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REVIEW

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Deep-frying impact on food and oil chemical composition: Strategies to reduce oil absorption in the final product

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Abstract

During frying, oils can deteriorate due to autoxidation and hydrolytic alterations, processes influenced by the oil's fatty acid composition (FAC) and antioxidant content. However, there are different techniques to improve fried food quality and reduce oil absorption. This review aims to assess existing literature on the interactions between frying methods, oil selection, and the chemical composition of foods. To achieve this goal, the article examines the impact of oil FAC, antioxidants, pretreatments, and alternative frying technologies. A literature search was conducted from 2016 to 2023. The keywords used were (AND/OR) frying, fried foods, oil, oil absorption, and fatty acids. Oils rich in monounsaturated fatty acids and antioxidants, such as olive oil, are recommended for their nutritional benefits and improved oil stability. The water content and structure of the food also play a significant role in oil absorption. Pretreatments to diminish food moisture content contribute to a lower oil absorption in the fried food while mitigating excessive accumulation of lipid oxidation products. Proper selection of frying oils, incorporation of antioxidants, and the use of pretreatments could help prevent chemical changes and minimize oil absorption during frying. These measures contribute to maintaining the nutritional quality and safety of fried foods while also enhancing their overall sensory appeal.

KEYWORDS
aldehydes, fatty acids, fried foods, lipid oxidation products, thermal oxidation

1 | INTRODUCTION

Frying food is one of the world's most popular and oldest culinary techniques, used to produce tasty, stable, and easy-to-prepare foods (Berk, 2018). During frying, food is immersed in hot oil at temperatures ranging from 160 to 180°C, which results in heat and mass transfer (Garcimartín et al., 2020). This process causes the cell walls in the food to rupture and form pores that facilitate oil absorption (Oke et al., 2018). The food's direct contact with hot oil results in a dry, crispy, golden crust that acts as a barrier against excessive oil absorption while dehydrating the food, leaving a moist center (Asokapandian et al., 2020). The amount of oil absorbed mainly depends on the reduction in internal pressure due to moisture loss (Chang et al., 2020). The absorption of oil in fried food increases with higher

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polyunsaturated fatty acids (PUFA) content in oils, lower frying temperatures, longer exposure times, and the use of flat, porous, and moist foods (Multari et al., 2019; Yang et al., 2020).

Moreover, during frying, oils can deteriorate due to accelerated autoxidation of triglycerides and hydrolytic alterations, a process highly influenced by the oil type and its fatty acid composition (FAC) (Dobarganes & Márquez-Ruiz, 2015). Various oils from different origins are available, including coconut oil, which is rich in saturated fatty acids (SFA); olive, avocado, and canola oils, which have a higher content of monounsaturated fatty acids (MUFA); and corn, soybean, sunflower, and grape seed oils, which primarily contain polyunsaturated fatty acids (PUFA) (Kenar et al., 2017; Medeiros et al., 2020). High temperatures during frying alter the oil's FAC, reducing the content of polyunsaturated fatty acids (PUFA) while increasing the levels of SFA and trans fatty acids (TFA) (Ekiz & Oz, 2019). Oils rich in PUFA are more prone to peroxidation and the formation of lipid oxidation products (LOPs) such as aldehydes compared to oils rich in monounsaturated fatty acids (MUFA) and SFA (Le Gresley et al., 2019). These LOPs can potentially penetrate the food and pose health risks when consumed (Grootveld et al., 2020). Frequent consumption of fried foods (four or more times a week) is associated with an increased risk of developing type 2 diabetes, heart failure, obesity, and hypertension (Gadiraju et al., 2015). It also promotes the development of noncommunicable diseases (NCDs) and raises mortality rates (Kim et al., 2019; Srour et al., 2019). Therefore, dietary guidelines recommend reducing fried food consumption. Additionally, varying frying parameters should be considered to minimize potential health risks in the general population. Considering these antecedents, this review aims to assess existing literature on the interactions between frying methods, oil selection, and the chemical composition of foods. To achieve this goal, the article examines the impact of oil FAC, antioxidants, pretreatments, and alternative frying technologies. By analyzing this information, the paper presents evidence-based recommendations for strategies to reduce the risks associated with deep-frying and improve the nutritional quality of fried foods.

2 | METHODS

This article is a narrative review of the deep-frying process and its relationship with the FAC of foods and oils subjected to this culinary technique. Moreover, different factors affecting oil absorption were revised. A literature search was conducted in the scientific databases PubMed, Web of Science, and Scopus for studies published from 2016 to 2023. This review period was chosen to include the most current and relevant research on the deep-frying process and the latest advancements and emerging trends in frying methods. The keywords used in the study included frying, fried foods, oil, oil absorption, and fatty acids, with the conjunctions ‘AND’ and ‘OR’ applied as appropriate. Articles that discussed superficial frying or evaluated natural oils not commonly available on the market were excluded from the study.

2.1 | Fundamentals of the frying process

Frying is a thermal process where fatty matter is a medium for transferring heat to foods (Berk, 2018). Deep frying entails immersing food items in hot oils, typically within the temperature range of 160–180°C, for a sufficient duration to facilitate rapid heat transfer (Erickson, 2015). This results in the formation of a uniform layer on the surface of the food, simultaneously generating substantial changes in its chemical, physical, and sensory properties (Asokapandian et al., 2020). These transformations include protein denaturation, hydrolysis, starch gelatinization, and food dehydration (Berk, 2018; Oke et al., 2018; Van Koerten et al., 2017), ultimately resulting in a reduction of its moisture content (Pankaj & Keener, 2017). Furthermore, it contributes to the formation of acrylamide in most food products (Baskar & Aiswarya, 2018).

