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REVIEW ARTICLE

Review on deep-fat fried foods: physical and chemical attributes, and consequences of high consumption

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Abstract

Deep-fat frying is a widely discussed topic globally in the field of food processing due to the growing consumer demand. These foods are known for their appealing outer appearance, crispy texture, and rich taste. The increased consumption of deep-fat fried foods has raised concerns regarding potential health issues, as they are often high in calories and may contain unfavorable compounds formed during the process of deep frying. This review aims to provide an overview of previous studies examining the physical, chemical, and nutritional changes that occur in fried foods, the mechanisms of fat uptake during frying, and the health implications associated with the consumption of these foods. This increasing rate in consumption has been linked to various adverse health conditions. There has been a significant research focus on reducing the fat content in deep fried foods, particularly investigating the process of fat uptake during deep-fat frying. It is crucial to increase consumer awareness regarding the potential problems arising from excessive intake of deep-fat fried foods. Furthermore, further studies are needed to meet the rising demand for deep-fat fried foods while minimizing the impact on health and preserving their desirable taste.

Graphical abstract

Keywords Deep-fat frying · Nutritional changes · Chemical and physical changes · Health issues

Introduction

The deep-frying method has been utilized for centuries, and deep-fried foods have achieved significant popularity and are widely appreciated. They are extensively enjoyed in the

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catering industry, restaurants, and also in home kitchen. The appeal of deep-fried foods rises from their reasonable pricing, delicious taste, and the convenience of their quick and easy preparation process [1]. It is preferred by various age groups because of their distinctive sensory characteristics. Frying stands out as a widely practiced technique globally in the food processing sector and culinary services [2]. Deep-frying is a dry cooking method where food is submerged in hot oil or fat at a high temperature. No water is used in this process. The appropriate frying temperature varies based on the thickness and type of food being cooked, but typically falls within the range of 175–190 °C [3]. It is the process of cooking food using oil or fat as the medium for heat transfer at temperatures ranging from 160 to 180 °C or greater than this range [4]. During the frying process, the moisture present in food is eliminated as steam due to absorption of heat from the oil or any other sources of energy used. This leads to a noticeable decrease in the volume, moisture level, and weight of the food [5]. A wide range of chemical reactions occurs during deep-fat frying, including protein denaturation, Maillard reaction, hydrolysis, sugar dehydration, polymerization, lipid oxidation, and starch gelatinization. These reactions contribute to the darkening of food color, the development of aroma and unique texture. Among these reactions, lipid oxidation and the Maillard reaction play particularly vital roles in shaping the final flavor profile [6]. The process of frying contains a sequence of physical and chemical changes, which include water evaporation, protein denaturation, starch gelatinization, and the formation of a crispy crust on the fried surface. Additionally, frying can effectively destroy microorganisms, deactivate enzymes, and decrease the water activity of food items [7]. These effects contribute to the preservation and safety of fried foods [8]. Deep-frying not only enhances the sensorial qualities of food but also increases the nutrient content, including essential fatty acids, vitamins, and calories. The traditional frying technology, which utilizes a fryer with simple structures offers an easy and efficient method. This makes it suitable for both domestic and industrial purposes, allowing for quick and convenient frying of various food items [9]. Deep-frying is a rapid cooking method that enhances the flavor and texture of certain foods. The process allows the food to develop a delicious crispiness and a desirable texture, making it a popular choice for preparing certain food items [3].

During the process of deep-fat frying, the oil used not only acts as a medium of heating but also gets absorbed into the food being fried, thereby increasing the overall fat content. Consequently, the consumption of deep-fat fried foods has been linked to an increased risk of coronary heart diseases, type 2 diabetes, and obesity. In recent years, growing concerns for better health have led to an increased focus on various dietary components, with particular attention given to fat [10]. Therefore, understanding the impact of fat consumption, especially from fried foods, is crucial for promoting healthier dietary practices and reducing the risk of these adverse health conditions.

Consumers concern has begun to rise regarding acrylamide, a potential carcinogenic substance that has been found in fried foods when subjected to high temperature [11]. Heterocyclic aromatic amines (HAAs) are known to be potent mutagens and are associated with an increased risk of certain types of cancer [3]. HAAs are produced due to heat treatment of meat and its products or foods rich in protein [12]. Cooked foods can contain over 20 different types of these harmful compounds [3]. HAAs produced by deep-frying techniques are typically found at levels lower than 1 ng/g (nanogram per gram) [3]. The formation of acrylamide in food poses a significant concern due to its potential to cause cancer as well as heritable mutations [13]. During the frying process, the oil can undergo degradation due to the combined effects of water, heat, and oxygen. As a result, toxic compounds may form and be present in the oil bath [14]. Consuming an excessive amount of calorie-rich foods can lead to obesity, increased blood pressure, and diabetes, all of which are three risk factors associated with the development of heart failure. Additionally, the consumption of fried foods in excess poses a potential health risk due to the formation of toxic substances during the frying process [7]. Researchers have been involved in studies to develop innovative technologies aimed at producing healthier and safer fried foods by reducing their oil content [15]. Many researchers are focused on studies exploring techniques such as lowering frying temperatures, implementing pretreatment methods, and minimizing the exposure to oxygen to prevent the formation of toxic substances in fried foods [7]. However, it is important to note that these techniques may significantly diminish the intensity of the characteristic fried flavor, consequently impacting the sensory quality of deep-fried products [1].

