\left(-\exp\left[\frac{k \times e}{F_{eq}} (\lambda - t) + 1\right]\right)$$
(2)

where *F* is the furan content (ng furan/g dried defatted solids), the parameter F_{eq} is related to the asymptotic or equilibrium value of the function when $t \rightarrow \infty$, *k* (ng furan/g defatted solid min) is the maximum rate (determined by the slope of the steepest tangent to the exponential phase), *e* is the Euler number, and λ (min) is the lag time (determined at the interception of the base line with the steepest tangent line in the exponential phase).

Total color change (ΔE) and polar compounds content were fitted to a first-order kinetic model proposed by Krokida and others (2001):

$$Y = Y_{ea} \times (1 - \exp(-k \times t)) \tag{3}$$

where Y is the total color change (adim), or polar compounds content (%) at any time, Y_{eq} is the value of the response at equilibrium conditions $(t \rightarrow \infty)$, k is the specific rate for the first-order model (min⁻¹), and t is the frying time (min). In this model at t = 0, the responses are null, and for long times, responses become the equilibrium value.

On the other hand, oil uptake was fitted to a mass balance model proposed by Moyano and Pedreschi (2006):

$$O = \frac{O_{eq} \times k \times t}{1 + k \times t} \tag{4}$$

where *O* is the oil absorption (g oil/g defatted solids) at any time, O_{eq} is the value of the response at equilibrium conditions ($t = \infty$), *k* is the specific rate for the model (min⁻¹), and *t* is the frying time (min). In this model at t = 0, the response is null, and for long times, response becomes the equilibrium value.

The parameters of Eq. (2) to (4) were obtained by nonlinear regressions by means of the Solver tool of Microsoft Excel (Microsoft Corp., Redmond, Wa., U.S.A.), using as objective function the residual sum of squares defined as:

$$\% RMS = \sqrt{\frac{1}{N} \sum \left(\frac{V_{obs} - V_{pred}}{V_{obs}}\right)^2} \times 100\%$$
 (5)

where RMS is the root mean square error, V_{obs} is the observed or experimental value, V_{pred} is the predicted value, and N is the number of data points.

Finally, the relationship between the rate constants of evaluated responses (furan formation, color development, lipid oxidation, and oil uptake) and temperature was determined using an Arrhenius-type equation:

$$k = k_0 \exp\left(\frac{E_A}{R \times T}\right) \tag{6}$$

where k is the rate constant (min⁻¹), k_0 is the frequency factor (min⁻¹), E_A is the activation energy (kJ/mol), R is the universal gas constant (8.314 × 10⁻³ kJ/mol K), and T is the absolute temperature (K).

Statistical analysis. The experiments were replicated 3 times. Statistical analysis was carried out using Statgraphics Centurion XVI software (Manugistic Inc., Warrenton, V.I., U.S.A.). Oneway variance analysis was performed to confirm that there were no significant differences between measurements of a sample processed under same specific conditions. Differences between treatments were analyzed by least significant difference test using the linear general model. All significant differences were determined with a confidence level of 95%.

Results and Discussion

During frying of foodstuffs, several changes take place in the food matrix. The high temperatures reached in the process trigger chemical reactions not only between the food components but also in the heating medium, such as Maillard reaction and lipid oxidation, respectively. Likewise, physical phenomena, which are highly influenced by temperature, such as moisture loss and oil absorption, occur. Interestingly, the furan formation in foods has been related with all these chemical reactions which are also influenced by the physical properties of food matrix previously described (Mariotti and others 2012; Mariotti and others 2013).

Starchy foods are characterized by their high content of reducing sugars. Additionally, amino acids and ascorbic acids are constituents of this food category (EFSA 2010). When these foods are fried, many chemical reactions simultaneously occur, producing the thermal degradation of all furan precursors. Therefore, to elucidate the main route of furan formation is extremely complex. Moreover, since furan is a nonpolar compound, the oil penetrated into the food during frying could also present a retention effect over it (Becalski and others 2005; Mariotti and others 2012).

Based on this analysis, the kinetics of furan formation, color development, lipid oxidation, and oil absorption were determined and modeled with the aim to improve the understanding of furan occurrence in this food category. The results obtained from these analyses are presented and discussed in the following sections.

Kinetic of furan formation in fried wheat flour-based model systems

The kinetic of furan formation in wheat flour-based model systems was followed at different temperatures (160, 170, 180, and 190 °C) during frying in order to determine the effect of processing parameters (temperature and time) over furan occurrence. Our results clearly show that higher levels of furan were generated when higher process temperatures were applied. In the same way, at longer frying times, higher furan concentrations were determined (Figure 1). The highest furan level was reached at 190 °C and 13 min of frying (approximately 503 ng/g dried defatted solids). This value is higher than those values (150 to 200 ng/g) reported in furan exposure studies performed in real starchy foods (Juániz and others 2016). Differences in the furan levels can be explained since for furan exposure assessment studies, furan determination in foods was developed considering the real food consumption conditions in which furan can be lost by evaporation.