The deep-frying process comprises four stages (Figure 1). First, during the initial heating period, food is placed in the oil and its surface water reaches boiling point, with heat transferred by free convection. Next, in the surface boiling stage, water vapor bubbles appear and a crispy crust forms as the oil's heat transfer capacity increases, driven by forced convection. The third stage, the falling rate phase, is the longest, where the core heats up, moisture is lost, starch gelatinizes, and proteins denature. Finally, the bubble endpoint stage occurs when the remaining water in the food vaporizes completely, concluding the frying process (Cabreriso et al., 2017; Safari et al., 2018). Overall, understanding these stages and their effects on food could help to optimize frying methods to achieve the desired culinary and health outcomes.

2.2 | Chemical alterations that take place during frying

During frying, numerous chemical reactions such as hydrolysis, oxidation, and polymerization occur in the oil. These reactions are influenced by factors such as food moisture, atmospheric oxygen, and high temperature (Ngobese et al., 2017). The moisture in the food reacts with the triacylglycerol ester bonds present in the oil, leading to hydrolysis and the production of diacylglycerols, monoacylglycerols, and free fatty acids (Segura et al., 2019). These factors also can lead to a rapid autoxidation of fatty substances, modifying triglycerides by at least one of the three fatty acid chains (Bazina & He, 2018). Atmospheric oxygen generates oxidation compounds, producing free radicals, peroxides, and hydroperoxides (Hwang & Winkler-Moser, 2016), which result in the polymerization of fats, forming non-volatile polar compounds, dimers, and triacylglycerol polymers (Zribi et al., 2016). Lipid peroxidation results from the autoxidation process, which takes place in the presence of oxygen and is accelerated by factors such as heat (e.g., during frying), radiation, or metal ions/metalloproteins. This complex process can be divided into three distinct phases. The first phase of lipid peroxidation, initiation, begins with the removal of a hydrogen atom from the methylene group adjacent to a double bond, resulting in lipid alkyl

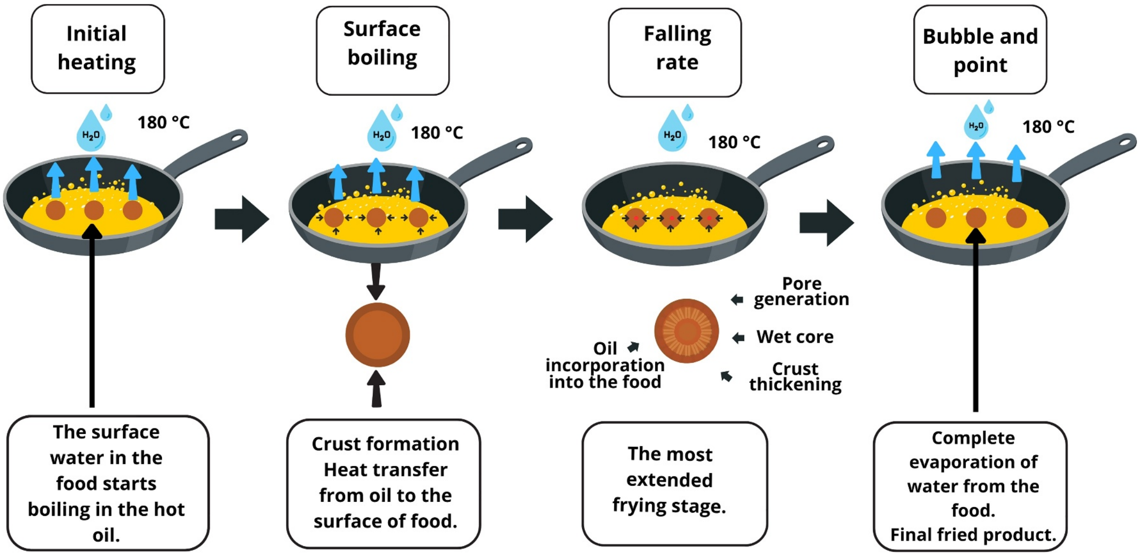


FIGURE 1 Stages of the deep-frying process. (1) Initial heating, (2) Surface boiling, (3) Falling rate, (4) Bubble end point.

radicals (R·) (Zamuz et al., 2022). In the propagation phase, R· reacts with molecular oxygen (O_2) to form lipid peroxyl radical (ROO), which is highly reactive and generates more R· and hydroperoxides (ROOH) (Hwang & Winkler-Moser, 2016; Zamuz et al., 2022). ROOH degrades into secondary LOPs such as alkanes, aldehydes, ketones, and others (Hwang & Winkler-Moser, 2016). The final phase, termination, occurs when R· or ROO· react with other radicals or antioxidants to form stable end products (O'Brien & O'Connor, 2022; Zamuz et al., 2022).

These chemical reactions produce volatile and nonvolatile compounds, which, under ideal deep-frying conditions, can be kept at minimal levels (Ahmad Tarmizi & Kuntom, 2021). In this regard, Table 1 presents the effect of different frying methods on chemical characteristics of oils and processed foods. For instance, deep-fried potato chips have shown lower levels of hydroperoxides and aldehydes (including *trans*-2-alkenals, *trans*, *trans*-alka-2,4-dienals, and *n*-alkanals) when fried in olive oil compared to sunflower seed oil (Moumtaz et al., 2019). These nonvolatile compounds accumulate more in sunflower oil and are absorbed into the food as frying progresses, unlike olive oil (Lozano-Castellón et al., 2022). This can be attributed to the higher susceptibility of oils rich in polyunsaturated fatty acids (PUFA) to oxidation, which results in accelerated degradation at high temperatures (Hashempour-Baltork et al., 2016; Nieva-Echevarría et al., 2016). This degradation leads to increased intermolecular forces and greater molecular stability, consequently raising oil viscosity (Sahasrabudhe et al., 2017). Thermal degradation involves the cleavage and reformation of double bonds, transforming *cis* into *trans* isomers, resulting in TFA (Nieva-Echevarría et al., 2016; Romano et al., 2021). The main LOPs found in frying oils comprise hydroperoxides and aldehydes (Nayak et al., 2016). While volatile compounds (such as carbonyl compounds) do not typically accumulate significantly in fried foods, nonvolatile compounds (e.g., ketone, aldehyde, acid, hydrocarbons, and lactones) tend to accumulate over time as the frying process continues (Al Faruq et al., 2022; Luo et al., 2024). These compounds may interact with other constituents present in the food, including proteins, sugars, pigments, vitamins, and minerals, ultimately diminishing the nutritional quality of the product (Al Faruq et al., 2022). These changes are also reflected in the appearance, texture, and potential emergence of undesirable rancid flavors and aromas in the food (Tzompa-Sosa et al., 2022). Aldehydes and ketones play a pivotal role in contributing to the undesirable and unpleasant flavors and aromas often detected in highly oxidized or rancid oils, such as those resulting from extended periods of frying and the reuse of frying oils (Hu et al., 2023; Rani et al., 2023). When ingesting foods contain aldehydes, these compounds easily cross cell membranes and enter intracellular environments, generating reactive oxygen species and stimulating aldehydes' further production (Kamal-Eldin et al., 2022). Aldehydes are usually toxic and can be carcinogenic, damaging cells, tissues, and organs and increasing the risks of NCDs, cancer, cardiovascular and neurological diseases (Hosseini et al., 2016). In summary, the accumulation of these compounds could impact the nutritional quality and sensory attributes of fried foods, potentially leading to undesirable flavors and health risks. Proper management of frying conditions can help minimize these negative effects and maintain the quality of fried foods.

