Frying kinetics and physical properties of air-fried french fries

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ABSTRACT

French fries are processed products made of partially cooked frozen potatoes. The most essential step in making french fries is frying, aiming to produce soft and crunchy product. Using air fryers in the frying process offers the benefit of significantly reducing oil consumption, thereby making it a favorable option for producing lower-fat fried foods. The objectives of the present study were to analyze the physical and chemical characteristics of french fries on the use of oil and time variation in the air frying method and to determine the frying kinetics under the air fryer. Finding the best frying method was carried out using some attributes of Zeleny, such as the frying rate. Frying was controlled at a constant temperature of 180 °C with time variations of 10, 13, and 16 minutes, and variation in the amount of oil, i.e., 2 mL, 4 mL, and without oil. The results showed the physical characteristics of french fries that include moisture content (26.85 – 45.56%), color with indicators L* (64.44 – 68.66), a* (0.01 – 4.80), b* (21.32 – 35.54), color differences (4.57 – 10.60), hardness (120.83 – 559.8 g), springiness (1.15 – 2.82 mJ), chewiness (0.33 – 3.98 mm), gumminess (28.6 – 213.43 g), and cohesiveness (0.2 – 0.41). The variations in the amount of cooking oil in the air frying method significantly affect the redness parameters. The time variation in the air frying method significantly affects moisture content, hardness, gumminess, chewiness, and cohesiveness parameters. Lightness, yellowness, colour differences, and springiness parameters have no significant effect on the variation of oil and time. The chemical characteristic of french fries includes fat content (5.78 – 22.42 %). The air frying method without oil used for 13 minutes was considered as the best treatment for frying french fries.

KEYWORDS

Air Frying
French Fries
Frying Kinetics
Physicochemical Characteristics

Introduction

Potatoes are tubers that are widely consumed, have many benefits, and have been widely cultivated worldwide. With their various varieties, potatoes are rich in carbohydrates, dietary fiber, vitamins, and minerals (Haverkort et al., 2023). They are the main source of carbohydrates and can be prepared by boiling, baking, frying, and others (Ogliari et al., 2020). Potatoes offer a wide range of culinary possibilities and are used in dishes, such as fries, chips, soups, and salads (Giampiccoli et al., 2023). French fries, also known as chips in British culture, are very popular worldwide, both as a main dish and as a snack in some cultures (Singh et al., 2022). These potato slices undergo a transformative process during the frying (Saini et al., 2023).

Deep frying and air frying are two popular cooking methods used to prepare a variety of foods. Deep frying involves immersing the food completely in hot oil, producing a crispy texture and rich flavor (Carapiso et al., 2022). On the other hand, air frying uses hot air circulation to cook food with little to no oil, providing a healthier alternative with a lighter and crispier outcome (Castro-López et al., 2023). Both methods have their unique advantages, with deep frying offering a traditional fried experience (Lumanlan et al., 2020) and air frying providing a healthier option (Ferreira et al., 2017). The choice between the two ultimately depends on personal preferences and dietary considerations, although both techniques offer unique ways to cook delicious and crispy dishes.

The process of air frying has gained popularity as a healthier alternative to traditional deep frying, as it requires little to no oil (Wang et al., 2021). However, the time and amount of oil used in air frying can still have an impact on the final outcome of the food. The cooking time in an air fryer can

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affect the texture and doneness of the food, as longer cooking times tend to result in a crispier exterior (Fikry et al., 2021). On the other hand, using oil in air frying can enhance the food’s flavor, texture, and browning (Ganesan and Xu, 2020). By adding a small amount of oil, such as a spritz or coating, is expected to contribute to a more satisfying and indulgent experience. Finding the right balance between cooking time and oil use in air frying is essential to achieve the desired outcome, strike the right balance between health-conscious cooking, as well as the desired taste and texture. Previous studies have focused on the nutritional content of French fries after frying, but no one has analyzed the kinetics of changes in moisture content during frying. The objectives of the present study were to investigate the physical and chemical characteristics of French fries with different frying methods and to determine the frying kinetics under the air fryer. A comparative study of the frying behaviour (i.e., moisture content, lightness, redness, yellowness, color differences, hardness, springiness, gumminess, chewiness, cohesiveness, fat content, and frying kinetics of French fries) was carried out.

