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Review Paper / Derleme Makale

Physicochemical and Toxicological Changes in Foods and Frying Oils during Deep-Frying

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ABSTRACT

Deep frying is one of the most common processes used in food preparation to improve aroma, taste, crispness, and flavor characteristics. However, the simultaneous Maillard reactions, caramelization, and thermal decomposition of sugars occurring in the food and oil phases during frying, along with oxidation, hydrolysis, and polymerization processes in the oil, may trigger the formation of certain heat treatment contaminants, primarily acrylamide, nutritional losses in heat-sensitive components, increased energy density due to oil intake, and sensory quality defects (burnt/stale taste/odor, irregularities in texture and crispness). In addition, the gradual accumulation of total polar compounds (TPC/TPM) in frying oil, the increase in volatile oxidation products, and physical quality shifts such as increased viscosity, darkening of color, and a decrease in foaming and smoke points, limit the shelf life of the oil; make process control more difficult through fluctuations in heat transfer and cooking kinetics; weaken product standardization; and ultimately create a more negative risk profile in terms of food safety. Toxic compounds such as acrylamide and acrolein, which are formed as a result of polymerization, especially during frying, cause diseases such as cardiovascular disease, Alzheimer's disease, diabetes, and tumors. In this review, the physical, chemical, and nutritional changes occurring in the food-oil system during deep frying and their effects on human health were evaluated with the guidance of studies in the literature. The focus of the study was to consider all parameters (oil-food and other factors) together in the frying system. In addition, application suggestions were presented that could preserve food quality and pose the least risk in terms of health and nutrition during the frying process. Furthermore, it was aimed to increase consumer awareness about the possible health risks arising from excessive consumption of fried foods.

Keywords: Deep frying, Acrylamide, Lipid oxidation, Polar compounds, Food safety

Derin Yağda Kızartma Sırasında Gıdalar ve Kızartma Yağlarındaki Fizikokimyasal ve Toksikolojik Değişimler

ÖZ

Derin kızartma işlemi gıdaların hazırlanmasında, aroma, tat, gevreklik ve lezzet özelliklerinin geliştirilmesinde kullanılan en yaygın işlemlerden biridir. Ancak kızartma sırasında gıda ve yağ fazında eş zamanlı ilerleyen Maillard reaksiyonları, karamelizasyon ve şekerlerin termal bozunması ile yağda görülen oksidasyon, hidroliz ve polimerizasyon süreçleri; gıdada akrilamid başta olmak üzere bazı ısıl işlem kontaminantlarının oluşumunu, ısıya duyarlı bileşenlerde besinsel kayıpları, yağ alımına bağlı enerji yoğunluğunun artmasını ve duyusal kalite kusurlarını (yanık/bayat tat-koku, doku ve gevreklikte düzensizlik) tetikleyebilmektedir. Buna eşlik eden şekilde kızartma yağında toplam polar bileşiklerin (TPC/TPM) kademeli birikimi, uçucu oksidasyon ürünlerinin artışı ve viskozite yükselmesi, renk koyulaşması, köpürme ile dumanlanma noktasında düşüş gibi fiziksel kalite kaymaları yağın kullanım ömrünü sınırlandırmakta; ısı transferi ve pişme kinetiğindeki dalgalanmalar üzerinden proses kontrolünü güçleştirerek ürün standardizasyonunu zayıflatmakta ve nihayetinde gıda güvenliği açısından daha olumsuz bir risk profiline zemin hazırlamaktadır. Özellikle kızartma sırasında polimerizasyon sonucu oluşan akrilamid ve akrolein gibi toksik bileşikler kardiyovasküler, Alzheimer, diyabet, ve tümör gibi hastalıkların oluşumuna sebep olmaktadır. Bu çalışmada, derin kızartma sırasında gıda-yağ sisteminde meydana gelen fiziksel, kimyasal, besinsel değişiklikleri ve insan sağlığı üzerine olan etkileri literatürdeki çalışmalar rehberliğinde değerlendirilmiştir. Kızartma sisteminde tüm parametrelerin (yağ-gıda ve diğer faktörler) birlikte ele alınması çalışmanın odağını oluşturmuştur. Bununla birlikte kızartma işleminde gıda kalitesini koruyan, sağlık ve beslenme bakımından en az risk oluşturacak uygulama önerileri sunulmuştur. Ayrıca kızartılmış gıdaların aşırı tüketiminden kaynaklanan olası sağlık riskleri konusunda tüketici farkındalığının artırılması amaçlanmıştır.

