Transfer of Synthetic Antioxidants During Deep Frying: A Case Study on BHA and BHT

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This study investigates the transfer of synthetic additives into food during the deep-frying process, with a particular focus on Butylated Hydroxyanisole (BHA) and Butylated Hydroxytoluene (BHT), which are commonly used in frying oils. Sunflower oil containing these synthetic additives was obtained from a production facility, and the actual amount of additives in the oil was determined. The oil was then fortified with BHA and BHT to the maximum concentrations allowed by regulations, and French fries of specified dimensions were fried under controlled conditions. The quality characteristics of both the potatoes and the oil were analysed.

The study adopted a full factorial experimental design, selecting 170°C and 300 seconds as the temperature and time parameters based on sensory data. Following the frying process, physico-chemical analyses were conducted on the oil and potato samples. The research meticulously measured the concentration of additives transferred under varying time frames and conditions, providing detailed insights into the dynamics of this process.

This result is critical for understanding the behaviour of additives in high-temperature cooking environments and their consequent presence in fried foods. The implications of this study are far-reaching, affecting both the food processing industry and consumer health. By providing detailed data on the transference of additives during deep frying, this study is contributing to the development of safer frying practices and more informed decisions regarding additive usage in food preparation. This research can serve as a valuable resource for food scientists, health professionals, and regulatory bodies, guiding them in creating and enforcing standards that ensure the safety and quality of fried foods.

Keywords: Synthetic antioxidants, additive transfer, oil physico-chemical properties, fried potatoes

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1. INTRODUCTION

Ensuring the safe production and supply of food is crucial, along with preventing quality losses during the production process and extending the shelf life of the product as much as possible. To achieve these goals, foods can be preserved using special packaging methods or by incorporating additives. However, when products are exposed to high temperatures, oxidized, or stored at high temperatures, undesirable effects such as rancidity and bad odour can occur in oils. To prevent these effects, synthetic antioxidants are used in oils [1], [2], [3]. Antioxidants used as preservatives in foods are components that protect the substance in which they are used by delaying spoilage, rancidity, and colour deterioration. These components are added to maintain the quality of the product and extend its shelf life by preventing spoilage reactions during the procurement, storage, distribution, sale, and consumption processes of the food [4], [5], [6]

The use of synthetic additives in the food industry, particularly in frying oils,

has been th subject of growing interest and concern. Deep frying, a widely employed cooking method, involves submerging food in hot oil, leading to the transfer of various substances between the food and the oil. Among these substances, synthetic antioxidants such as Butylated Hydroxyanisole (BHA) and Butylated Hydroxytoluene (BHT) are commonly used to prevent oil rancidity and extend shelf life [7], [8], [9]. BHA is an antioxidant and food preservative also used in cosmetics, pharmaceuticals, rubber, and petroleum products [10]. It is a mixture of two chemical isomers, 3-tert-butyl-4-hydroxyanisole (3-BHA) and 2-tert-butyl-4-hydroxyanisole (2-BHA). BHA appears as a white or yellowish waxy solid with an aromatic odour and a slightly bitter, burnt taste [11]. BHA can be used individually or in combination with other antioxidants in foods at a maximum permissible level of 200 mg/kg [12]. Additionally, BHT is permitted at levels up to 100 mg/kg in fats and oils, either alone or combined with other antioxidants like BHA [13]. BHA and BHT, which are classified as GRAS (Generally Recognized As Safe) antioxidants, are commonly found in foods containing solid or liquid fats, as well as in cosmetics and pharmaceuticals [14], [15]. Some antioxidants, when used together, can exhibit a much greater effect than when used individually. These substances are known as synergists. BHA and BHT are chemicals that exhibit synergistic effects [16], [17]. Other chemicals known to have antioxidant activity (such as propyl gallate, citric acid, phosphoric acid, ascorbic acid, etc.) are often combined with BHA and BHT to enhance their antioxidant activities [15]. However, despite their low usage levels, some studies suggest that these synthetic additives can accumulate in the body and cause tissue damage when consumed under certain conditions [18], [19].

The primary objective of this study is to investigate the transfer of these synthetic additives from frying oil to food during the deep-frying process. Specifically, the research focuses on the quantification of BHA and BHT transfer into French fries, analysing the impact of frying conditions on the concentration of these additives in both the oil and the fried food.