Many issues have been observed in the traditional method of deep-fat frying, prompting researchers to conduct studies aimed to overcome these issues. The problems associated with consuming fried foods, nutritional, physical and chemical changes that occur during the frying process, and process of fat-uptake as well as methods to minimize it, these factors are to be studied parallel to design further studies for the advancement of deep-fat frying technology. This review aims to summarize the results of existing studies on the aforementioned topics (Fig. 1) and consolidate the information into a single paper. It will provide valuable insights about all the changes occurring during the process of deep frying, health problems due to excess consumption of deep-fat fried foods, fat-uptake in the food during frying. It aims to provide holistic information that can support in the design and planning of studies focused on the fat uptake in fried foods, minimizing unfavourable nutritional and

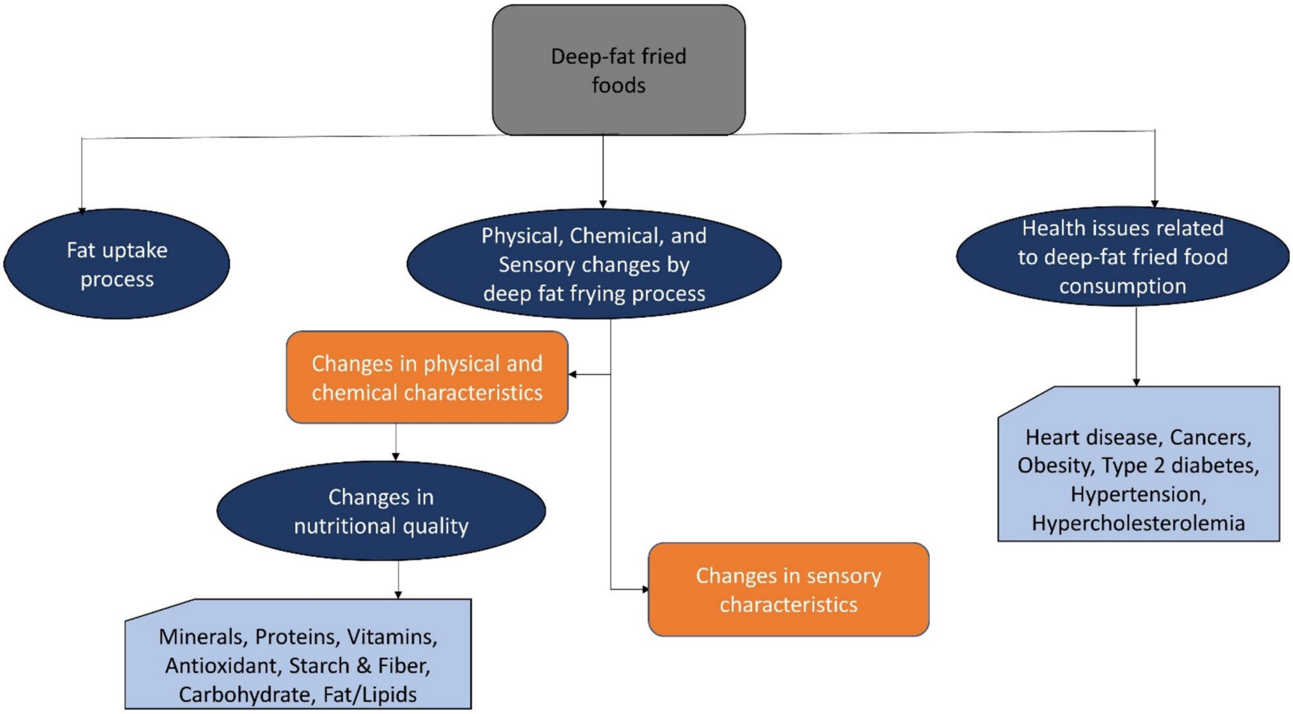

Fig. 1 Overview of this review

physical changes, and addressing health issues—all while maintaining the delicious taste of fried foods and meeting the growing demand worldwide.

Fat-uptake process in fried foods

For a precise evaluation of the nutritional value of frying, the transfer of heat and mass must be taken into consideration [16]. Frying induces significant changes in the composition of food, mainly involving water loss, oil absorption, and the formation of acrylamide through the Maillard reaction. The frying process involves both convection as well as conduction for the transfer of heat and mass [17]. Mass transfer and lipid exchanges play crucial roles in this process as the significant physical transformations which greatly influence the overall quality of fried food. These alterations impact various aspects such as palatability, composition, and texture of the final product [18]. Fried raw materials undergo two types of mass transfer processes. The first involves the movement of water and soluble components from the interior of the foods towards the surface crust. The second mass transfer process is the evaporation of surface water from the fried products, along with the movement of oil into the products (Fig. 2). As water evaporates from the surface, it creates voids that allow the oil to permeate the food. Therefore, the amount of oil uptake during frying primarily depends on the amount of water in the raw materials being fried [19].

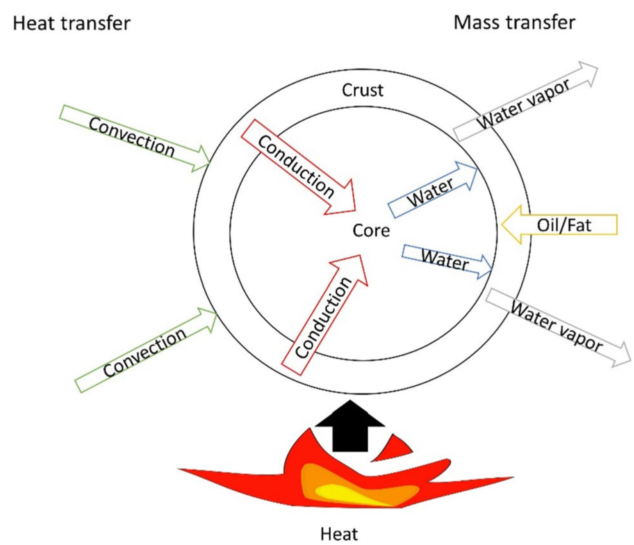

Fig. 2 Fat uptake in food during the process of frying [21]

A pressure gradient results from a portion of the moisture within the fried item being converted into steam during the frying process. This steam is released through channels and capillaries in the cellular structure of the food. Oil that stuck to the surface of the food or infiltrated the empty spaces left by the evaporated water is effectively expelled. The oil cannot fill the empty spaces as long as steam continues to be produced. The movement of oil can be characterized as a retreat and advance process, primarily influenced by the pressure of the steam and the characteristics of the capillaries. When the product cools down, the internal vapor pressure decreases due to condensation, which resulted in a 'vacuum effect.' The absorption of oil into the product is resulted due to this effect [20].