Anahtar Kelimeler: Derin kızartma, Akrilamid, Lipit oksidasyonu, Polar bileşikler, Gıda güvenliği

INTRODUCTION

Deep frying is one of the most commonly used pre-treatments in food to improve color, aroma, taste, and flavor characteristics. It gives food a crispy texture, a dehydrated surface texture, and a soft internal structure, while also producing distinctive color and aroma profiles that cannot be achieved with other cooking methods [1]. The basic characteristics of the deep-frying process include high temperature, short time, and rapid heat transfer. However, it can also bring nutritional disadvantages such as increased fat intake and energy density, loss of heat-sensitive micronutrients and bioactive compounds, and the possible formation of process-induced contaminants under intense time-temperature conditions [2].

Frying is also defined as a process involving complex physicochemical reactions influenced simultaneously by numerous factors such as the composition of the food, the triglyceride profile of the oil, frying time, frying temperature, replenishment with fresh oil (rejuvenation), filtration, and cooling [2, 3]. Depending on the product and method applied, the frying process generally occurs at temperatures ranging from 160°C to 190°C for 2 to 4 minutes [4, 5]. As a natural consequence of conducting the process at high temperatures, numerous physicochemical reactions occur simultaneously in both the oil and the food matrix. Some of the chemical compounds formed during these reactions adversely affect human health and lead to a reduction in the biological value of the oil and food, as well as to chemical and biological food safety issues [6, 7]. The key parameters influencing these physicochemical reactions are identified as frying temperature and duration, the triglyceride composition of the oil, and the composition and geometry of the food material [8]. Therefore, the aim of this study is to systematically characterize the fundamental physicochemical changes occurring in both frying oil and the food matrix under controlled deep-frying conditions, and to identify the critical process parameters that govern quality degradation, nutrient losses, and the formation of potentially hazardous compounds. The changes that occur in foods and oils during frying are generally evaluated under two main categories [9].

CHANGES IN FOODS DURING DEEP FRYING

- Dehydration (water loss in food), cooking, and crust formation
- Fat absorption and increased fat content in food
- Volume reduction
- Starch gelatinization
- Protein denaturation and oxidation
- Non-enzymatic browning reactions (Maillard) and acrylamide formation in foods
- Changes in color, taste, and aroma

Among the primary physical changes occurring in foods during deep frying are oil absorption and simultaneous moisture loss through evaporation, which together result in a reduction in product volume. During this process, the high heat transfer capacity of the frying medium promotes desirable developments in the color, taste, and aroma of the food. Numerous factors influence oil absorption during frying (Figure 1).

Figure 1. The factors that affect oil absorption during frying [16]

These include the fatty acid composition and rheological behavior of the frying oil, frying temperature and duration, the chemical composition of the food being processed, pre-frying treatments, the microscopic structure of the food, and post-frying oil removal techniques [4, 10-12]. In a study conducted by Li et al. [13], it was reported that foods subjected to pre-frying and freezing exhibited lower final oil uptake. The same study found that high-oleic sunflower oil resulted in lower oil absorption, whereas oils with a high proportion of polyunsaturated fatty acids (PUFAs), such as soybean and corn oils, exhibited higher oil uptake, particularly during pre-frying [15]. In another study by Bouchon et al. [14], the oil present in fried potatoes was classified into three distinct categories:

structural oil, representing oil retained within the food matrix; surface oil absorbed during frying; and oil absorbed into the food during post-frying cooling, in addition to oil remaining on the product surface.