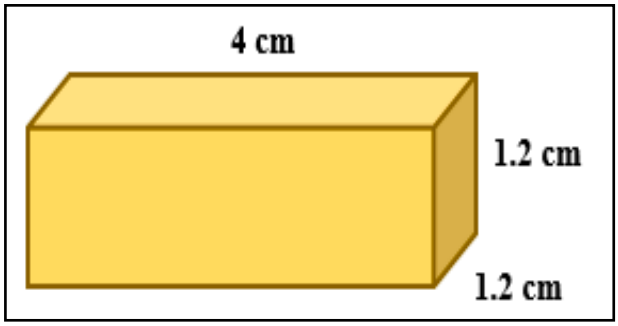


Figure I - Standard dimensions of the potato samples used in frying (1.2 × 1.2 × 4 cm)

Previous studies have highlighted the importance of understanding the behaviour of synthetic additives under high-temperature cooking conditions. For instance, they have estimated the maximal daily dietary intake of BHA and BHT, emphasizing the need for stringent control over additive levels in food products [20], [21]. Moreover, the physical and chemical properties of frying oils, such as peroxide value and free fatty acid content, have been shown to significantly influence the transfer and degradation of these additives during frying [1], [2]

In this study, sunflower oil containing known amounts of BHA and BHT was used to fry French fries under controlled conditions. The frying parameters, including temperature and time, were selected based on sensory data and established regulatory limits for additive concentrations. The physico-chemical properties of the oil and the fried potatoes were then analysed to determine the extent of additive transfer.

The findings of this research are crucial for the food industry, since they provide valuable insights into the dynamics of additive behaviour during deep frying. By understanding the factors that influence the transfer of BHA and BHT, food scientists and manufacturers can develop safer frying practices and make more informed decisions regarding the use of synthetic additives.

2. MATERIAL AND METHODS

2.1. MATERIAL

Sunflower oil samples were obtained from a local producer and stored in a cool, dark place until analysis. Initial analyses of the oil samples for BHA and BHT were also conducted by an external laboratory, which confirmed that neither additive was present. BHA and BHT were then added to the oil at the maximum levels specified in the food additives regulation, which are 200 mg/kg and 100 mg/kg, respectively. The

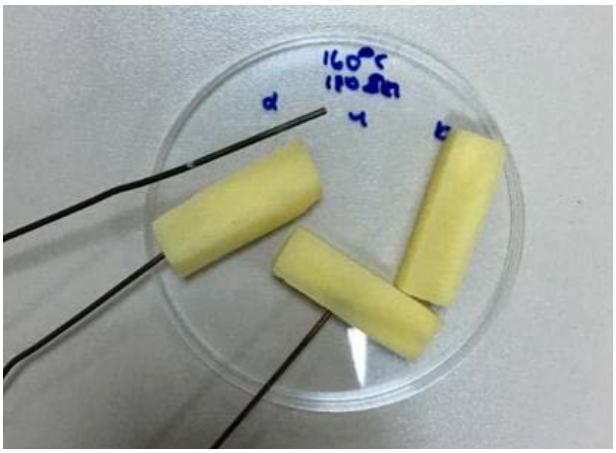


Figure II - Locations of thermocouples: vertically (d), horizontally (y), and control (b)

additives were thoroughly mixed into the oil using a magnetic stirrer to ensure homogeneity [20].
For the frying process, potatoes of a variety suitable for frying were selected and procured from a local market.

2.2. FRYING AND SAMPLE COLLECTION

The potatoes were cut into thin, long, equal rectangular prisms (1.2 x 1.2 x 4 cm) and temperature probes (T-type) were placed vertically and horizontally to reach the centre points of the potatoes as shown in Figure I and Figure II, with details provided in Table II. Additionally, one probe was placed in the environment to monitor ambient temperature, and another probe was immersed in the oil in the fryer to monitor oil temperature. At the beginning of each time interval, three potato samples, each weighing approximately 6 grams, were placed into 1 L of oil in a 5-litre capacity fryer for frying. The experimental design is provided in Table I.

Table I - Full Factorial Design Used in Frying Experiments (Temperature × Time Combinations)

Temperature (ºC)	Time (s)	Code
160	180	160180
	240	160240
	300	160300
	360	160360
	420	160420
170	180	170180
	240	170240
	300	170300
	360	170360
	420	170420
180	180	180180
	240	180240
	300	180300
	360	180360
	420	180420

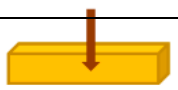
2.3. DETERMINATION OF PHYSICO-CHEMICAL PROPERTIES OF SAMPLES

Colour measurement of the fried potato samples at 25±5oC was carried out by colour meter (Konica Minolta CR-5, USA) readings of brightness (L*), a* and b* values and Chroma (C) value. ΔE value was evaluated by calculating ΔL, Δa and Δb against measured values of the control oil sample by using Eq. (1) [22].

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{(1/2)} \quad (1)$$

Texture analysis of the fried potatoes was performed using a Texture Analyzer (TA-XT Plus). Although the use of a cylindrical probe was initially planned, it was decided to use the TA-42 45° cutting-edge shear probe. In a study conducted by Sadeghi et al. (2021), the use of a similar blade was reported in the literature to have a positive correlation with human sensory attributes [23].
The oven method was used for calculating moisture content. Potatoes were dried at 105°C, and the moisture content was calculated. The oil content of the potato samples after frying was determined using the classical Soxhlet method according to the AOCS (American Oil Chemists Society) standards [24]. During the frying process, samples of potatoes were taken at different periods, with 3-5 g of each sample weighed, and dried in an oven to remove moisture. The dried samples were then brought to a constant weight in a desiccator. The dried potato samples were placed in cartridges of the oil determination apparatus (Gerhardt Type: EV 16, Germany) and approximately 150 ml of solvent (hexane) was added for oil extraction. Subsequently, the solvent was collected in a balloon using a rotary evaporator. The oil balloon was placed in an oven at 105°C for 15 minutes to evaporate any remaining solvent, and the process continued until a constant weight was achieved in the desiccator.
Determination of the FFA and PV of oil samples was performed following AOCS standard methods Ca