Research Methods
Materials
The ingredients used in making French fries are frozen French fries (Golden Farm, PT Sukanda Djaya, Indonesia) with a moisture content of 54.43%, and cooking oil (Tropical, PT Bina Karya Prima, Indonesia) purchased from a supermarket in Malang, East Java Province, Indonesia.

Research stages
The frozen French fries were fried using an air fryer at 180°C for 10, 13, and 16 minutes with the use of oil 2 mL, 4 mL and no oil. For control, the frozen French fries were deep-fried at 180°C for 4 minutes. Frozen French fries (100 g) were fried for each treatment. All treatments were performed in triplicate.

The quality of French fries was analyzed 10 min after the samples were removed from the fryer. The quality analysis was performed on moisture content, color, texture, and fat content.

The moisture content of the sample was determined using the gravimetric method (Hawa et al., 2021). The samples were placed into an oven at 105°C until constant weight was achieved. The samples were placed on an aluminum dish and the moisture contents were calculated based on the weight loss and expressed on a dry basis.

CIE L*a*b* of French fries was determined by a colorimeter according to the method of Cruz-Romero et al. (2007). Standardization was done using a white tile and a black cup before each round of tests. Each sample was measured in triplicate. Color change (ΔE) was calculated by Equation 1:

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

where \( L_0^* \), \( a_0^* \) and \( b_0^* \) correspond to the color values of fried French fries, and \( L^* \), \( a^* \) and \( b^* \) correspond to color values of frozen samples.

Hardness, springiness, gumminess, chewiness, and cohesiveness of sample was measured using texture analyzer. The parameters are precompression speed (2 mm/s), compression speed (1 mm/s), upward velocity (1 mm/s), trigger point load (6.8 g), and the probe test distance (3 mm).

The fat content of sample was determined by the Soxhlet method, which involves a semicontinuous fat extraction process using non-polar organic solvents (Bija et al., 2022). By heating, evaporating, and condensing the solvent onto the sample, fat-soluble chemicals can be extracted (Kunene and Mahlambi, 2020). The extraction cycle restarts every 15 to 20 minutes, with solvent returning to the heating flask. Fat content is determined by measuring sample weight loss or the weight of extracted fat. The procedure commences with preparing tools and materials, dissolving the sample in ethanol within a Mojonnier tube, and hydrolyzing it with NH₄OH to free fatty acids. It was followed by an extraction using diethyl ether and petroleum ether was carried out to obtain fat. Around 2 g of fat samples are weighed, placed in an aluminum foil dish, and dried at a constant 100°C. The final sample mass is measured and recorded, enabling the calculation of fat content using the specified Equation 2.

\[ \%\ Fat = \frac{g\ of\ fat\ extracted}{g\ of\ dried\ sample} \times 100\% \]  

Frying kinetics is a scientific field that investigates the chemical and physical changes occurring during frying, focusing on several parameters, such as moisture content to understand the time-temperature relationship and food transformations (Devi et al., 2020). Mathematical models are used to predict the changes over time and optimize the frying process (Verboven et al., 2020). Understanding the kinetics of frying is
essential to improve frying processes and product quality (Islam et al., 2019). Eight mathematical models based on Table 1 were used in this study. The fittest model was selected based on statistical parameters such as $R^2$, RMSE, and $\chi^2$ values. Non-linear regression analysis using Microsoft Excel 2019 was conducted to obtain the fittest constants for each model. This approach provides valuable insights into frying kinetics, enabling process optimization and improved product quality.