Physical, chemical and sensory changes caused by deep-fat frying process

Changes in physical and chemical characteristics

One of the fundamental objectives of frying is to make food more acceptable. The practice of food frying in restaurants and institutions can pose challenges due to the prolonged exposure of oil to high temperatures and the insufficient replenishment and disposal of oil [22]. During the process of frying, some part of water in the food is displaced by the penetration of the fat/oil used for frying [23], as a result the fried food becomes much more appealing. Because of the tenderizing and wetting effects of the absorbed fat, the deep fat fried foods receives its typical flavor, texture, color which are mostly preferred by the consumers [24]. Foods that have been under-fried have partially cooked or ungelatinized starch in the center and, a white or a light brown color around the edges [25].

During the process of deep-fat frying, various chemical reactions take place. These reactions include oxidation, hydrolysis, polymerization, and isomerization, leading to the formation of several products. These products are small molecular alcohols, lactones and hydrocarbons, free fatty acids, cyclic and epoxy compounds, acids, diglycerides and monoglycerides, trans isomers, monomers, dimers, oligomers and, aldehydes and ketones [26]. Short-chain unsaturated fatty acids dissolve better in water compared to long-chain saturated fatty acids, making hydrolysis in oil more desirable [27]. Triacylglycerol (TAG) dimers and polymers, along with non-volatile polar compounds, are the main products resulted due to degradation of frying oil, and are relatively greater than the cyclic compounds [18]. Depending on the fatty acid profile of the fat/oil and the type of reaction that occurs, dimers or polymers can either be cyclic or acyclic [28]. In deep-fat frying, the process of formation of dimers and polymers are radical processes [27]. The prolonged use of oil can significantly impact its quality. During the frying process, the water removed from the food may mix with triacylglycerols (TAG) in the oil, leading to various chemical changes. Hydrolysis of these compounds can occur, resulting in the formation of free fatty acids, diacylglycerols (DAG), and monoacylglycerols (MAG). Additionally, when oxygen from the environment incorporates into the surface of oil oxidation can take place, leading to the formation of conjugated dienes, hydroperoxides, peroxides, ketones, epoxides, and hydroxides. These chemical compounds may either break down into smaller parts or stays within the molecule of TAG, bonding with one another to form dimers and polymers of TAG [29].

The primary factor influencing the oxidative stability of oil is the degree of unsaturation present in the fatty acids. Oils with higher unsaturation tend to undergo oxidation more quickly than those with lower unsaturation. Additionally, the frying stability of oil can be negatively affected by minor components like, mono- and diacylglycerols, free fatty acids (FFA) [30]. Frying with oil that has been reused offers superior attributes to the fried food compared to fresh oil. It is due to the presence of polar compounds that infuse the surface of food. These compounds enhance the flavor, improve the interaction between the water and oil on the food's surface, and act as catalysts to facilitate better heat transfer during frying [31].

[32] studied the influence of temperature (180 and 220 °C) and time of heating (30, 60 and 120 min) on palm oil, soybean oil and pomace olive oil. All these vegetable edible oils were found to be influenced by the two studied variables, even if with a different effect, showing a progressive deterioration in the physicochemical parameters. In a study conducted on sunflower seed oil heated at 180, 210 and 240 °C for 15, 30, 60 and 120 min, the authors have found an increase in free acidity, *p*-Anisidine value and Totox, whereas a decrease in antioxidant activity and total phenolics was measured. The two-way ANOVA demonstrated a different influence on the fatty acid composition [33]. The same experimental design was applied to extra virgin olive oil, in which temperature and heating duration caused the increase in free acidity, *p*-Anisidine value and Totox, whereas, also in this case, a decrease in antioxidant activity and total phenol content was measured. No influence was found on refractive index. Fatty acids were differently influenced [34].

Effect of deep-fat frying in nutrition of foods

The alterations that occur in the nutritional value of fried food are influenced by various factors, including the composition of the frying fat and the food itself, as well as the size, shape, and texture of the food. Additionally, frying conditions such as time, temperature, and other cooking parameters play a significant role in determining the extent of these changes (Table 1). The final nutritive value of the fried food is influenced by these factors collectively [23].

Vitamins

High temperature and enzymatic oxidation during preparation, or prolonged frying are the main causes for vitamin loss

Table 1 Effect of deep-fat frying in nutrition of foods

Nutritive parameters	References
Vitamins	[9, 25, 35–40, 42, 43]
Antioxidant activity	[6, 23, 44]
Minerals	[31, 45–51]
Proteins	[3, 7, 12, 23, 31, 45, 51, 53–55]
Carbohydrate	[37, 47]
Alteration in the lipid content of foods	[30, 47, 56–62]
Modifications in starch and fibers	[7, 25, 45, 63–66]

(Table 1) [35]. Certain vitamins are susceptible to oxidation and high temperatures. The internal temperature typically falls between 70 °C and 90 °C during frying. Within this temperature range, the retention of vitamins is significantly influenced by the internal temperature of the food rather than the temperature of the frying oil [36]. In most cases, both deep frying and shallow frying methods better retained vitamins B_1, B_2, B_6, and C compared to stewing, boiling, and steaming [37].