Table II - Positions of the thermocouples

Code	Definition of the positionings	
d	Probe placed vertically into the center of potato sample	
y	Probe placed horizontally through the center of potato sample	
b	Potato sample with no probe (control)	

3d-63 and Cd 8b-90 respectively [25]. Fatty acid composition evaluation of the samples was conducted following European Official Methods of Analysis [26]. The total polar materials (TPM%) of oil samples were measured using a Testo 265 sensor (probe) (Lenzkirch, Germany). Previous research has found that measuring TPM% using a probe is the simplest and most reliable method. This method has been shown to correlate well with the column chromatographic method for measuring total polar materials. [27]. The temperature of the oil samples was raised to 50±5oC for proper measurement and the probe was immersed for 10 sec. [22], [28].
The analysis of BHA and BHT was performed on oil samples using The AOAC 983.15 method, utilizing HPLC-DAD (High-Performance Liquid Chromatography with Diode-Array Detection) as the analytical instrument [29], [30].

2.4. MATHEMATICAL MODELLING

Pedreschi and Zuniga (2009) have noted that the deep-frying process can also be considered a drying process [31]. Using this information, the moisture ratio (Mr, dimensionless) for each temperature and time parameter was calculated using Equation (2). [32]

$$Mr = \frac{(M - M_e)}{(M_0 - M_e)} \quad (2)$$

Subsequently, the calculated Mr values were used to determine the rate constant "k" (min–1) using Fick's second law of diffusion, represented by Equation (3), and Newton's semi-empirical model, represented by Equation (4) [33]. In these equations, L represents the half-thickness of the sample (m).

$$Mr = \frac{8}{\pi^2} \exp\left(\frac{\pi^2}{4L^2} D_{eff} \cdot t\right) \quad (3)$$

$$Mr = e^{(-k \cdot t)} \quad (4)$$

Using Equation (5), the effective moisture diffusivity (Deff, m^2/min) was calculated for each temperature parameter based on the "k" value [34].

$$k = \frac{\pi^2}{4L} D_{eff} \quad (5)$$

The activation energy (Ea, kJ/mol) for the entire frying process was calculated using Equation (6). In this equation, "R" represents the universal gas constant (8.31451 J/mol/K), and "D_0" is the pre-exponential factor in the Arrhenius equation (m^2/s) [33].

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T + 273{,}15)}\right) \quad (6)$$

These equations were also applied to the process of oil absorption in the potatoes (Equations (7) and (8)).

$$Or = \frac{O - O_e}{O_0 - O_e} \quad (7)$$

In Equation (7), Or represents the oil ratio (dimensionless), O_e is the equilibrium oil content (g/g, dry basis), and O_0 is the initial oil content (g/g, dry basis).

$$k_0 = \frac{\pi^2}{4L} D_{eff,o} \quad (8)$$

In Equation (8), k_o is the rate constant for oil absorption (min–1), and $D_{eff,o}$ represents the effective oil diffusivity (m^2/min).

$$D_{eff,o} = D_0 \exp\left(-\frac{E_{a,o}}{R(T + 273{,}15)}\right) \quad (9)$$

In Equation (9), Ea,o represents the activation energy for oil absorption during the frying process (kJ/mol).

2.5. STATISTICAL METHOD

All physico-chemical analyses were performed in triplicate, and the mean of the measurements was used for statistical analysis. The data were subjected to ANOVA (Analysis of Variance), and further analysis was conducted using Tukey's HSD test's method for multiple comparisons. Statistical software (SPSS 18, USA) was used for the ANOVA test and Pearson correlation to determine the linear relationship between variables.

3. RESULTS AND DISCUSSION

3.1. PHYSICO-CHEMICAL PROPERTIES OF SAMPLES

The Maillard reaction significantly impacts colour changes during frying. Key factors affecting colour and aroma formation in fried foods include the properties and production date of the oil used, the applied temperature and duration, prior heat treatment of the oil, the thickness and surface properties of the food, and post-frying treatments. Major degradation products in frying oils include non-volatile polar compounds, dimers, and polymers of triacylglycerols. An increase in the number of frying cycles and frying temperature results in higher polymer content in the oil. Polymers formed during deep frying are rich in oxygen, which accelerates the oxidation of the oil, leading to faster deterioration, increased viscosity, reduced heat transfer, and undesired colour development in the fried product [35], [36].
In a study by Pedreschi et al. (2005), colour change and acrylamide formation in fried potato slices were examined. Potato slices were either blanched at 85°C or left unblanched and then fried at 120, 150, and 180°C

for 250 seconds. The results showed an increase in the a* value of unblanched potatoes, attributed to increased acrylamide and Maillard reactions. They noted that the colour of fried potatoes results from Maillard reactions, which depend on reducing sugar content, temperature, and frying time. To slow down or prevent Maillard reactions, many producers blanch potatoes as a pre-treatment, reducing the a* value and preventing browning [32].