**Research design**

Test parameters, i.e., moisture content, color attributes (lightness, redness, yellowness, and color differences), also texture analysis (hardness, springiness, chewiness, gumminess, and cohesiveness) using a Two-way ANOVA was performed with a 95% confidence level. Following the ANOVA, the Duncan test was carried out with a 95% confidence level. All experiments were repeated three times (n=3). For all statistical analysis, $P<0.05$ (a significance level) was used. For the frying modelling behaviour of air-fried french fries, these parameters were analyzed: coefficient determination ($R^2$), chi-squared, and root mean square error (RMSE), which were used to express the goodness of fit models. All the statistical analysis was performed using the Microsoft Excel.

**Results and Discussion**

**Moisture content**

As shown in Table 2, there is a significant difference ($p$-value<0.05) in moisture content between the different frying time of french fries. As represented by Figure 1, it was observed that the moisture content of french fries varies depending on the frying method and duration. The deep-fried french fries have the highest moisture content, while the air-fried french fries without oil for 16 minutes show the lowest moisture content. In air frying, longer frying times lead to decreased moisture content due to water evaporation (Ahmed et al., 2023). This research suggests that prolonged frying times cause water within the food to heat up and evaporate (Asokapandian et al., 2020). Additionally, deep frying, which uses oil as a heat conductor, accelerates water evaporation (Xu et al., 2020). Comparatively, deep frying is faster than air frying, with water evaporation occurring more rapidly on the material’s surface (Ran et al., 2023).

**Color changes**

Table 2 shows that variation in the amount of oil and frying time did not significantly affect the lightness value of french fries ($p$-value>0.05). As represented by Figure 2a, the lightness ($L^*$) values of french fries range from 64.44 - 68.66, with the highest value obtained in the air-fried sample using 2 mL of oil for 16 minutes. The lowest lightness value was obtained in the air-fried sample without oil for 10 minutes. The $L^*$ value of 0 indicates a tendency to be black while value of 100 indicates a tendency to be white (Hematian et al., 2023). These results indicate that the longer the frying times, the higher of the lightness values of the french fries. Research suggests that the lightness of the french fries is influenced by temperature and frying time (Fikry et al., 2021). The brightness of the fries is also influenced by the number of frying cycles (Pantalone et al., 2023).

The redness ($a^*$) is a color parameter that indicates the level of red color in a product (Milovanovic et al., 2020). Table 2 shows that the redness of french fries affected by the variation in the amount of oil ($p$-value<0.05). The average redness values for french fries range from 0.013 to 4.780. As represented by Figure 2b, the highest redness value was obtained in the deep-fried french fries, while the lowest value was obtained in the air-fried sample using 2 mL of oil for 13 minutes. The high redness value in deep frying is attributed to the caramelization reaction that occurs due to the heating of sugars present in potatoes at high temperatures (Wang et al., 2023). Research indicates that redness is influenced by factors such as temperature (Vaitkevičienė et al., 2022), heating duration (Botinestean et al., 2021), and pigment structure changes caused by decomposition (Yang et al., 2022).

**Table 1. Frying kinetics models for air-fried french fries**

<table>
<thead>
<tr>
<th>Model name</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis</td>
<td>$MR = \exp(-kt)$</td>
</tr>
<tr>
<td>Page</td>
<td>$MR = \exp(-kt^2)$</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>$MR = a\exp(-kt)+c$</td>
</tr>
<tr>
<td>Midili et al.</td>
<td>$MR = a\exp(-kt)+b+t$</td>
</tr>
<tr>
<td>Two-term</td>
<td>$MR = a\exp(-kt)+b\exp(-kt)$</td>
</tr>
<tr>
<td>Wang-Singh</td>
<td>$MR = 1+at+bt^2$</td>
</tr>
<tr>
<td>Diffusion app.</td>
<td>$MR = a\exp(-kt)+(1-a)\exp(-kt)$</td>
</tr>
<tr>
<td>Verma et al.</td>
<td>$MR = a\exp(-kt)+(1-a)\exp(-kt)$</td>
</tr>
</tbody>
</table>
**Table 2.** Effect of variation in the amount of oil and frying time on physicochemical characteristics of air-fried french fries