Deep-fried vegetables experienced twice the loss of β-carotene compared to shallow-fried foods. Additionally, some β-carotene had the potential to migrate into the frying oil during the frying process. For instance, the frying of cabbage led to the destruction of 29% of β-carotene [38]. There was an average loss of 14% of vitamin A in boiling and 24% of vitamin A in frying [39]. Analysis of heated palm oil revealed the presence of carotene oxidation products, suggesting that the loss of β-carotene during frying is partly attributed to the oxidation [39]. When oils with varying degrees of unsaturation lacked tocopherols, degradation was notably higher [40]. Due to leaching into the frying oil, 24% loss of vitamin A was reported in fried Thai vegetables [39]. The duration of frying directly affects the loss of vitamin A.

During the frying process, about 30% of the thiamin decreases. B vitamins being water soluble could be the reason for the loss [41]. When frying chicken meat, riboflavin showed better retention compared to thiamin, particularly when frying dark meat. However, losses of riboflavin was found to be 42.5% in fried calves liver and 43.5% in fried swine liver [38]. During the frying process, there is a notable increase in riboflavin content, likely due to the generation of riboflavin from precursors of riboflavin [37]. Niacin, on the other hand, is relatively stable during frying, yet losses of about 45% have been reported in frying chicken meat, beef, and pork muscle. But in peanuts, frying increased the niacin content [38].

Vitamin C has higher retention in stir-frying compared to methods involving extensive water cooking or microwave usage [42]. Broccoli when stir fried retained 76.6% of its vitamin C content, whereas cooking with excess water should 44.8% of retention, and using a microwave showed 72.2% of retention [25].

The heating process causes the oxidation of unsaturated fatty acids, leading to a loss of vitamin E. The amount of frying oil absorbed during deep frying is influenced by the quality of the cooking oil used, impacting the vitamin E intake. In a study using vegetable shortening oil, virgin olive oil, or sunflower oil, retention of vitamin E was found to be about 50% up to 4 to 5 continuous frying session. 15–49 mg of α-tocopherol equivalents per 100 g is available in vegetable oil used for frying. Consequently, fried foods become enriched with this vitamin due to the fat uptake that occurs during the frying process [36]. Chicken nuggets after fried in soybean and corn oils showed an increase in total vitamin E to 4.9 mg per 100 g from 4.6 mg per 100 g before frying. Similarly, fried breaded shrimp showed an increase in vitamin E content to 5.1 mg per 100 g from 0.6 mg per 100 g [43].

Antioxidant activity

In terms of ABTS radical scavenging capacity, garlic experienced losses higher than 50% in antioxidant activity, while asparagus showed losses ranging between 30 and 40%. Swiss chard, cauliflower, and pepper demonstrated losses between 5 and 30% (Table 1) [44].

Minerals

There appears to be no significant loss in the content of minerals during frying of food [31]. Due to the water soluble characteristics, the alteration of mineral components mainly occurs during boiling (Table 1) [45]. Several studies have found that minerals are relatively well-preserved when foods are fried at high temperatures within the range of 165–185 °C and for short cooking durations [46]. The mineral, specifically potassium, in fried skipjack increased to 8316.22 from 7966.54 ppm [47]. In deep-fried food, losses of mineral in potatoes and beef varied from 1 and 26% respectively. However, these losses are significantly lower than those observed in boiling [45]. The mineral losses in meat and fish without coating was significantly higher in comparison to the deep-fried breaded samples in which the loss varied from 2 to 8%. The breadcrumbs in the coating appear to absorb minerals dissolved in the meat's gravy. On the other hand, baking or frying mackerel fatty fish does not lead to changes in their mineral content. In the case of lean fishes like grouper and snapper, minimum loss of mineral was found [45].

Fish processing, specifically frying, resulted in a slight increase in the concentration of minerals. This increase is likely due to a concentration effect during the frying process [48]. Rainbow trout fillets during frying showed a significant increase in mineral content [49]. It was found that the frying of frozen seafood significantly increased amount of both macro as well as microelements and heavy metals content. However, there were exceptions for the potassium (K) content in mussels and magnesium (Mg) content in shrimps, which did not increase during frying. The process of frying increase significantly the content of macro and microelements [50]. The concentration effect of frying can be the reason of increase in minerals [31].

Protein

Due to the concentration effect and the fact that frying is a dehydrating operation, frying generally results in a higher protein content (Table 1) [31]. After being fried, the protein content of grass carp fillets increased [51]. The digestibility of protein in fried foods is influenced by the ingredients used in the food preparation [45]. When food is fried without any added ingredients, as is commonly done, the digestibility of the protein remains unaffected by the frying process. However, if reducing substances like carbohydrates are introduced to the food before frying, the digestibility of the protein can be slightly decreased [23]. It was observed that the protein content in fried sardine was higher compared to untreated. This increase in protein content might be attributed to the formation of new compounds during the frying process comparable to protein. As a result, the determination of protein content using the Kjeldahl method could have been influenced by these changes [52]. Research findings have indicated that the retention of protein in deep-fried potatoes, fish, and meat ranged within 96–100% [45].

Thermal treatment has the potential to alter the protein composition in food by destroying certain amino acids and reducing the overall protein content [53]. The impact on essential amino acids remains uncertain as the literature lacks evidence on their loss. Nevertheless, it is widely believed that lysine is the first amino acid involved in the Maillard reaction and is expected to be lost during frying [31]. When *Trachurus trachurus* underwent the frying process, there was a significant decrease of 6.21% in its total amino acid content [54]. The reduction in amino acid content was observed during the frying process, with the lowest values recorded in palm oil fried samples. Studies have indicated that deep-fat frying can lead to a decline of 17% in available lysine in fish fillets, and this percentage may increase to 25% when fish oil is continuously used for frying over 48 h due to interactions between the carbonyl compounds and amino group of lysine [55].

