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French Fries' Color and Frying Process in Relation to Used Plant Oils

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Abstract: Fast-food establishments today often sell fried food without proper control over the frying oil, and french fries are a prime example. Neglecting the maintenance of frying oil can lead to decreased taste, health concerns, and operational inefficiencies. The following plant oils were used in the frying process: rapeseed, sunflower, and palm oil. The degree of frying was measured by the total polar meter (TPM), until the achievement of 24%. To accurately assess the color characteristics of the french fry samples, Minolta CM 2600d color measurement instrument was used. Statistically significant differences were observed between some color parameters (L, a, b, C, and h) and TPM values. The following correlations were observed: 0.530 was obtained for TPM and h (hue angle) in french fries fried in palm oil; negative correlation (-0.214) between TPM and L (lightness) was obtained in french fries fried in rapeseed oil. While we have observed certain correlations from our experimental data, it is important to note that the color of french fries may not be the sole determinant of fried oil quality. Other external factors, such as temperature, chemical composition, and potato cultivar, can also significantly influence the color of french fries.

Keywords: processes in rapeseed oil; sunflower oil; palm oil; frying process; total polar material; correlation

1. Introduction

One of the most common ways for food preparation today is deep-fat frying. Immersion of food pieces in the hot vegetable oil gives them a nice golden color, crispy texture, and pleasant taste [1]. The main goal during that way of food preparation is to form the crisp crust using the high temperatures (170–190 °C) and to keep the flavors and juices inside [2]. In many nations, the bulk of potato crop production is used in processing channels, making potatoes (*Solanum tuberosum* L.) an essential staple food required to fulfill the needs of a growing worldwide population [3].

French fries can be considered as the main representative among the fried foods today. It is estimated that more than 30% of all processed potatoes go to french fries in the US [4]. The frying process influences the physical, chemical, and sensory properties of fried food [2]. After a final deep-fat frying phase, french fries (also known as chips or fries), either fresh or pre-frozen, are frequently produced industrially. Exposure studies have shown that french fries are a significant dietary source of the probable human carcinogen acrylamide, which is produced during this procedure [5].

Since it is a practice to use the same oil in the repeated process, various undesirable reactions occur in the oil as well [6]. Frying at high temperatures induces the reactions of hydrolysis, thermal degradation, oxidation, and polymerization [7]. The most reliable way

for the determination of stability and quality of frying oils during food preparation is the measurement of total polar matter (TPM). Those polar compounds are mainly dimers and polymers of triglycerides formed in oil at high temperatures [8]. The disposal of frying oil is recommended when the level of TPM reaches 24% (for US, Germany, and France) [9]. It should be emphasized that many fast foods do not control the quality, such as TPM level, of used oils [10]. According to the previous literature data, it can be stated that the main sign for determining how fast frying oil is degrading is the growth of TPM [11].

One of the major sensory characteristics of fried french fries that have impact on consumers' acceptance is the color [12]. Formation of color on french fries' surface during frying is caused by a Maillard reaction: interactions between amino acids and reducing sugars. The final color of the fries' surface is influenced by frying temperature and duration and frying medium [1,4].

The measurement and characterization of the french fries' color can be done with ease and accuracy using an instrumental method that employs a colorimeter with L*a*b* colorimetric parameters [13].

By instrumentally obtaining values of parameters L (lightness), a (redness: green to red), b (yellowness: blue to yellow), C (chroma value, saturation), and h (hue angle, color angle), it is possible to objectively track eventual changes in the color of french fries fried in oils in different stages of degradation [14,15].

Literature findings are limited to the measurements of the color of french fries in differently treated fresh oil [2] or measurements after a certain number of frying cycles with no association with TPM% in the oil [16,17]. A significant change of oil color during repeated frying was recorded [18], but there is a lack of data about its effect on fries' color. The objective of the study was to investigate the relationship between the color characteristics of french fries and the quality of frying oil, as measured by the total polar meter (TPM) using different plant oils (rapeseed, sunflower, and palm oil) in the frying process. Potential industrial applications include improving quality control in fast-food establishments, optimizing frying processes, and selecting suitable frying oils to enhance the overall quality and safety of french fries.