In our study, as the frying time increased, an increase in ΔE values, indicating colour changes in fried products, was observed. This colour change is a known and expected effect based on the literature. In this study, no statistically significant difference was observed in the ΔE values of potatoes fried at 170°C for different frying times (180, 240, 300, 360, 420 s) during colour analysis ($P > 0.05$).

Table III presents the texture analysis results of potatoes cut in different manners and fried at various temperatures and durations (Wavy cutting: KDJ2, Traditional cutting: HDD, ZGZD, HBHB, ZXJP, LXJZJ, HLS, KDJ1, DKS, BJL) [37]. In the study conducted by Li et al. (2020), ten different potatoes were sourced from a local fast-food restaurant in the Wuxi region, China. Among these, only one potato underwent wavy cutting (KDJ2), while the others (HDD, ZGZD, HBHB, ZXJP, LXJZJ, HLS, KDJ1, DKS, BJL) were subjected to traditional cutting methods. Frying processes were conducted at various temperatures (140°C, 160°C, 170°C, 175°C, and 177°C) and durations (2 min 45 s, 3 min, 4 min, and 5 min). Texture analysis of the resulting products was performed using different methods. Firmness values of the ten samples ranged from 4.74 to 10.3 N in the cutting test, which was found to be lower compared to other studies. This difference was attributed to the atmospheric frying conditions in their study, whereas vacuum frying conditions were employed in other studies, influenced by the climate and soil conditions of potato cultivation. Within the same study, minor variations in firmness and toughness values were observed among potatoes subjected to identical temperature and similar frying durations (ZGZD, HBHB, LXJZJ, ZXJP), aligning closely with our findings [37].

In the study by Sadeghi et al. (2021), ten varieties of potatoes grown in America (Russet Burbank, Clearwater Russet, Ranger Russet, Umatilla Russet, Pomerelle Russet, Russet Norkotah, Payette Russet, A03921 variety) were cut into 1 cm thick strips, blanched in hot water at 92°C for 6 minutes, and dehydrated in an oven at approximately 100°C for 3 minutes. Following pre-processing, frying was conducted at approximately 208.5°C for 40 seconds. Texture analysis using a 45° cutting probe revealed firmness values ranging from 38.1 to 51.9 N and toughness values from 121.8 to 166.3 N·s. Differences were noted when comparing our study's findings with theirs, where frying was conducted under vacuum conditions and for longer durations [23].

Comparative evaluation of texture data from our study and these studies indicates that vacuum frying of potatoes results in higher firmness and toughness values compared to atmospheric frying conditions (Table IV). Conversely, similar firmness and toughness values were observed in the other two studies conducted at 170°C and similar durations. The studies applied different parameters and production criteria

Table IV - Texture data of potatoes fried at different durations at 170°C

S	Firmness (N)	Toughness (N.s)
420	5.317877	16.82744
360	4.531854	16.59242
300	4.565561	14.15049
240	5.737407	14.90995
180	4.633972	10.35258

Table III - Texture analysis results of potatoes cut in different shapes and fried at different temperatures and for different durations (Crinkle-cut: KDJ2, traditional cut: HDD, ZGZD, HBHB, ZXJP, LXJZJ, HLS, KDJ1, SS, BJL) (adapted from Li et al., 2020)

Code	Frying Temperature (°C)	Duration	Firmness (N)	Toughness (N.s)	Dimensions (cm)
HDD	160	4 s	8.82 ± 0.59	21.41 ± 3.39	0.6 x 0.6 x 5
ZGZD	170	3 s	8.60 ± 1.57	21.27 ± 4.39	0.6 x 0.6 x 5
HBHB	170	3 s	8.01 ± 0.86	20.78 ± 3.70	0.6 x 0.6 x 5
LXJZJ	170	5 s	10.31 ± 0.82	28.29 ± 4.51	0.6 x 0.6 x 5
HLS	175	5 s	8.87 ± 0.95	22.62 ± 3.59	0.6 x 0.6 x 5
KDJ1	177	2 s 45 sec	9.54 ± 1.21	24.33 ± 3.64	0.6 x 0.6 x 5
SS	177	2 s 45 sec	8.57 ± 0.2	21.79 ± 3.41	0.8 x 0.8 x 5
BJL	140	4 s	8.38 ± 0.93	22.14 ± 5.47	0.5 x 0.5 x 5
KDJ2	177	2 s 45 sec	8.22 ± 0.70	23.57 ± 3.54	0.9 x 0.9 x 5
ZXJP	170	3 s	4.74 ± 0.47	11.86 ± 3.14	0.6 x 0.6 x 5

to potatoes cultivated in various countries, regions, climates, and soil conditions. These differences are thought to stem from these varying factors. ANOVA (Analysis of Variance) of the results shows that no statistically significant difference in firmness analysis was observed among potatoes fried at 170°C for varying durations (180, 240, 300, 360, 420 s) ($P > 0.05$). However, a statistically significant difference was observed in toughness analysis ($P < 0.05$).