One of the most important compounds formed in foods during frying that poses a food safety risk is acrylamide. In foods, acrylamide is generated as a result of thermal processes such as frying, baking, and grilling, whereas it has not been detected in raw or boiled foods. Acrylamide formation occurs particularly in carbohydrate-rich foods during heat treatment above 120°C, at levels ranging from 100 to 4000 µg/kg, while lower amounts (<100 µg/kg) have been detected in protein-rich foods [17]. Multiple mechanisms have been reported to be involved in acrylamide formation during the frying process (Figure 2) [18]. However, the primary mechanism responsible for acrylamide formation is the non-enzymatic browning (Maillard) reaction, which begins when the frying temperature exceeds 120°C. In this reaction, the amino group of proteins reacts with the carbonyl group of reducing sugars, leading to the formation of a toxic and carcinogenic compound [19-23]. In studies conducted by Yaylayan and Stadler [24], fructose was identified as the most effective sugar in the formation of acrylamide through the reaction of asparagine with reducing sugars [24-26]. Fructose, a monosaccharide, possesses reducing properties. The Maillard reaction, a chemical reaction between amino acids and reducing sugars responsible for the browning of foods during frying and cooking, also plays a significant role in this process.

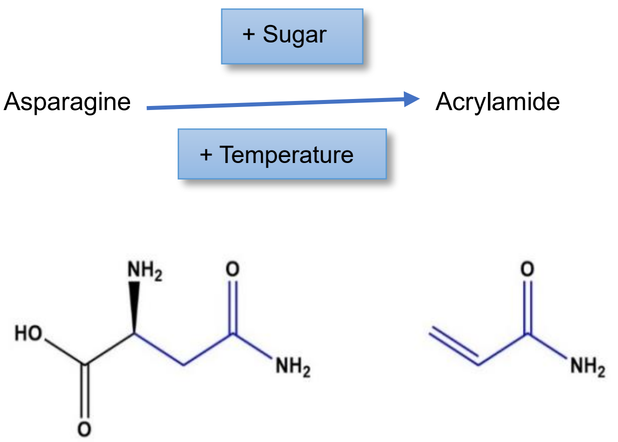

Figure 2. Acrylamide formation reaction in foods during frying [18]

In the study conducted by Nizamlıoglu and Nas [27] a linear relationship was reported between the concentration of free asparagine in the food matrix and the acrylamide concentration formed during frying, with the main skeleton of the acrylamide molecule being derived from the asparagine amino acid, as illustrated in Figure 2 [18]. In addition to asparagine, trace amounts of acrylamide have been found to originate from other amino acids, including glutamine, cystine, arginine, methionine, and aspartic acid [26, 28]. The primary factors influencing acrylamide formation include the composition of the food (carbohydrates, proteins, pH), water activity, volume-to-surface area ratio, frying temperature, and frying duration [29]. Furthermore, the degree of unsaturation of the frying oil has been reported to influence acrylamide formation [22]. In the same study, a linear correlation was observed between acrylamide formation and frying time, whereas no similar correlation was found with frying temperature. According to Lee et al. [29]. acrylamide formation is also affected by the frying method, as well as by oxidation and polymerization reactions occurring during the process [30].