<table>
<thead>
<tr>
<th>Amount of Oil</th>
<th>Frying Time (min)</th>
<th>Moisture Content (%)</th>
<th>Fat Content (%)</th>
<th>Lightness</th>
<th>Redness</th>
<th>Yellowness</th>
<th>Color Differences</th>
<th>Hardness</th>
<th>Springiness</th>
<th>Gumminess</th>
<th>Chewiness</th>
<th>Cohesiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>No oil</td>
<td>10</td>
<td>33.61aA</td>
<td>5.78</td>
<td>64.44aA</td>
<td>0.95</td>
<td>2.435A</td>
<td>5.129a</td>
<td>154.9</td>
<td>1.15aA</td>
<td>28.60aA</td>
<td>0.33aA</td>
<td>0.20aA</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>31.79abA</td>
<td>6.37</td>
<td>67.15aA</td>
<td>1.79</td>
<td>2.612A</td>
<td>4.657a</td>
<td>302.7</td>
<td>1.64aA</td>
<td>72.63dbB</td>
<td>1.18bB</td>
<td>0.25abAB</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>31.26acA</td>
<td>7.84</td>
<td>66.02aA</td>
<td>0.76</td>
<td>2.3874A</td>
<td>6.067a</td>
<td>445.2</td>
<td>1.87aA</td>
<td>125.50c</td>
<td>2.34c</td>
<td>0.34bB</td>
</tr>
<tr>
<td>2 mL oil</td>
<td>10</td>
<td>34.02aA</td>
<td>6.40</td>
<td>66.40aA</td>
<td>0.04</td>
<td>2.1607A</td>
<td>4.834a</td>
<td>120.8</td>
<td>2.82aA</td>
<td>33.27abA</td>
<td>0.91A</td>
<td>0.28aA</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>33.96abA</td>
<td>7.85</td>
<td>64.65aA</td>
<td>0.01</td>
<td>2.1320A</td>
<td>7.698a</td>
<td>226.4</td>
<td>1.82aA</td>
<td>74.47dbB</td>
<td>1.34bB</td>
<td>0.33abAB</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>29.86acA</td>
<td>8.41</td>
<td>68.66aA</td>
<td>0.86</td>
<td>2.4470A</td>
<td>5.234a</td>
<td>559.8</td>
<td>1.91aA</td>
<td>213.43c</td>
<td>3.98c</td>
<td>0.41bB</td>
</tr>
<tr>
<td>4 mL oil</td>
<td>10</td>
<td>37.61aA</td>
<td>7.08</td>
<td>65.03aA</td>
<td>0.54</td>
<td>2.3123A</td>
<td>5.002a</td>
<td>142.7</td>
<td>1.50aA</td>
<td>32.10abA</td>
<td>0.47aA</td>
<td>0.23aA</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>34.84abA</td>
<td>7.45</td>
<td>65.67aA</td>
<td>0.71</td>
<td>2.3010A</td>
<td>7.911a</td>
<td>299.1</td>
<td>1.96aA</td>
<td>122.43b</td>
<td>2.30bB</td>
<td>0.37abAB</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>30.33acA</td>
<td>8.47</td>
<td>67.86aA</td>
<td>0.78</td>
<td>2.2980A</td>
<td>5.250a</td>
<td>376.9</td>
<td>2.22aA</td>
<td>140.00c</td>
<td>3.05c</td>
<td>0.39bB</td>
</tr>
</tbody>
</table>

*Rows with lowercase denoted significant (p<0.05) differences between amount of oil. Rows with uppercase denoted significant (p<0.05) differences between frying time.

**Figure 1.** Moisture contents of french fries
Figure 2. Color analysis of french fries (a) lightness (L*), (b) redness (a*), (c) yellowness (b*), (d) color differences (∆E)

The yellowness (b*) is a color parameter that indicates the level of yellowness in a product (Milovanovic et al., 2020). Table 2 shows that variation in the amount of oil and frying time did not significantly affect the yellowness value of the french fries (p-value>0.05). The average yellowness values for french fries range from 0.013 to 4.780. As represented by Figure 2c, the highest yellowness value was obtained in the air-fried sample using the deep-frying method, while the lowest value was obtained in the air-fried sample with 2 mL of oil for 13 minutes. A previous study also suggests that the yellowness value in frying is not significantly influenced by temperature or time (Faloye et al., 2021).