We conducted a full factorial design with temperature parameters of 160°C, 170°C, and 180°C, and duration parameters of 180 s, 240 s, 300 s, 360 s, and 420 s for the frying process. Following frying, the calculated Moisture Ratio (Mr) values corresponding to frying durations are presented in Figure III.

In the study by Farinu and Baik (2007), sweet potatoes were fried at 150°C and 180°C in deep oil for 80-300 s, and the moisture change profile was obtained. Comparing our results, it was observed that moisture behaviours exhibited similar characteristics, with faster moisture evaporation at higher frying temperatures and slower evaporation at lower temperatures during frying processes [38].

In their study, Li et al. observed that temperature parameters (155°C, 170°C, 185°C) did not significantly affect total fat absorption in cylindrical potatoes fried for 60 seconds under deep frying conditions. Therefore, short frying times (180 s and 240 s) were not considered in the experimental design. In the same study, minimal fat absorption was observed at 155°C, with higher fat absorption at 170°C and 185°C during frying; however, there was no statistically significant difference in fat absorption between these two temperatures. The researchers noted a parallel relationship between high fat content and low dry matter content. Dry matter content without fat was determined in products obtained after deep frying at 170°C for 180 s, 240 s, 300 s, 360 s, and 420 s, with the highest dry matter content observed in fries fried for 300 s, 360 s, and 420 s [37]. Visual and sensory evaluation of potato samples revealed browning in potatoes fried for 360 s and 420 s. These longer durations were not considered in the experimental design as they deviated from sensory quality criteria such as the golden yellow colour preferred by consumers.

Kim et al. (2011) conducted a study i 1x1x4 cm potato slices were fried in soybean oil at 170°C for 2 minutes, observing a 15% oil absorption rate in potatoes [39]. Our sample absorbed approximately 10% oil during 300 s of frying (Fig V). The graph obtained by Farinu and Baik (2007) contains similar results to those obtained in our study. Based on these findings, temperature and duration parameters were selected for considering the sensory properties of fried potatoes for subsequent physico-chemical analyses [38]. Based on the sensory evaluation of fried potatoes, it was concluded that potatoes fried at 170°C for 300 s exhibited desirable characteristics. Processes were evaluated according to this temperature parameter.

Frying time and temperature, type of frying oil, antioxidants, and the type of fryer contribute to the polymerization, oxidation, and hydrolysis of oil during frying [40]. The oxidation, hydrolysis, and polymerization reactions observed in frying oil can be determined by analysing free fatty acids [41]. In their study, Yaşdağ et al. (2017) applied frying processes using sunflower oil and rice bran oil, periodically adding both oils. They sampled oil during the process and analysed the levels of free fatty acids. As discussed initially, the free fatty acid content of sunflower oil decreased, followed by an increase. This trend was correlated with the amount of oil added [41]. In our study, the free fatty acid content did not exhibit such a linear increase. It is believed that this may be attributed to the

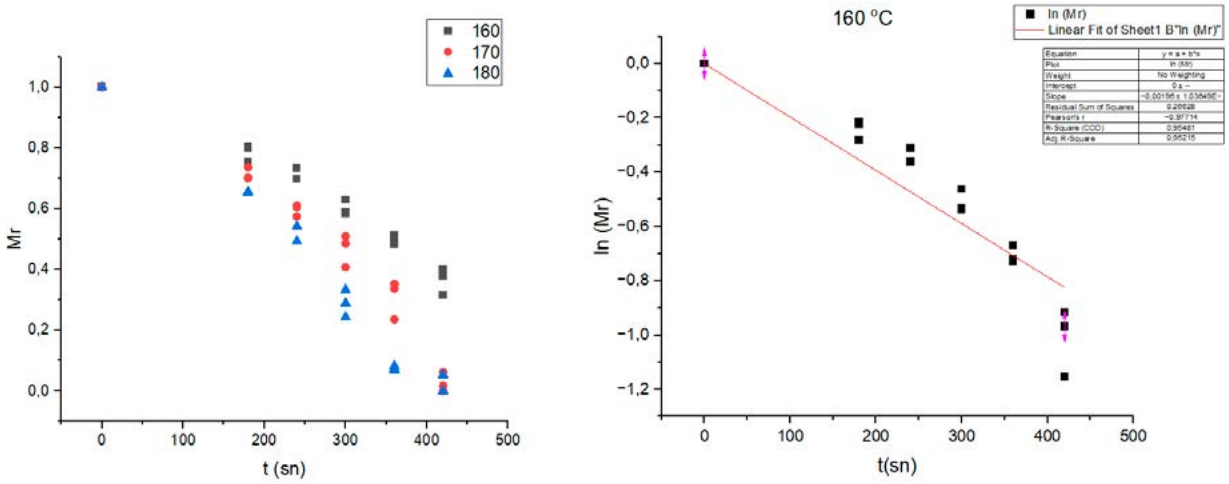


Figure III - The graph of Mr(Moisture Ratio) versus t (time-sn) at different frying temperatures (left). The ln(Mr) graph for different t time parameters for the frying process at 160°C (right).

presence of chemicals in the frying oil, such as BHA and BHT, which can retard oxidation.