Becalski et al. [30] reported that the use of olive oil in frying resulted in higher acrylamide formation compared to corn oil and other vegetable oils [31]. Similarly, frying with palm olein oil was found to produce higher acrylamide levels than other oils [26]. This increased acrylamide formation in olive oil and palm olein is thought to result from the transfer of compounds such as carbohydrates and proteins from the fruit source into the oil during extraction. In a study conducted by Mottram et al. [19] the reaction between asparagine and reducing sugars was found to yield the highest acrylamide concentration at a frying temperature of 175°C, whereas higher temperatures led to a decrease in acrylamide content. This reduction has been attributed to the degradation and polymerization of the acrylamide molecule at temperatures above 175°C [19-32]. In this context, the application of vacuum-assisted low-temperature and short-term high-temperature frying has been proposed as a critical processing step to minimize acrylamide formation in foods [33,34]. The potential risks associated with acrylamide have drawn significant attention in health-related research. This compound is considered highly toxic, with experimental animal studies demonstrating its genotoxic and neurotoxic effects, as well as its ability to induce cancer in multiple organs [33-36]. Furthermore, studies conducted on experimental animals have revealed that acrylamide increases insulin resistance and contributes to the development of hypertension, obesity, and cardiovascular diseases [25, 37-41]. To mitigate acrylamide formation during the frying process, several strategies have been recommended, including optimization of frying time, careful selection of raw materials, and the implementation of pre-frying treatments such as washing, drying, shaping, blanching, marinating, coating, pre-cooking, seasoning, and the preference for foods with low carbohydrate content [42].

It has been reported that high levels of acrylamide can form in foods with high protein and carbohydrate content when subjected to prolonged high-temperature processing methods such as roasting and deep frying, posing a potential risk to food safety [43]. Following the declaration by the European Food Safety Authority (EFSA) that acrylamide is a carcinogenic compound, the European Commission adopted Commission Regulation (EU) 2017/2158 in November 2017, which entered into force in April 2018, establishing measures to limit acrylamide levels in food. According to this regulation, the daily intake for humans should not exceed 0.012 mg/kg body weight/day [44]. Among the harmful compounds formed in foods during frying as a result of the Maillard reaction are furan and its derivatives. These compounds are produced through complex reactions induced by high-temperature processing, including the degradation of carbohydrates or amino acids (such as serine and cysteine), oxidation of ascorbic acid, and oxidation of polyunsaturated fatty acids [45]. During frying, depending on the composition of the food and the frying conditions, a certain amount of 5-hydroxymethylfurfural (HMF) is generated, which subsequently migrates into the frying oil. With repeated frying, the accumulation of HMF in the oil increases, leading to greater transfer into the food [46].

According to a report prepared by the European Food Safety Authority (EFSA), furan compounds exhibit hepatotoxic and nephrotoxic effects and have been shown to cause genotoxicity [47]. In recent years, healthier frying equipment such as air fryers has been introduced. In these devices, the frying process is performed using high-speed hot air circulation instead of immersing the food in oil [48]. This method has been shown to reduce acrylamide formation while preserving the texture, color, flavor, and nutritional value of the food, and simultaneously lowering the total caloric intake [28].

CHANGES IN OILS DURING DEEP FRYING

In the frying process, the triglyceride composition of the oil is the most critical parameter. While temperature and duration are the primary factors influencing oil degradation during frying, the concentration of degradation products and the specific triglyceride profile of the oil also play a decisive role [49]. The composition and moisture content of the food, as well as the oil's contact surface with air, have been reported to contribute to oil degradation, exerting a synergistic effect on the occurrence of oxidation and polymerization reactions [50]. As a result of these reactions, numerous volatile and non-volatile compounds are formed in frying oils, many of which pose potential risks to food safety [51]. Changes occurring in frying oils are generally evaluated under two main categories.