2. Materials and Methods

Samples

For the frying purposes, the french fries (Hearty Food Co., Tesco, Czech Republic) were purchased in the local supermarket. Rapeseed, sunflower, and palm oils (the most often used frying oils in the Czech Republic) were chosen for use as frying mediums. The rapeseed and sunflower oils originated from the Czech Republic and the palm oil was packed in Austria.

Frying process

An FR 2035 deep-fat fryer (Concept, Choceň, Czech Republic) was used for the frying experiments. Frying batches consisted of 100 g of frozen french fries that were fried in about 3.3 L of oil at an average temperature of 175 °C. Each cycle consisted of a 5-minute frying sequence, draining in the frying basket for 1 min, and oil stabilization time of 4 min prior to the TPM measurements. TPM values were recorded by a Testo 270 TPM meter (Testo SE & Co. KGaA, Titisee–Neustadt, Germany). Samples of fried fries were taken for the color measurements after 3 cycles of frying and, further, when the TPM reached values of 10, 15, 20, and 24%. Sample batches and their abbreviations are presented in Table 1. The frying vessel was refilled with the necessary amount of oil each time the level of oil in it dropped below the minimum mark.

Color measurement

Color measurements of the french fry samples were carried out using a Minolta CM 2600d and Spectra Magic 3.61 color data software (Konica Minolta, Tokyo, Japan). A total of 50 measurements were performed for each group of samples. The color values were ex-pressed using the CIELab color space as L (lightness), a (redness/greenness), and b

(yellowness/blueness). C (chroma) and h (hue) values were internally calculated by the instrument (C = (a2 + b2)1/2 and h = arctan (b/a) [19].

Table 1. Description of french fries' sample abbreviations and corresponding oil TPM% levels (R—rapeseed oil fried samples; S—sunflower oil fried samples; P—palm oil dried samples).

Sample	Abbreviation	Oil TPM Level (%)		
		R	S	P
Sample 1 batch	1R/1S/1P	6.5	9	6.5
Sample 2 batch	2R/2S/2P	10	10	10
Sample 3 batch	3R/3S/3P	15	15	15
Sample 4 batch	4R/4S/4P	20	20	20
Sample 5 batch	5R/5S/5P	24	24	24

Statistics

Obtained results are presented in the tables, including the mean values and standard deviations. The color was measured 50 times for each parameter in each batch. Statistical analysis was done using the one-way ANOVA for the determination of differences with-in the sample group (rapeseed-, sunflower-, and palm-oil-fried fries). Pearson correlation analysis was done for the observation of associations between the TPM% and color values. The interpretation of correlation coefficients was undertaken as follows: 0.00–0.10—negligible correlation; 0.10–0.39—weak correlation; 0.40–0.69—moderate correlation; 0.70–0.89—strong correlation; 0.90–1.00—very strong correlation [20]. For discussion of the results, the square of the correlation coefficient (coefficient of determination) was used as the proportion of variance once that was accounted for by the other. IBM SPSS software was used for conducting statistical analysis.

3. Results and Discussion

The impact of french fry frying cycles and the number on the TPM value of rapeseed, sunflower, and palm oil are presented in Figure 1. The number of frying cycles needed to reach 24% TPM was the lowest in sunflower oil (80 cycles), followed by rapeseed oil (84 cycles) and palm oil with the highest number after 94 cycles. Palm oil stands out as the most stable among the three oils in our experiment, primarily because of its high content of saturated fatty acids, especially palmitic and stearic fatty acids. This composition leads to a significantly slower rate of deterioration when compared to the other oils studied. This stability makes palm oil a favored choice in the food industry, particularly for products requiring extended shelf life, as it helps maintain flavor and texture over time [21].
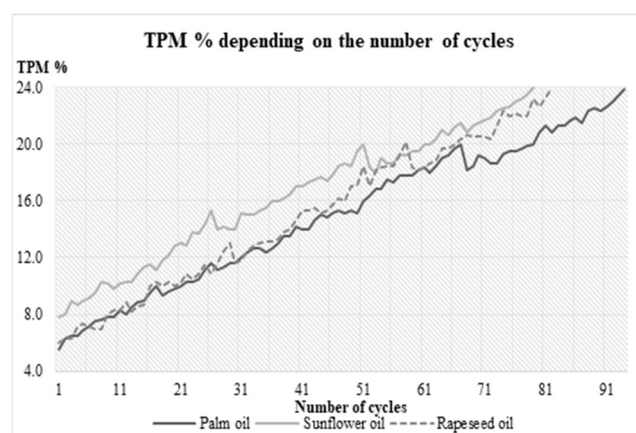

Figure 1. Impact of number of frying cycles on TPM value.

