

Article

Deep Fat Frying Characteristics of Malpoa: Kinetics, Heat, and Mass Transfer Modeling

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Abstract: This article investigated deep-frying characteristics of malpoa for varied frying time (2–10 min) and temperature (170–190 °C). The evaluation encompassed a comprehensive analysis of textural and color kinetics and heat and mass transfer modeling during deep fat frying of malpoa balls. Such investigations confirmed an enhancement in fat content from 10.2 to 41.65%. On the other hand, textural properties such as hardness, cohesiveness, and springiness varied from 3.14 to 22.59 N/mm, 0.22 to 0.76, and 15.5 to 49.56, respectively. Similarly, color parameters such as b^*/a^* and ΔE varied from 3.31 to 1.55 and 55.36 to 75.48. For the textural and color kinetics, the activation energies ranged between 58.65 and 85.82 kJ/mol and 31.34 and 64.34 kJ/mol. Similarly, for a variation in frying time from 2 to 10 min, responses (hardness, cohesiveness, springiness, and overall color) varied across the following ranges: 3.15–13.57 N, 0.22–0.66, 15.5–35.5, and 55.63–63.50 and 5.60–20.60 N, 0.30–0.77, 22.35–49.56, and 62.26–75.65 for temperatures of 170 and 190 degrees, respectively. On the other hand, heat and mass transfer analysis indicated a Biot number and heat transfer coefficient within the range of 0.31–0.65 and 25.58–34.64 for 170–190 °C. Thus, this investigation provides a deeper insight of the deep fat frying characteristics of malpoa. This provides a guideline for the food processing sector for such products.

Keywords: color kinetics; deep fat frying; fat uptake; heat and mass transfer; malpoa; texture kinetics



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1. Introduction

Traditional food products hold a special place in the culinary heritage of nations, serving as a reflection of cultural history and regional identity. These time-honored dishes and ingredients continue to be cherished and enjoyed by people around the world. According to statistics, the market for traditional food products has been steadily growing, with global sales reaching an estimated USD 1.2 trillion in 2020. This growth can be attributed to a growing interest in culinary tourism, the increasing popularity of traditional and authentic flavors, and a desire for healthier, locally sourced options [1]. In fact, a significant percentage of consumers actively seek out traditional or artisanal food products when shopping, citing a preference for quality, taste, and a connection to cultural roots. As the demand

for traditional food products continues to rise, it underscores their enduring appeal and importance in preserving culinary traditions across the globe [2].

India is the leading country, with diverse sweet products being produced traditionally. These sweet products include sandesh, kalakand, malpoa, srikhand, rasogolla, and gulab jamun, among others [3]. These are prepared using various methods such as cooking, frying, roasting, grinding, and fermentation. Among various processes being adopted for such cases, deep fat frying is considered to be one of the simplest methods of cooking. It is a form of cooking that uses edible oil at temperatures beyond the boiling temperature of water. This temperature typically ranges from 120 to 210 °C, with 150–190 °C being the most prevalent range [4]. The aim of the deep-frying process is to maintain flavor, a crunchy crust, and a moist cooked interior by sealing the meal in the heat of the oil. Malpoa is one of the popular deep-fried foods widely consumed across India [5]. Additionally, it is eaten during high tea and as a brunch item.

During the deep fat frying process, water is removed, creating pores inside the food sample. On the other hand, oil is initially adsorbed on the surface of the food [6]. Subsequently, it penetrates the pores, providing the desired food characteristics. The development of oil countercurrent flows and water vapor on the food's surface fosters simultaneous transfer heat and mass [7]. Other modifications of the food product during the frying process include the gelatinization of carbohydrates, denaturation of protein chains, and the disruption of middle lamellar cell adhesion [8]. These variations are key for customer acceptance. On the other hand, the frying process causes physical and chemical changes in food that depend on the constitution of the food. Such changes include the development of the desired texture, flavor, and brown color. A percentage of the frying oil and polar compounds created by oil degradation are absorbed by food and contribute to the overall quality of the finished product. Furthermore, taste emerges, crispness is generated, and holes are formed [9]. This results in the desired texture and sensory qualities.

Among various modifications during the deep fat frying of malpoa, texture and color are important as desired characteristics of the fried product. The variables are greatly affected with the variation in frying temperature and time [10]. On the other hand, frying temperature and time significantly affect caramelization and crust formation, which results in a definite effect on the texture and color of the product. Therefore, it is very necessary to investigate the variation in responses with frying temperature and time. Further, the kinetic study of the variation in color and texture would facilitate process–product optimization and the design of frying equipment. Mondal et al. (2017) examined the development and characterization of Chenna jhili balls using deep fat frying. The authors evaluated color and texture kinetics with a varied temperature and time from 120 to 140 °C and 3 to 20 min, respectively. The literature affirmed a variation in L^* of 46.53–26.76, in b^*/a^* of 3.944–0.4412, in ΔE of 32.460–52.668, in hardness of 0.822–2.452 N/mm², in stiffness of 1.214–5.750 N/mm², and in firmness of 2.875–9.126 N/mm [11]. Similarly, Salehi (2018) investigated the variation in color with regard to the variation in the frying temperature of carrots during deep fat frying. The product was deep fat fried at a temperature of 130–190 °C and a frying time of 90–180 s. For such a case, the optimum values reported were redness (a^*) 22.30, yellowness (b^*) 48.44, and lightness (L^*) 55.74–49.21 [12]. Hindra et al. (2006) investigated quality parameters of deep fat tofu in relation to the variation in frying temperature (147–172 °C) and time (5–35 min). Authors have studied the kinetics of color variation during this process. This investigation affirmed a variation in L^* , a^* , and b^* from 85.5 to 68.0, 1.17 to 6.72, and 18.8 to 34.5 [13]. Further, the activation energy for the color variation was reported to be 76–165 kJ/mol.

On the other hand, the transfer of heat from the oil bath to the exterior of the produce occurs through convection, and then through conduction to the inner core. As the food reaches the boiling point of water, moisture evaporates and escapes, while fat from the surrounding oil infiltrates into the food. Therefore, frying can be characterized as a complex process of both heat and mass transfer [14]. The available literature affirms few investigations for heat and mass transfer modeling of various food materials during deep fat frying.

For chena jhili, heat and mass transfer coefficients reported were 69.80–103.18 W/m²·K and $2.848\text{--}7.543 \times 10^{-5}$ m/s for 120–140 °C, respectively [15]. Similarly, the corresponding values for deep fat fried gulab jamun were 94.10–122.34 W/m²·K and $10.41\text{--}14.35 \times 10^{-5}$ m/s for 120–140 °C, respectively [16]. On the other hand, heat conductivity and thermal diffusivity for the variation in frying temperature from 5 to 80 °C reported were 0.24–0.43 W/m²·K and $7.6 \times 10^{-8}\text{--}1.15 \times 10^{-7}$ m²/s. The study of heat transfer in a plant-based fishball alternative revealed a thermal diffusivity of 7.56×10^{-6} m²/s [17,18].

A comprehensive study of existing state-of-the-art research confirmed limited studies on the characterization of deep-fried food products, including gulab jamun, tofu, sweet potatoes, and French fries. Most of the available literature focused on color and texture dynamics in the deep fat frying process. However, there are very few studies that have addressed heat and mass transfer modeling during deep fat frying and the textural parameters, including firmness, hardness, and stiffness. According to the available literature, deep fat fried malpoa has not been investigated for any characterization, including color, texture, heat, and mass transfer characterizations. Based on this, the objective of this study is to provide a detailed characterization of deep-fried malpoa that includes color and textural kinetics, as well as heat and mass transfer modeling during the deep fat frying process of malpoa. The ultimate goal of this work is to contribute to the identification of the optimal qualities of malpoa, which facilitates the process of designing products and processes, as well as the design and development of frying equipment for commercial usage.

2. Materials and Methods

2.1. Raw Material

Refined wheat flour, baking powder (brand: Weikfield), refined sunflower oil (brand: Fortune), milk powder (Nestle), and sugar were procured from the local market, in Phagwara, Punjab, India. These raw materials were mixed with the addition of water to prepare the malpoa balls.

2.2. Kinetics of Various Parameters for Malpoa During Deep Fat Frying

2.2.1. Preparation of Malpoa Balls

For the preparation of malpoa balls, initially, 38 mL of water was added to 20 g of milk powder to prepare reconstituted milk. Further, refined wheat flour (100 g), baking powder (1 g), and powdered sugar (80 g) were blended by adding the standardized milk to obtain smooth dough. Thereafter, the dough was rolled into spherical balls of 30 mm in diameter for deep fat frying. For the preparation of malpoa, about 1.5 L of refined sunflower oil was used for each subsequent experiment.

2.2.2. Deep Fat Frying

For frying, a deep fat fryer (Americon Micronic, Deep Fryer, 2000 W, 3 L capacity) with a temperature regulator was used to carry out the experiment. For monitoring the temperature of the oil bath while frying, a thermoelectric thermometer was used. Before the initiation of the frying process, the vessel was filled with 1.5 L of oil and preheated up to the required temperature.

The malpoa balls were deep fried at temperatures of 170, 175, 180, 185, and 190 °C for various time intervals between 2 and 10 min of frying. For a specific temperature, 5 malpoa balls were fried in a batch. The fried malpoa balls were taken out at 2, 4, 6, 8, and 10 min from the oil vessel and wiped with tissue after to remove the excess oil. Thereafter, the fried balls were allowed to cool to ambient temperature and packed in poly bags. Further, the samples were also evaluated for various parameters such as color, texture, fat content, and moisture content of the balls. Each experiment was carried out three times to ensure the reproducibility of the data obtained.

2.2.3. Textural and Color Change Kinetics

The variations in texture and color with frying time and temperature during deep fat frying of Malpoa were quantified using chemical reaction kinetics. Kinetic studies on quality changes during the frying process as a function of heating time at a specific temperature were investigated to determine temperature-dependent reaction rate constants [15]. Most foods follow a zero-order or first-order kinetics for the variation in texture and color with frying temperature and time. Therefore, the kinetics of textural and color changes were assessed using the zero- and first-order reactions (Equations (1) and (2), respectively) presented as follows:

$$Q = Q_0 - kt \text{ (Zero-order reaction)} \quad (1)$$

$$\ln \frac{Q}{Q_0} = -kt \text{ (First-order reaction)} \quad (2)$$

The quality attribute, rate constant, time, and order of reaction are represented by Q , k , t , and n , respectively.

On the other hand, the Arrhenius equation presented below (Equation (3)) was used to quantify the activation energy for variation in textural and color parameters.

$$k = k_0 \exp \left[-\frac{E_a}{RT} \right] \quad (3)$$

where k_0 , E_a , R , and T are the rate constants at time $t = 0$, activation energy, universal gas constant, and absolute temperature, respectively.

Texture Parameters Evaluation

The samples were subjected to a single cycle penetration test using a probe (Compression Platen P/75) with the force of 0.050 N and 5 kg load. The test was carried out using a texture analyzer (Stable Micro systems, model: TA-HD plus C). The data were analyzed using the Texture Expert Exceed Software Version 2.64 that came with the instrument. The force–distance graph was used to calculate hardness, cohesiveness, and springiness [19] using the following equations (Equations (4)–(6)):

$$\text{Hardness} = \text{Maximum force (N)} / \text{Maximum deformation (mm)}, \quad (4)$$

$$\text{Cohesiveness} = \frac{\text{Area under 1st compression}}{\text{Area under 2nd compression}} \quad (5)$$

$$\text{Springiness} = \text{Length 1} / \text{Length 2} \quad (6)$$

2.2.4. Color Parameters Evaluation

The color of the crust was measured using a Hunter lab colorimeter and Universal software. The results were expressed in terms of L^* (lightness, ranging from 0 to 100), a^* (ranging from 160 to 260), and b^* (ranging from 160 to 260). Total color change can be expressed with the following equation (Equation (7)).

$$\delta E = \sqrt{\left((L_0^* - L_t^*)^2 + (a_0^* - a_t^*)^2 + (b_0^* - b_t^*)^2 \right)} \quad (7)$$

where δE denotes the total color; L_0^* , a_0^* , b_0^* , L_t^* , a_t^* , b_t^* represent lightness, redness, and yellowness at zero and t time, respectively. The data were obtained for three identical balls. Further, three different locations on the surface of each ball were measured [20].