One of the primary factors leading to the deterioration in quality and usability of cooking oils is rancidity, with oxidation being cited as the most influential factor in rancidity formation [42]. Hydroperoxides are the initial products released during oxidation, and their levels are determined through peroxide value analysis. These hydroperoxides, which are the primary products of oxidation, are not stable at frying temperatures and break down into secondary products. Therefore, a low peroxide value in an oil does not necessarily indicate that it has not deteriorated [43].

In a study by Aksoy (2014), initial peroxide values ranged from 0.64 to 4.78 meqO_2/kg, while after frying, these values varied between 2.97 and 11.49 meqO_2/kg. The addition of propolis extract at a level of 1500 ppm showed effects similar to those of BHT added to the oils used in the study. According to the Turkish Food Codex Regulation on Oils Named with Plant Names (Turkish Food Codex Regulation on Oils Named with Plant Names, Regulation No. 2012/29 Official Gazette, 2012), refined oils must have a peroxide value of no more than 10 meq O_2/kg [35]. Significant decreases in peroxide values observed during prolonged frying times may indicate the activation of BHA and BHT.

The chemical changes occurring during frying also lead to physical changes. Viscosity increase is associated with polymerization, darkening of colour with Maillard reaction, and increase in dielectric constant with the increase in total polar materials (TPM) in the oil [35]. Many countries define the maximum limit of polar materials as 25%, while others range between 20% and 27%. All degradation products outside the non-polar fraction are termed 'polar fraction' or 'total polar materials'. Numerous chemical reactions during thermal processes result in high molecular weight polar components. In a study, frying was conducted at 170°C for 3 minutes continuously for 5 hours daily. The TPM content of sunflower oil remained around 21% after 35 hours. Additionally, fried potatoes were noted as having a dark colour and oily sensation. Chen et al. (2013) examined the total polar compounds of repeatedly used frying oils and concluded that the type of oil is a significant parameter for total polar compounds, especially after 23 hours when soybean oil exceeded the limit value of total polar compounds [44]. In a study by Arroyo et al. (1996), the TPM content of sunflower oil before frying was found to be 4% [45]. It is reported that the carcinogenic effect begins when the total polar material content in frying oils exceeds 25% [46]. In our findings TPM values in the oil samples taken at different time parameters were found to be below

Table V - The external laboratory BHA and BHT analysis results of the oil sample taken under frying conditions of 170°C for 300 seconds

Additive	Amount (ppm)	Method	Measurement Uncertainty	Measurement Limit
BHA	160 ± 17,76	AOAC 983.15 HPLC-DAD	17,76	10 mg/kg*
BHT	60,7 ± 10,73	AOAC 983.15 HPLC-DAD	10,73	10 mg/kg*

*Method detection limit based on HPLC-DAD sensitivity

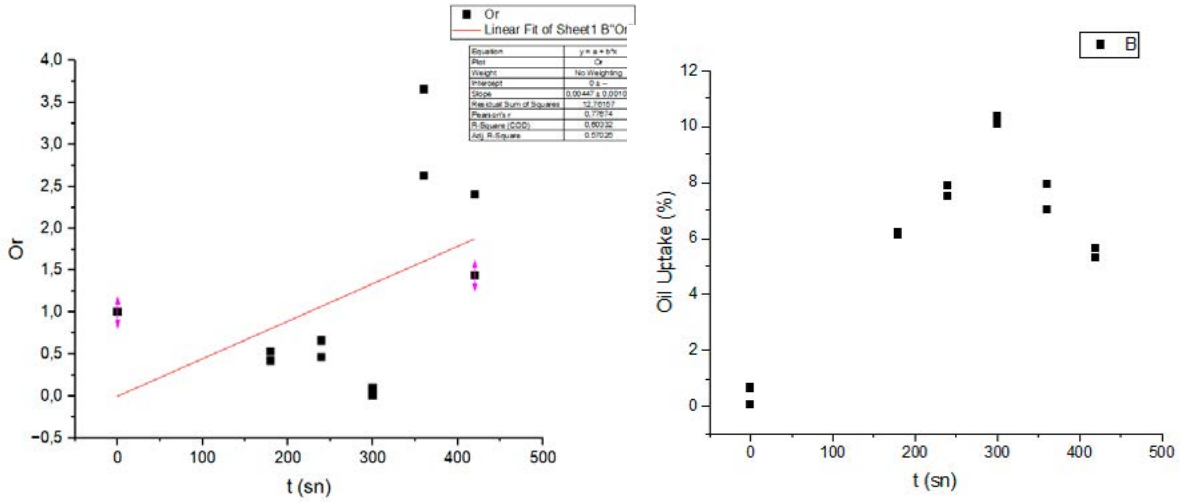


Figure V - The Or (Oil Ratio) graph for different t (time-sn) parameters at 170°C frying temperature (left). The oil absorption rates of potato samples at different time parameters at 170°C (right).