In addition to the price, because of its desirable properties, palm oil has emerged as the most widely utilized frying oil [22]. Furthermore, palm oil imparts a waxy or greasy flavor to the products, particularly in colder climates. The cause is the high melting point of palm oil, which is 38 °C and higher than the average body temperature [23]. Otherwise, in addition to higher saturated fatty acids content (mainly palmitic fatty acid), palm oil has a high smoke point of around 230 °C [24].

On the other hand, rapeseed and sunflower oil contain mainly unsaturated fatty acids, with negligible amounts of polyunsaturated fatty acids (PUFA). Rapeseed oil exhibits a polyunsaturated fatty acid (PUFA) content of around 20%, while sunflower oil PUFA content reaches up to 71% [25,26]. The accelerated degradation rate and attainment of the fastest critical point in sunflower oil, characterized by its high polyunsaturated fatty acid (PUFA) content, specifically reaching up to 24% TPM (total polar materials), can be attributed to the inherent susceptibility of PUFA to rapid degradation at elevated temperatures. The thermally induced oxidative breakdown of PUFA molecules is facilitated by their greater number of double bonds, making them more prone to oxidation compared to other types of fatty acids present in oils [27].

As a result of the substantial abundance of polyunsaturated fatty acids (PUFA) found within sunflower oil, it becomes particularly susceptible to degradation when exposed to elevated temperatures. This heightened vulnerability to deterioration underscores the importance of proper storage and handling practices for this type of cooking oil, especially in circumstances where higher cooking temperatures are employed [27].

In a related study conducted by Enríquez-Fernández and colleagues in 2019, an experiment akin to ours was carried out to assess the stability of palm olein and a blend comprising palm olein and canola oil. In this investigation, the researchers subjected these oils to a rigorous frying experiment involving the preparation of french fries. Over a span of 12.9 h of continuous frying, the researchers observed results in terms of the total polar matter (TPM%) values, which are indicative of oil degradation and deterioration. The findings of this study revealed that palm olein, which is primarily derived from palm oil, exhibited a TPM% value of 12%. Conversely, the palm olein and canola oil blend demonstrated a slightly lower TPM% value of 11.5%. These results suggest that both oils, in isolation and as a blend, have commendable stability during prolonged frying, further highlighting the remarkable resilience of palm-derived oils in high-temperature cooking scenarios [17].

This research by Enríquez-Fernández and colleagues corroborates our own findings regarding the stability of palm oil. It underscores the suitability of palm-based oils for frying applications, particularly when blended with other oils like canola, as it enhances their performance and extends their usability. Such insights are invaluable to the food industry, where the maintenance of oil quality during frying is crucial not only for flavor and texture but also for cost-effectiveness and food safety considerations.

In the context of the current research investigation, it was observed that the duration required to attain a 24% total polar matter (TPM) concentration averaged approximately 16 h. This finding provides valuable insights into the temporal dynamics of TPM accumulation and emphasizes the need for a thorough understanding of these time-dependent processes in order to make informed decisions and optimizations in various relevant fields or applications. Experiments of this kind underscore the intricate and multidimensional nature of the frying processes implicated in the production of french fries. They illuminate the complex interplay of numerous variables, including temperature, oil composition, moisture content, and frying duration, all of which wield a profound influence on the final attributes of this culinary product. The instrumental values for L, a, b, C, and h color parameters are presented in Tables 1–4.

Table 2. Color values of french fries fried in rapeseed oil in different stages of frying (different lowercase letters (a, b, c, and d) indicate statistically significant differences ($p < 0.05$) between rows; the results are presented as the mean values ± standard deviation).