Physical Changes

Deep frying progressively degrades the frying medium via oxidation, hydrolysis, and thermal/oxidative polymerization, generating polar and high-molecular-weight products that measurably shift the oil's bulk and interfacial behavior. As these degradation products accumulate, frying oils typically darken, become more viscous, foam more readily, and exhibit a reduced smoke point, consistent with the build-up of surface-active species and increasing acidity/free fatty acids [52,53] The viscosity change is also closely linked to total polar materials: in a recent dataset spanning 0.1–29.3% TPM, viscosity increased from ~85 to ~150 cP as TPM rose, underscoring TPM as a practical proxy for handling behavior and heat–mass transfer resistance [54]. However, viscosity is strongly temperature-dependent; differences evident at room temperature may become negligible above ~60 °C, so interpretation must match the measurement temperature window [55] Interfacially, surface tension decreases mainly with temperature and can be comparatively insensitive to oil quality, whereas wettability/contact-angle behavior can shift with degradation due to the formation of surface-active polar compounds [55]. Finally, for process modeling and mechanistic tracking, thermophysical properties such as specific heat capacity can be quantified by modulated DSC across a broad temperature range and related to compositional indices (e.g., TPC/polymers) as frying progresses [56]

Chemical (Changes) Reactions

During frying, the chemical stability of oils has long been shown to deteriorate as a function of time-temperature history and food-oil interactions. Early work on thermally processed lipids emphasized that heating initiates multiple, concurrent pathways in fats and oils, leading to quality loss and the accumulation of degradation products [57]. More recent evidence under practical frying conditions likewise reports measurable increases in free fatty acidity and oxidative deterioration as frying proceeds, underscoring the progressive nature of oil breakdown [51]. Within this context, three primary chemical degradation reactions are commonly recognized in frying oils: hydrolysis, oxidation, and polymerization, which occur simultaneously and interactively, collectively driving both the sensory deterioration and the safety-relevant chemical changes observed in used frying oils [51,57]. The harmful compounds formed as a result of these reactions are generally classified into two groups: volatile and non-volatile compounds. Volatile compounds include aldehydes, ketones, alcohols, carboxylic acids, esters, hydrocarbons, and aromatic compounds [50, 58-60]. These compounds are primarily responsible for the structural deterioration, color changes, and off-flavors in frying oils. In particular, the sharp odor released during thermal degradation of oils has been attributed to acrolein, an unsaturated aldehyde [58, 61]. Acrolein is formed through the dehydration of glycerol and the oxidation of polyunsaturated fatty acids [62].

During frying, acrolein can be released into the air as well as migrate into foods. Acrolein is recognized as a highly toxic compound that contributes to the onset and progression of various pathological conditions, including cardiovascular diseases, alcoholic liver disease, Alzheimer's disease, diabetes, and chronic obstructive pulmonary disease (COPD) [63-65]. It has also been reported to cause DNA damage and to induce tumorigenic processes [65]. Furthermore, acrolein and similar reactive compounds not only reduce the biological value of foods but also pose serious food safety concerns, exerting direct adverse effects on human health [66]. These toxic and carcinogenic compounds formed as a result of heat treatment during frying are classified as process contaminants (chemical contaminants) [67]. Among the most significant compounds is 3-monochloropropane-1,2-diol (3-MCPD), a chemical contaminant with carcinogenic properties. This compound is formed from fatty acid esters and has been reported to occur during the refining of vegetable oils, particularly at high temperatures in the deodorization stage [68]. During frying, non-volatile compounds such as malondialdehyde (MDA) are also generated in oils. MDA and 4-hydroxy-2-nonenal (HNE) are two of the most important reactive carbonyl compounds in foods, formed during the peroxidation of polyunsaturated fatty acids such as linoleic acid (C18:2) and linolenic acid (C18:3) [69, 70].

In addition to their biological toxicity, these compounds can react with myoglobin and myofibrillar proteins, thereby affecting food color, gelation properties, hydrophobicity, and other quality attributes [69,70]. The food safety risk associated with MDA arises from its ability to react with free amino acids such as lysine, arginine, and histidine, as well as with amino groups of proteins, exhibiting cytotoxic, neurotoxic, and mutagenic effects [71- 73].