20%. Therefore, it was concluded that there was no observed carcinogenic effect due to frying in the oil. In the ANOVA (Analysis of Variance) and Post-hoc Tukey's HSD test conducted, significant differences in TPM analysis were observed only between frying times of 300 s and 420 s at 170°C ($P < 0.05$).

Prior to frying, oil confirmed to be devoid of BHA and BHT was fortified in accordance with Turkish Food Codex (TGK) guidelines stipulating maximum concentrations of 200 mg/L BHA and 100 mg/L BHT (Turkish Food Codex Food Additives Regulation, 2013). Oil samples were obtained under selected frying conditions of 170°C for 300 seconds. Post-frying analysis revealed BHA levels of 160 ± 17.76 mg/kg and BHT levels of 60.7 ± 10.73 mg/kg (Table V). The observed reduction in BHA and BHT concentrations in the oil post-frying suggests possible chemical degradation or migration into the food matrix due to transfer to potatoes during frying or chemical transformations occurring during the process. Furthermore, while the concentrations of BHA and BHT in the oil were quantitatively analyzed after the frying process, it is important to acknowledge a methodological limitation of this study: the absence of direct measurement of these antioxidants in the fried potato matrix. The observed reduction in oil-phase concentrations may result not only from migration into the food but also from oxidative degradation at high temperatures [47].

The analytical method employed (HPLC-DAD, AOAC 983.15) is validated for detecting non-oxidized BHA and BHT, but it does not allow the identification or quantification of potential oxidation products such as BHT-CHO, BHT-OH, or TBBQ [48], [49]. Consequently, the method may underestimate the total transformation or transfer of these compounds during frying.

To address this limitation, future studies should consider using advanced analytical techniques such as LC–MS/MS or GC–MS/MS, which have been successfully applied for the detection of synthetic antioxidants and their degradation products in complex food matrices [49], [50], [51]. Such techniques would provide a more comprehensive understanding of the fate of BHA and BHT during high-temperature processes.

