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A modified predictive model for colour changes in French fries during frying

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Abstract. During frying, heat and mass transfer phenomena happen and cause the physiochemical changes that affect the colour of french fries. Moisture content, oil content, and colour are important quality parameters in frying french fries, while temperature, frying time, and sample thickness will affect the french fries. In this study, we developed a modified mathematical model for colour changes of French fries during frying. The colour changes were formulated using a first-order ordinary differential equation that was solved using the 4th order Runge-Kutta method in the MATLAB software. The formulation for rate constant was modified using the Arrhenius equation and the sum squared error (SSE) of the proposed model was compared with the SSE of existing models. The colour was evaluated based on two parameters which are oil temperature (150°C, 170°C, 190°C) during frying and sample thickness (5 mm, 10 mm, 15 mm) of french fries. The results showed that incorporating the factor of moisture into the model provides a better prediction of lightness and yellowness of french fries during frying. Overall, we conclude that moisture plays a significant role in the colour changing of french fries.

Keywords: French fries, colour, sum squared error (SSE), MATLAB, mathematical model

1. Introduction

Frying is known as one of the most complicated and aged techniques in food production [1]. Frying removes water in food, while oil acts as an efficient heat transfer mechanism [2]. Frying can be categorised into four phases which are preliminary heating, plumping rate, geometric surface boiling, and final spot bubble [3].

Frying is a simultaneous heat and mass transport procedure [4]. During frying, the mass transport phenomenon which consists of moisture loss and oil uptake happens [5]. Usually, the oil temperatures used for frying french fries are between 150°C and 190°C. The estimation of moisture loss related to the first-order kinetics model moisture content has been considered [6] [7].

Frying converts the physical and chemical features of french fries. Elements that influence the physical characteristics of french fries are moisture and oil content [8]. French fries' quality relies on its colour, shape, texture, nutrition, and odour [9]. Colour is the foremost visual attribute in the judgment of french fries' quality [2]. Colour is the prominent quality parameter judged by a user and it determines the acceptance of the product [10].

French fries will form a golden colour or a combination of the yellow and brown colours during frying [11]. Dark spots that may appear on french fries during frying should be avoided. These dark areas typically occur on the surface of french fries that are parched after frying for too long. The light



golden colour is the guideline colour for frying french fries [12]. Prudent supervision is needed to attain the optimal colour change from raw potatoes into french fries [13].

This study aims to improved modified mathematical model that ascertains the colour change when frying french fries. The effect of the primary process variables, L and parameter b of french fries on colour kinetics has been examined based on oil temperature, sample thickness, and frying time of the french fries. L values, also known as lightness, show the whiteness of french fries, while parameter b shows yellowness.

2. Mathematical Modelling

During the frying of french fries, the water diminution rate rises, causing water to start to vaporise and bubbles to circulate along the oil. Darkening is caused by unsaturated carbonyl compounds or non-polar food compounds solubilised in the oil [14].

In this section, the conventional mathematical model of colour change in french fries during frying is described. Then, it is followed by the proposed mathematical model. The colour changes were formulated using the first-order ordinary differential equation.

As presented by Krokida et al. [15], the empirical mathematical equation is:

$$x_e = x_{0e} \left[\frac{T}{170} \right]^{x_T} \left[\frac{d}{10} \right]^{x_d} \tag{1}$$

$$K_x = K_{0x} \left[\frac{T}{170} \right]^{K_{xT}} \left[\frac{d}{10} \right]^{K_{xd}} \tag{2}$$

where x_{0e} represents initial colour equilibrium, T is the oil temperature, x_T is the effect of temperature on the colour parameter (L, b), x_d indicates the effect of sample size on the colour parameter (L, b), K_{0x} is the initial rate constant of the colour parameter (L, b), K_{xT} represents the effect of temperature on the rate constant of the colour parameter (L, b), K_{xd} is the effect of sample size on the rate constant of the colour parameter (L, b), and d is the cross-section thickness of the french fries (mm).

Then, the equation (1) and (2) will be substitute into the convectional equation as below:

$$\frac{dx}{dt} = -K_x(x - x_e) \tag{3}$$

where x is the colour parameter (L, b), t is time (min), x_e represents the equilibrium value, and K_x is the rate constant (min^{-1}) of colour.