Sample	L	a	b	C	h
1R	67.73 ± 3.41 [a]	0.74 ± 0.93 [a]	28.87 ± 4.74 [a]	28.89 ± 4.76 [a]	88.68 ± 1.63 [a]
2R	56.22 ± 7.58 [b]	6.93 ± 3.60 [b]	33.14 ± 4.99 [b]	34.04 ± 5.00 [b]	78.19 ± 6.08 [b]
3R	61.36 ± 3.88 [c]	5.20 ± 2.78 [b]	33.24 ± 3.96 [b]	33.74 ± 4.07 [b]	81.22 ± 4.46 [c]
4R	58.67 ± 4.86 [bd]	5.53 ± 2.57 [b]	32.96 ± 4.11 [b]	33.51 ± 4.21 [b]	80.54 ± 4.06 [bc]
5R	60.66 ± 8.31 [cd]	3.06 ± 3.00 [c]	29.56 ± 3.80 [a]	29.85 ± 3.93 [a]	84.22 ± 5.39 [d]

Table 3. Color values of french fries fried in sunflower oil in different stages of frying (different lowercase letters (a, b, c, and d) indicate statistically significant differences ($p < 0.05$) within the column; the results are presented as the mean values ± standard deviation).

Sample	L	a	b	C	h
1S	58.80 ± 7.30	2.16 ± 2.32 [ab]	27.03 ± 4.63 [ad]	27.20 ± 4.69 [ad]	85.60 ± 4.98 [ab]
2S	60.20 ± 4.97	2.71 ± 3.06 [a]	29.06 ± 3.88 [ab]	29.32 ± 4.07 [ab]	85.02 ± 5.36 [a]
3S	60.15 ± 7.62	0.92 ± 3.35 [bc]	31.05 ± 4.62 [bc]	31.22 ± 4.69 [bc]	88.61 ± 5.95 [bc]
4S	58.91 ± 5.75	0.29 ± 1.71 [c]	31.80 ± 4.34 [c]	31.85 ± 4.33 [c]	89.49 ± 3.21 [c]
5S	60.03 ± 6.22	0.60 ± 1.45 [c]	26.31 ± 4.27 [d]	26.35 ± 4.28 [d]	88.79 ± 3.18 [c]

Table 4. Color values of french fries fried in palm oil in different stages of frying (different lowercase letters (a, b, c, and d) indicate statistically significant differences ($p < 0.05$) within the column; the results are presented as the mean values ± standard deviation).

Sample	L	a	b	C	h
1P	66.82 ± 4.20 [ab]	3.51 ± 2.67 [a]	29.20 ± 4.29 [a]	29.51 ± 4.44 [a]	83.46 ± 4.70 [a]
2P	67.88 ± 4.84 [a]	3.48 ± 2.77 [a]	33.67 ± 3.57 [b]	33.94 ± 3.73 [b]	84.26 ± 4.19 [a]
3P	64.63 ± 5.13 [bc]	2.63 ± 1.91 [ab]	34.08 ± 4.98 [b]	34.23 ± 5.00 [b]	85.58 ± 3.22 [ab]
4P	64.13 ± 5.82 [b]	1.65 ± 3.07 [b]	34.92 ± 3.70 [b]	35.09 ± 3.68 [b]	87.33 ± 5.10 [b]
5P	67.46 ± 5.64 [ac]	−0.65 ± 1.80 [c]	35.56 ± 4.18 [b]	35.61 ± 4.17 [b]	91.11 ± 2.95 [c]

The coloration of french fries is a multifaceted phenomenon influenced by several key variables. Among these variables, temperature, frying time, and the thickness of the potato slices stand out as crucial determinants of the final visual appeal of this popular food commodity. Temperature plays a pivotal role by initiating the Maillard reaction, which is responsible for browning and flavor development during frying. The precise temperature must be carefully controlled to achieve the desired golden-brown color while avoiding undercooking or over-browning. Frying time is equally important, as it impacts the extent of the Maillard reaction and caramelization, with longer times resulting in deeper coloration. Lastly, the thickness of potato slices affects cooking time, and achieving the right balance is essential for ensuring that french fries boast a uniform, appetizing appearance [28]. The Maillard reaction takes place during frying and involves carbohydrate and aldehyde reactions with amino molecules. When potatoes are fried, the carbon element in them leaches into the oil, giving fried dishes their distinctively black hue. Fat contains unsaturated fatty acids that are subject to heat polymerization and oxidation, which produces nonvolatile breakdown products. Deep frying produces pigments, such as nonvolatile decomposition products and carbonyl compounds, as a byproduct of the oxidation and breakdown of fatty acids, giving the oil its distinctive dark brown hue [29].