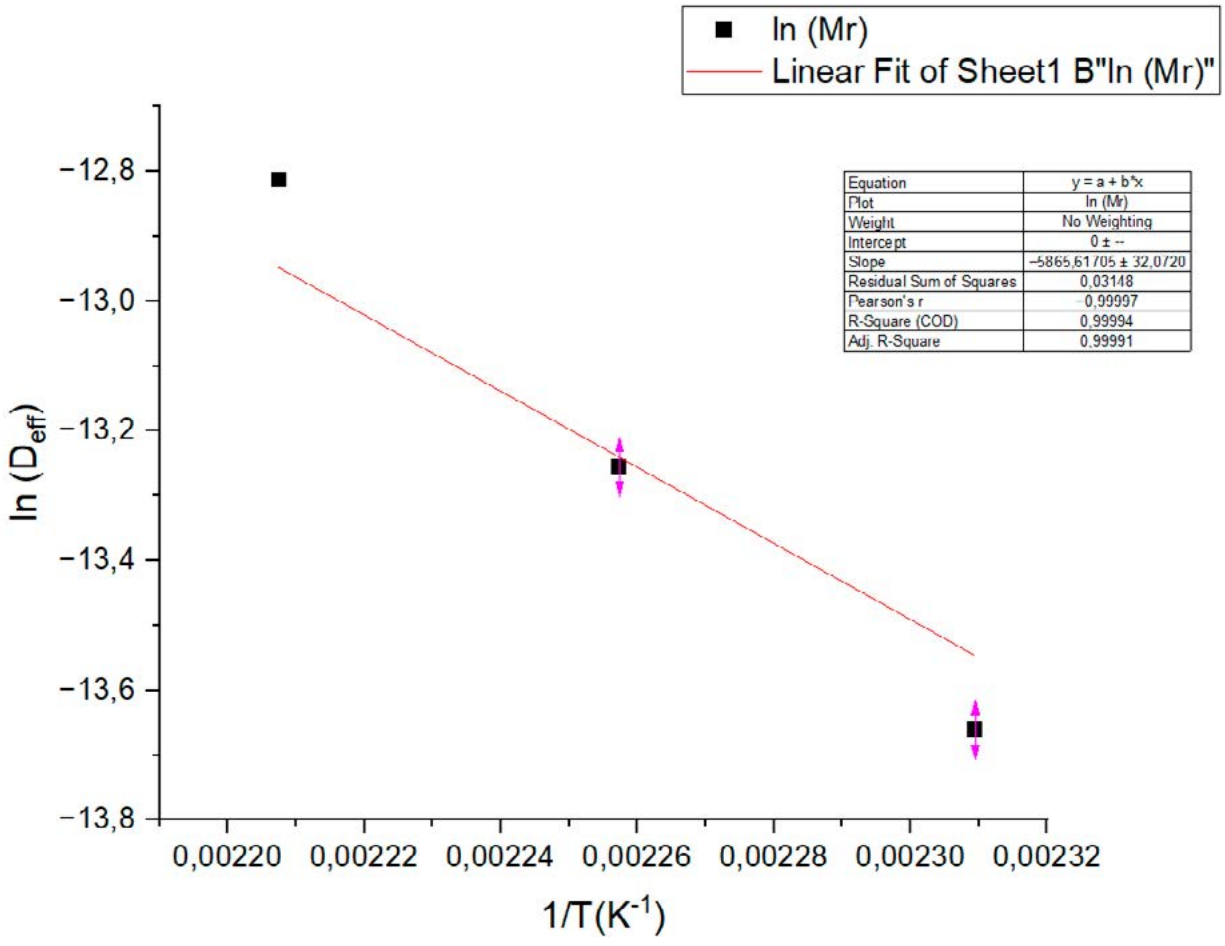


Figure IV - The ln(Deff) (ln (m²/min)) graph for different absolute temperatures (160, 170, 180°C + 273.15) against the frying process.

3.2. MATHEMATICAL MODELS

Using the moisture ratio (Mr) values calculated from the frying results, ln(Mr) graphs against time (t) were plotted for each temperature parameter using Fick's second law of diffusion, represented by Equation (3) (Fig III) (Equation (10)) [33]

$$\ln(Mr) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2} D_{eff} \cdot t\right) = \ln(a) + (-k \cdot t) \quad (10)$$

The slopes of the equations represent the rate constant k (min–1). Using Newton's semi-empirical model, represented by Equation (4), and the k values for each temperature parameter were calculated as shown in Table VI Using Equation (5), the effective moisture diffusivity (D_{eff}, m^2/min) for each temperature parameter was calculated [34].

In a study, the D_{eff} values for potato slices deep-fried at 150 and 180°C were found to be 9.86 ± 0.57 × 10–9 m_2/s and 1.72 ± 0.02 × 10–8 m_2/s, respectively. Considering the difference in the shape of our potato samples, this difference is reasonable [31].

Using Equation (6) and the plot in Figure IV, the activation energy (Ea, kJ/mol) for the entire frying process was calculated. Here, R represents the universal gas constant (8.31451 J/mol/K), and D0 is the pre-exponential factor in the Arrhenius equation (m^2/s) [33]. All calculated values for different temperature parameters are presented in Table VI.

The same calculations were performed for oil absorption at 170°C. According to Equation (7), and using Figure V, Mr was updated as O_r (Oil ratio, dimensionless). The equilibrium oil content (O_{re}) was assumed to be the maximum oil absorption.

Using Equation (5) and Newton's semi-empirical model, represented by Equation (4). With the help of Fig V, k_o (rate constant for oil absorption, min–1 was calculated as -0.0012 min-1. Subsequently, using Equation (9), the effective oil diffusivity ($D_{eff,o}$, m^2/min) for oil samples fried at 170°C was calculated as 2.92x10-7 m^2/min.

Table VI - Kinetic parameters for moisture loss at different temperature parameters

Temperature (°C)	K (min^{-1})	D_{eff} (m^2/min)	E_a (kJ/mol)
160	-0.002	$1.16x10^{-6}$	$4,87x10^4$
170	-0.0042	$1.75x10^{-6}$	
180	-0.0083	$2.72x10^{-6}$	

4. CONCLUSION

The study focused on the consumer-preferred sensory qualities of fried potatoes, specifically colour and texture, evaluating various frying parameters. It was determined that, at a constant temperature of 170°C, the optimal frying duration for sensory preference was 300 seconds. Across different frying durations, no adverse texture formation was observed, and colour changes in the fried potatoes were consistent with expectations, unaffected by the addition of BHA and BHT to the frying oil.

Examining peroxide values as an indicator of oil oxidation, longer frying durations were correlated with decreased peroxide levels. Analysis of free fatty acids, a marker of oxidation, showed no increase during frying; in fact, samples with different frying durations had lower free fatty acid content compared to the control group, suggesting that BHA and BHT may have stabilized the oil against oxidation.

Evaluation of total polar materials (%TPM) in frying oils, known for their carcinogenic potential above 25%, revealed that all durations (180s – 240s – 300s – 360s – 420s) at 170°C remained below this threshold, indicating no significant risk from TPM formation due to frying.

Considering all analyses, including moisture content and oil composition changes pre- and post-frying, it was found that, while BHA and BHT effectively reduced peroxide content in the oil, their impact beyond this was minimal. The estimated intake of BHA and BHT from consuming one portion of fried potatoes was within safe limits based on regulatory standards.

In conclusion, due to potential health risks associated with synthetic antioxidants like BHA and BHT, it is recommended that natural alternatives be explored. This study contributes valuable insights into the effects of synthetic antioxidants in food processing and suggests further research in order to better understand their implications. However, a methodological limitation of this study is the exclusive quantification of BHA and BHT in the oil phase. The possible migration of these compounds into the food matrix and their oxidative degradation during frying were not directly analyzed. Future research should focus on advanced analytical approaches such as LC-MS/MS or GC-MS/MS to quantify both the parent compounds and their potential degradation products within the food, providing a more comprehensive risk assessment.

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