2.3. Heat and Mass Transfer Modeling of Malpoa During Deep Fat Frying

2.3.1. Moisture and Fat Content Measurements

Each fried malpoa ball was taken at 2, 4, 6, 8, and 10 min of frying time at 170–190 °C and evaluated for moisture content. The oil adhered to the malpoa and was allowed to

drain in a stainless-steel perforated vessel lined with tissue paper. Thereafter, the sample was ground using a mortar and pestle. Further, the moisture and fat content of the sample were determined using the oven drying and Soxhlet extraction methods, respectively [15]. For moisture content, about 5 g of fried samples were taken in a Petri dish and kept in an oven at 105 °C for 4–6 h. After drying, the sample weight was measured, and we determined the moisture content using the following expression (Equation (8)):

$$\text{Moisture content (\%)} = \frac{\text{Weight of sample before drying} - \text{weight of sample after drying} \times 100}{\text{sample weight}} \quad (8)$$

On the other hand, fat content was determined using the Soxhlet extraction method [15,17]. About 10 g of sample was taken in an extraction thimble. The boiling flask was filled with hexane, then the solvent was heated to reflux for six to eight hours to guarantee full fat extraction. Following extraction, the fat and hexane mixture was dried at 105 °C to evaporate the solvent with a rotary evaporator. Further, the following expression (Equation (9)) was used to calculate the fat content of the sample:

$$\text{Fat content (\%)} = \frac{\text{Weight of sample before drying} - \text{weight of sample after drying} \times 100}{\text{sample weight}} \quad (9)$$

2.3.2. Temperature Measurement

From the sample, core temperature was measured after frying using a long-stem thermocouple-type thermometer (model Min-Max, Oakton Instruments, Vernon Hills, IL, USA). The samples were taken out after the specified frying times of 2, 4, 6, 8, and 10 min for 170–190 °C. Thereafter, instantly, the probe of the thermometer was pierced into the geometric center of the sample to measure the core temperature. Further, the temperature of the oil bath was measured by inserting the probe into it.

2.3.3. Heat Transfer Modeling

For the development of mathematical models, the following assumptions were considered. Firstly, the transport phenomenon during frying was assumed to be one-dimensional unsteady-state heat and mass transfer along the radial direction of the sample. Secondly, the sample was homogeneous, isotropic, and spherical with constant dimensions with no internal heat generation. Lastly, initial temperature, moisture, and fat content were considered constant throughout the frying process.

With the above assumptions, the heat transfer coefficient was calculated from the time–temperature data using the lumped thermal capacity model (Holman, 1997) [21] and the one-dimensional transient heat conduction equation (Kopelman and Pflug, 1968) [22].

Model of Lumped Thermal Capacity

Thermal capacity was measured with assumptions that refer to small internal temperature gradients and surface heat transfer resistance, and the integrated form of the energy balance at the surface for boundary conditions $T = T_{(i)}$ at $t = 0$ and $T = T_{(t)}$ at $t = t$ is expressed as Equation (10):

$$\frac{T_t - T_0}{T_i - T_0} = \exp\left(\frac{-hS}{mC_p}t\right) \quad (10)$$

where T_i , T_0 , T_t , and S are the initial temperature of the product, the temperature of the frying medium, the temperature of the product at any time “ t ”, and the product’s surface area (m^2). C_p is the specific heat ($\text{J/kg}\cdot\text{K}$) of the product, m is the product’s mass (kg), and the convective heat transfer coefficient ($\text{W/m}^2\cdot\text{K}$) and frying time (sec) are denoted with h and t . The given model is applicable only in the condition of high Biot number (B_i), ($B_i = \frac{hL}{k} < 0.1$, where “ k ” is the thermal conductivity of the product (W/mK), “ L ” is the characteristic length ($L = \frac{R}{3}$ for sphere), and “ R ” is the radius (m) of the sample) [17].

Transient Heat Conduction During Deep Fat Frying of Malpoa

For analyzing transient heat conduction during deep fat frying of malpoa, the partial differential equation for one-dimensional heat conduction through a sphere with an initial temperature of “ T_i ” when suddenly exposed to a constant temperature environment “ T_0 ” is expressed with the following equation (Equation (11)) [23,24]:

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) \quad (11)$$

where “ α ” and “ r ” are thermal diffusivity (m^2/s) and radial distance from the sample center, respectively. The initial and boundary conditions are established as $T(r, 0) = T_i$ and $\frac{\partial T}{\partial r} = 0$ at $r = 0$ and $-k \frac{\partial T}{\partial r} = h(T_i - T_0)$ at $r = R$ for $t \geq 0$.

The heat transfer coefficient was calculated using the analytical solution of Equation (11) given as Equation (12):

$$\frac{T_t - T_0}{T_i - T_0} = \sum_{n=1}^{\infty} \frac{2[\sin \mu_n - \mu_n \cos \mu_n]}{\mu_n - \sin \mu_n \cos \mu_n} \exp(-\delta_n^2 F_{O_h}) \frac{\sin(\delta_n \frac{r}{R})}{\delta_n \frac{r}{R}} \quad (12)$$

where “ δ ” is the characteristic coefficient based on the product’s geometry. The first term in the equation (Equation (12)) is significant, and the other terms can be ignored if the heat transfer is not significant. Fourier coefficient $F_{O_h} = \frac{\alpha t}{R^2} > 0.2$, and the term $\frac{\sin(\delta_1 \frac{r}{R})}{\delta_1 \frac{r}{R}}$ is simplified to unity since $\frac{r}{R} = 0$ (at the center) as temperature was measured at the sample core [24]. Therefore, using the first term of the infinite series and linearizing resulted in the following expression (Equation (13)):

$$\ln \left(\frac{T_t - T_0}{T_i - T_0} \right) = \ln \frac{2[\sin \mu_1 - \mu_1 \cos \mu_1]}{\mu_1 - \sin \mu_1 \cos \mu_1} - \delta_1^2 F_{O_h} \quad (13)$$

The heat transfer Biot number (B_i) and heat transfer coefficient were calculated using Equation (14):

$$B_i = 1 - \frac{\delta_1}{\tan \mu_1} = \frac{hR}{k} \quad (14)$$

2.3.4. Mass Transfer Modeling

Moisture Transfer Modeling

The partial differential equation for moisture content as a function of frying time and location for a sphere is expressed as Equation (15):

$$\frac{\partial M}{\partial t} = D_m \left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r} \right) \quad (15)$$

where D_m denotes moisture diffusivity (m^2/s), M represents moisture content, and r denotes the radial distance from the center of the sample. The initial and boundary conditions were established as $M(r, 0) = M_i$ and $\frac{\partial M}{\partial r} = 0$ at $r = 0$; $-D_m \frac{\partial M}{\partial r} = k_c(M_t - M_0)$ at $r = R$ for all $t \geq 0$.

Here, M_i represents initial moisture content, M_t is the moisture content at any time t , M_0 represents the moisture content of oil, and k_c is the mass transfer coefficient. The Fourier number of moisture transfer is $F_{O_m} = \frac{D_m t}{R^2} > 0.1$ using the first term of the infinite series expression (Equation (16)) given as [15]:

$$\frac{M_{r,t} - M_0}{M_t - M_0} = \frac{2(\sin \mu_1 - \mu_1 \cos \mu_1)}{\mu_1 - \sin \mu_1 \cos \mu_1} \times \frac{\sin(\mu_1 \frac{r}{R})}{\mu_1 \frac{r}{R}} \times \exp(-\mu_1^2 F_{O_m}) \quad (16)$$

where $M_{r,t}$ is the moisture content at any point inside the product at any time. The last term $\frac{\sin(\mu_1 \frac{r}{R})}{\mu_1 \frac{r}{R}}$ could be equated to $\frac{3}{\mu_1^3}(\sin \mu_1 - \mu_1 \cos \mu_1)$ since the average moisture content of

the sphere is known. On the other hand, the average moisture content at time t is given by Equation (17).

$$\left(\frac{1}{V} \int_0^V M_{r,t} \cdot dV \right) \quad (17)$$

V is the product volume. The average moisture content is known; therefore, integrating $M_{r,t}$ throughout the whole volume, the equation for average moisture content M_t in a spherical solid is obtained using Equation (18):

$$\frac{\overline{M}_t - M_0}{M_t - M_0} = \frac{6(\sin\mu_1 - \mu_1\cos\mu_1)^2}{\mu_1^3(\mu_1 - \sin\mu_1\cos\mu_1)} \times \exp(-\mu_1^2 F_{O_m}) \quad (18)$$

Further, the above expression can be expressed using Equation (19):

$$\ln\left(\frac{\overline{M}_t - M_0}{M_t - M_0}\right) = \ln\left(\frac{6(\sin\mu_1 - \mu_1\cos\mu_1)^2}{\mu_1^3(\mu_1 - \sin\mu_1\cos\mu_1)}\right) - \mu_1^2 F_{O_m} \quad (19)$$

Therefore, the above can be used to determine the moisture transfer Biot number (B_{i_m}) and moisture transfer coefficient (k_c) using the following equation (Equation (20)):

$$B_{i_m} = 1 - \frac{\mu_1}{\tan\mu_1} = \frac{k_c R}{D_m} \quad (20)$$

On the other hand, the Arrhenius relationship (Equation (21)) was used to describe the temperature dependency of moisture diffusivity.

$$D_m = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (21)$$

where E_a is the activation energy, D_0 represents the frequency factor (m^2/s), R denotes the gas constant ($8.314 \text{ J/mol}\cdot\text{K}$), and T is the absolute temperature (K).

Fat Transfer Modeling

The fractional conversion first-order reaction kinetic model (Equation (22)), as shown below, was used to model fat uptake:

$$\frac{F_e - F_t}{F_e - F_i} = \exp(-kt) \quad (22)$$

where F_i , F_e , and F_t are initial, maximum, and fat content at a given time t . k is the reaction rate constant (s^{-1}) [25]. Further, the Arrhenius relationship was used to determine the activation energy for fat transfer during frying.

2.3.5. Statistical Analysis

To determine the effects of frying time and temperature on the moisture and fat contents of fried Malpoa, a two-way analysis of variance was performed using SPSS software (v. 15.0, SPSS Inc., Chicago, IL, USA) [26]. The level of significance was set at "0.05". Duncan's multiple range test (DMRT) was used to compare treatment means in pairs. At each temperature, the frying experiments were repeated three times. Linear regression in SPSS was used to fit the relationship between moisture and fat content. The moisture transfer model's adequacy was assessed using the coefficient of determination (R^2) and mean relative percent deviation modulus (percent P).

3. Results

3.1. Frying Kinetics of Various Parameters for Malpoa During Deep Fat Frying

3.1.1. Textural Kinetics

The textural qualities of fried malpoa balls evolve because of several physical, chemical, and structural changes that occur during frying. The textural characteristics of deep fat frying were affected by frying temperature and duration. For the first few minutes of frying, a crust is formed for the product. Such crust formation alters the textural properties of the sample, such as hardness, cohesion, and springiness. These parameters varied with frying temperature and time. This technique caused a composite structure with a rigid crust and a soft core.

3.1.2. Hardness Kinetics

Figure 1 depicts the change in hardness with frying time and temperature for a deep fat fried malpoa sample. It is evident that the hardness elevated progressively as frying time increased for a particular frying temperature. Further, greater hardness value and faster crust formation were caused by frying at a higher temperature over a given time period. This is due to a greater loss of moisture from the prepared malpoa as they were being fried at a higher temperature. The initial hardness of the sample was 3.15 N/mm. For frying times 2, 4, 6, 8, and 10 min, for the variation in frying temperature of 170–190 °C, hardness enhanced from 3.15–5.06, 3.23–22.59, 6.23–13.44, 9.57–15.39, and 13.57–22.59 N/mm, respectively. Higher frying temperature and time caused the formation of hard crust on the surface. As moisture was removed during the course of the frying process, this hard crust moved inward towards the center of the sample due to which the hardness of the fried malpoa balls was enhanced with prolonged frying and higher frying temperature. It was observed that the zero-order kinetics was the best-fit model for hardness with reduced chi-square and R^2 values of 0.3037–1.47 and 0.9293–0.9856, respectively (Table 1). A comparative representation of zero- and first-order kinetics is presented in Figure 2a,b. The rate constant varied from 3.14 to 5.06 for the variation frying temperature from 170 to 190 °C. On the other hand, according to the Arrhenius plot, as presented in Figure 3, the activation energy was found to be 85.825 kJ/mol. The activation energy observed was marginally higher compared to the activation energy of gulab jamun (77.58 kJ/mol) [27]. Also, a similar value for activation energy was obtained for chena jhili (82.04 kJ/mol) [15].