Another important contaminant formed during frying is polycyclic aromatic hydrocarbons (PAHs). These compounds have been reported to interact with various proteins and DNA in the human body, leading to serious health risks such as cardiovascular diseases, cancer, and immunotoxic effects [74]. During the frying process, oxidation and polymerization reactions in oils primarily occur through unsaturated fatty acids. In particular, long-chain polyunsaturated fatty acids such as linoleic acid (C18:2) and linolenic acid (C18:3) undergo rapid oxidation and polymerization, leading to their degradation. In a study by Bansal et al. [74], the increase in palmitic acid levels after frying was attributed to the oxidative degradation of linoleic acid at high temperatures [75].

Linoleic acid (C18:2) has been suggested as a reliable indicator for evaluating the oxidative stability of edible oils because it is more susceptible to oxidation than palmitic acid (C16:0). In this context, the ratio C18:2% (linoleic acid) / C16:0% (palmitic acid) expressed in equation (I) was used [76,77]. Furthermore, Cosgrove et al. [77] proposed an equation (II) for calculating oxidation stability that encompasses all unsaturated fatty acids, as given below:

$$(I)\ C16{:}0\% \ /\ C18{:}2\ \%$$

$$(II)\ Oxidation\ stability = [C18{:}1\ \%\ (Oleic\ acid) + 50\ x\ C18{:}2\ \%\ (Linoleic\ acid) + 100\ x\ C18{:}3\ \%\ (Linolenic\ acid)]\ /\ 100$$

The results obtained from equations (I) and (II), which are used to calculate the oxidation stability of frying oils, are important parameters that assist in selecting the appropriate oil for frying. In equation (I), oxidation stability is calculated solely based on the linoleic acid to palmitic acid ratio, whereas equation (II) incorporates all unsaturated fatty acids into the calculation, providing a more reliable measure of oxidation stability [77,78]. Oils rich in polyunsaturated fatty acids (PUFAs) are more prone to peroxidation and the formation of lipid oxidation products, such as aldehydes, compared to oils rich in monounsaturated fatty acids (MUFAs) or saturated fatty acids (SFAs) [79]. Due to its high susceptibility to oxidation, the proportion of linolenic acid (C18:3) in frying oils is recommended to be kept below 3% [80, 81]. In recent years, the use of oils rich in polyunsaturated fatty acids (PUFAs) in frying has been reported to result in the formation of various oxidation compounds with distinct structures, such as epoxy fatty acids and aldehydes, which may pose significant health risks [82].

The physical and chemical changes occurring in oils during the frying process are presented in Figure 3. The most notable change is a rapid decrease in the degree of unsaturation, accompanied by increases in free fatty acid content, viscosity, and polar compound concentration. The reduction in the degree of unsaturation has been attributed to the degradation of polyunsaturated fatty acids through oxidation and polymerization [50]. The volatile and non-volatile polymerization products formed in oils and foods during frying are listed in Table 1 [7].

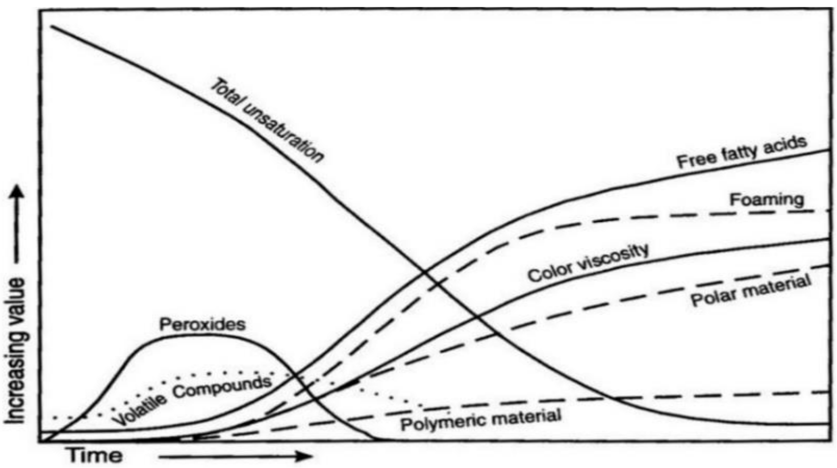

Figure 3. Physical and chemical changes occurring in oil during frying [50].