Frying fries that are rich in water content takes a longer time to get the desired colour. The kinetic of colour change in fries is closely associated with factors such as temperature, sample thickness, and moisture content (water activity). Our proposed model considers moisture as a factor that affects the colour changes in food.

Krokida's model was modified using the Arrhenius relationship to formulate the rate constant of colour as follows:

$$K_x = K_{0x} \exp \left(-\frac{E_a r}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right) \tag{4}$$

where T_{ref} represent the reference oil temperature, E_a is the activation energy, R is the universal gas constant (8.314 J/mol-K) and r is the moisture content which decays exponentially according to,

$$r = \exp(-r_0 t) \tag{5}$$

where r_0 represents the initial moisture content.

The new model consisting of equations (1), (2), (4), and (5) was solved numerically using the 4th order Runge-Kutta method and the coding was written in the MATLAB software. All the seven parameters ($K_{0x}, E_a, T_{ref}, x_{0e}, x_T, x_d, r_0$) can be determined simultaneously using a fitting technique called the Nelder-Mead algorithm.

The model predictions were compared with the experimental data and the sum squared error (SSE) was computed to quantify the goodness-of-fit.

$$SSE = \sum_{i=1}^N (x \exp_i - xcal_i)^2 \tag{6}$$

where $x \exp_i$ is the experimental value of the dependent variable of the i th experiment, $xcal_i$ is the calculated value from the model for the i th experiment, and N is the total number of experiments.

3. Results and discussion

The two approaches (Krokida’s model and the newly proposed model) were compared based on their SSE values. The Maillard reaction which depends on the sugar and amino acid or protein reduction content on the surface, surface temperature, and frying time, is considered as the french fries’ colour change [16]. Browning processes such as baking, drying, and frying are essential phenomena in food handling and processing because they affect appearance consistency [17].

Lower L values will contribute to undesirable french fries colour [16]. The data reported in [15] which was based on the oil temperature and sample thickness of french fries was used. The oil temperatures observed were 150 °C, 170 °C, and 190 °C for sample thickness of 10 mm. For the sample thicknesses of 5 mm, 10 mm, and 15 mm, the oil temperature was set up at 170 °C. All values of the colour parameters ($K_{0x}, E_a, T_{ref}, x_{0e}, x_T, x_d, r_0$) for lightness and yellowness are presented in Table 1 and Table 2, respectively.

Table 1. Values parameters ($K_{0x}, E_a, T_{ref}, x_{0e}, x_T, x_d, r_0$) for lightness

Parameter	Lightness values with sample thickness 10mm			Lightness values with oil temperature 170°C		
	150°C	170°C	190°C	5mm	10mm	15mm
K_{0x}	1.1720	4.0601	1.4259	0.5265	2.3309	2.0115
E_a	0.8496	17.0138	0.7729	-1.3260	1.4209	2.0138
T_{ref}	-0.0668	-0.9576	-0.0871	-0.0861	-0.1099	-0.0790
x_{0e}	75.8196	74.0754	73.0388	71.6062	74.6617	76.4807
x_T	-0.1258	0.9403	-0.1322	-0.9473	-0.2010	-0.1657
x_d	0.0913	0.0185	0.0884	-0.0348	0.0472	0.228
r_0	1.433	0.0699	0.5561	1.9697	0.1353	0.4318

Table 2. Values parameters ($K_{0,x}, E_a, T_{ref}, x_{0e}, x_T, x_d, r_0$) for parameter b

Parameter	Parameter b values with sample thickness 10mm			Parameter b values with oil temperature 170°C		
	150°C	170°C	190°C	5mm	10mm	15mm
$K_{0,x}$	0.0792	0.0063	0.0789	0.1386	0.0238	0.3290
E_a	-1.1547	-15.7438	-2.458	-41.0255	0.0964	-0.0515
T_{ref}	0.1882	-0.8042	-0.00231	-3.2998	0.0055	0.0005
x_{0e}	23.8152	99.4390	55.2691	20.4590	44.4242	34.8926
x_T	-2.8492	1.1477	-3.6582	3.9446	1.8734	-1.6389
x_d	-0.2025	-1.8869	-0.7869	-1.0635	-0.6200	-0.2900
r_0	4.6480	0.2807	2.8592	3.9308	0.1603	2.3138

Figures 1-4 visualise the predicted model. The black dots represent the experimental data reported in [15] and the curve lines represent the model’s prediction.