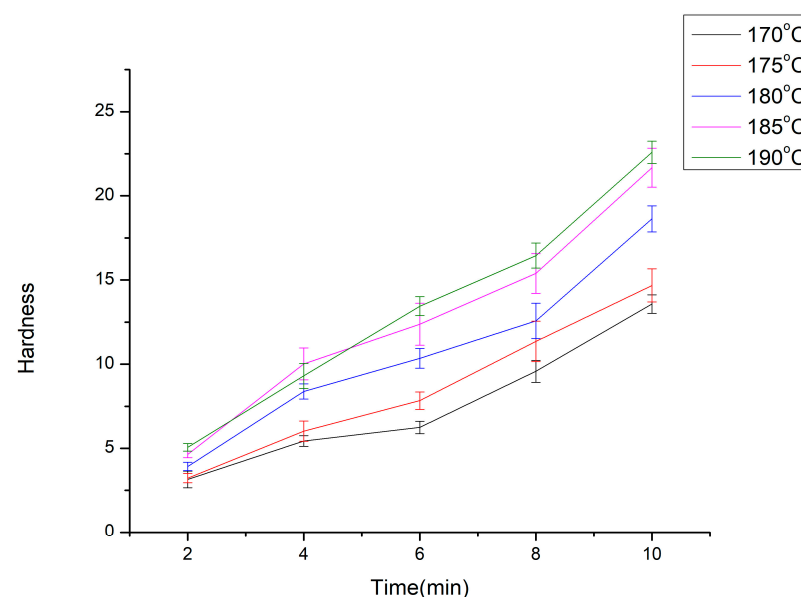
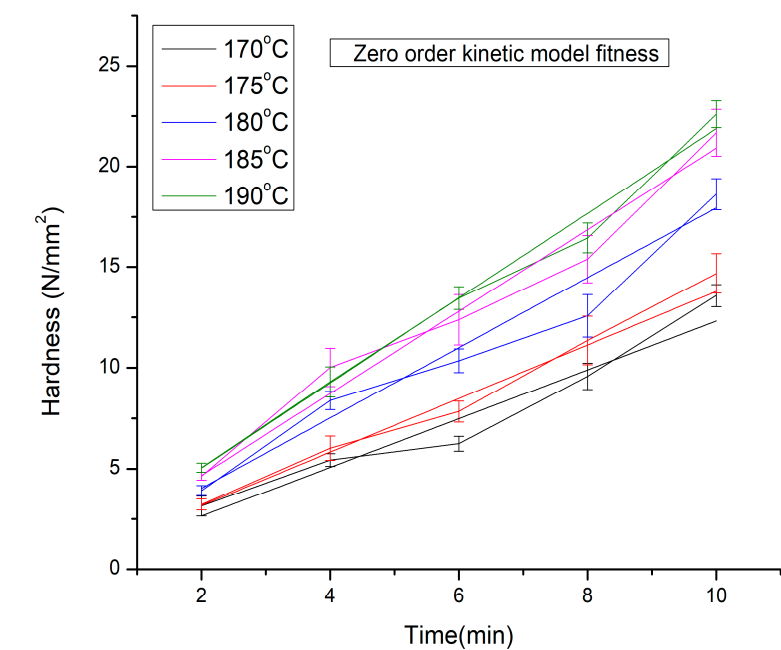


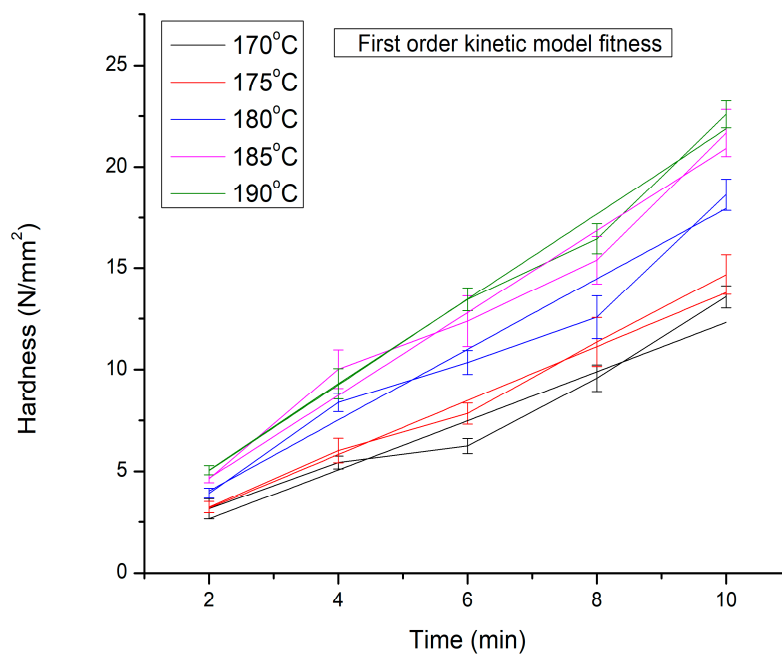
Figure 1. Variation in hardness with frying time for various temperatures. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

Table 1. Summary of textural parameters for deep fat fried malpoa. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

Parameter	Order of Reaction	Activation Energy (kJ/mol)	R ²
Hardness	Zero	85.82 ± 1.45	0.964
Cohesion	Zero	54.78 ± 0.56	0.954
Springiness	Zero	NA	NA



(a)



(b)

Figure 2. Model fitness plot for (a) zero-order and (b) first-order reaction for hardness. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

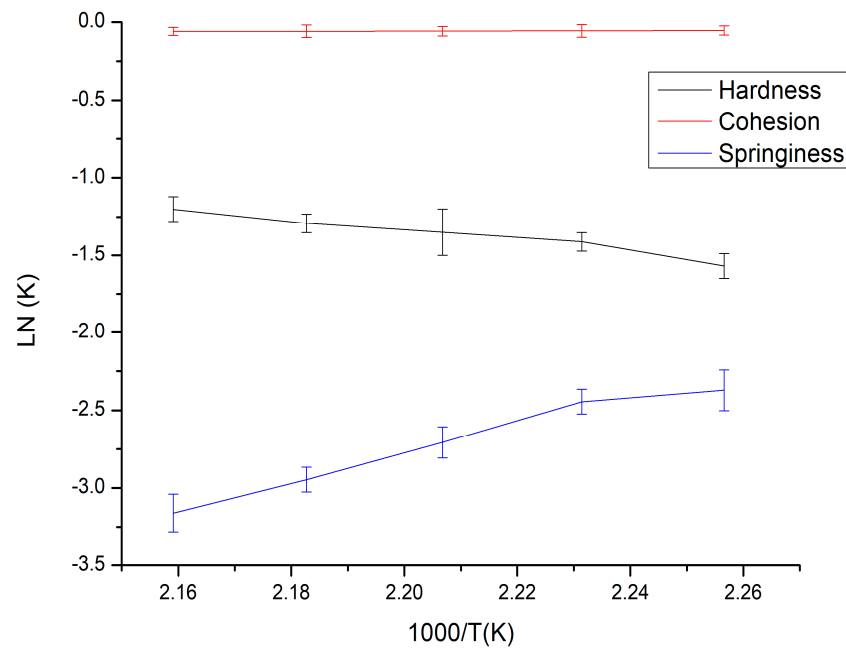


Figure 3. Arrhenius plot of temperature dependence of rate constant for various textural parameters. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

3.1.3. Cohesiveness Kinetics

The cohesiveness of malpoe balls is a fundamental textural quality. The capacity of food product particles to adhere together upon deformation is referred to as cohesiveness. It constitutes one of the measures used to assess the viscoelastic characteristics of food. Variation in cohesiveness with frying temperature and time is presented in Figure 4. For a frying temperature of 170 °C, cohesiveness enhanced from 0.22 to 0.29 for frying time varying from 2 to 10 min. Similarly, the variable varied from 0.40 to 0.52 for a frying temperature of 175 °C, and frying time varied from 2 to 10 min. Corresponding variations in cohesiveness were 0.48–0.57 and 0.65–0.76 for 180, 185, and 190 °C, respectively. Cohesiveness increases with increasing frying temperature and frying duration. The removal of moisture from the sample caused shrinkage of the mass that brought particles together. Due to this reason, the cohesive force between the particles of the sample increased. The extent of such an interaction is enhanced with higher frying temperature and time due to higher moisture diffusivity. Among various kinetic models, the most appropriate model for cohesiveness was found to be the zero-order model (Figure 5). For such cases, the reduced chi-square and R^2 values were 6.89×10^{-4} –0.00117 and 0.9582–0.9751, respectively. On the other hand, the rate constant varied from 0.40 to 0.52 for the variation in the frying temperature from 170 to 190 °C. Figure 3 depicts the temperature dependence of the rate constant using the Arrhenius plot. The activation energy was determined to be 60.325 kJ/mol (Table 1). This finding is consistent with previous findings for Akara iwe [28]. The variation in cohesiveness for the malpoe sample is attributed to starch alteration during frying. High frying temperatures caused higher moisture loss in the product, which affected the viscoelastic characteristics of the sample, and, thus, varied the cohesiveness characteristics of the sample during deep fat frying [29].

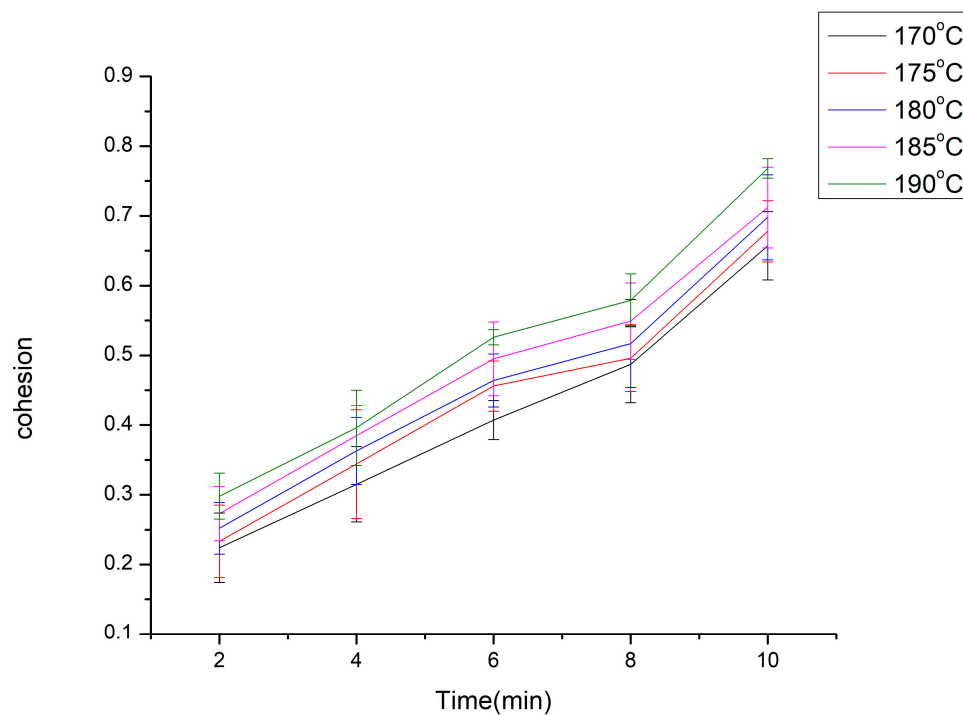


Figure 4. Variation in cohesion with frying time at various temperatures. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

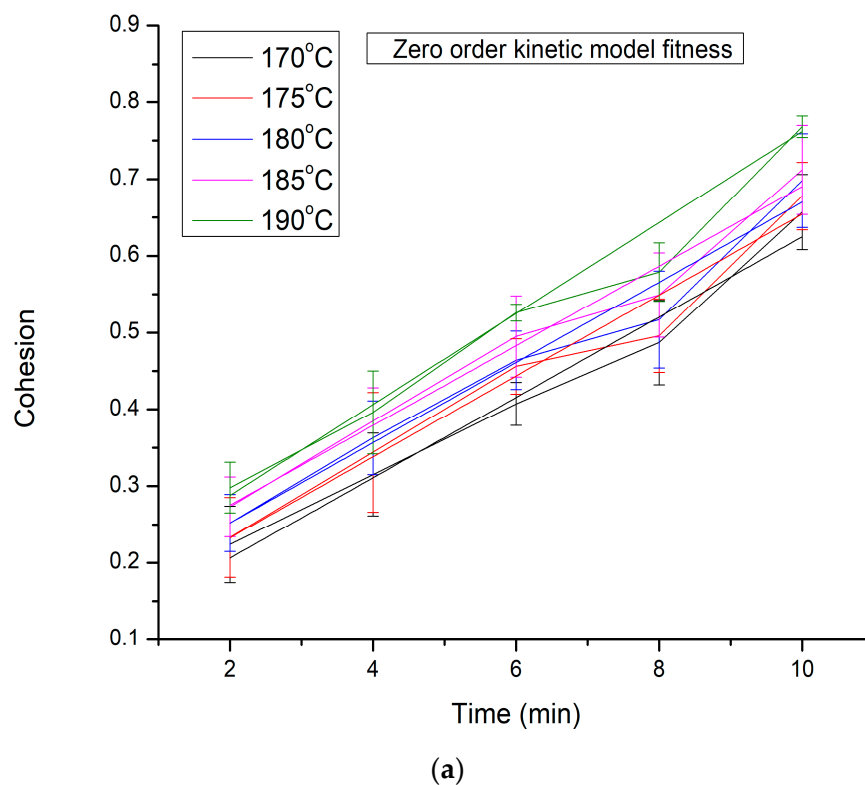


Figure 5. Cont.