Carbohydrate

The carbohydrate content of fresh and fried skipjack on dry basis was found to be 3.067% and 3.099% respectively (Table 1) [47]. It was found that the retention of carbohydrates ranged from 95 to 100% across different kinds of food, and the frying method had no impact on this retention. This observation was consistent across various food items, including breaded meat and fish, and potatoes as well its products [37].

Alterations in the lipid content of foods

One of the main issues with eating fried foods is an increase in calorie consumption (Table 1) [56]. An increase in oxygen concentration and temperature may speed up the oxidation of certain lipids found in fried food [57]. When catfish fillets are subjected to the frying process for 6 min at 180 °C, the fat content can increase significantly, ranging from 2.23 to 9.65% [58]. Fresh skipjack fish contained 30 different types of fatty acids, which were categorized as follows: 12 saturated fatty acids (SAFA), 7 monounsaturated fatty acids (MUFA), and 11 polyunsaturated fatty acids (PUFA). However, after undergoing the frying process, the fatty acid composition decreased to 25 types, specifically: 12 saturated fatty acids (SAFA), 6 monounsaturated fatty acids (MUFA), and 7 polyunsaturated fatty acids (PUFA) [47]. The cholesterol level of fresh skipjack was measured at 49.12 mg/100 g, and it significantly increased to 173.92 mg/100 g after undergoing the frying process [47]. The frying process applied to seabass (*Dicentrarchus labrax*) has been found to lead to a reduction of approximately 30% in eicosapentaenoic acid (EPA) and about 28% in docosahexaenoic acid (DHA) [59]. Trans fatty acids (TFAs) can be generated through the frying process. The intake level of these compounds is associated with the risk of developing cardiovascular disease (CVD) [60]. Selecting the appropriate frying oil is crucial, not only for its technological characteristics but also for its nutritional attributes [61]. The hazardous compounds currently recognized in reused frying oils include molecules with cancer-causing potential like carbonyl compounds or monoepoxides, as well as certain aldehydes that result from the breakdown of linoleic acid. One specific example is 4-hydroxy-2-transnonenal, which has been demonstrated to have cytotoxic properties [62]. When the method uses used oils or fats, the digestibility of the fat is also altered. Despite the establishment of frying oil regulations, which set limits on polar compounds (up to 25%) and polymer content (up to 12%), there is a possibility of potentially toxic compounds forming in the oil. These compounds can pose risks to health, even with adherence to the specified limits [62]. Thus, caution should be exercised when reusing frying oils to avoid the formation of harmful substances.

Modifications in starch and fibers

In the process of deep frying, the percentage of resistant starch experiences a significant increase, while the overall starch composition remains unaffected (Table 1) [45]. Starch is the prevalent polysaccharide found in food. Upon heating, both amylose and amylopectin dissolve in water, creating a polymer structure, which results in gelatinization of starch. This process takes place following the denaturation of globular proteins under higher temperature and also includes proteins, water, lipids, and carbohydrates [63]. The transformation of starch is a critical factor when frying raw potato products. Once exposed to hot oil, starch granules rapidly undergo gelatinization. As a result, the rigid structure of raw potatoes is lost within 1–2 min of frying, leading to a soft texture in the fried chips. However, with further heating, a firm and crispy crust develops on the fried particles, which is highly preferred by consumers [64]. During the process of preparing French fries decomposition of dietary fiber occurred, which is particularly notable when using low-specific gravity tubers. In certain instances, the dietary fiber content actually increases during the frying process. This could be attributed to the creation of melanoidins or other substances that are not easily digestible. Additionally, as the heating begins, polysaccharides create a dense film on the surface, which hinders the migration of fat into the fried food and helps retain water [65]. Research on the dietary fiber content revealed that cooking frozen French fries did not affect the starch composition compared to fresh samples. However, the frying process significantly increased the resistant starch. This increase is partly linked to the formation of an amylose–lipid complex, which contributes to the overall increase of fiber [64]. Dietary fibers play a crucial role in preventing various diseases, including diabetes, cardiovascular disease, and colonic cancer. When comparing frozen French fries to raw samples, the baking process does not significantly impact the composition of starch, but deep-frying does lead to a notable increase in the resistant starch percentage. The formation of amylose–lipid complexes can be partly responsible for the increase. Despite the decrease in digestible starch content caused by frying, the dietary fiber amount is actually increased [66].

Changes in sensory characteristics

Thermal treatment plays a crucial role in the food industries (Table 2). This unit operation is highly significant due to its wide range of applications in ensuring microbial food safety. However, it is important to note that thermal processing leads to alterations in the physical, chemical, and sensory properties of foods [67]. The primary cause of the fried flavor could be due to the products resulting from the breakdown of lipids in the fat/oil used for frying.

Table 2 Sensory characteristics related to deep-fat frying

Sensory parameters	References
Taste	[1, 3, 18, 31, 76–80, 83]
Color	[6, 17, 24, 25, 31, 68–70, 72–75]
Flavor	[1, 3, 6, 24, 31, 68, 69, 75, 77, 80–84]
Texture	[3, 6, 7, 18, 24, 57, 64, 68, 69, 71, 75, 77, 80, 85–87]

The development of a deep-fried flavor is primarily influenced by two key chemical reactions: the Maillard reaction and lipid oxidation. They are influenced by a diverse array of complex volatile compounds present in different quantities, adding to the unique and intricate flavor profile [1]. The most significant reaction involved in the browning of food is considered to be the Maillard reaction, also known as non-enzymatic browning [68]. The surface color of a fried product holds great significance in determining the overall quality of food. It has a crucial impact on consumer perception and acceptance [69]. One of the most important characteristics of every food product is its color [70]. Changes in the surface of food can be attributed to various factors, including caramelization, the Maillard reaction, and evaporation of the surface water. The first two processes contribute to the development of golden to brown hues, while the evaporation of surface water plays a role in creating the desired crispy texture commonly associated with fried food and evaporation is responsible for the formation of a crust, which significantly influences the texture of fried food [68]. The color of fried products is subject to the influence of various process variables. These variables include the choice of oil, the temperature at which frying occurs, the duration of the frying process, and any pretreatments applied to the raw materials before frying [71]. Caramelin, Caramelans, and Caramelens are the three main compounds that give food its characteristic brown color [69]. The color development in potato chips, for instance, is directly related to the quantity of reducing sugars present in the potatoes. This is because both the browning reaction and the Maillard reaction are influenced by the extent of oxidation in the food [68].