Color difference (∆E) is a measure of distinction between two points in the Lab color space (Akl et al., 2022). Table 2 shows that variation in the amount of oil and frying time did not significantly affect the color differences value of the french fries (p-value<0.05). The average ∆E values for french fries range from 3.360 to 10.603. As represented by Figure 2d, deep-fried fries exhibit the highest ∆E value, while air-fried fries with 2 mL of oil for 16 minutes show the lowest ∆E value. The significant color difference in deep frying is attributed to the Maillard reaction (Cao et al., 2020). Temperature (Calín-Sánchez et al., 2020) and the proportion of lightness, redness, and yellowness (Hughes et al., 2020) also affect the color differences.

Texture

Hardness represents the force required to break a food product (Zahari et al., 2020). Based on Table 2, it can be concluded that frying time has a significant effect on the hardness of the french fries (p-value<0.05). As indicated in Figure 3, the highest hardness value was obtained in the air-fried treatment with 2 mL of oil for 16 minutes, while the lowest was obtained in the air-fried treatment with 2 mL of oil for 10 minutes. Longer frying times in the air fryer correspond to higher hardness values (Mokhtar and Thow, 2022). Increasing frying time...
and temperature increases fried product’s hardness (Ganjloo et al., 2022).

Springiness refers to the rate at which a food sample recovers its shape after being subjected to stress (Nishinari et al., 2013). As shown in Table 2, the springiness of the french fries was not affected by the variation in the amount of oil and frying time (p-value>0.05). Based on Figure 3, the highest springiness value (2.82) was obtained in the air-fried treatment with 2 mL of oil for 10 minutes, while the lowest value of 1.15 was obtained from the air-fried treatment without oil for 10 minutes. Longer frying times in the air fryer were found to increase the springiness value (Joshy et al., 2020).

Figure 3 Texture analysis of french fries (a) hardness, (b) springiness, (c) gumminess, (d) chewiness, (e) cohesiveness
Gumminess represents the energy required to compress food ingredients (Tarahi et al., 2023). Table 2 shows that the longer the frying time, the higher the gumminess value of the french fries (p-value<0.05). Figure 3 shows that the air-fried treatment with 2 mL of oil for 16 minutes had the highest gumminess value (213.4), while the air-fried treatment without oil for 10 minutes had the lowest gumminess value (28.6). Gumminess is influenced by both hardness and cohesiveness, with higher values of these parameters resulting in an increase in gumminess (Sivaranjani et al., 2022). The frying method, temperature, and time also impact the gumminess (Yu et al., 2020).

Chewiness represents the energy required to chew food and indicates chewing power (Du et al., 2023). Based on Table 2, it can be concluded that the frying time significantly affects the chewiness value of the french fries (p-value<0.05). Figure 3 reveals that the highest chewiness value of 3,980 mJ was obtained in the air-fried treatment with 2 mL of oil for 16 minutes, while the lowest value of 0.333 mJ was obtained in the air-fried treatment without oil for 10 minutes. Chewiness is influenced by hardness, springiness, and cohesiveness (Suliman et al., 2023). The choice of frying method also affects chewiness (Kutlu et al., 2022), with air frying generally producing higher chewiness values than deep frying (Tamsir et al., 2021).

Cohesiveness represents the ability of a material to maintain its structure under mechanical crushing (Nishinari et al., 2019). Table 2 shows that the frying time significantly affects the cohesiveness of french fries (p-value<0.05). Figure 3 shows that longer frying times result in higher cohesiveness values, while shorter frying times yield much lower values. A previous research indicates that frying time significantly affects cohesiveness (Wang et al., 2019), while the use of oil in air frying does not have a significant impact (Vu et al., 2022). The frying method and pre-treatment of ingredients do not affect cohesiveness. Moreover, increasing frying time leads to increased cohesiveness values (Jouki et al., 2021).