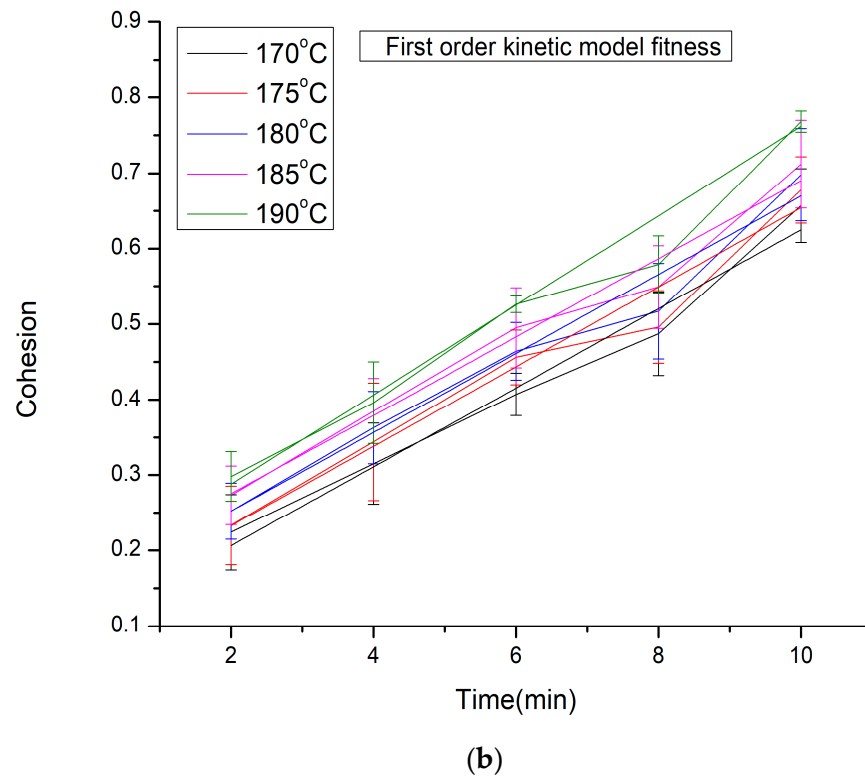


Figure 5. Model fitness plot for (a) zero-order and (b) first-order reaction for cohesion. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

3.1.4. Springiness Kinetics

Springiness is the speed and degree with which a deformed material recovers to its original state once the force is withdrawn. Springiness varies with heat treatment, protein interaction, flexibility, and the degree of protein unfolding [30]. Figure 6 depicts the variation in springiness for varied frying temperatures and time. For 170 °C frying temperature and 2–10 min frying, the variation in springiness was 15.50–22.35. Similarly, for a frying temperature of 175 °C, the response varied from 27.56 to 40.34 for a frying time of 2–10 min. Further, springiness enhanced from 15.50 to 22.35, 31.4 to 44.4, and 35.5 to 49.56 for 180, 185, and 190 °C for the variation in frying time from 2 to 10 min. The enhancement of springiness is due to the coagulation in the sample due to an increase in temperature [30]. The moisture is removed during the course of frying, leaving behind pores that oil penetrates into. This causes shrinkage and development of a hard layer around the sample, causing coagulation of the sample [15]. On the other hand, the corresponding value of springiness is higher for higher frying temperatures in comparison to lower frying temperatures. This is due to the reaction happening due to temperature increase and factors such as protein interactions, flexibility, and the degree of protein unfolding, which constitute the elements involved during deep frying. After frying for 10 min at 170–190 °C, the springiness of the fried malpoa balls ranged from 15.5% to 27.61–49.56%. Among various models, the zero-order model was the best-fit model for springiness, with lower reduced chi-square (2.71–12.60) and higher R^2 (0.8814–0.9591) values (Figure 7). Springiness does not follow the Arrhenius equation as it shows irregular behavior (Figure 3). The springiness of malpoa balls was substantially ($p < 0.05$) affected by frying temperature and time. This demonstrated that the springiness increased as the frying temperature and duration rose [28].

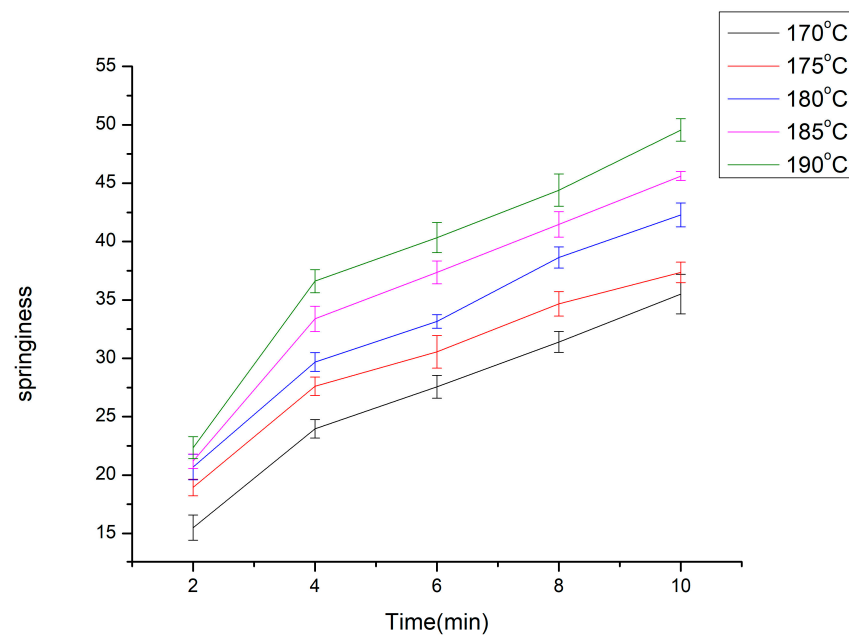


Figure 6. Variation in springiness with frying time for various temperatures. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

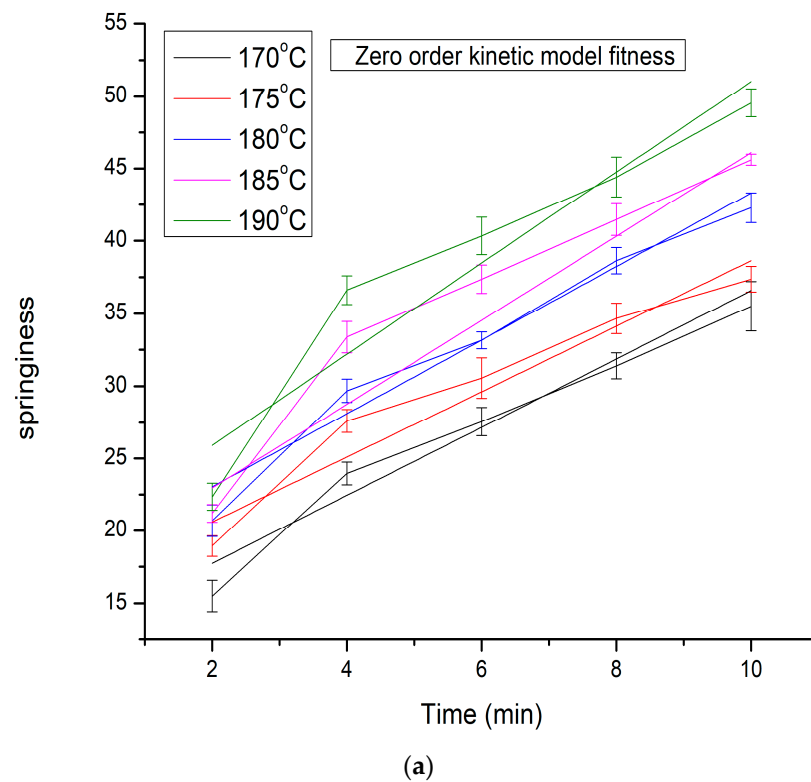


Figure 7. Cont.

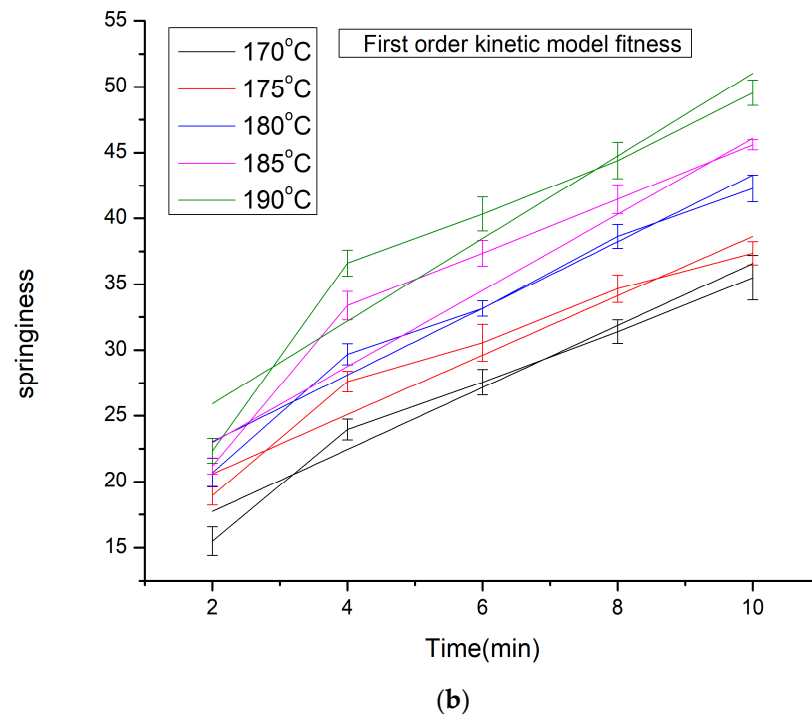


Figure 7. Model fitness plot for (a) zero-order and (b) first-order reaction for springiness. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

3.1.5. Color Kinetics

One of the most vital aspects of fried food quality is color development. The Maillard process and caramelization are responsible for the color that develops on the malpoa ball as it is being fried. Malpoa ball color evolution is a function of time and temperature, and it significantly influences how the final product looks. The assessments of the product malpoa are represented by the letters L^* , a^* , and b^* , which stand for the spectrum of light and dark. This shows that L^* stands for lightness, with a range of 0 to 100 (white) representing the hue of darkness. The other green–red spectrum is represented by the parameter a^* , which reflects the color with the red range if a positive value is acquired and the color with the green range if a negative number is obtained. The other blue–yellow spectrum, designated by the b^* parameter, measures the product's yellowness and blueness; if the range is positive, the yellowness, and if the range is negative, the blueness. The hue angle, which measures chromaticity, reveals a wide spectrum of colors as 0° for red, 90° for yellow, 180° for green, and 270° for blue. The luminosity (L^*) value dropped as the frying duration and oil bath increased. The a^* and b^* value increases coincided with this drop in L^* . As a result, as the frying process continued, the product became more red and yellow in comparison to the raw samples [20]. To assess how the color of chhena jhili changes over time, the kinetics of brightness (L^*), the hue parameter (b^*/a^* value), and the overall color (ΔE) were considered. A summary of color change kinetics during deep fat frying of malpoa is shown in Table 2.

Table 2. Summary of color parameters for deep fat fried malpoa. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

Parameter	Order of Reaction	Activation Energy (kJ/mol)	R^2
L^*	Zero	58.19 ± 0.76	0.992
b^*/a^*	First	42.21 ± 1.38	0.954
ΔE	First	64.34 ± 1.17	0.981

Lightness (L^*) Kinetics

The crust lightness variation in malpoa during deep fat frying is shown in Figure 8. As the frying time was extended, the L^* value was reduced. For frying temperature of 170–190 °C, the initial L^* value reduced to 65.57–21.14, 63.28–19.27, 60.61–17.3, 57.53–15.64, and 52.34–10.47, respectively, for 2, 4, 6, 8, and 10 min of frying time. The lightness of fried malpoa is negatively influenced by the temperature of the oil. For the same frying time, lightness reduced as the temperature was raised. The Maillard process and the caramelization of lactose are responsible for the drop in L^* value. These reactions are functions of frying temperature and time. As the frying temperature and time increase, the browning and caramelization reactions also increase. However, temperature possesses a significant effect as it affects these reactions. A higher temperature accelerated the caramelization process and hastened the crust's browning. Similarly, the extent of such reactions is enhanced with frying time. As the frying is continued for a long time, a greater browning reaction between amino acid and reducing sugar occurs, as well as the caramelization reaction. This causes the reduction in L^* value with higher frying temperature and time. The response variable was best described with zero-order kinetics (reduced chi-square 12.50–34.58 and R^2 0.9035–0.9656) (Figure 9). The Arrhenius plot of rate constants for changes in lightness during the frying of malpoa in the temperature range of 170–190 °C is shown in Figure 10.