Regarding to processing conditions, furan generation was significantly affected by both temperature and time ($P \le 0.05$). These findings are in agreement not only with the results obtained in our previous research (Mariotti and others 2012), but also with those obtained by other authors who studied furan formation in different types of food matrixes (Gül Akıllıoğlu and others 2015; Huang and Barringer 2016). Interestingly, the same trend has been observed for furan and other food processing contaminants (for example, acrylamide and hydroxymethylfurfural) generated during the frying of wheat flour-based foods such as bread-coated

frozen foods (Juániz and others 2016), Spanish "rosquillas," and Spanish "churros" (Morales and others 2008; Delgado-Andrade and others 2010). For all these studies, authors have concluded that the drastic temperature applied to starchy foods during frying would dramatically increase the formation of food processing contaminants. On the other hand, although the temperature is the catalyst of multiple chemical reactions, which are responsible for the formation of food processing contaminants, the extent of thermal treatment also influences the final content of these potential carcinogen compounds in the product (Martins and others 2001).

Therefore, keeping frying temperature below 180 °C and controlling the extent of frying time would contribute to reduce the final furan occurrence in wheat flour fried foods. In this sense, the kinetic modeling of furan generation should be considered as a powerful tool to control its final occurrence in foods, since kinetic parameters can help to predict the influence of processing conditions over its concentration.

Figure 1 shows a transition in the furan formation behavior, when frying temperature changes from the lowest (160 °C) to the highest (190 °C) level. From 160 °C to 180 °C, an exponential-type behavior for furan can be seen. However, at 190 °C, data follow a sigmoid shape. Since furan generation is a chemical reaction, it is logical to think that the furan content should reach an equilibrium value given by the consumption of the precursors or because a fried matrix reduces its water content to very low levels (it becomes vitreous) preventing contact between the reactants. Based on this behavior, a modified Gompertz model was used to fit all the data of furan formation in fried wheat flour-based model systems.

As shown in Figure 1, only for 190 °C, the furan concentration of wheat flour-based model system increased during frying following a sigmoid trend, namely, a lag phase at the beginning, an intermediate exponential phase, and an equilibrium state at the end. Hence, furan formation data presented a good fit ($RMS_{190^{\circ}C}$: 7.6%, see Table 1) only for the highest temperature in which the



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Table 1-Parameters for the modified Gompertz model fitted forfuran generation.

	Frying temperature (°C)					
Parameter	160	170	180	190		
Feg (ng/g dds*)	1207359	803936	2109	514		
$k_{\rm max}$ (ng/g dds [*] × min)	11095.9	10905.7	66.0	61.1		
λ (min)	64.30	43.03	7.80	1.23		
RMS (%)	17.2	29.9	15.0	7.6		

*dds: dry defatted solids.





asymptotic level is in the same magnitude order of the data. On the other hand, the model did not fit on a proper way (RMS > 10%) for the lower temperatures studied (RMS_{160°C}: 17.2%, RMS_{170°C}: 29.7%, and RMS_{180°C}: 15.0%). This behavior can be explained, since at 160, 170, and 180 °C, furan generation did not reach the asymptotic concentration level. Longer frying times should have been applied in order to get the plateau. However, to extend the frying of samples should be considered unrealistic if we pretend to mimic real food processing conditions (Saguy and Dana 2003).

Interestingly, studies of furan formation performed in spinach pure and soy sauce reveal that its generation in these liquid food matrixes followed a zero-order kinetic (Gül Akıllıoğlu and others 2015; Huang and Barringer 2016). For these products, the rate constant was positively proportional to time, thus the reaction rates were not related to the substrates producing furan in the food (Hinshelwood 2005). Differences between these and our results could be attributed to the fact that during frying, the structure of wheat flour-based model systems changes from an amorphous to a vitreous state, in which the mobility of precursors of furan is very low (Moraru and Kokini 2003). Therefore, a plateau in furan concentration is reached.

Likewise, the specific rate values obtained in this research were higher ($k_{190^{\circ}C}$: 0.97 nmol/g min and $k_{180^{\circ}C}$: 0.90 nmol/g min) than those reported in previous studies in tomato paste ($k_{70^{\circ}C}$: 0.0071 nmol/g min and $k_{90^{\circ}C}$: 0.0168 nmol/g min) and soy sauce ($k_{80^{\circ}C}$: 6.7 × 10⁻⁵ nmol/g min) performed at pasteurization conditions (Gül Akıllıoğlu and others 2015; Huang and Barringer 2016). This fact could be explained since our experiments were developed under frying temperatures (160 to 190 °C) in which the food matrix is subjected to more aggressive thermal treatment.

Kinetics of other physicochemical changes that take place during frying

During the frying of starchy foods, several physicochemical changes, such as color development, lipid oxidation, and oil uptake, among others, occur (Moyano and Pedreschi 2006). Under the experimental conditions explored in this research, the previous 3 mentioned responses were evaluated.