During the frying process, the main reaction that affects sugars is the Maillard reaction. This reaction involves the interaction between free amino groups found in amino acids, peptides, proteins, and the carbonyl groups of sugars, aldehydes, and ketones. At frying temperatures, a series of intermediate products known as Amadori products or pre-melanoidins are formed, and they quickly polymerize to create dark-colored molecules called melanoidins. It is important to note that browning occurs more rapidly at temperatures above 150 °C [72], indicating that higher frying temperatures promote the Maillard reaction and the development of desirable color in the fried food. In addition to caramelization and the Maillard reaction, the frying oil itself can contribute to the non-enzymatic browning process. This occurs through the reaction of lipid oxidation products, which are formed during the frying process, with amines, amino acids, and proteins present in the food [73]. When the deep-frying time is increased, the color of the hairtail fillets turns more golden and brown [74]. The type of raw materials used, the composition of fat/oil used, various parameters of the frying process, and the deep-frying technique all have an impact on the flavor, texture, color of the deep-fat fried food [75].

Pleasurable tastes are preferred by humans, whereas unpleasant tastes are avoided [76]. Fried food products are widely consumed because of their typical flavor, taste, and crispy texture [77]. In order to determine qualitative changes in vegetable oils and deep-fat fried foods, sensory evaluation is usually performed [78]. Sensory evaluation is a process where selected experts are kept in the panelists and the food item is evaluated in terms of the human senses of hearing, touch, seeing, smell (aroma), and taste. As per the scientific detailed sensory evaluation (especially smell and taste) of French fries by [79], high-oleic (HO) edible oils were identified to be potential substitutes for conventional frying oils in the production of French fries, as they had lower levels of saturated and trans fats. The degree of oxidation of the used fat/oil in frying that results in generation of aldehydes, ketones, and peroxides determines the sensory characteristics like smell, texture, taste, and appearance of any deep-fried foods [80].

Products as a result of secondary or tertiary breakdown from pyrolytic, oxidative, and hydrolytic reactions are often responsible for the production of compounds responsible for flavors either acceptable or unacceptable [81]. The combination of chemical reactions and compounds that the frying oil absorbs also contribute to the development of the color, and flavor attributes of deep fried foods [31]. The flavors developed through frying and the flavors from the oil penetrated inside the food combine to create the flavor of potato chips [81]. Compounds like trans, trans-2, 4-decadienal created as a product of oxidation of linoleic acid contribute to the richness in flavor of fresh prepared deep-fried chips of potatoes [82]. Food is combined and diluted with saliva during intake by mastication, and salivary amylase breaks down starch to some degree. The volatile composition of food can be affected by the disintegration of the food matrix [83]. Perception of flavor depends not only on the effects of every volatile compounds but also on the masking, additive, synergistic, and interactive actions among the volatile compounds [84].

Food when introduced in hot oil with exposure to oxygen, three factors contribute to alterations in the composition of oil. First, the water present in the food leads to hydrolytic changes. Secondly, oxygen comes into contact with the oil, resulting in oxidative changes that occur from the outer surface to the interior of the food. Lastly, the higher temperature induces thermal changes, such as isomerization and scission reactions (generating aldehydes and ketones), leading to the formation of various degradation products like hydroperoxides and epoxides [68]. Linoleic acid plays a crucial role in contributing to the desirable flavor in deep-fried foods [69]. The changes in color and flavor during the frying process are influenced by several key factors. These include the type of oil used, thermal changes, storage conditions, interfacial tension between the food product and the oil, frying temperature and duration, size and characteristics of the food surface, moisture content, and treatments applied before frying. Additionally, lipid oxidation occurring during frying produces both volatile as well as non-volatile compounds that can significantly impact the taste and flavor of the fried food [31]. When amino acids are subjected to heat, they can produce characteristic aromas. For example, the amino acid proline can emit an aroma that closely resembles the smell and taste of potato, mushroom, and burnt egg [69].

The texture of food plays a crucial role in how consumers perceive and value them in the market. Texture characteristics are significant not only for ensuring quality but also from the perspective of food safety [85]. The developed texture within food during the frying process is resulted due to the interaction between modifications in polymers of carbohydrate, fats, and proteins. These changes are comparable to the ones that take place during boiling or baking [57]. As proteins undergo decomposition and partial pyrolysis, the texture of the food becomes crisper and develops a porous structure [69]. The formation of pores represents a significant structural transformation. These pores arise from the process of water evaporation and capillary formation. When subjected to high temperatures, the water evaporation becomes forceful, causing the pores to widen. Consequently, a protective outer layer (crust) is formed quickly, reducing further water loss, and preserving the moisture inside the food. Additionally, the protein denaturation and gelatinization of starch also plays a role in pore development and food shrinkage. The gelatinized starch typically disperses within the continuous phase resulting from denaturation of protein [57]. The existence of pores significantly influences the mechanical characteristics of the food, consequently impacting its texture and overall acceptance. The protein's structure arises from multiple interactions involving attraction and repulsion between molecules, including interactions between protein groups and water molecules. Modifications in the protein's natural structural conditions can occur due to variations in surface tension, pH levels, the presence of salts, temperature, and other factors that disturb both intra and intermolecular interactions. As a result, these changes in the structure cause the protein to break down into chains of amino acids [86]. The ratings for texture progressively increased as the frying duration increased, which may be connected to preference of consumers for chewy and crunchy foods [87].