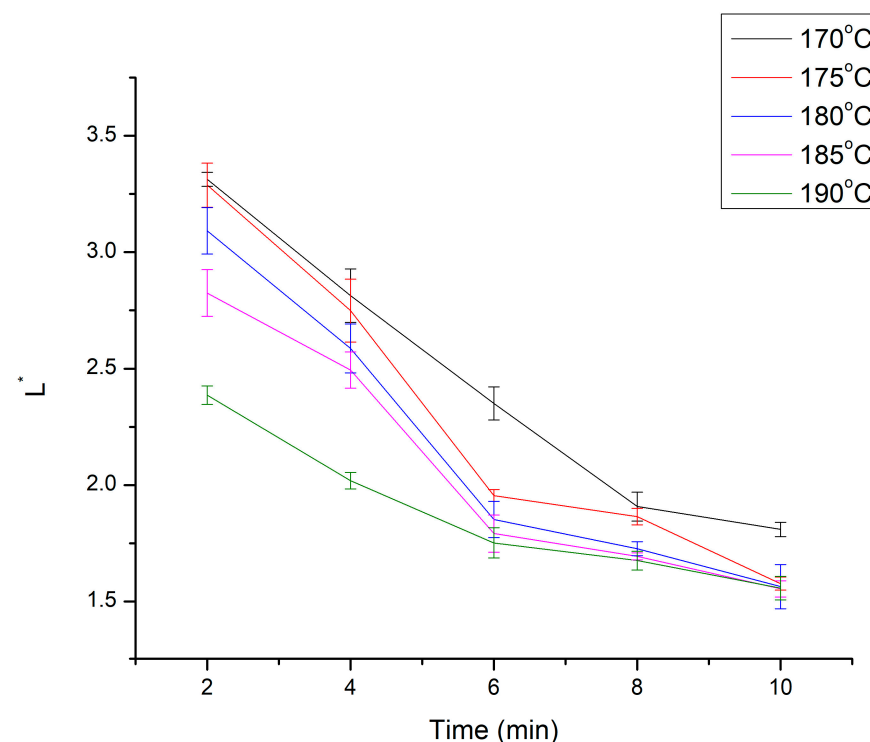
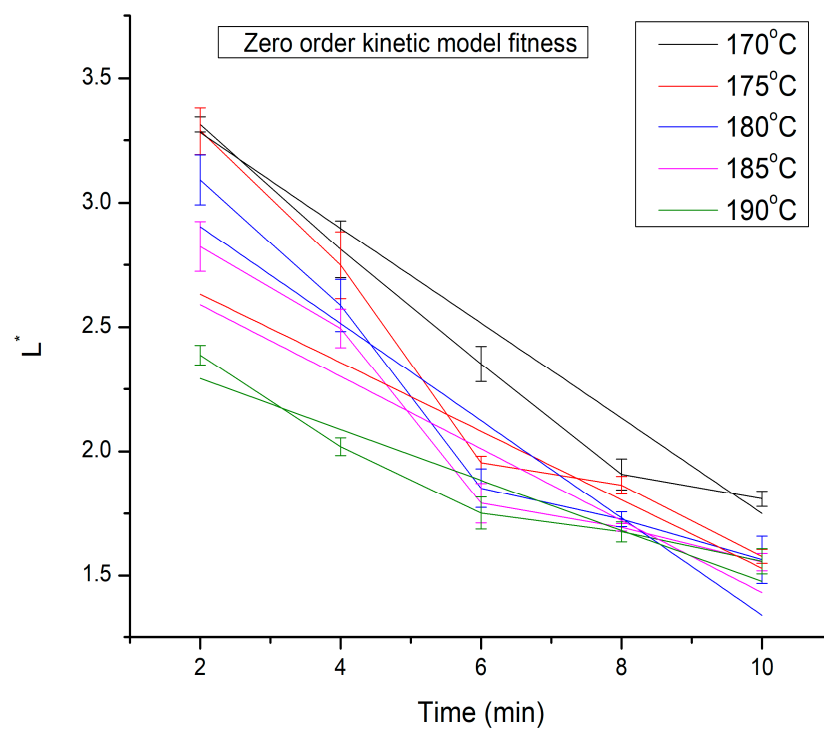
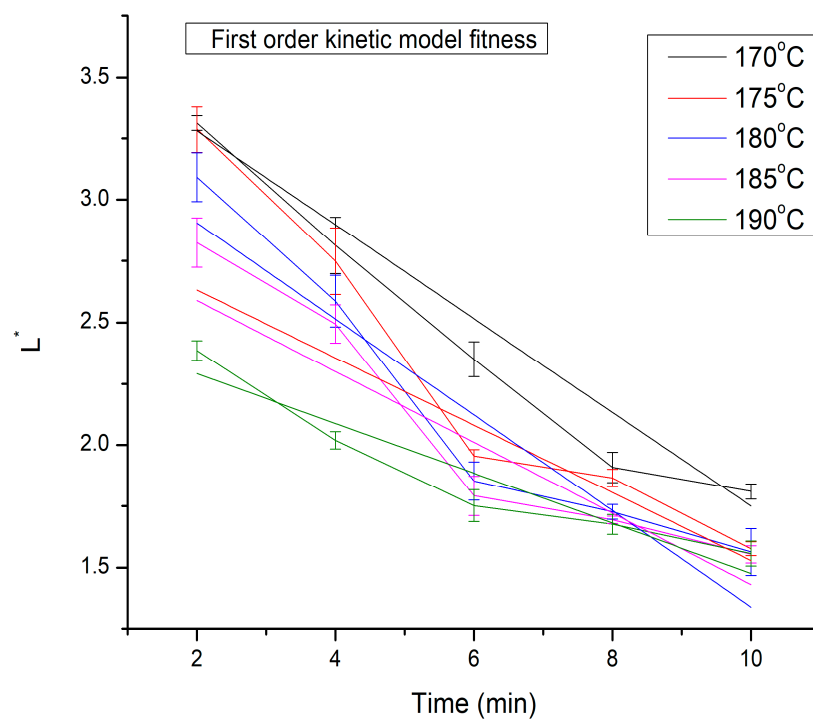


Figure 8. Variation in L^* with frying time for various temperatures. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

Table 2 summarizes various activation energies for color parameters. For deep fat fried malpoa, the variation in crust lightness affirmed an activation energy of 58.19 kJ/mol. This is comparable with the value of gulab jamun with an activation energy of 43.52 kJ/mol [27]. Additionally, according to Villota & Hawkes (2018), the activation energy for nonenzymatic browning in foods typically ranges from 37–167 kJ/mol [31]. However, it was higher than that of wheat-based doughnuts (18.2 kJ/mol) [32] and lower than the activation energy reported for tofu (76.0 kJ/mol) [33].



(a)



(b)

Figure 9. Model fitness plot for (a) zero-order (b) first-order reaction for L^* . Results are expressed as mean $\pm$ standard deviation ($n = 3$).

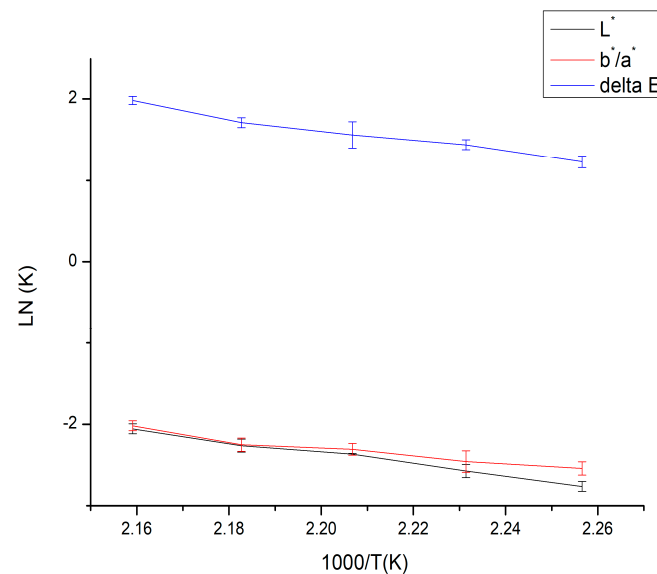


Figure 10. Arrhenius plot of the temperature dependence of rate constant for color parameters. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

Hue Parameter (b^*/a^*) Kinetics

Figure 11 illustrates the variation in the hue parameter (b^*/a^* value) with frying temperature and time. For frying time 2, 4, 6, 8, and 10 min and temperature variation in 170–190 °C, b^*/a^* value enhanced from 3.31–1.80, 3.28–1.57, 2.82–1.55, and 2.38–1.55. In the first six min, there was a sharp decline in the b^*/a^* value followed by a gradual reduction up to 10 min. The reduction in the hue parameter is due to an increase in the brownness of the sample during the course of frying. Higher frying temperature further reduces the hue value. This is due to enhanced browning and caramelization reactions. The b^*/a^* change reaction adhered to first-order kinetics with R^2 ranging between 0.8728–0.9501. A graphical representation of zero- and first-order reaction kinetics is shown in Figure 12. The rate constant for such cases varied from 0.1–0.19 for 170–190 °C. Figure 10 presents the variation in rate constant with temperature. On the other, the activation energy for hue parameter kinetics was 42.21 kJ/mol (Table 2). A similar comparable activation energy of 31.34 kJ/mol was reported for deep fat frying of gulab jamun [27].

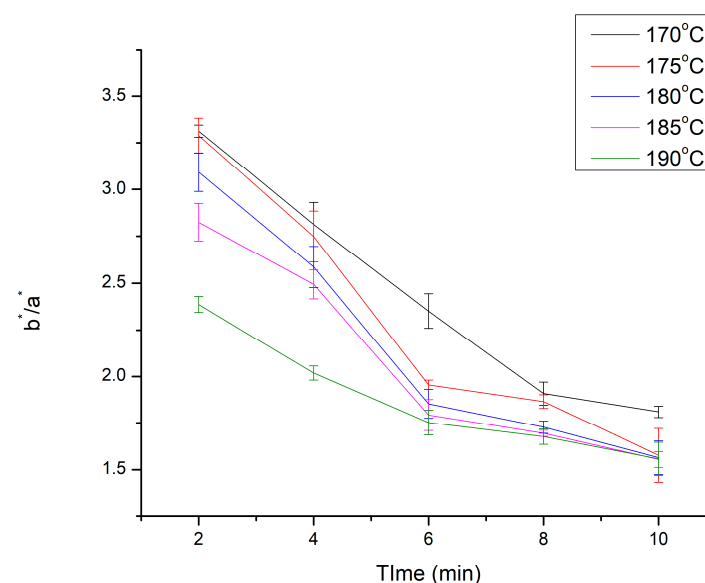


Figure 11. Variation in a^*/b^* with frying time for various temperature. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

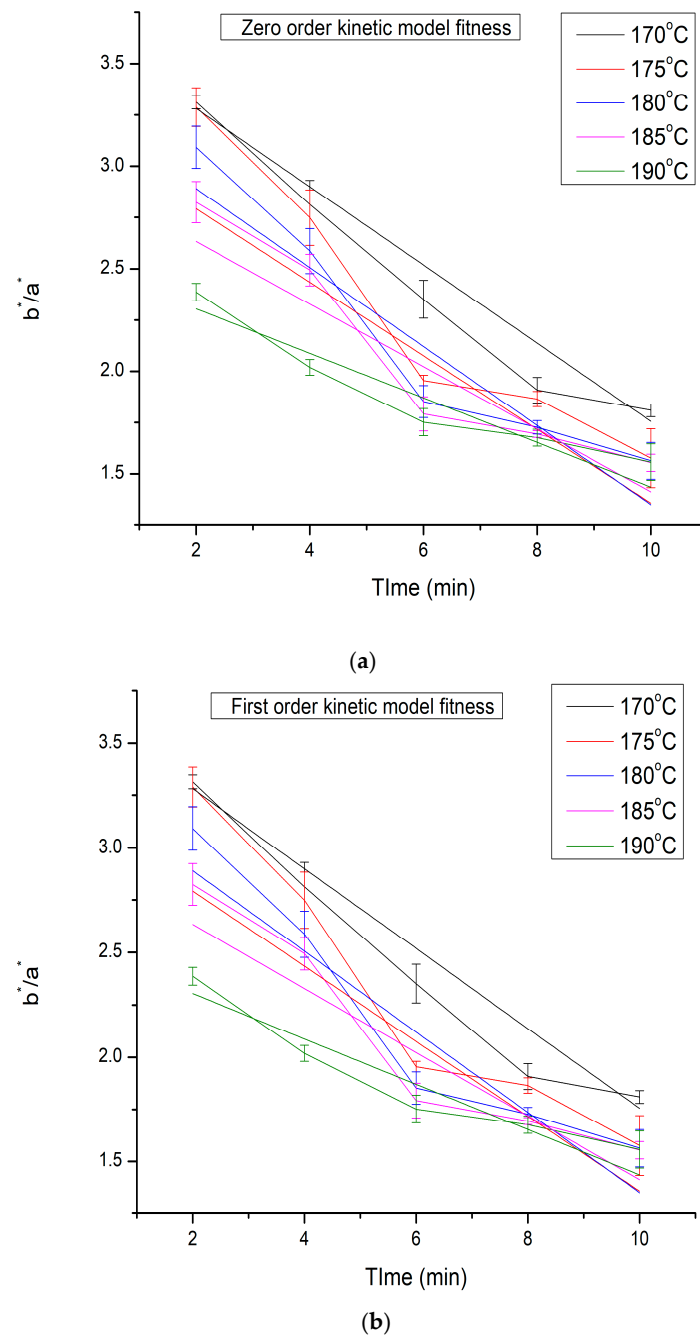


Figure 12. Model fitness plot for (a) zero-order and (b) first-order reaction for b^*/a^* . Results are expressed as mean $\pm$ standard deviation ($n = 3$).