3.1 Lightness

French fries’ colour development during frying depends on its moisture loss, oil uptake, and heat transfer coefficient at the various frying stages [18]. Figure 1 shows the effect of oil temperatures (150 °C, 170 °C, and 190 °C) on the lightness of french fries during frying using samples that were 10 mm thick. The frying time was set to 20 min for each temperature tested. At the early stage of frying, the french fries’ lightness increased and remained almost constant afterwards.

The initial increase in lightness value is due to loss of moisture, causing the french fries to become whitish. This condition then remains almost constant due to oil impingement and the formation of Maillard reaction in the french fries due to reducing sugars and proteins [19]. Results on the low lightness values may also be caused by dark patches forming due to non-enzymatic browning reactions. Non-enzymatic browning is the outright term for a product’s darkening due to any reaction and not because of enzymatic activity [17]. Increases in temperature and frying time showed reductions in moisture content.

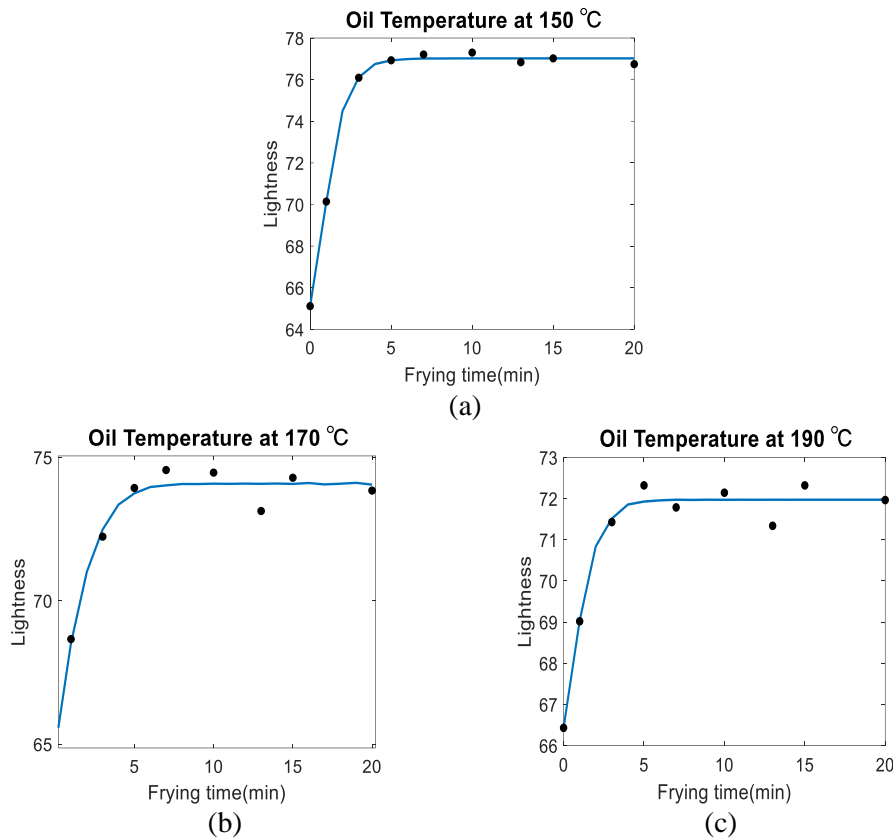


Figure 1.Lightness level versus frying time at different oil temperatures: (a) 150 °C, (b) 170 °C, (c) 190 °C

The sample thickness' effect on lightness with oil temperature constant at 170 °C during frying is shown in Figure 2. At first, the initial lightness increased, however, the lightness level remained almost constant at $t = 5$ and after. This behaviour happened because the lightness value depends on the amount of free water present on the sample's surface which favours the reflection of light, therefore explaining the low lightness values in pre-dried samples [18]. Thinner french fries will give an acceptable lightness level compared to thicker french fries, causing food to look pale and uncooked. This shows that sample thickness significantly influences the lightness to produce french fries of excellent quality and colour. Decreases in sample thickness also cause darker colouration compared to increased sample thickness [18].