2.3 | Stability of oils used during the deep-frying process

Oils have different fatty acid profiles and other components (e.g., antioxidants) that determine their stability during frying. It is widely accepted that the presence of more double bonds produces a greater oxidative degradation of lipids as there are more reactive hydrogen atoms (Pooja & Sukhneet, 2021; Rauf et al., 2017). Thus, the available information shows that the highest levels of LOPs are produced in PUFA-rich oils (e.g., corn, soybean, sunflower, and grape seed oils),

TABLE 1 Evaluation of frying methods on chemical characteristics of oils and processed foods.

Reference	Raw material	Frying oil	Methods of frying	Parameters	Main results
Luo et al. (2024)	Fish cakes (surimi)	HOSO PO	Frying at 180°C	Total polar compounds content Degree of oxidation	After 18 h of frying, the total polar compound content of PO and HOSO reached 25.67% and 27.50%, respectively. HOSO had a lower degree of oxidation than PO after 24 h of continuous frying.
Hu et al. (2023)	Carp fillets	SO	The fillets were padded with SO (AF). The fillets are covered with a small amount of SO (RF). SO was poured into a nonstick cookware (PF).	Oxidation index Glycosylated hazardous products	As frying progressed, the level of carbonyl protein and lipid oxidation products increased significantly (following AF > PF > RF). Higher increment of alcohols in RF, higher increase of aldehydes and ketones in AF, and more abundant pyrazines and furans in PF.
Ioannou et al. (2023)	Fresh potatoes	OO, EVOO Addition of 5%, 10%, and 20% of SEO	Domestic deep frying electric fryer at a temperature of 170 ± 5°C	Antioxidant capacity, TPC, and PC	The addition of SEO to OO reduced the rate of formation of secondary oxidation products. EVOO was more resistant to oxidation than OO.
Córdoba et al. (2023)	EVOO	EVOO	Culinary techniques: Frying, boiling (water/oil mixture), and sautéing.	Antioxidant capacity before and after the use of culinary techniques. The behavior of the phenols present in the oil.	The antioxidant capacity showed an increase after sautéing and decreased after boiling and frying. The behavior of bioactive compounds depends on the temperature and cooking medium.
Yılmaz and Yorulmaz (2023)	Potato sticks	RSO blended with ROPO	Frying at 180°C	Free fatty acids, peroxide values, total polar contents, fatty acid profiles, *p*-anisidine values, *α*-tocopherol contents, and photometric color indices.	Thermo-oxidative degradation products increased as the frying progressed for all oils; however, the decomposition rate was found to slow down in blend oils by stabilizing with ROPO. Blending RSO with ROPO decreased linoleic and linolenic but increased the oleic and palmitic acid percentages of the blends.
Szabo et al. (2022)	Potatoes	PO, RO, SO, SUO, and EVOO	Frying at 180°C	Trans fatty acids	The highest linoleic acid and alpha-linolenic acid values were measured in fresh samples, whereas significantly lower values were detected in almost all samples following the heating sequences. The lowest levels of trans fatty acids were detected in the fresh oils, while their

(Continues)

TABLE 1 (Continued)

Reference	Raw material	Frying oil	Methods of frying	Parameters	Main results
					values significantly increased in almost all samples during heating.
Romano et al. (2021)	Purple potatoes	HOSO	Frying at 180°C with and without food matrix.	Aldehydes and alkanes in thermally oxidized, and frying oils.	Oxidative stability increases during frying, with a correlation existing between PC versus UFA/SFA and PC versus C18:2/C16:0. Oil or fat with a low degree of unsaturation is the best option.
Wann et al. (2021)	Edible oils	Spanish EVOO, Italian EVOO, AO, CO, SO	Simulated laboratory-frying episodes at 180°C.	Detection of lipid oxidation products, and aldehydes.	PUFA-rich SO and corn oils yielded the highest concentrations of oil aldehydes, whereas monounsaturated fatty acid (MUFA)-rich avocado and olive oils were much more resistant to the peroxidation process
De Alzaa et al. (2021)	Chips, chicken nuggets, and broccoli	Extra virgin olive oil (EVOO), CO, and GO	Frying at 180°C	Fatty acid profile, antioxidant content, and PC.	All food presented more antioxidants and MUFA after having been cooked with EVOO than after cooking with CO and GO. EVOO was shown to decrease the PC in chips and chicken nuggets.
Sohu, (2020)	French fries	Commercial oil blend (CO, SUO, CSO, and SO)	Frying at 170°C	Free fatty acids (FFA), *p*-anisidine value (p-AV), viscosity, and fatty acid composition (FAC)	Results showed that increasing repetitive cycles leads to an increase in FFA, AV, p-AV, and viscosity, which is an indicator of frying oil deterioration.
Segura et al. (2019)	SUO	SUO	Vacuum frying Traditional frying	Thermo-oxidation	SUO showed a slower deterioration rate for vacuum thermo-oxidation compared to traditional conditions, hence being a better option for the preservation of bioactive compounds.
Moumtaz et al. (2019)	Potatoes	SUO, CO, EVOO, monounsaturated algae oil.	Deep frying (170°C for 10 min).	SFA, MUFA, and PUFA	SFA, MUFA, and PUFA were for SUO 11.0%, 28.0%, and 61.0% respectively, for CO 14.4%, 23.3%, and 61.4%; for CO 7.0%, 64.4%, and 28.5%; for EVOO 13.0%, 77.4%, and 9.4%; and for monounsaturated algae oil 4.0%, 91.2%, and 4.2%.
Ben Hammouda et al. (2018)	Potatoes	ROPO mixed with RCO (80:20)	Frying at 180°C	Total polar compounds, anisidine value, *trans* fatty acids, and free fatty acids.	The mixture of ROPO/RCO showed higher chemical stability than