Total Color (ΔE) Kinetics

Malpoa's surface color darkens as it is fried. As a result, the whole color shift symbolizes the darkness. Figure 13 illustrates the variation in ΔE with frying time and temperature for the sample. Additionally, the ΔE change adhered to first-order reaction kinetics with reduced chi-square and R^2 ranging from 0.43 to 2.24 and 0.9326 to 0.9707, respectively. Depending on the temperature, ΔE grew rapidly from 55.364 to 75.485. For all frying instances, first-order kinetic was the best-fit model (Figure 14) with reduced chi-square and R^2 values of 0.2 and 0.968, respectively. With time (2–10 min) and temperature (170–190 °C), variations in ΔE were from 55.63 to 63.59, 56.54 to 67.48, 58.25 to 69.15, 61.32 to 72.31, and 62.15 to 75.64. Such an increase in ΔE is due to the darkening of the malpoa sample during the frying process. The darkening of the sample is intensified with higher frying

temperature and time. Higher temperature and time cause a greater degree of Maillard and caramelization reactions, which causes darkening of the malpoa sample. As a result of this, ΔE also reduces with frying temperature and time. Good agreement was seen, much like with other color factors. The temperature dependence of the rate constant (Figure 10) resulted in an activation energy of 64.34 kJ/mol, as shown in Table 2. This was like the activation energy of ΔE reported in the instance of gulab jamun (28.66 kJ/mol) [27]. The Maillard browning and caramelization might be the cause of the rise in the overall color reflecting the darkening of the crust. Further, numerous variables such as temperature, duration, pH, water activity, and status of the food system fluctuate throughout the frying process, affecting the extent of the browning reaction during the frying process.

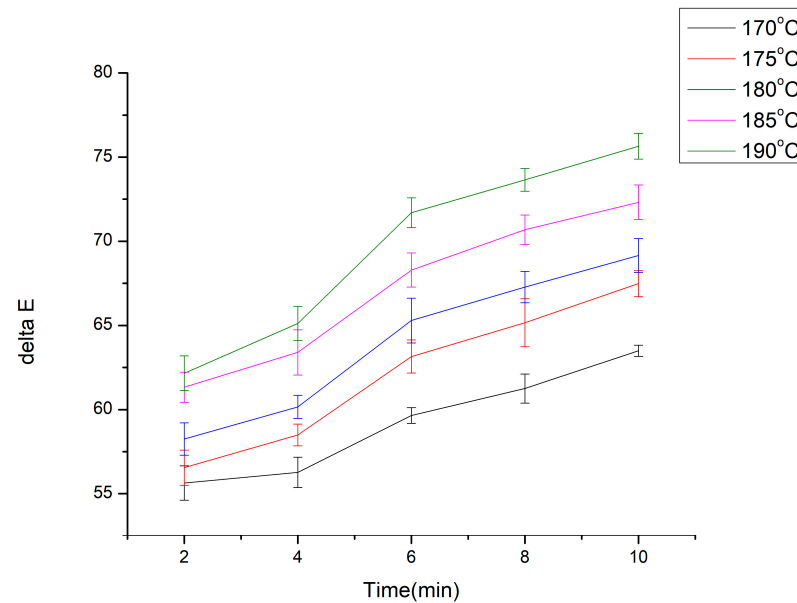


Figure 13. Variation in ΔE with frying time for various temperatures. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

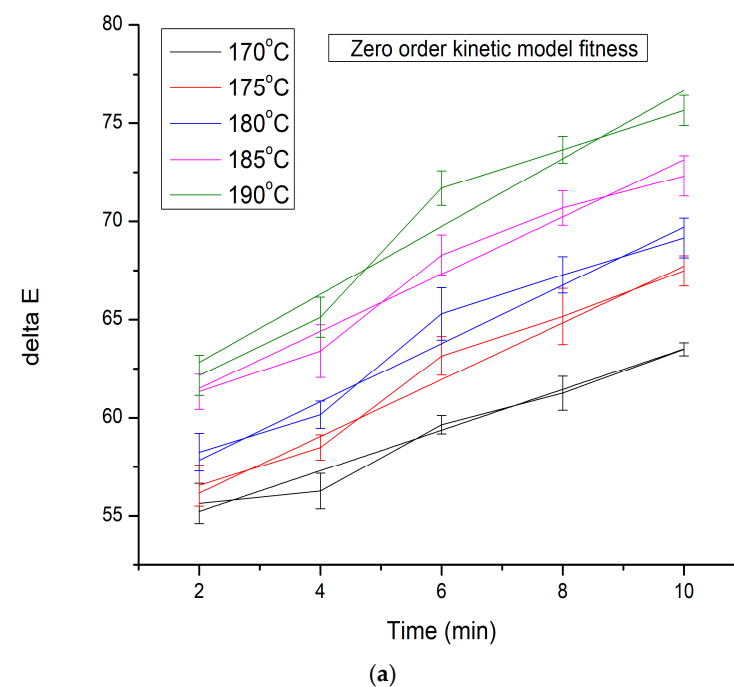


Figure 14. Cont.

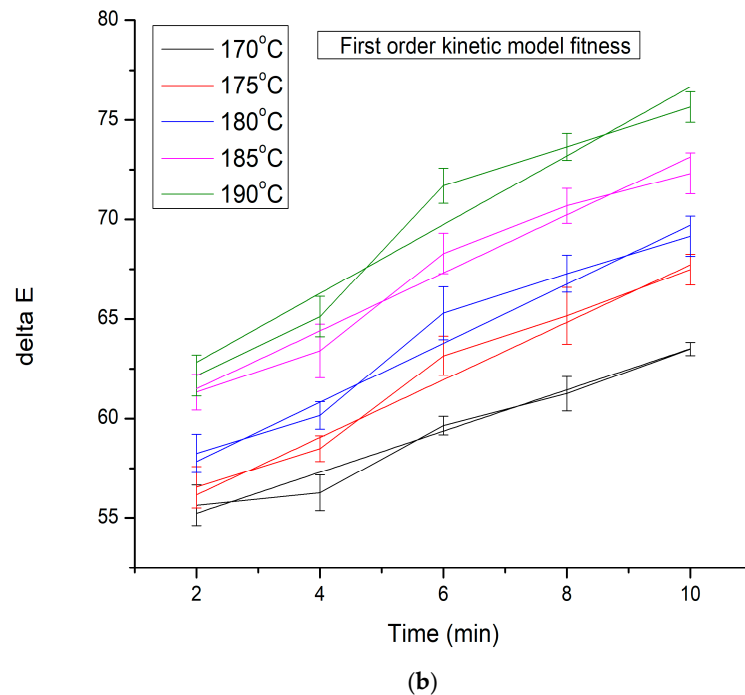


Figure 14. Model fitness plot for (a) zero-order and (b) first-order reaction for ΔE . Results are expressed as mean $\pm$ standard deviation ($n = 3$).

3.1.6. Malpoa Sphericity

The uncooked malpoa ball possessed a sphericity of 0.979. The sphericity of the malpoa ball varied during the frying process from 0.95 to 0.97 for the variation in frying temperature from 170 to 190 °C. Sphericity fluctuation with frying temperature was not significant ($p > 0.05$). A similar observation was also reported for the fried pantoa sample [23]. The sphericity was lowest at a lower temperature range. Lower temperatures led to the formation of a soft crust, which could not hold the shape. On the other hand, higher temperatures facilitated the formation of a hard crust to retain the shape of the sample. Similar results have been observed for gulab jamun, with a sphericity of 0.96–0.98 [24].

3.2. Heat and Mass Transfer Modeling of Malpoa During Deep Fat Frying

3.2.1. Heat Transfer Modeling

Heat transfer is an important phenomenon that occurs during deep fat frying of food samples. The heat transfer during deep fat frying involves conduction and convection. Conduction is driven by the temperature difference between the sample core and the surface. On the other hand, convection is due to the temperature gradient between the oil medium and the sample surface. Sample core and surface temperature were significantly enhanced with frying temperature and time. For frying times of 2, 4, 6, 8, and 10 min and frying temperature variation from 170 to 190 °C, sample core temperature was enhanced from 41.8 to 68 °C, 43 to 71 °C, 45.6 to 67 °C, 50.1 to 77 °C, and 54.8 to 77 °C, respectively. As malpoa balls continued along the frying process at a particular temperature, heat transfer took place, which enhanced the temperature of the sample core. Such an increase in sample core temperature is higher for higher temperatures due to the higher rate of heat transfer during the process. During deep fat frying of malpoa samples, the surface temperature increased up to 100 °C, followed by a stagnant period of about 1 min. Such a stagnant period is accompanied by a transition of phase, converting moisture to vapor, and subsequent removal from the sample surface. On the other hand, the temperature of the frying oil was found to be relatively stable, with marginal variations of ± 3 °C. Thereafter, the temperature of the sample surface increased to about the temperature of the oil medium. On the other hand, the temperature difference ratio ($\frac{T_t - T_0}{T_i - T_0}$) varied from 0.92 to 0.72, 0.90 to

0.71, 0.89 to 0.75, 0.87 to 0.69, and 0.84 to 0.70 for the variation in frying temperature from 170 to 190 °C for 2, 4, 6, 8, and 10 min of frying time, respectively.

Lumped capacity model fitness to $\ln\left(\frac{T_i - T_0}{T_f - T_0}\right)$ versus frying time (Figure 15) affirmed a variation in convective heat transfer coefficient from 25.584 to 34.648 W/m²·K. For such a case, the heat transfer parameters for deep fat fried malpoa sample are comparable with few previous findings for various food materials. For instance, potato slices exhibited a heat transfer coefficient ranging from 90 to 200 W/m²·K [34]. Similarly, corresponding values for deep fat fried gulab jamun and chhena jhili reported were 90–130 W/m²·K [16] and 43.593–52.922 W/m²·K [15], respectively. Marginal variation in heat transfer coefficient for various food materials is due to variations in product geometry, moisture removal rate, and frying temperature. Corresponding dimensionless Biot number ranged between 0.65 and 0.318. These values exceeded the permissible limit for the lumped capacity model. Therefore, the model was not appropriately fitted to the experimental data. Further, an alternate approach known as the transient heat conduction approach (Equation (14)) was employed to determine associated heat transfer parameters for the frying process.