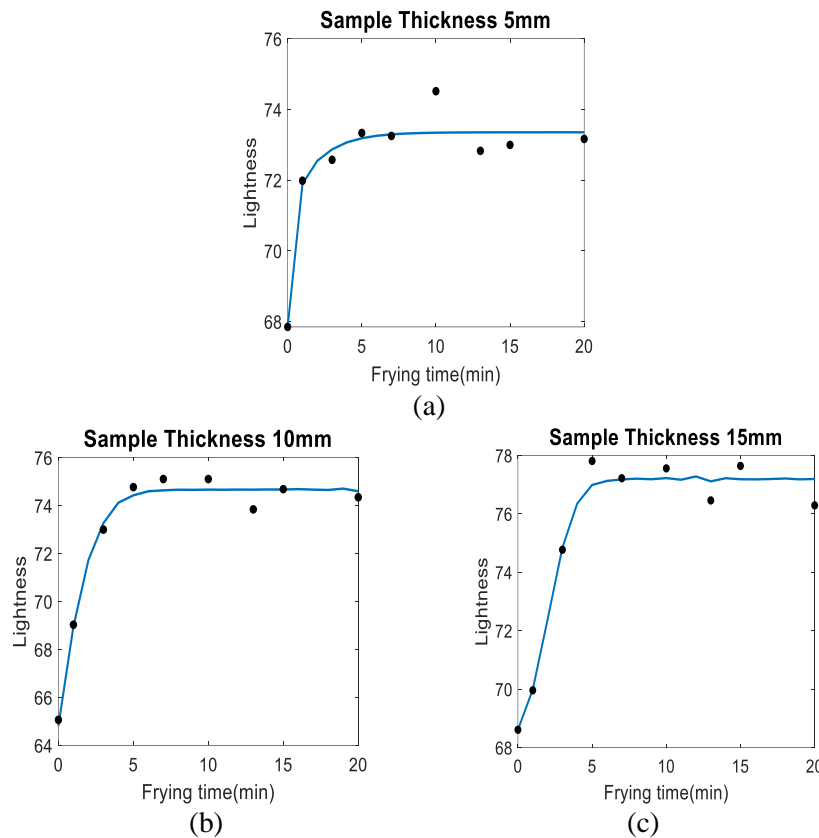


Figure 2.Lightness level versus frying time for different sample thicknesses: (a) 5 mm, (b) 10 mm, (c) 15 mm

3.2 Yellowness (parameter *b*)

Figure 3 shows that the yellowness (parameter *b*) of french fries increased with frying time with maximum $t = 20$ at oil temperatures of 150 °C, 170 °C, and 190 °C and sample thickness of 10mm for each oil temperature. Parameter *b* rapidly increased until the end of frying time for each oil temperature. Table 3 indicates the value of *b* at $t = 20$ min. Increases in oil temperature increased the value of parameter *b*. The chromatic color of parameter *b* increases with frying time and oil temperature because of the formation of compounds from the Maillard non-enzymatic reaction [1]. Higher parameter *b* values produce yellower products which is a desirable trait for fried products. Increasing values indicating yellowness have a strong correlation with browning. During frying, the golden colour of french fries that occurs is primarily related to yellowness and the appropriate colour for french fries.