TABLE 1 (Continued)

Reference	Raw material	Frying oil	Methods of frying	Parameters	Main results
					pure ROPO based on PC and polymers. The rate of PC formation was 23.3% for the mixture and 30.6% for the pure oil.
Flores et al. (2018)	Deep-fried foods sold by unlicensed street vendors.	Blends of edible oils	Frying	Acidity index, peroxide index, TOTOX index, PC, and fatty acid profile.	Most food samples (80%) had at least a 10% fat content. Many samples also had high peroxide values (1.7–103.3 meqO2/kg), p-anisidine (100.2–311.0), TOTOX (>103.6), and PC (14.2%–49.7%).
Santos et al. (2018)	Potatoes	SUO, SO, CO, and OO	Conventional frying and air frying	Color, moisture, lipid composition, tocopherols, antioxidant activity, and acrylamide.	All tested oils behaved similarly and were mainly responsible for potato enrichment in tocopherols, phenolics, and β-carotene, but lower lipid oxidation was observed with olive oil.
Yu et al. (2018)	Potatoes	(RCO), SO, OO, and vegetable shortening.	Frying at 180°C	Physicochemical properties and oxidative stability.	The total polar compounds of all the oils after 80 frying cycles were between 8.1% and 9.5%, not exceeding the rejection limit after frying. Tocopherols in SO, OO, and vegetable shortening, and DPPH radical scavenging activities of OO and vegetable shortening significantly decreased after frying.
Ngobese et al. (2017)	Irish potatoes	Commercial canola oil	Blanching at 75°C for 10 min or 85°C for 5 min. Frying at 160°C for 2 min or 180°C for 1 min.	Physical and sensory quality of potatoes Mineral elements.	Blanching and frying treatments LTLT (low temperature for a long time) and HTST (high temperature for a short time) have significant effects on the physical and sensory quality of French fries. LTLT blanching resulted in better retention of mineral elements.
Nieva-Echevarría et al. (2016)	Fillets of farmed gilthead sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*)	EVOO and SUO.	Shallow frying in a conventional pan and microwave using a domestic baking dish. At 170°C for 25 min on each side of the fillet.	Secondary oxidation products	No thermo-oxidation was observed in the extra-virgin olive oil used for frying fish. The highest concentration of secondary oxidation compounds was found in the sunflower oil heated in the pan. Frying in a pan caused a higher degree of thermos-oxidation of the oil than frying in the microwave.

(Continues)

TABLE 1 (Continued)

Reference	Raw material	Frying oil	Methods of frying	Parameters	Main results
Zribi et al. (2016)	Potatoes	A mixture of refined oils (SO + PO, OO, and OO + PO)	Frying 9 min at 180°C	Total polar compounds and volatile compounds, fatty acid profile, and phytosterols.	The degradation of linoleic acid and β-sitosterol was significantly observed for the SO/PO mixture. The results showed that the appropriate blend of monounsaturated OO with PO increases its stability, thus improving the quality of the olive oil during frying.

Abbreviations: AF, Air-frying; AO, avocado oil; CA, canola oil; COO, corn oil; CSO, cottonseed oil; EVOO, extra virgin olive oil; GO, grapeseed oil; HOSO, high oleic sunflower oil; MUFA, monounsaturated fatty acids; OO, olive oil; PC, polar compounds; PF, pan-frying; PO, palm oil; PUFA, polyunsaturated fatty acids; RCO, refined coconut oil; RF, roasted-frying; RO, rapeseed oil; ROPO, refined olive pomace oil; RSO, refined safflower oil; SEO, sesame oil; SFA, saturated fatty acids; SO, soybean oil; SUO, sunflower oil; UFA, unsaturated fatty acids.

followed by MUFA-rich oils (e.g., olive, avocado, and canola) and, to a lesser extent, SFA-rich oils (e.g., coconut and palm oil) (Frakolaki et al., 2023; Rauf et al., 2017). Linseed and chia oils are also PUFA-rich but less used in frying because they have lower oxidative stability due to their higher alpha-linolenic acid (ALA, C18:3n-3) content (Heck et al., 2019). When comparing different oils (sunflower, corn, soy, canola, extra virgin olive, avocado seaweed rich in monounsaturated, and/or coconut oils) submitted to deep-frying at 180°C for 90 min, PUFA-rich oils (e.g., sunflower and corn oil) present the highest levels of LOPs and toxic aldehydes (Khor et al., 2019; Wann et al., 2021). Moreover, when comparing different PUFA-rich oils, those rich in n3 PUFA are less stable than those mainly composed of n6 PUFA (e.g., soy oil vs. corn oil) (Arslan et al., 2018). Furthermore, MUFA-rich oils (i.e., virgin olive and avocado oil) exhibit a lower content of LOPs and aldehydes than PUFA-rich oils, even after six reheating cycles (Ioannou et al., 2023; Wann et al., 2021). The lowest content of LOPs is found in SFA-rich oils, such as coconut oil (Ben Hammouda et al., 2018; Grootveld et al., 2020).