Color development, polar compound generation, and oil uptake presented a very similar behavior (Figure 2–4). A step increase in the rate of change of the response was observed for short periods of time (<3 min), following by a decrease in rates (up to 7 min) until reaching almost an asymptotic level. Similarly, all the

responses were significantly affected ($P \le 0.05$) by frying time and temperature, an increase in color development, polar compound generation, and oil uptake was observed, when these parameters augmented.

Considering that both color change and polar compound generation are consequences of chemical reactions, a first-order kinetic model, proposed by Krokida and others (2001), was successfully used to fit the data. For both responses, good fit of data was obtained at all evaluated temperatures, with RMS values between 4.4% and 12.5% and 2.6% and 7.4%, for color change and polar compound generation, respectively. The specific rates of color change and polar compound generation presented similar magnitude (Table 2) to those reported before by (Gupta and others 2000; Moyano and others 2002; Saguy and others 2003; Yost and others 2006), to describe the kinetics of nonenzymatic browning and lipid oxidation in fried potato, respectively.

On the other hand, based on the fact that oil absorption is a physical phenomenon, a mass balance model was employed to fit the data (Moyano and Pedreschi 2006). Our results presented a good fit to the model applied (RMS: 10.0% to 19.8%). The specific rate of oil absorption (k: 0.126 to 0.532 min⁻¹) increased with frying temperature, while the equilibrium oil content O_{eq} decreased with frying temperature (Table 2). This behavior agrees with the claimed fact that higher frying temperatures lead to lower absorbed oil (Pedreschi and Moyano 2005).

Effect of temperature over the specific rate of studied responses

Our results revealed that frying temperature presented a significant influence over furan generation, color development, polar compounds formation, and oil absorption in the studied fried wheat flour-based model systems. In order to do that, we determined the temperature dependence of the specific rates of these responses applying an Arrhenius-type equation. The apparent activation energy E_A was calculated by the fit of specific rate (*k*) against





Table 2-Specific rate constant and equilibrium values of the kinetic models for oil uptake, color development, and formation of polar compounds.

Frying temperature (°C)	Oil absorption			Color change			Polar compounds		
	$k \pmod{1}$	O _{eq} (g/g dds*)	RMS (%)	$k \ (\min^{-1})$	ΔE_{eq} (–)	RMS (%)	$k \pmod{1}$	CP _{eq} (%)	RMS (%)
160	0.126	0.561	19.8	0.435	33.08	12.5	0.359	0.052	3.4
170	0.233	0.470	14.2	0.481	38.24	4.4	0.376	0.057	2.6
180	0.312	0.485	10.0	0.545	39.29	8.3	0.385	0.069	7.4
190	0.532	0.474	10.0	0.568	44.15	7.8	0.407	0.073	5.7

*dds: dry defatted solids.

the inverse of absolute temperature (1/T), as can be observed in Table 3-Parameters for the Arrhenius-type equation. Figure 5.

Under the experimental conditions studied in this research, the furan formation did not present an Arrhenius temperature dependency. This behavior can be explained, since for the lower studied temperatures (160, 170, and 180 °C), furan generation did not reach the asymptotic concentration level. For these conditions, the specific rate, which can be defined as the slope of the steepest tangent to the exponential phase, is highly overestimated for the 2 lower temperatures (Table 1).

On the other hand, color development (RMS: 1.7%), polar compounds formation (RMS: 0.7%), and oil absorption (RMS: 6.3%) presented an excellent fit to the Arrhenius-type equation. As

Phenomena	Arı		
	$k_0 \ (\min^{-1})$	E_A (kJ/mol)	RMS
Oil absorption	2.51×10^{8}	76.98	6.3
Color change	32.16	15.47	1.7
Lipid oxidation	2.28	6.67	0.7

can be observed in Table 3, our results are in agreement with those reported by other authors in fried vegetal food matrixes, such as potato, where similar activation energy (E_A) values were reported (Gupta and others 2000; Moyano and others 2002; Pedreschi and



Figure 5–Effect of temperature over the specific rate of studied responses.

others 2005; Moyano and Pedreschi 2006; Pedreschi and others Juániz I, Zocco C, Mouro V, Cid C, De Peña MP. 2016. Effect of frying process on furan 2007b).

Conclusion

Based on our results, we can conclude that for fried wheat flourbased model systems, furan formation is highly dependent on the frying conditions: heating medium temperature and frying time. Its occurrence in fried starchy foods seems to be consequence of the interaction of multiple chemical mechanisms and physic phenomena that commonly take place during the frying of this food category. In terms of transferring the knowledge generated in this research, our results clearly show that keeping frying temperature below 180 °C contributes to reduce the final furan occurrence in fried samples. Additionally, a similar behavior was observed for oil uptake. Thus, we concluded and recommended to fry at temperatures lower than 180 °C in order to reduce not only the furan content of the samples but also the oil uptake. Finally, regarding to frying time, our results also revealed that it is a critical issue to control the extent of the process, since longer times would increase both furan and oil content of fried products.

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