**Fat content**
The fat content in french fries’ samples was determined using the Soxhlet method, which involves extracting the fat by heating the sample in a Soxhlet flask. The fat is collected as the steam condenses and drips onto the material. The solvent subsequently evaporates, leaving the fat in the flask (Pargiyanti, 2019). Figure 4 indicates that the highest fat content on deep frying was 22.42%, while air frying without oil for 10 minutes resulted in the lowest fat content (5.78%). The disparity in fat content between deep frying and air frying is substantial, with the air frying exhibiting 62.22 – 74.22% lower fat content compared to the deep frying. The lower fat content in the air-fried products can be attributed to the evaporation of water during the frying process, which creates empty pores that are not directly filled with oil. Conversely, deep frying utilizes oil as the primary medium, allowing it to penetrate the empty pores created by water evaporation, leading to higher fat content. Therefore, air frying is favorable method for achieving low-fat content (Habibi and Utami, 2022). The fat content in fried products is influenced by the use of oil during frying (Fikry et al., 2021) and prolonged frying times (Wang et al., 2022), while the volume of oil used directly impacts the resulting fat content (Andrés et al., 2013).

![Figure 4. Fat content of french fries](image-url)

**Figure 4. Fat content of french fries**
Frying kinetics
The moisture content data of air-fried French fries were converted into a non-dimensional expression of the moisture ratio. The curves of the moisture ratio were non-linearly regressed against 8 kinetics frying models listed in Table 1 using Microsoft Excel 2019 to obtain the fittest constants for respective models. The models were evaluated based on $R^2$, $\chi^2$, and RMSE. Table 3 summarizes the model constants and statistical parameters for the air-fried and deep-fried French fries, respectively. The statistical parameters revealed that the Midili et al. model has the highest value of $R^2$ and also the lowest $\chi^2$ and RMSE values for all samples except air-fried French fries with 2 mL of oil for 16 minutes. Therefore, it can be concluded that the Midili et al. model is the fittest model for the air-fried French fries except air-fried French fries with 2 mL of oil for 16 minutes, as illustrated in Figure 5. The Wang-Singh model has the highest value of $R^2$ and the lowest $\chi^2$ and RMSE values for samples with 2 mL of oil for 16 minutes. Therefore, it can be concluded that the Midili et al. and Wang-Singh models are the fittest model for the air-fried French fries with 2 mL of oil, as illustrated in Figure 5.
The data regarding the moisture content of air-fried french fries were transformed into a nondimensional expression of the moisture ratio. The frying process is closely related to the drying process because heat and mass transfer occur, influencing the material's decrease in water content. Using the assumption that thin layers of drying occur during air-frying of french fries, Table 1 is used to fit eight mathematical models. The models were assessed using $R^2$, $\chi^2$, and RMSE.

Table 3 summarizes model constants and model accuracy parameter tests for treatments with and without oil. The results of the french fry model indicate that the model developed by Midilli et al delivers more accurate predictions than the other seven models. However, the treatment with 2 mL of oil (16 minutes) showed the best results for a different model, namely the Wang-Singh model. The best model for predicting the decrease in water content during air-fried french fries is shown in Figure 5.

The evaluation for determining the best treatment is when the $R^2$ above 0.9900, RMSE below 0.0300, and $\chi^2$ below 0.0018. The Wang-Singh model is the best model besides the Midilli et al. (dominant) model, which shows the initial phase on the initial curve during the period of decreasing water content of air-fried french fries before a constant rate occurs (Hawa et al., 2023). Model Midilli et al. propose a model that may represent each phase of decreasing water content during air-frying french fries, beginning with the starting phase and ending with the rate of decrease.