The degradation process of frying oils is primarily associated with oxidative, hydrolytic, and polymerization reactions, and the resulting non-volatile polar compounds are considered the most important indicators of quality loss in oils. The rate of formation of polar compounds varies depending on the fatty acid composition of the oil, the food matrix, and the frying equipment used [84, 85]. These compounds are among the most hazardous substances formed in oils during frying in terms of food safety [6, 85,]. A relationship has been reported between the formation of polar compounds and the degree of unsaturation of fatty acids, with a particularly strong positive correlation observed between linoleic acid (C18:2) content and polar compound formation [85, 86].

Table 1. Volatile and non-volatile compounds formed in oils and foods during frying [7].

Volatile Compounds – Frying Oil	Non-Volatile Compounds – Frying Oil
Hydrocarbons	Free fatty acids
Aldehydes	Monoacylglycerols
Ketones	Diacylglycerols
Alcohols	Oxidized TAG polymers
Esters	Dimers, trimers, and oligomers
Lactones	
Volatile Compounds – Foods	**Non-Volatile Compounds – Foods**
Polycyclic aromatic hydrocarbons	Acrylamide
Polychlorinated benzenes	Heterocyclic amines
Dioxins	

The effects of polar compounds on health have been reported to include alterations in carbohydrate, protein, and lipid metabolism, regulation of enzyme systems, and the exertion of toxicological and cytotoxic effects, thereby predisposing individuals to the development of various diseases upon consumption [85, 86]. The primary factors contributing to the formation of polar compounds include the triglyceride composition of the frying oil, high temperature, frying duration, type of frying equipment, and prolonged use of the same oil without replenishment [84, 87-89]. In a study conducted by Koher et al. [89], it was determined that the rate of polar compound formation was higher during the frying of protein-based foods [90]. Another study reported that high-protein foods cause faster peroxidation compared to carbohydrate-based foods [91]. The high food safety risk associated with polar compounds is directly related to the increase in their concentration in oils during frying and their subsequent migration into the food [60]. Consumption of foods with a high proportion of polar compounds has been reported to create a predisposition for the presence of cancerous cells in the digestive system [7, 92]. Therefore, the oxidation and polymerization products formed during frying adversely affect both food safety and healthy nutrition [51, 93].

The 24–27% "stop-use" band frequently reported in the literature for total polar compounds (TPC/TPM) is not a unified limit belonging to a single country/supervisory authority, but rather a framework with practical application based on the clustering of threshold values from national legislation and official control authorities within the same range. French legislation sets upper limits of ≤25% for composite polars and ≤14% for polymeric triglycerides in frying oils, considering exceeding these levels as "unsuitable for consumption" [94]. In Belgium, the Royal Decree of 22.01.1988 stipulates a threshold of 25 g/100 g for polar compounds, and the AFSCA/FAVV Scientific Committee explicitly references this norm in its inspection practice [95, 96]. In Switzerland, the EDI/DFI regulation requires that the polar fraction in frying oils be ≤27% (Federal Department of Home [97]. In Austria, the official food codex, Österreichisches Lebensmittelbuch, directly specifies a 27% threshold for polar compounds among the indicators of "non-compliance" in frying oil [98]. In Germany, official control reporting uses a critical threshold indicating that the oil is unsuitable for consumption when the "maximum" level of polar compounds exceeds 24% [98]. These regulatory/institutional thresholds are consistent with the finding in current reviews and kinetic-based studies that TPC/TPM is mostly limited to the 24–30% range across countries, and that the 24-27% range is reported as a common "discard/rejection" window [99, 100]. Due to the high temperatures applied during frying, partial formation of trans fatty acids from unsaturated fatty acids occurs [101]. In particular, a strong correlation has been reported between the formation of C18:1 trans fatty acids and the formation of polar compounds [86]. Furthermore, when partial or selective hydrogenation techniques are employed to enhance thermal stability in the preparation of frying oils, a significant amount of trans fatty acids can be generated. Considering that foods absorb approximately 20-30% oil during frying, a substantial quantity of trans fatty acids can migrate into the product. Trans fatty acids have been identified as a risk factor in the development of cardiovascular diseases, coronary heart disease, cancer, and diabetes [102,103]. Given the approximate 20-30% oil absorption during frying, the presence of trans fatty acids in fried products is considered to pose serious food safety concerns.