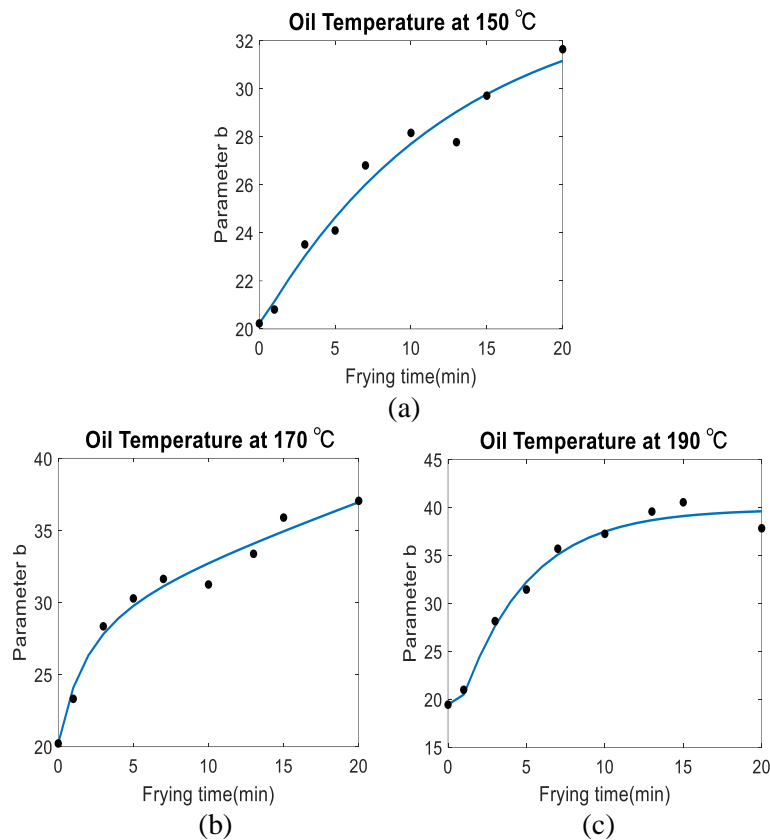


Figure 3. Parameter b versus frying time at different oil temperatures: (a) 150 °C, (b) 170 °C, (c) 190 °C

The b values increased with frying time as the oil temperature increased. Higher levels of yellowness of the french fries will make the french fries more desirable.

Table 3. b values at $t=20$ min at oil temperatures (150°C,170°C,190°C)

Oil temperature (°C)	b values at $t=20$ min
150	31.16
170	37.06
190	38.08

Using samples with thicknesses 5 mm, 10 mm, and 15 mm and a constant temperature of 170 °C, Figure 4 shows that the thickness of french fries influenced its yellowness with time of frying of 20 min for every sample thickness. Table 4 indicates the b values for each sample thickness at $t = 20$. The parameter b slightly increased with decreases in sample thickness and increases in frying time. This could be due to a higher thermal gradient across the thinner samples since the oil temperature remained constant [9]. Heat conduction in thinner french fries samples caused it to fry faster compares to thicker french fries samples. Higher levels of parameter b produced more desirable yellowness in the french fries' colour.

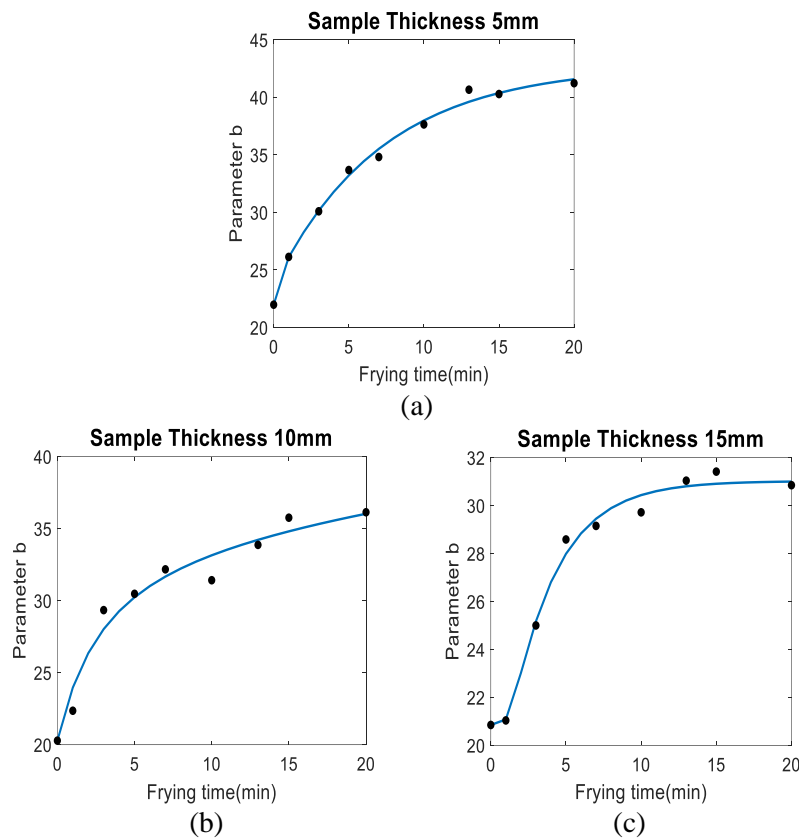


Figure 4. Parameter *b* versus frying time for sample thicknesses: (a) 5 mm, (b) 10 mm, (c) 15 mm.