The best model of Midilli et al. during the frying has also been reported by Mojaharul Islam et al. (2019) on edamame commodities using the hybrid vacuum frying method. In addition, the characteristics of the moisture reduction curve with the best Wang-Singh model are identical to those

<table>
<thead>
<tr>
<th>Sample</th>
<th>Best Model</th>
<th>Model Constant</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air frying no oil 10 min</td>
<td>Midilli et al.</td>
<td>$k=0.0074$; $a=1.0134$; $b=-0.0399$; $n=2.0864$</td>
<td>0.9968</td>
<td>0.0200</td>
<td>0.0012</td>
</tr>
<tr>
<td>Air frying no oil 13 min</td>
<td>Midilli et al.</td>
<td>$k=0.0143$; $a=1.0017$; $b=-0.0159$; $n=2.0864$</td>
<td>0.9979</td>
<td>0.0157</td>
<td>0.0005</td>
</tr>
<tr>
<td>Air frying no oil 16 min</td>
<td>Midilli et al.</td>
<td>$k=0.0143$; $a=1.0025$; $b=-0.0100$; $n=1.7463$</td>
<td>0.9983</td>
<td>0.0143</td>
<td>0.0004</td>
</tr>
<tr>
<td>Air frying 2 mL of oil 10 min</td>
<td>Midilli et al.</td>
<td>$k=0.0109$; $a=1.0048$; $b=-0.0172$; $n=2.1925$</td>
<td>0.9970</td>
<td>0.0197</td>
<td>0.0012</td>
</tr>
<tr>
<td>Air frying 2 mL of oil 13 min</td>
<td>Midilli et al.</td>
<td>$k=0.0137$; $a=1.0097$; $b=-0.0190$; $n=2.1925$</td>
<td>0.9962</td>
<td>0.0210</td>
<td>0.0009</td>
</tr>
<tr>
<td>Air frying 2 mL of oil 16 min</td>
<td>Wang-Singh</td>
<td>$a=0.0402$; $b=-0.0013$</td>
<td>0.9950</td>
<td>0.0235</td>
<td>0.0007</td>
</tr>
<tr>
<td>Air frying 4 mL of oil 10 min</td>
<td>Midilli et al.</td>
<td>$k=0.0080$; $a=1.0181$; $b=-0.0161$; $n=2.3423$</td>
<td>0.9957</td>
<td>0.0242</td>
<td>0.0018</td>
</tr>
<tr>
<td>Air frying 4 mL of oil 13 min</td>
<td>Midilli et al.</td>
<td>$k=0.0073$; $a=1.0125$; $b=-0.0141$; $n=2.3423$</td>
<td>0.9985</td>
<td>0.0136</td>
<td>0.0004</td>
</tr>
<tr>
<td>Air frying 4 mL of oil 16 min</td>
<td>Midilli et al.</td>
<td>$k=0.0073$; $a=1.0168$; $b=-0.0182$; $n=1.8374$</td>
<td>0.9977</td>
<td>0.0162</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

The evaluation for determining the best treatment is when the $R^2$ above 0.9900, RMSE below 0.0300, and $\chi^2$ below 0.0018. The Wang-Singh model is the best model besides the Midilli et al. (dominant) model, which shows the initial phase on the initial curve during the period of decreasing water content of air-fried french fries before a constant rate occurs (Hawa et al., 2023). Model Midilli et al. propose a model that may represent each phase of decreasing water content during air-frying french fries, beginning with the starting phase and ending with the rate of decrease.

The best model of Midilli et al. during the frying has also been reported by Mojaharul Islam et al. (2019) on edamame commodities using the hybrid vacuum frying method. In addition, the characteristics of the moisture reduction curve with the best Wang-Singh model are identical to those
previously reported (Hawa et al., 2023) for button mushroom commodities dried via vacuum drying.

Identifying the optimal treatment in both deep frying and air frying methods, which involved various treatments with different oil and time combinations, was determined using the multiple attribute Zeleny method. This approach assigns priority to the analyzed parameters by considering the overall data, aiming to select the treatment that yields the lowest or highest values based on the objective of each parameter (Alfian et al., 2023). To determine the superior frying method, an assessment was conducted on several parameters, including water content, lightness, redness, yellowness, color differences, hardness, springiness, gumminess, chewiness, cohesiveness, and fat content. The comprehensive analysis of determining the optimal frying method for french fries is presented in Table 4.