CONCLUSION

Frying, one of the most commonly used methods in food consumption, alters both the sensory properties and composition of foods. These changes lead to the formation of numerous compounds in fried foods that are detrimental to human health. Therefore, it is essential to produce fried foods in a manner that does not pose nutritional and health risks. In this context, to ensure the production of healthy foods in compliance with food safety standards, the parameters that must be considered during the frying process can be summarized as follows:

An approach to optimizing both product quality and food safety in deep-frying requires managing the process through critical control points. In this context, the use of deep-fryer/frying equipment that allows for precise temperature control and operation in the 150-200°C range, and in most applications in the 170-180°C range depending on the product, offers a practical operating framework to limit high heat treatment and associated oil degradation [104,105]. As a frying medium, refined oils with relatively low unsaturation, rich in MUFA (especially oleic acid), and with suitable initial quality indices (e.g., acidity, peroxide, *p*-anisidin, total polar compounds) (e.g., high oleic canola/rapeseed or high oleic sunflower; rice bran oil) can be more advantageous in terms of heat-oxidative stability; It has been reported that the tendency for oxidative degradation increases as the PUFA ratio increases [106]. On the operational side, structuring the product:oil ratio in a way that does not impair temperature recovery, reducing product surface moisture, removing crumbs by filtration, and minimizing oxygen/light/heat load by removing the oil from the heat source between uses are fundamental process hygiene steps aimed at slowing down total polar compound accumulation [107].

In reuse scenarios, instead of a “fixed refresh percentage’’, management with indicators monitoring the chemical degradation of the oil is recommended; for this purpose, TPM/TPC measurement (laboratory analysis or rapid kit/dielectric sensors in the field) stands out among the decision support parameters [107, 108].

In addition to traditional deep-frying, alternatives such as vacuum frying, two-stage frying, and electric field-assisted approaches, as well as hot air/air frying, also have the potential to reduce oil absorption. However, it is emphasized that lipid oxidation can progress in a pro-oxidant environment, particularly in hot air frying, and that a matrix/condition-based risk-benefit assessment is necessary [104,109]. While boiling is the ‘standard pre-treatment, pre/post-treatments such as edible coating, osmotic dehydration, pre-drying, freezing, microwave or ultrasound should be considered holistically with design variables aimed at both reducing oil uptake and processing contaminants (e.g., acrylamide; thermally derived compounds from oil) and sensory quality [104,105].

This study comprehensively evaluated the effects of physicochemical changes occurring simultaneously in the food-oil system during the frying process and changes in the food matrix on quality and health. The frying process is not merely a process that improves the sensory properties of food; it also reveals that it is a multidimensional complex system involving oil deterioration, nutrient losses, and the formation of toxic compounds. Optimizing key parameters in the frying process, such as temperature, duration, type of oil, and food (matrix and size), can significantly reduce the formation of toxic compounds. This is critical in terms of quality and health. In conclusion, for frying to be carried out safely and sustainably, the food matrix, oil properties, and process conditions must be evaluated together. Furthermore, excessive consumption of fried foods may pose potential health risks in the long term; therefore, raising consumer awareness and promoting healthy frying practices can be considered an important strategy.

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