Health issues related to the consumption of deep-fat fried foods

An overconsumption of fats has been linked to obesity and various health-related problems (Table 3) [41]. Excessive intake of deep-fat fried foods is considered risky for health, because of the toxic properties of the compounds formed during the frying process [88]. The risk of atherosclerosis would increase due to the production of trans fatty acids and reduction of essential fatty acids in the overused oils [89]. The degradation of fried fats can produce toxic compounds that have been linked to various diseases, including Parkinson's, cancer, Alzheimer [90], as well as thymus necrosis [91]. The consumption of polar compounds in cooking oil have independent and positive relation with the risk of hypertension, while the concentration of monounsaturated fatty acids (MUFA) in blood has inverse relation with the risk of hypertension [92].

As the temperature and duration of frying increased, the creation of HAAs significantly improved [3]. Deep-fat frying can lead to the production of furan and acrolein through various pathways, including the degradation of carbohydrates and amino acids, Maillard reaction, and lipid oxidation. These compounds have the potential to negatively impact human health [93]. The toxicity of aldehydes, which are the well-known volatile compounds produced during deep-frying, is heavily reliant on their ability to create intra- and intermolecular cross-linkages, leading to modifications in nucleic acids and proteins, and hinder the metabolisms of cell [94]. Study has shown that air-frying pork loin resulted in a 70% reduction in the total amount of HAAs compared to deep-frying. However, the sensory satisfaction of the air-fried pork loin was significantly lower in comparison to the deep-fried [95].

Table 3 Health issues related to deep-fat frying

Health issues	References
Atherosclerosis	[89, 93]
Parkinson	[90, 93]
Cancer	[22, 62, 90, 103–111]
Alzheimer	[90, 93]
Obesity	[41, 115, 116]
Hypertension	[92, 112–114, 117]
Heart disease	[60, 96–102]
Diabetes	[101, 118, 119]
Hypercholesterolemia	[120–124]

Heart disease

Consuming fried food is commonly regarded as unhealthy because of various reasons (Table 3). Frying alters the chemical characteristics of both the food being fried and the cooking oil, raises the total amount of trans fats, and reduces the amount of unsaturated fats available [96]. In older adults, the consumption of fried fish has been linked to certain negative cardiovascular effects. These effects include a decrease in ejection fraction, an increase in systemic vascular resistance, and a reduction in cardiac output [97]. In a research study involving 165 patients diagnosed with coronary heart disease (152 men and 13 women, with a mean age of 43 ± 6 years), and 199 of controls (175 men and 24 women, with a mean age of 43 ± 6 years), it was found that patients with coronary heart disease had a significantly higher intake of deep fried food (15 ± 25 g/day) and shallow fried food (24 ± 60 g/day) compared to the controls with respective intake of 1 ± 5 g/day for deep fried food and 3 ± 17 g/day for shallow fried food [98]. In a study, researchers observed a positive relation between the consumption of fried food and the heart failure. Comparing subjects who reported consuming fried food once a week, the adjusted hazard ratios for heart failure for those who consumed fried food 1–3 times per week was 1.24, 4–6 times per week was 1.28, and 7 or more times per week was 2.03 [99]. The consumption of fried fish, specifically more than one serving per week at baseline, was found to be linked to a 48% greater risk of heart failure [100].

In the study, researchers found that the risk of coronary artery disease was similar between subjects who consumed fried food seven or more times per week and those who reported consuming fried food less than once per week. Additionally, they did not observe a significant association between an increased risk of coronary artery disease and the frequency of total fried food consumption at home or away from home. But, when looking at the unadjusted risk, there appeared to be a significant association between higher consumption of fried food and the risk of coronary artery disease. However, this association almost entirely disappeared after adjusting for demographic data (such as age and gender), dyslipidemia, body mass index (BMI), and hypertension [101].

The idea that excessive fried food intake needs to be minimized for preventing ischemic heart disease is not supported by data from recent epidemiological studies. A primary concern revolves around the fact that the influence on cardiovascular risk could be more significantly influenced by the quality of fried food, as opposed to its quantity [102].

Cancer

A portion of polar compounds extracted from frying oils used in restaurants exhibited mutagenic properties as demonstrated by the Ames test in Salmonella. This mutagenic activity showed a direct relationship with thiobarbituric acid reactive substances (TBARS), which are generated from fatty acids containing three or more double bonds. This particular fraction contains malondialdehyde (MDA). In many research studies, it is known to show mutagenic effects (Table 3) [22]. The concentration of MDA significantly increased after extended frying. According to the Ames test, MDA is a mutagen that alters DNA by primarily interacting with cytidine and guanine, and also depleting these base pairs [103].There is a growing focus on harmful substances such as acrylamide, out of all the substances generated through the Maillard reaction. Acrylamide is categorized as a likely human carcinogen and also shows genotoxic, carcinogenic, and neurotoxic effects in animals. The complete mechanism behind acrylamide formation isn't completely understood, but it is confirmed that it develops through the Maillard reaction when reducing sugars and asparagine (non-essential amino acid) are subjected to higher temperature [104]. In a study by [105], as the treatment time and temperature increased in potato chips, it also increased the amount of acrylamide. Additionally, the water activity level was found to impact the creation of acrylamide; when water activity decreased, there was an increase in the formation of this compound [105]. Cooking oils that have been heated repeatedly create a variety of by-products, including aldehydes and polycyclic aromatic hydrocarbons (PAHs). These compounds are widely recognized to cause cancer, mutagenesis, and tumorigenesis. In recent times, repeatedly heated cooking (RCO) are frequently utilized for frying or cooking purposes. However, their consumption can lead to an increased risk of several types of cancer affecting various organs and many other dangerous health effects [106].