Table 4 reveals that the analysis of each frying method yielded values ranging from 1.457 to 1.748. The lowest value, indicating the best frying method for french fries, was achieved through air frying without oil for 13 minutes. Detailed information on the physical characteristics of the optimal frying method can be found in Table 5. This research is limited to testing the parameters of physical characteristics and fat content of french fries. Then it can be further developed regarding the chemical characteristics (i.e., free fatty acids, peroxide value, and protein) of french fries. Further research is also needed regarding sensory (organoleptic) characteristics (i.e., appearance, smell, taste, and texture quality) related to consumer acceptance of a product.

### Table 4. Analysis of best frying methods

<table>
<thead>
<tr>
<th>Treatment</th>
<th>L∞</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep frying</td>
<td>1.503</td>
</tr>
<tr>
<td>Air frying without oil for 10 minutes</td>
<td>1.672</td>
</tr>
<tr>
<td>Air frying without oil for 13 minutes*</td>
<td>1.457</td>
</tr>
<tr>
<td>Air frying without oil for 16 minutes</td>
<td>1.609</td>
</tr>
<tr>
<td>Air frying with 2 mL of oil for 13 minutes</td>
<td>1.748</td>
</tr>
<tr>
<td>Air frying with 2 mL of oil for 16 minutes</td>
<td>1.629</td>
</tr>
<tr>
<td>Air frying with 4 mL of oil for 10 minutes</td>
<td>1.644</td>
</tr>
<tr>
<td>Air frying with 4 mL of oil for 13 minutes</td>
<td>1.613</td>
</tr>
<tr>
<td>Air frying with 4 mL of oil for 16 minutes</td>
<td>1.610</td>
</tr>
</tbody>
</table>

### Table 5. Characteristics of air-fried french fries without oil for 13 minutes

<table>
<thead>
<tr>
<th>Physical and Chemical Quality</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content</td>
<td>30.01%</td>
</tr>
<tr>
<td>Lightness (L*)</td>
<td>67.146</td>
</tr>
<tr>
<td>Redness (a*)</td>
<td>1.791</td>
</tr>
<tr>
<td>Yellowness (b*)</td>
<td>26.162</td>
</tr>
<tr>
<td>Colour Differences (ΔE)</td>
<td>4.657</td>
</tr>
<tr>
<td>Hardness</td>
<td>302.77 g</td>
</tr>
<tr>
<td>Springiness</td>
<td>1.64 mm</td>
</tr>
<tr>
<td>Chewiness</td>
<td>1.18 mJ</td>
</tr>
<tr>
<td>Gumminess</td>
<td>72.63 g</td>
</tr>
<tr>
<td>Cohesiveness</td>
<td>0.25</td>
</tr>
<tr>
<td>Fat Content</td>
<td>6.37%</td>
</tr>
</tbody>
</table>
Conclusions
In air frying, the amount of oil significantly affects the redness, while the frying time affects moisture content, hardness, gumminess, chewiness, and cohesiveness. Lightness, yellowness, colour differences, and springiness parameters have no significant effect on the variation in the amount of oil and frying time. Based on Zeleny multiple attributes method, the air frying without oil for 13 minutes is the best frying method for french fries with the moisture content of the french fries was 30.01%. The colour test on french fries was obtained with lightness (L*) 67.15; redness (a*) 1.79; yellowness (b*) of 26.16; and colour differences of 4.66. In the texture test, hardness 302.77 g; springiness 1.64 mm; chewiness 1.18 mJ; gumminess 72.63; and cohesiveness 0.25. In this method, the fat content is 6.37%. The statistical parameters revealed that the Midili et al. and Wang-Singh models are the best models for predicting the decrease in water content during air-fried french fries, which have the highest value of R² also the lowest χ² and RMSE values.

Declarations

Conflict of interests The authors declare no competing interests.

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