Oil processing, extraction method, and refinement level will influence its stability during frying (Percival et al., 2019). For example, extra virgin olive is only produced with mechanical processes maintaining a naturally lower level of TFA and a high level of antioxidants (Córdoba et al., 2023; Percival et al., 2019). Refined oils are bleached and heated during the industrial process, while different antioxidant additives can be added to oils to improve their stability (Ahmad Tarmizi & Kuntom, 2021). The antioxidant content is pivotal in the oil's thermal resistance. Thus, adding natural or synthetic antioxidants to PUFA-rich oils increases the oxidative stability of oil subjected to deep-frying (Yang et al., 2022; Yılmaz & Yorulmaz, 2023). Wang et al. (2020) evaluated the oxidative stability of sunflower oil added with natural antioxidants (peppermint essential oil) and synthetic antioxidants (butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA) and tertiary butylhydroquinone (TBHQ)) subjected to deep-frying at 180°C in a continuous process for 30 h. A decrease in LOPs such as conjugated dienes and trienes, aldehydes, and polymers was observed compared to sunflower oil without antioxidants (Wang et al., 2020). The reported data indicate that oils differ in their fatty acid profiles and antioxidant content, affecting their stability during frying and the levels of LOPs they generate. Therefore, careful selection and treatment of oils, along with the addition of natural or synthetic antioxidants, can greatly enhance their oxidative stability and improve the quality and safety of fried foods.

2.4 | Fatty acid profile changes in frying oil and fried foods

Heating and reusing frying oils can change oil's FAC. However, palm oil (rich in SFA) exhibits minor changes in fatty acid profile during frying, even after 40 h of frying cycles of 10 min (180°C). On the contrary, sunflower seed oil (rich in PUFA) reduced their PUFA and MUFA content over time (Liu et al., 2021). Sohu et al. (2020) compared the FAC of a mixture of vegetable oil (canola, sunflower, cottonseed, and soybean) subjected to deep-frying at 170°C for 13 min for six cycles (Sohu et al., 2020). The authors observed an increase in SFA content (from 13.6% to 21.6%) mainly of lauric (C12:0), myristic (C14:0), palmitic (C16:0), stearic (C18:0), and arachidic (C20:0). At the same time, there was a decrease in unsaturated fatty acids, oleic acid (OA; C18:1), linoleic acid (LA; C18:2 n–3) and ALA from 80.8% to 71.2% from the first to the sixth cycle. Moreover, the TFA content progressively increased (from 1.1% to 6.5%) (Sohu et al., 2020). These studies indicate that repetitive frying deteriorates the oil's fatty acid profile toward a higher content of SFA and TFA to the detriment of MUFA and PUFA (Cui et al., 2017; Flores et al., 2018; Sohu et al., 2020).

In addition, frying induces an interchange of fatty acids between the food and the frying oil, altering their respective fatty acid profiles (Szabo et al., 2022). Santos et al. (2018) compared the nutritional quality of potato chips deep-fried at 175°C (for a total of 28 h; 8 h/d, frying cycles every 30 min) using peanut, canola, and Extra virgin olive oil (EVOO). TFA levels increased with prolonged frying time, with olive and canola oil yielding the lowest and the highest TFA content (Bhardwaj et al., 2016; Santos et al., 2018). In another study, the nutritional profiles of pre-cooked French fries, chicken nuggets, and broccoli were assessed after deep-frying at 180°C for 4 min, employing EVOO, canola oil, or grapeseed oil through four frying cycles (De Alzaa et al., 2021). When canola and grapeseed oils were used, PUFA decreased, while MUFA increased in cooked foods compared to their raw counterparts. In contrast, frying with olive oil led to an increase in PUFA and a decrease in MUFA in chicken nuggets and French fries compared to the raw versions. Fried broccoli exhibited a fatty acid profile similar to the oil used. Remarkably, olive oil resulted in reduced formation of LOPs. Additionally, potatoes fried in canola and grapeseed oil exhibited the highest levels of polar compounds, followed by chicken nuggets and broccoli. Nonetheless, olive oil reduced the accumulation of polar compounds in French fries and chicken nuggets by approximately 20%. Foods cooked with grapeseed oil had an increased trans fatty acid (TFA) content, followed by canola oil, whereas foods cooked with olive oil either maintained stable TFA levels or experienced a reduction of approximately 70% (De Alzaa et al., 2021; Dordevic et al., 2020). In general, heating, and reusing frying oils could modify the FAC of both the oil and fried food. Repetitive frying degrades the oil, increasing saturated and trans fatty acids and reducing monounsaturated and polyunsaturated fatty acids. Different oils impact the nutritional profiles of fried foods differently, with olive oil demonstrating a significant reduction in polar compound accumulation and maintaining more stable trans fatty acid levels compared to other oils.