At the end of the frying process, the *b* values of French fries decreased with increasing thickness. The browning reaction that occurred during frying decreased the yellowness of French fries as the samples' thickness increased.

Table 4. *b* values at *t*=20 min for samples' thicknesses (5 mm,10 mm,15 mm)

Sample thickness (mm)	<i>b</i> values at <i>t</i> =20 min
5	41.23
10	36.13
15	32.30

3.3 SSE values

Table 5 shows the SSE values between the existing model [15] and the modified predictive model for lightness using oil temperatures of 150 °C, 170 °C, and 190 °C and sample thickness of 10 mm. Table 6 shows the SSE values of both models for sample thicknesses of 5 mm, 10 mm, and 15 mm at oil temperature of 170 °C. For parameter *b*, the SSE values of each model are as indicated in Table 7 for oil temperature (150 °C, 170 °C, and 190 °C) with sample thickness 10mm, and Table 8 indicates the samples' thickness (5 mm, 10 mm, and 15 mm) at oil temperature of 170 °C. As the oil temperatures changes, the sample thickness remained constant at 10 mm, and as the sample thickness changes, the oil temperature stayed constant at 170 °C.

Based on Tables 5-8, the SSE values for the modified predictive model quantify that the data is more accurate around the regression line compared to the existing model because the modified predictive model has lower SSE values compared to the existing model. Equation (3) in Krokida et al.

[15] that has been modified using the Arrhenius relationship is proven better in quantifying data in this research. Our prediction model matches the data trendline as shown in Figures 1-4.

Table 5. Comparison of error between existing model and modified predictive model on lightness of samples at varying oil temperatures and sample thickness of 10 mm

Oil temperature (°C)	SSE value of existing model [15]	SSE value of modified predictive model
150	1.3652	0.22811
170	1.7973	1.5411
190	0.8942	0.7494

Table 6. Comparison of error between existing model and modified predictive model on lightness of samples at varying thicknesses and oil temperature of 170 °C

Sample thickness (mm)	SSE value of existing model [15]	SSE value of modified predictive model
5	2.2114	1.9345
10	1.8004	1.4133
15	7.2177	2.2431

Table 7. Comparison of error between existing model and modified predictive model on parameter *b* for varying oil temperatures with sample thickness of 10 mm

Oil temperature (°C)	SSE value of existing model [15]	SSE value of modified predictive model
150	3.3412	3.3259
170	3.3412	3.1270
190	14.0912	5.6583

Table 8. Comparison of error between existing model and modified predictive model on parameter *b* for varying sample thicknesses at oil temperature of 170 °C

Sample thickness (mm)	SSE value of existing model [15]	SSE value of modified predictive model
5	3.5181	2.0752
10	11.3634	8.6457
15	5.1231	1.3292

4. Conclusions

Colour is influenced by oil temperature and frying time. Lightness (*L*) causes the pale and whiteness colour of french fries, while yellowness (*b*) will give the desirable yellowness colour of french fries. The resulting french fries get darker due to non-enzymatic browning reactions that depend heavily on oil temperature and frying time. Physical features of french fries change significantly during frying. If the oil temperature rises, the samples' moisture content falls even for the same frying time because an increase in temperature tends to cause higher kinetic energy in water molecules, resulting in a rapid loss of moisture as vapour. In this study, a modified model for colour change in french fries during frying was developed. The modified model incorporated the moisture factor as a better predictor of lightness and yellowness (parameter *b*) of french fries during frying. The proposed mathematical model has been validated and fitted the data adequately compared to the existing model. In terms of low value SSE value of the two models, suggesting that it improves the proposed model significantly.

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