The link between cancer and diet is complex and is still largely unknown, the absence of extensive prospective studies prevents us from arriving at definitive conclusions. The study supports the idea that consuming larger amount of fried foods might contribute to an increased risk of prostate cancer [107].

One of the most prevalent forms of danger among women is breast cancer (BC), which affects about 2.1 million women annually. This form of cancer is known to contribute to a high proportion of cancer-related fatalities among females in middle as well as high-income countries [108]. The risk of breast cancer is closely linked to the dietary pattern of an individual, which is strongly influenced by the specific foods and nutrients they consume [109].

An association between lung cancer in women and the vapors released during fish frying has been observed in both Taiwan and China [110]. The compounds formed as a result of oil oxidation have the potential to be carcinogenic. Certain volatile oxidation products have been identified as having mutagenic properties, especially when inhaled as vapors during the frying process [111].

Melanoidin (MDA) has the potential to harm proteins and phospholipids through by forming covalent bonds and cross-linkage. Rats exposed to MDA developed skin cancer, and DNA solution cross-linked with amino groups. Since MDA is not generally evaluated when frying, these findings require more research [103]. Rats that were provided with a diet containing MDA exhibited retardation in growth, anemia, unusual intestinal functions, enlargement of the kidneys and liver, as well as decreased levels of serum and vitamin E in the liver [103].

Hypertension

Making lifestyle adjustments and changing from unhealthy cooking practices like frying to healthier alternatives such as boiling can have positive effects on managing blood pressure and obesity among the general public (Table 3) [112]. The available evidence on the direct link between fried food consumption and hypertension is limited and inconsistent. However, a study conducted in Spain revealed that a higher intake of fried foods was associated with an increased chances of hypertension [92]. According to the study by Seguimiento Universidad de Navarra (SUN) among Mediterranean cohort, individuals who frequently consume fried foods at baseline have a higher risk of developing hypertension. The study found that the adjusted hazard ratios were 1.18 for those consuming fried foods 2–4 times per week and 1.21 for those consuming fried foods more than 4 times per week compared to those who consume fried foods less than 2 times per week [113]. During the process of frying, an increased level of trans-fatty acids in the food is observed due to oxidation. An increased risk of hypertension has been positively linked with the increase of trans-fatty acids [114].

Obesity

A direct correlation between the consumption of fried foods and being overweight has been found in many research studies (Table 3) [115]. In two extensive studies, frequently consuming fried food has been linked to an increased risk of developing overweight or obesity. The European Prospective study demonstrated a direct relation between the intake of fried food, and both central as well as overall obesity [116]. In the SUN study, an adjusted odds ratio of 1.37 was reported for the likelihood of developing obesity when individuals consumed fried foods more than four times per week compared to those who consumed them less than two times per week [117].

Type 2 diabetes

Type 2 diabetes (T2D) has been linked to excessive intake of fried foods (Table 3) [101]. The risk of developing T2D showed a positive correlation with the consumption of fast food and fried foods from restaurants [118]. In the study of women, there was a positive link between the consumption of potatoes and French fries and the development of type 2 diabetes. The risk was particularly significant when potatoes replaced whole-grain products in their diets. However, this association remained independent of various established risk factors for type 2 diabetes. The correlation between potato intake and the risk of type 2 diabetes was most noticeable among overweight and inactive women [119].

Hypercholesterolemia

The risk factors linked to hypercholesterolemia include BMI (body mass index), consumption of fried foods, and physical activity levels (Table 3). Among these factors, fried food consumption is the most significant influencing risk factor for the development of hypercholesterolemia [120]. The chances of developing hypercholesterolemia can be decreased from consumption of a well-balanced diet [121]. There was higher risk of developing hypercholesterolemia in people who consume fried foods in quantities greater than or equal to 67 g per day i.e., 3.33 times compared to those who consume less than 67 g of fried foods per day [120]. Consuming fried foods rich in saturated fat can lead to elevated LDL (Low-density lipoprotein) cholesterol levels, which, in turn, can cause the narrowing of blood vessels [122]. Engaging in physical activity has the ability to lower LDL cholesterol and reduce overall cholesterol levels in the body [123]. With the occurrence of dyslipidemia, there is a notable correlation between the type of fried food, the frequency of fried food consumption, and the amount of fat intake from fried foods [124].

Conclusions

Deep-fat frying is a traditional and widely practiced technique for preparation of food. Consumers are drawn to deep-fried foods primarily due to their sensory attributes, including taste, flavor, and texture. However, the consumption of these foods presents challenges due to their higher fat content, contributing to a higher calorie count. During the process of deep-fat frying, the food undergoes through a numbers of physical, chemical, as well as nutritional changes. These changes can be both desirable and undesirable. The process of frying can bring changes in the oil used for cooking. These changes can result in formation of carcinogenic compounds. Obesity is one of the major problems resulting due to the overconsumption of fried foods and can create cardiovascular issues. Many health issues like heart disease, cancer, type 2 diabetes, hypercholesterolemia are interlinked with the consumption of deep-fat fried foods.

Deep-fat fried foods have been the subject of several studies to date. These studies have been focused to know about the changes in food, changes in the cooking oil used, formation of carcinogens, reduce the undesirable changes and limit the fat uptake in foods during frying. Fried foods continue to be in high demand among consumers despite growing health concerns about them. Therefore, the studies should be concentrated on limiting the growing health risks associated to fried foods without reducing the sensory features of the foods so that consumers can enjoy the food with higher nutritional values and minimum concerns about health-related issues.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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