The frying of french fries in rapeseed oil resulted in the lowering of the lightness value (*L*). The mean value for lightness was 67.73 for samples fried in oil that had 6.5% TPM (1R) and 60.66 for samples fried in oil with the highest TPM level (5R). A significant ($p < 0.05$) negative correlation was obtained between TPM% and *L* parameters, though the correlation can be described as weak: coefficient equals −0.214 (Table 5). The square of the correlation coefficient (coefficient of determination, R^2) was 0.046, meaning that TPM accounted for 4.6% in the variance of the *L* parameter of rapeseed-oil-fried french fries. On the other hand,

no significant ($p > 0.05$) correlation was found between these parameters for fries fried in other two oils (sunflower and palm). The lightness of samples fried in sunflower oil ranged from 58.80 (1S)–60.20 (2S), and no significant difference was found between all samples in the mentioned group.

Table 5. Correlation of TPM% with some measured french fries color values (r—correlation coefficient; R^2—square of correlation coefficient (coefficient of determination); * significant correlation ($p < 0.05$).

Rapeseed-Oil-Fried Fries			Sunflower-Oil-Fried Fries			Palm-Oil-Fried Fries		
Relation	**r**	**R^2**	**Relation**	**r**	**R^2**	**Relation**	**r**	**R^2**
TPM%/L	−0.214 *	0.046	TPM%/L	0.012	0.000	TPM%/L	−0.075	0.006
TPM%/a	0.110	0.012	TPM%/a	−0.312 *	0.097	TPM%/a	−0.495 *	0.245
TPM%/b	0.027	0.001	TPM%/b	0.008	0.000	TPM%/b	0.410 *	0.168
TPM%/C	0.028	0.001	TPM%/C	−0.007	0.000	TPM%/C	0.390 *	0.152
TPM%/h	−0.137 *	0.019	TPM%/h	0.317 *	0.100	TPM%/h	0.530 *	0.281

　　　In a prior study, the lowest changes in color were also observed when sunflower oil was employed in the frying process. Sunflower oil, like rapeseed oil, is known for its impact on color stability during frying. This is attributed to its relatively high smoke point and excellent resistance to oxidative degradation, factors that contribute to a more controlled and gradual browning of the food being fried. The phenomenon of minimal color changes when sunflower oil is utilized underscores the importance of oil selection in culinary applications, especially when visual appeal is a key consideration [30].

　　　No significant ($p > 0.05$) difference in *L* color value was obtained between measurements on the 1P and 5P samples (palm-oil-fried samples). In the investigation conducted by Li et al. (2020), the lightness values of potato strips that underwent frying in different oils were documented. According to their findings, the lightness values recorded for the potato strips fried in rapeseed, sunflower, and palm oil were 66.05, 58.96, and 58.49, respectively. Furthermore, in the study conducted by Enríquez-Fernández and colleagues in 2019, an exploration of the color transformation in french fries was undertaken, particularly in the context of repeated frying cycles. Through the examination of various color parameters, their research provided valuable insights into how multiple rounds of frying affect the visual attributes of french fries [17]. Their results indicate that there was no statistically significant ($p > 0.05$) change in *L* value in the samples fried in palm olein/canola oil after 40 cycles and after 200 frying cycles. The same experiment with palm olein oil revealed an increase in *L* value from 58.15 (recorded in fries fried in oil after 40 cycles) to 63.06 (recorded in fries fried in oil after 200 cycles). The *a* color parameter showed no significant ($p > 0.05$) correlation in respect to change in the TPM% of rapeseed oil. Sample 1R had the lowest mean value (0.74), while the highest mean value (6.93) was recorded in the 2R sample. Oppositely, the color of fries fried in sunflower and palm showed a decrease in the *a* parameter with an increase in TPM% with correlation coefficients of 0.312 (weak correlation, $R^2 = 0.097$) and 0.495 (moderate correlation, $R^2 = 0.245$), respectively (Table 5). Samples fried in sunflower oil had an *a* value that ranged from 0.60 to 2.71, and the ones fried in palm oil ranged from −0.65 to 3.51. The measured *a* value in the work of Enríquez-Fernández et al. (2019) [17] ranged from 1.66–2.48 for french fries fried in palm olein/canola blend and from −0.55–2.91 for fries fried in palm olein oil.