2.5 | Antioxidant content changes in fried foods

As previously discussed, antioxidants are crucial in maintaining oil stability by neutralizing free radical species. Consequently, the frying process can significantly impact the levels of antioxidants, including phenolic compounds, flavonoids, tocopherols, and other bioactive substances, within the food and the frying oil. These changes are closely related to the choice of frying oil and the type of food being fried (Adu et al., 2019). Different oils (refined coconut, refined soy, pure olive, and vegetable shortening (a blend of palm oil)) were subjected to deep-frying at a temperature of 180°C for 4 min, repeating this process 80 times (Yu et al., 2018). After 80 frying cycles, a decrease of tocopherols was observed in soybean oils (from 89.9 to 82.9 mg/100 g of oil), olive (from 14.9 to 2.3 mg/100 g of oil), and vegetable shortening (8.7 to 0.6 mg/100 g oil), correlated with lower antioxidant activity (assessed by DPPH). No tocopherols were detected in coconut oil (Yu et al., 2018). Adu et al. (2019) evaluated frying oils from roadside food vendors after frying three different groups of products: legumes and tubers, pastry products, and animal protein (meat or fish). In their study, phenolic, flavonoid, vitamin A, and vitamin E contents decreased in oils with subsequent use, except for oils used for frying meat products, which showed increased total phenolic and flavonoid content with use. Therefore, the antioxidant content of foods may be affected by repeated use of frying oil, with retention largely dependent on factors such as the characteristics of the food being fried and the type of oil used. In addition, De Alzaa et al. (2021) found that potatoes, broccoli, and chicken nuggets deep-fried in grapeseed, extra virgin olive, or canola oil (180°C for 4 min) presented an increase in the content of total antioxidants (6653 ppm) only when fried with EVOO. This is explained by increased phenols, squalene, and tocopherols (vitamin E) contributed by olive oil (Wu et al., 2019). Thus, olive oil exhibits a higher antioxidant content, enhancing fried foods' nutritional value (Rinaldi de Alvarenga et al., 2019). Considering the oil absorption during the frying process, the frying oil enrichment of antioxidants could improve the nutritional profile of the fried food (De Alzaa et al., 2021; Rinaldi de Alvarenga et al., 2019). However, in some cases, antioxidants or bioactive compounds may remain in the frying oil (Ramírez-Anaya et al., 2019). and not be transferred to food (e.g., products of animal origin) (Adu et al., 2019). For example, fat-soluble vitamins, carotenoids, and tocopherols migrate into the oil due to their solubility in fats, which implies a loss or decrease in their content in the food (Devi et al., 2021). A reduction of up to 60% in ascorbic acid content was observed in French fries during frying cycles ranging from 30 min to 28 h in different oils (peanut, canola, or extra virgin olive). Total carotenoids experienced a slight decrease in the initial hours of frying (between 8 and 12 h), while tocopherols increased when olive oil was used and decreased with canola oil (Santos et al., 2018). Regarding phenolic compounds, they exhibited a two-fold increase in fries fried in olive oil after 28 h of frying but remained relatively constant in fries fried in other oils. Antioxidant activity significantly decreased after 12 h of frying in all oils (Santos et al., 2018). Thus, frying for extended periods (>12 h) led to notable losses in ascorbic acid, reduced antioxidant activity, and increased oxidative stress in frying oils (Wu et al., 2019; Yu et al., 2018). Shorter frying periods show different outcomes, especially when compared with other cooking methods (Cattivelli et al., 2021). For instance, Cattivelli et al. (2021) evaluated the impact on antioxidant content of different cooking methods. The phenolic compound contents of onions subjected to four cooking methods were compared: baking at 180°C for 30 min, boiling for 30 min, deep-frying with sunflower seed oil at 140°C for 8 min, and grilling at 110°C for 15 min, were assessed. The results revealed a notable increase in the total phenolic content, primarily driven by quercetin derivatives, during frying (61.6% increase), followed by baking (58.7% increase) and grilling (41.2% increase), as compared to the raw samples. Boiling, in contrast, led to a 37.5% decrease in the total phenolic content (Cattivelli et al., 2021), probably because phenolic compounds tend to be lost during cooking in water (Zhao et al., 2019).

On the contrary, in other cooking methods, such as baking, frying, and grilling, the food is dehydrated, causing water loss and the breakdown of its structure, which in turn allows the compounds phenolics separate from the fiber and increase its phenolic content (Zhao et al., 2019; Zhao et al., 2021). Ramírez-Anaya et al. (2019) evaluated the antioxidant capacity of EVOO using four different cooking methods for 10 min: deep-frying (180°C), sautéing (80–100°C), boiling (water at 100°C), and boiling with water and oil (in a ratio of 4.5:0.5; 100°C). Five types of vegetables (potato, squash, sweet potato, tomato, and eggplant) were cut into one-cm cubes and cooked (Ramírez-Anaya et al., 2019). Cooking using water increased the total phenolic content while cooking with oil decreased phenolic compounds (Ramírez-Anaya et al., 2019). In conclusion, an increase in the total phenolic content of the water in which the vegetables were cooked was observed. At the same time, the antioxidant capacity showed lower values when no oil was added (Cattivelli et al., 2021). On the other hand, cooked olive oil reduced phenolic content and antioxidant capacity compared to crude oil (De Alzaa et al., 2021). These findings could be attributed to the transfer of phenols to the food during cooking and the possible decrease or loss of these compounds due to prolonged heat (Ramírez-Anaya et al., 2019; Zhao et al., 2019; Zhao et al., 2021). Available information indicates that the frying process could have a significant impact on the levels of antioxidants and phenolic compounds in both food and frying oil, depending on the type of oil used and frying duration. While olive oil demonstrates higher antioxidant content and enhances the nutritional value of fried foods, prolonged frying can lead to losses in antioxidant activity and other bioactive compounds. Therefore, careful selection of frying oils and consideration of frying periods are essential for preserving the nutritional quality and safety of fried foods.

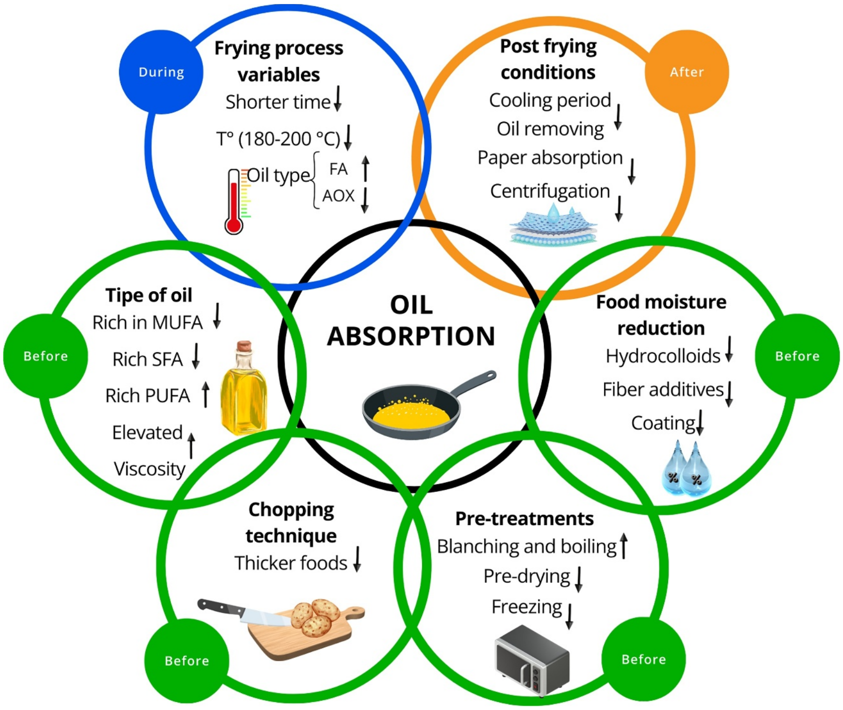
2.6 | Factors affecting oil absorption during frying