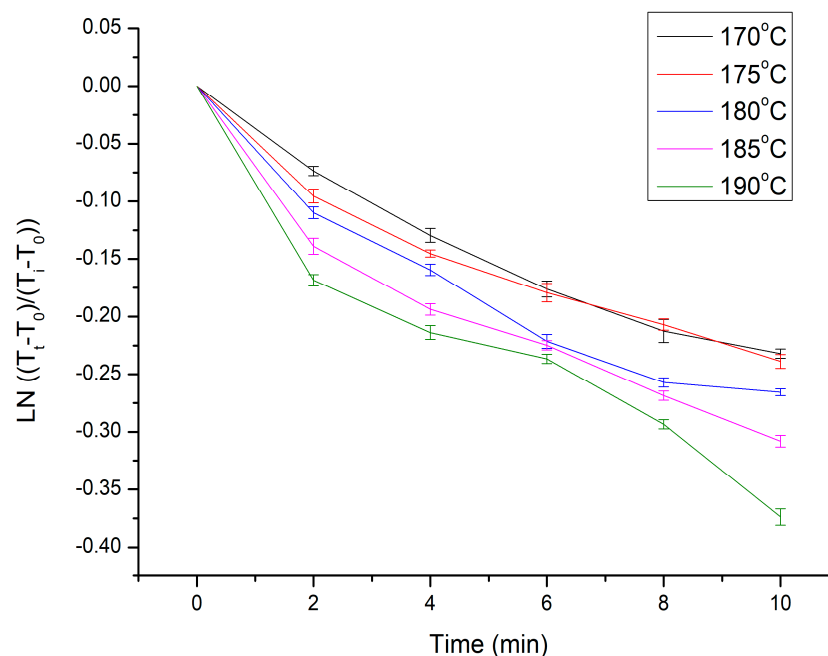


Figure 15. Variation in the logarithm of temperature ratio with frying time for various temperatures. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

Using linear regression analysis at various temperatures, the slope of the linear section was equated to $\left(\frac{-\alpha\delta^2}{R^2}\right)$. The value of δ was derived from the thermal diffusivity and radius at various temperatures. Using this information, the heat transfer Fourier number was determined by $\left(F_{Oh} = \frac{\delta t}{R^2}\right)$. Subsequently, Equations (13) and (14) were utilized to derive the heat transfer coefficient and Biot number. Thermal characteristics of malpoa at selected temperatures are summarized in Table 3. For frying temperatures of 170–190 °C, thermal diffusivity and Fourier number increased from 1.424 to 1.481×10^{-5} and 0.456 to 0.288, respectively. On the other hand, heat transfer coefficients and corresponding Biot numbers varied from 135.587 to 94.396 W/m²·K and 7.496 to 5.634, respectively. It was evident that with frying temperatures, the thermal diffusivity increased significantly. On the contrary, the Biot number and heat transfer coefficient decreased. The reductions in heat transfer coefficient and Biot number with frying temperature during the frying of malpoa balls were similar to deep fat fried potato slices and gulab jamun [16,35]. This was attributed to higher moisture loss rates at elevated temperatures, leading to a reduction in the coefficient of heat transfer [35]. Thus, the transient heat conduction model could effectively explain

heat transport during malpua frying for the chosen temperature range, as evidenced by the high coefficient of determination (R^2) value of 0.967.

Table 3. Summary of heat transfer parameters for deep fat fried malpua. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

S. No	Frying Temperature ($^{\circ}\text{C}$)	Thermal Conductivity	Thermal Diffusivity	Fourier Number	Heat Transfer Coefficient	Biot Number
1.	170	0.4403 ± 0.018	$1.424 \times 10^{-5} \pm 0.006 \times 10^{-5}$	0.456 ± 0.005	135.587 ± 2.26	7.496 ± 0.51
2.	175	0.4429 ± 0.029	$1.439 \times 10^{-5} \pm 0.003 \times 10^{-5}$	0.459 ± 0.013	124.653 ± 1.48	6.972 ± 1.28
3.	180	0.4457 ± 0.022	$1.466 \times 10^{-5} \pm 0.0026 \times 10^{-5}$	0.279 ± 0.022	117.767 ± 0.72	6.403 ± 0.42
4.	185	0.4483 ± 0.033	$1.470 \times 10^{-5} \pm 0.0018 \times 10^{-5}$	0.281 ± 0.006	107.961 ± 1.65	5.975 ± 0.28
5.	190	0.4496 ± 0.028	$1.481 \times 10^{-5} \pm 0.0014 \times 10^{-5}$	0.288 ± 0.008	94.396 ± 2.6	5.634 ± 0.36

3.2.2. Mass Transfer Modeling

During the deep fat frying process, moisture transport is one of the major phenomena that occur due to the vapor pressure gradient, owing to the higher temperature. The results indicate a substantial decrease in moisture content with an increase in frying temperature. Specifically, over a duration of 10 min, for the variation in frying temperature from 170 to 190 $^{\circ}\text{C}$, the moisture content exhibited a notable decline from initial values as follows: 45.56–45.50%, 44.78–35.8%, 42.99–33.53%, 41.88–41.66%, and 40.2–24.2% for 2, 4, 6, 8, and 10 min frying time. This reduction is primarily attributed to higher moisture diffusivity and subsequent removal of moisture from the product surface.

Initially, a rapid loss of moisture was observed (shown in Table 4), gradually diminishing as the frying process continued. The moisture content reduced from 50.82 to 32.5, 50.82 to 30.11, 50.82 to 29.74, 50.82 to 25.5, and 50.82 to 23.51%, respectively, for 2–8 min and 170–190 $^{\circ}\text{C}$. On the other hand, variations in moisture ratio were 1–0.6388, 1–0.5917, 1–0.5844, 1–0.5008, and 1–0.4616, respectively. Such variation is due to the removal of moisture from the sample. Higher frying temperature and time possess higher moisture diffusivity, due to which the moisture content of fried malpua balls is reduced. The development of a crust on the product's surface played a pivotal role in reducing the rate of moisture loss. The formation of this crust led to a decrease in diffusivity, impeding the escape of moisture from the product.

Table 4. Summary of moisture transfer parameters for deep fat fried malpua. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

S. No	Frying Temperature ($^{\circ}\text{C}$)	Moisture Diffusivity	Fourier Number	Moisture Transfer Coefficient	Biot Number
1.	170	$2.33 \times 10^{-7} \pm 0.02 \times 10^{-7}$	0.683 ± 0.03	$16.948 \times 10^{-6} \pm 0.38 \times 10^{-6}$	6.899 ± 0.06
2.	175	$2.64 \times 10^{-7} \pm 0.008 \times 10^{-7}$	0.745 ± 0.028	$17.865 \times 10^{-6} \pm 0.16 \times 10^{-6}$	6.617 ± 0.03
3.	180	$2.95 \times 10^{-7} \pm 0.005 \times 10^{-7}$	0.781 ± 0.007	$18.652 \times 10^{-6} \pm 0.26 \times 10^{-6}$	6.542 ± 0.14
4.	185	$3.04 \times 10^{-7} \pm 0.017 \times 10^{-7}$	0.822 ± 0.018	$19.673 \times 10^{-6} \pm 0.13 \times 10^{-6}$	6.248 ± 0.03
5.	190	$3.44 \times 10^{-7} \pm 0.004 \times 10^{-7}$	0.869 ± 0.008	$20.364 \times 10^{-6} \pm 0.2 \times 10^{-6}$	6.112 ± 0.04

Figure 16 illustrates the natural logarithm of the dimensionless moisture ratio $\left(\ln\left(\frac{\bar{M}_t - M_0}{\bar{M}_t - M_0}\right)\right)$ versus frying time. The intercept of this plot provided the value of δ , facilitating the calculation of moisture diffusivity using the slope term of Equation (19). Furthermore, the Biot number and the coefficient of moisture transfer were calculated using Equation (20). This affirmed the variation in coefficient of moisture transfer and moisture diffusivity from 16.948 to 20.364×10^{-6} m/s and 2.33 to 3.44×10^{-7} m²/s, respectively, for 170–190 $^{\circ}\text{C}$. These findings align with prior studies for deep fat fried gulab jamun [16], chena jhili [15], potato slices [35], catla fish [36], and gethi strips [37]. On the other hand, Fourier and Biot number varied from 0.683 to 0.869 and 6.899 to 6.112. The outcomes consistently imply that higher

frying temperatures lead to increased moisture loss in food products. The Arrhenius plot of moisture diffusivity and temperature affirmed an activation energy of 68.267 kJ/mol. This comprehensive analysis sheds light on the intricate relationships between frying temperature, moisture content, and transport properties, contributing to a deeper understanding of food processing techniques and their impacts on product characteristics.

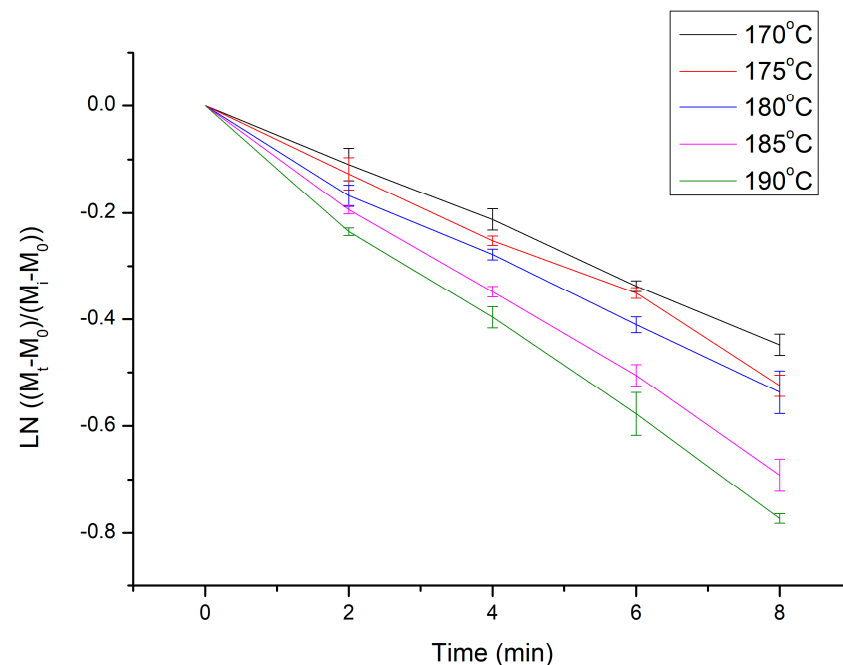


Figure 16. Variation in the logarithm of moisture ratio with frying time for various temperatures. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

3.3. Fat Kinetics

Frying temperature and duration significantly influenced the fat content of malpoa during the deep-frying process. The fat content exhibited a notable variation for 2–10 min frying time and 170–190 °C frying temperature. Figure 17 presents the effect of frying temperature and duration on fat absorption for deep fat fried malpoa. The variable increased from 13.98 to 27.94%, 14.52 to 33.61%, 15.19 to 35.67%, 16.06 to 38.38%, and 18.12 to 41.65%, respectively, for the variation in frying temperature from 170 to 190 °C for 2, 4, 6, 8, and 10 min frying time. The process of moisture evaporation from the product created pores and spaces that were subsequently occupied by oil, both on the surface and within the interior. As discussed by Gamble et al. (1987), the internal moisture transitioning into steam during frying induced a pressure gradient, allowing oil to adhere to and permeate the product surface [38]. Also, the results align with deep fat fried donuts [32]. Initial fat uptake rates were rapid but decelerated subsequently. At temperatures of 170–190 °C, fat content increased from an initial value of 10.24% to the range of 13.98–41.65%. Lower frying temperatures caused inadequate water outflow and facilitated the development of a surface crust conducive to enhanced oil absorption. Conversely, higher temperatures resulted in a tougher crust, reducing surface diffusivity and increasing resistance to fat adsorption [37].

The absorption kinetics of fat were appropriately characterized by first-order fractional conversion kinetics for all temperatures (R^2 0.944–0.68). The activation energy for fat absorption was determined as 52.67 kJ/mol with a reduction in the rate constant from 5.648×10^{-4} to 3.158×10^{-4} for frying temperature increasing from 170 to 190 °C. Notably, a negative correlation was observed between malpoa moisture and fat content, indicating that fat was absorbed into pores formed by moisture vaporization. A similar trend was reported for various food items during the frying process [36,39]. Furthermore, it was noted that the ultimate moisture content had a stronger association with fat content because of frying

temperature and time. This affirmed the interdependency of these factors on both moisture and fat content [38].