　　　Among all used oils, only frying in palm oil caused a significant change of the *b* color parameter of fries with the increase in the TPM% parameter. A positive correlation coefficient of 0.410 (moderate correlation, $R^2 = 0.168$) was obtained between these two parameters, and the *b* value ranged from 29.20 to 35.56. The *b* value in the work of Enríquez-Fernández et al. (2019) [17] ranged from 20.91 to 31.97.

　　　C (chroma) and *h* (hue angle) are the parameters that can be obtained from the *a* and *b* color values. Chroma ranged from 28.89 to 34.04 in rapeseed oil, from 26.35 to 31.85 in sunflower, and from 29.51 to 35.61 in palm-oil-fried samples. In the work of Kirmaci and

Singh (2018) [31], the mean chroma value for fried potato strips was 36.7. The hue angle (*h*) values for french fries fried in rapeseed oil ranged from 88.68 for the 1R sample as the maximum value to 78.19 for the 2R sample as the minimum value. A small but statistically significant ($p < 0.05$) negative correlation coefficient of -0.137 was obtained between the TPM% and *C* values (Table 5). Oppositely, positive correlation coefficients of 0.317 and 0.530 were obtained for those parameters in sunflower and palm oil, respectively. The *h* values ranged from 85.02 (2S) to 89.49 (4S) in sunflower-oil-fried fries and from 83.46 (1P) to 91.11 (5P) in palm-oil-fried fries.

In the research carried out by Kirmaci and Singh in 2018, a significant revelation emerged from their analysis of the mean hue value (h), which yielded an approximate value of 83. This particular value closely mirrored the 1P value observed in our own experimental study. This similarity between their findings and ours suggests a potential correlation between the hue characteristics identified in their work and the hue parameter identified in our investigation [31]. It suggests a potential correlation between the hue characteristics identified in their work and the hue parameter identified in our own investigation. Furthermore, this correlation emphasizes the importance of replicating and cross-referencing findings across different research endeavors. This highlights the importance of expanding upon established knowledge in order to acquire more profound insights into the complex realm of color analysis in both culinary and scientific research.

4. Conclusions

The study conducted revealed a noteworthy trend: oils containing fewer polyunsaturated and unsaturated fatty acids exhibited greater stability over the course of frying. This observation underscores the crucial role of fatty acid composition in determining oil stability during repeated frying cycles. Interestingly, the color analysis of the french fries did not unequivocally indicate the extent of oil deterioration that occurred after numerous frying cycles. This suggests that relying solely on visual cues, such as color changes, may not provide a complete assessment of frying oil quality. Of particular significance were the statistically significant ($p < 0.05$) correlations observed between TPM% and various color parameters (a, b, C, and h) in french fries fried in palm oil. These correlations highlighted the potential for color analysis to serve as a valuable indicator of frying oil degradation. Conversely, the minimal changes in the lightness parameter seen in sunflower oil samples suggest that this oil type exhibited the least impact from repeated frying cycles. While this study focused primarily on the color characteristics of french fries and their correlation with total polar matter (TPM) values, it is important to acknowledge that comprehensive assessments of frying oil quality may necessitate additional instrumental and chemical analyses. These supplementary methods can provide clearer and more comprehensive insights into the frying process and oil quality. The findings underscore the critical importance of monitoring frying oil quality, as the degree of total polar matter in oil may not be easily discernible by consumers or even producers based solely on visual cues like color changes. It is worth noting that this study, while shedding light on specific color-related aspects of frying oil quality, may not encompass all the factors that impact the overall quality of fried food. As such, further research and comprehensive assessments are necessary to gain a fuller understanding of the multifaceted nature of frying oil quality and its implications for fried food products.

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