Numerous factors influence oil absorption during frying (Figure 2), including oil composition and viscosity (Yu et al., 2018), frying temperature/duration (Millin et al., 2016), food chemical composition, pre-frying processing (Zhang et al., 2018), food microstructure (Alam & Takhar, 2016), and oil removal after deep-frying (Devi et al., 2021). The FAC of the oil not only affects its thermal stability but also relates to its viscosity. A higher viscosity is associated with increased oil absorption on the food surface and within its core during cooling (Mahmud et al., 2023; Wiege et al., 2020). Liu et al. (2021) evaluated the viscosity of two different oils (palm and soybean) by deep-frying potato strips at different temperatures (140 and 200°C) for 4 min. Higher viscosity was observed in the oils subjected to frying at 200°C, with soybean oil exhibiting a greater increase. However, the food's oil content followed an ascending trend from 140°C to 180°C and decreased at 200°C (Liu et al., 2021). This could be attributed to the rapid crust formation due to the very high temperature, which prevents oil penetration (Mahmud et al., 2023; Sandhu & Takhar, 2015). When the food is removed from the frying medium, its temperature begins to decrease below 100°C, leading to the condensation of water vapor within the product and a subsequent drop in internal pressure (Zhang et al., 2016). This reduction in pressure creates a vacuum effect that facilitates oil absorption (Ziaiifar et al., 2008). Consequently, the surface-adhered oil infiltrates the porous structure created by water molecule evaporation (Sandhu & Takhar, 2015). Indeed, both moisture content and chemical composition significantly influence oil absorption. Onipe et al. (2021) studied a dough formulated with the partial replacement of wheat flour with wheat or oat bran (0%–20%). Dough samples were subjected to two humidity levels (65% and 100 wt%) and deep-fried at 180°C for 5 min. Notably, incorporating oat bran at levels between 5% and 20% in the dough, particularly under lower moisture conditions, reduced oil content within the core of the fried food. The absorbed oil during frying predominantly belonged to the superficially penetrated type, primarily located in the food's crust (Onipe et al., 2021). Another study assessed corn amylose content (waxy 2.48%, normal 27.34%, and high 50.63%) and moisture (20% and 60%) effects on oil absorption during deep-frying at 180°C for 20 min (Chen et al., 2019). A lower amylose and a higher moisture content induced structural changes, including the loss of granular morphology and the disruption of crystalline structures. The waxy starch samples presented higher oil absorption (Chen et al., 2019). There is a negative correlation between amylose content and the final moisture of the product (Chen et al., 2019; Onipe et al., 2021). Water molecules are sequestered by amylose or fiber molecules, reducing free water content in the food and leading to lower moisture levels (Hemdane et al., 2016). Lower moisture levels in the food are associated with diminished oil absorption (Chen et al., 2019). Conversely, a higher initial moisture content during deep-frying results in greater water loss and oil absorption (Onipe et al., 2021; Ziaiifar et al., 2008). Finally, oil absorption during frying is influenced by numerous factors, including oil composition and viscosity, frying temperature and duration, food chemical composition, pre-frying processing, food microstructure, and oil removal after frying. By understanding and optimizing these variables, it is possible to reduce excess oil uptake and improve the nutritional characteristics of fried foods.

2.7 | Strategies for reducing oil absorption during frying

Different pretreatments for reducing moisture and oil absorption in food products have been studied. In general, pre-drying treatments lower the water content and consequently diminish the mass transfer gradient (water-oil), reducing surface oil penetration and the overall oil content absorbed by the food (Cruz et al., 2018; Jia et al., 2018). Various pre-drying methods, including hot air, vacuum microwave, and infrared techniques, have effectively reduced the total oil content in potato sticks fried in palm oil at 180°C, with the hot air treatment yielding the most substantial reduction in total oil content (Jia et al., 2018). Notably, pre-drying potatoes in a hot air oven at 60°C led to a 21% reduction in oil absorption, a parameter directly correlated with frying time (Cruz et al., 2018). Other pretreatments for reducing oil absorption have been studied. In one study, French fries were deep-fried (170°C for 3 min) in 10 different edible oils after blanching, pre-frying, or freezing. Pre-frying and freezing yielded a reduced fat content in the final product. High-oleic acid sunflower oil exhibited lower oil absorption, while lard, soybean, rice bran, and corn oil led to higher absorption, primarily during pre-frying (Li et al., 2020). Furthermore, frozen French fries fried using

FIGURE 2 Factors that influence oil absorption in foods during deep-frying.



sunflower seed or olive oil (at 180°C for 3 min) exhibited minimal oil absorption (Alkaltham et al., 2020). Conversely, blanching followed by freezing resulted in the highest absorption of both oils (Heredia et al., 2014). Blanching (pretreatment with water) has been shown to increase oil absorption due to cell wall rupture, forming a porous honeycomb-type structure (Alkaltham et al., 2020; Isik et al., 2016). Deep-frying exacerbates this effect as the evaporation of water generates greater vapor pressure, causing structural damage to the food and facilitating oil penetration, ultimately resulting in higher absorption (Dehghannya & Ngadi, 2021; Li et al., 2020). In addition, freezing before frying reduces oil absorption by forming rigid ice crystals, limiting the mobility of water (Adedeji & Ngadi, 2018). This pretreatment limits water mobility in the different cellular compartments (Alkaltham et al., 2020). The crystals gradually melt from the outer layers to the interior, forming a firm surface crust that hinders water evaporation (Adedeji & Ngadi, 2018). This preservation of internal moisture leads to reduced oil absorption (Isik et al., 2016).