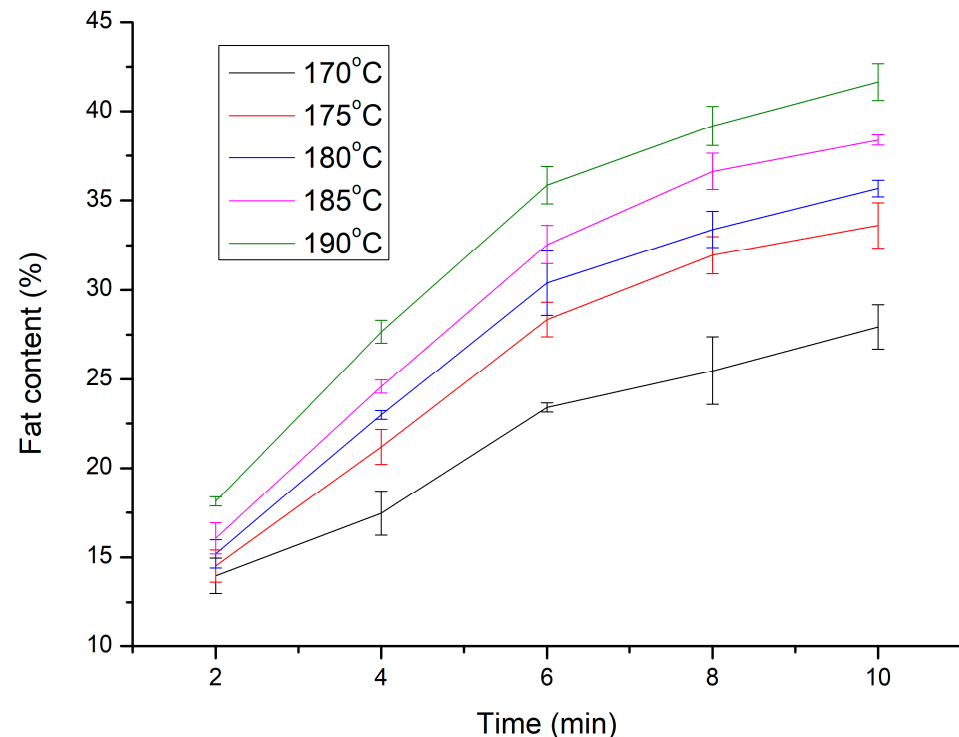


Figure 17. Variation in fat content with frying time and temperature for deep fat fried malpoa. Results are expressed as mean $\pm$ standard deviation ($n = 3$).

4. Conclusions

The findings from this investigation into the effect of deep frying on malpoa samples underscore the significant alterations induced by varying frying time and temperature. The substantial increase in fat absorption reached up to 41.65% from an initial value of 10.2% for 170–190 °C. This highlights the sensitivity of malpoa to the variations in temperature and time during deep frying. The diverse range of textural properties, such as hardness, cohesiveness, and springiness, for various frying temperatures and times reflects the complex impact of frying parameters on the physical characteristics of malpoa. On the other hand, color kinetics analysis revealed considerable alterations in L^* , b^*/a^* , and ΔE values, indicating significant changes in the color profile of malpoa due to deep fat frying. Further, the assessment of heat and mass transfer provides crucial insights into the heat and mass transport phenomena and resistances experienced within the malpoa samples during the deep fat frying process. Overall, these findings underline the intricate interplay between frying parameters and the resultant changes in fat absorption, texture, color, and heat and mass transfer characteristics of deep fat fried malpoa. Thus, these findings offer valuable implications for optimizing frying processes to achieve desired product attributes.

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References

- Pichierri, M.; Peluso, A.M. Underscoring flavor or healthiness? The effectiveness of different communication appeals in promoting local food and the moderating role of individual construal. *Psychol. Mark.* **2023**, *40*, 1521–1538. [\[CrossRef\]](#)
- Muhammad, A.; Adilbekova, K. Culinary Diplomacy: Unveiling the Palate as a Pathway to Stronger International Relations. *Ulus. Ve Uluslararası Sosyol. Ve Ekon. Derg.* **2023**, *5*, 431–449.
- Basak, S.; Chakraborty, S.; Singhal, R.S. Revisiting Indian traditional foods-A critical review of the engineering properties and process operations. *Food Control* **2023**, *143*, 109286. [\[CrossRef\]](#)
- Sankhyan, S.; Zabinski, K.; O'Brien, R.E.; Coyn, S.; Patel, S.; Vance, M.E. Aerosol emissions and their volatility from heating different cooking oils at multiple temperatures. *Environ. Sci. Atmos.* **2022**, *2*, 1364–1375. [\[CrossRef\]](#)
- Ananthanarayan, L.; Dubey, K.K.; Muley, A.B.; Singhal, R.S. Indian traditional foods: Preparation, processing and nutrition. In *Traditional Foods: History, Preparation, Processing and Safety*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 127–199.
- Asokapandian, S.; Swamy, G.J.; Hajjul, H. Deep fat frying of foods: A critical review on process and product parameters. *Crit. Rev. Food Sci. Nutr.* **2020**, *60*, 3400–3413. [\[CrossRef\]](#)
- Lee, C.C.; Taştemir, İ.A. Direct heat exchangers in the food industry. In *Thermal Processing of Food Products by Steam and Hot Water*; Woodhead Publishing: Sawston, UK, 2023; pp. 181–208.
- Bouchon, P.; Dueik, V. Frying of foods. In *Fruit Preservation: Novel and Conventional Technologies*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 275–309.
- El-Naggar, E.A. The evaluation of deep-frying oil quality with the spectrophotometric method for the rapid assessment of total polar compounds. *Zagazig J. Agric. Res.* **2019**, *46*, 1489–1502. [\[CrossRef\]](#)
- Uma, S.; Kumar, S.P.; Keran, A.D. Production of high-value compounds and innovative future products from banana: Creation of robust circular economy. *Int. J. Innov. Hortic.* **2022**, *11*, 243–258. [\[CrossRef\]](#)
- Mondal, I.H.; Dash, K.K. Textural, color kinetics, and heat and mass transfer modeling during deep fat frying of Chhena Jhili. *J. Food Process. Preserv.* **2017**, *41*, e12828. [\[CrossRef\]](#)
- Salehi, F. Color changes kinetics during deep fat frying of carrot slice. *Heat Mass Transf.* **2018**, *54*, 3421–3426. [\[CrossRef\]](#)
- Hindra, F.; Baik, O.D. Kinetics of quality changes during food frying. *Crit. Rev. Food Sci. Nutr.* **2006**, *46*, 239–258. [\[CrossRef\]](#)
- Thakur, A.; Dalbhat, C.G. Fundamentals, Methodologies, and Developments in Food Frying. In *Frying Technology*; CRC Press: Boca Raton, FL, USA, 2023; pp. 57–90.
- Franklin, M.E.E.; Pushpadass, H.A.; Ravindra Menon, R.; Rao, K.J.; Nath, B.S. Modeling the heat and mass transfer during frying of gulab jamun. *J. Food Process. Preserv.* **2014**, *38*, 1939–1947. [\[CrossRef\]](#)
- Dash, K.K.; Sharma, M.; Tiwari, A. Heat and mass transfer modeling and quality changes during deep fat frying: A comprehensive review. *J. Food Process Eng.* **2022**, *45*, e13999. [\[CrossRef\]](#)
- Ran, X.; Lin, D.; Zheng, L.; Li, Y.; Yang, H. Kinetic modelling of the mass and heat transfer of a plant-based fishball alternative during deep-fat frying and air frying and the changes in physicochemical properties. *J. Food Eng.* **2023**, *350*, 111457. [\[CrossRef\]](#)
- Nourian, F.; Ramaswamy, H.S.; Kushalappa, A.C. Kinetics of quality change associated with potatoes stored at different temperatures. *LWT-Food Sci. Technol.* **2003**, *36*, 49–65. [\[CrossRef\]](#)
- Riar, H.; Goel, N.; Singh, P.K.; Kumar, S.S.; Mishra, S.K.; Chawla, R. Changes in instrumental color and proximate parameters in yoghurt fortified with vitamin a and d nanoemulsion during storage. *Pharma Innov. J.* **2021**, *8*, 378–381.
- Holman, J.P. *Heat Transfer*, 8th ed.; McGraw-Hill, Ed.; Southern Methodist University: Dallas, TX, USA, 1997.
- Naveh, D.; Kopelman, I.J. Effect of some processing parameters on the heat transfer coefficients in a rotating autoclave. *J. Food Process. Preserv.* **1980**, *4*, 67–77. [\[CrossRef\]](#)
- Franklin, E.M.E.; Pushpadass, H.A.; Neetu, K.C.; Sivaram, M.; Nath, B.S. Modeling the kinetics of physicochemical and textural qualities of pantoa (Indian Dairy Dessert) during deep-fat frying. *J. Food Process. Preserv.* **2017**, *41*, e12805. [\[CrossRef\]](#)
- Kumar, M.; Manjunatha, M. Analysis of physico-thermal characteristics of Gulabjamun balls during hypobaric frying. *Pharma Innov. J.* **2022**, *11*, 3043–3047.
- Patel, P.; Gupta, S.; Mondal, P. Electrocoagulation process for greywater treatment: Statistical modeling, optimization, cost analysis and sludge management. *Sep. Purif. Technol.* **2022**, *296*, 121327. [\[CrossRef\]](#)
- Kheti, B.; Kamiliya, D.; Choudhury, J.; Parhi, J.; Debbarma, M.; Singh, S.T. Dietary microbial floc potentiates immune response, immune relevant gene expression and disease resistance in rohu, Labeo rohita (Hamilton, 1822) fingerlings. *Aquaculture* **2017**, *468*, 501–507. [\[CrossRef\]](#)
- Kumar, A.J.; Singh, R.R.B.; Patel, A.A.; Patil, G.R. Kinetics of colour and texture changes in Gulabjamun balls during deep-fat frying. *LWT-Food Sci. Technol.* **2006**, *39*, 827–833. [\[CrossRef\]](#)

27. Okon, U.B.; Sobukola, O.P.; Adebawale, A.A.; Bakare, H.A.; Omidiran, A.T.; Akinlade, F.A. Effect of process variables on some quality attributes of instant 'Akara iwe'—A cassava based fried snack from grits. *Appl. Food Res.* **2022**, *2*, 100115. [[CrossRef](#)]
28. Alothman, O.Y.; Fouad, H.; Al-Zahrani, S.M.; Eshra, A.; Al Rez, M.F.; Ansari, S.G. Thermal, creep-recovery and viscoelastic behavior of high-density polyethylene/hydroxyapatite nano particles for bone substitutes: Effects of gamma radiation. *Biomed. Eng. Online* **2014**, *13*, 125. [[CrossRef](#)] [[PubMed](#)]
29. Mathare, S.S.; Bakal, S.B.; Dissanayake, T.M.; Jain, S.K. Effects of coagulation temperature on the texture and yield of soy paneer (tofu). *J. Natl. Sci. Found. Sri Lanka* **2009**, *37*. [[CrossRef](#)]
30. Carabasa-Giribet, M.; Ibarz-Ribas, A. Kinetics of colour development in aqueous fructose systems at high temperatures. *J. Sci. Food Agric.* **2000**, *80*, 2105–2113. [[CrossRef](#)]
31. Vélez-Ruiz, J.F.; Sosa-Morales, M.E. Evaluation of physical properties of dough of donuts during deep-fat frying at different temperatures. *Int. J. Food Prop.* **2003**, *6*, 341–353. [[CrossRef](#)]
32. Baik, O.D.; Mittal, G.S. Kinetics of tofu color changes during deep-fat frying. *LWT-Food Sci. Technol.* **2003**, *36*, 43–48. [[CrossRef](#)]
33. Sahin, S.E.R.P.I.L.; Sastry, S.K.; Bayindirli, L. The determination of convective heat transfer coefficient during frying. *J. Food Eng.* **1999**, *39*, 307–311. [[CrossRef](#)]
34. Yıldız, A.; Palazoglu, T.K.; Erdoğdu, F. Determination of heat and mass transfer parameters during frying of potato slices. *J. Food Eng.* **2007**, *79*, 11–17. [[CrossRef](#)]
35. Pandey, M.C.; Jayathilakan, K.; Manral, M.; Radhakrishna, K.; Bawa, A.S. Heat and mass transfer kinetics of Catla catla fish during frying. *J. Food Sci. Technol.-Mysore* **2008**, *45*, 61–64.
36. Moyano, P.C.; Berna, A.Z. Modeling water loss during frying of potato strips: Effect of solute impregnation. *Dry. Technol.* **2002**, *20*, 1303–1318. [[CrossRef](#)]
37. Gamble, M.H.; Rice, P.; Selman, J.D. Relationship between oil uptake and moisture loss during frying of potato slices from cv Record UK tubers. *Int. J. Food Sci. Technol.* **1987**, *22*, 233–241. [[CrossRef](#)]
38. Troncoso, E.; Pedreschi, F. Modeling water loss and oil uptake during vacuum frying of pre-treated potato slices. *LWT-Food Sci. Technol.* **2009**, *42*, 1164–1173. [[CrossRef](#)]
39. Villota, R.; Hawkes, J.G. Reaction kinetics in food systems. In *Handbook of Food Engineering*; CRC Press: Boca Raton, FL, USA, 2018; pp. 225–484.

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