A viable strategy to mitigate oil absorption during frying involves adjusting the initial moisture, by regulating the amylose, or fiber content before frying, for instance, by applying hydrocolloid coatings. Potato samples coated with pea flour, pea flour with transglutaminase, chitosan, or pectin exhibited a reduction in oil content after frying at 170°C for 6 min in corn oil. Protein-based hydrocolloid coatings yielded oil reductions ranging from 9% to 15.9% (Al-Asmar et al., 2018). Hydrocolloid coatings reduced the heat transfer coefficient during frying (Kohajdová & Karovičová, 2009) and enhanced water retention within the food (Al-Asmar et al., 2018; Albert & Mittal, 2002).

The way potatoes are chopped before undergoing the frying process can wield a considerable influence on oil absorption. Different cut thicknesses (flat, batch-cooked, and ridged potato chips) were employed in a study involving potatoes of the same variety (Yang et al., 2017). Notably, the rigid potato chips displayed the highest porosity (50.78 ± 3.02%), featuring larger-diameter pores, followed by the flat chips (41.15 ± 3.56%) and the batch-cooked chips (32.58 ± 4.21%) (Yang et al., 2017). It is important to note that higher porosity was positively correlated with increased moisture content. Additionally, the batch-cooked chips exhibited smaller diameter pores and a trend toward lower oil content (non-significant) (Yang et al., 2017). In general, the total oil absorption in potato chips tends to rise when the food's microstructure presents larger pores and undergoes longer frying periods (Dehghannya & Ngadi, 2021). Post-frying handling can also modulate oil absorption. For instance, maintaining fried products at elevated temperatures employing centrifugation systems, or using absorbent paper (Debnath et al., 2009; Moreira et al., 2009) are common approaches.

In recent years, healthier frying options, such as air fryers, has become popular. Air fryers utilize rapid air circulation at high speeds rather than submerging food in oil (Ran et al., 2023). This method minimizes nutrient degradation, reduces the formation of acrylamides, and preserves the food's flavor, texture, and color while decreasing its fat content and overall caloric intake (Fikry et al., 2021; Santos et al., 2017). Sensory attributes of deep-fried falafel (178°C for 11 min and 180°C for 7 min) and air-fried falafel (140–200°C for 5–15 min) were compared. The air-fried falafel, particularly when cooked at 170°C for 15 min, received the highest scores for aroma, flavor, crunchiness, and overall preference. In addition, air-fried falafels reduced fat content (~45%), while deep-fried falafel increased the fat content by 32.8% (Fikry et al., 2021). Regardless of the oil and the specific air fryer equipment used, a 70% reduction in the total oil content is observed compared to deep-frying, reducing energy density by 45 kcal/100 g (Ran et al., 2023). Concordantly with the other studies, olive oil was the most stable (Santos et al., 2017). In general, when executed at optimal temperatures and durations, air-frying results in reduced nutrient degradation while preserving the food's color, flavor, and texture (Fikry et al., 2021). These emerging technologies provide an alternative for achieving healthier products while preserving sensory attributes similar to traditional fried foods, yet with significantly lower calorie and fat content (Ghaitaranpour et al., 2021). It is worth noting that these techniques offer ecological benefits, as they require minimal oil for cooking and do not generate effluents following the frying process (Santos et al., 2017). It is important to highlight that various pretreatments and emerging frying methods, such as air frying, could reduce moisture and oil absorption in food products, thereby enhancing their nutritional quality and sensory attributes. Air frying offers a healthier alternative to traditional frying by preserving the food's flavor, texture, and color while significantly lowering calorie and fat content. These strategies and technologies could be used to achieve healthier fried foods.

3 | CONCLUSION

Available data suggest that the interactions between frying methods, oil selection, and the chemical composition of foods highlight the importance of proper oil selection, incorporating antioxidants, and using pretreatments as key strategies to prevent chemical changes and reduce oil absorption during frying. Deep-frying alters food's physical, chemical, and sensory properties while posing health risks due to excessive consumption of LOPs. To mitigate these risks and enhance nutritional properties, oils rich in monounsaturated fatty acids and antioxidants, such as olive oil, are recommended for their nutritional benefits and improved oil stability. Additionally, pretreatments aimed at reducing food moisture content significantly lower oil absorption in fried foods and prevent the excessive accumulation of LOPs. Drying or freezing can decrease oil absorption, as can the addition of ingredients such as bran or increased amylose content in the foods. In addition, the retention of antioxidants in foods may be influenced by factors such as the characteristics of the food being fried and the type of oil used, underscoring the need to consider these variables when optimizing fried food quality and oil stability. Emerging technologies such as air frying provide options to lower the final fat and calorie content. Future research should prioritize an integral approach to combining various strategies to improve the nutritional profile of fried foods, thereby helping to reduce the risks associated with the consumption of these foods.

AUTHOR CONTRIBUTIONS

Consuelo Valle A.: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review & editing. **Francisca Echeverría**: Conceptualization; methodology; supervision; validation; visualization; writing – original draft; writing – review & editing. **Vilma Chávez**: Data curation; methodology; writing – original draft; writing – review & editing. **Rodrigo Valenzuela**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – original draft; writing – review & editing. **Andrés Bustamante**: Conceptualization; formal analysis; investigation; methodology; supervision; writing – original draft; writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors report there are no competing interests to declare.

ETHICS STATEMENT

None.

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