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Quality and stability of frying oils and fried foods in ultrasound and microwave–assisted frying processes and hybrid technologies

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Abstract

Frying is a popular cooking method that produces delicious and crispy foods but can also lead to oil degradation and the formation of health-detrimental compounds in the dishes. Chemical reactions such as oxidation, hydrolysis, and polymerization contribute to these changes. In this context, emerging technologies like ultrasound-assisted frying (USF) and microwave (MW)-assisted frying show promise in enhancing the quality and stability of frying oils and fried foods. This review examines the impact of these innovative technologies, delving into the principles of these processes, their influence on the chemical composition of oils, and their implications for the overall quality of fried food products with a focus on reducing oil degradation and enhancing the nutritional and sensory properties of the fried food. Additionally, the article initially addresses the various reactions occurring in oils during the frying process and their influencing factors. The advantages and challenges of USF and MW-assisted frying are also highlighted in comparison to traditional frying methods, demonstrating how these innovative techniques have the potential to improve the quality and stability of oils and fried foods.

KEYWORDS

frying oil quality, hybrid frying techniques, microwave-assisted frying, ultrasound-assisted frying

1 | INTRODUCTION

Frying is a widely utilized cooking method that imparts unique flavors and textures to various food products. In many cultures, a wide variety of foods are commonly consumed fried. Some of the most popular fried foods include French fries, chicken, fish, donuts, onion rings, spring rolls, potato chips, and fried chicken. These foods are often enjoyed for their unique flavor, texture, and aroma resulting from the frying process. Frying is a thermal food processing technique that entails simultaneous heat and mass transfer. Heat is transferred from the oil to the food, causing it to cook. Moisture is also transferred from the food to the oil, resulting in the loss of water from the food (Wang et al., 2021). These changes in the food's moisture content and temperature cause a variety of physicochemical and structural changes, including protein denaturation, starch gelatinization, and color formation. These changes result in the unique flavor, appearance, and taste of fried foods (Udomkun et al., 2019).

Traditional frying (TF) methods are frying techniques that have been widely used for many years and typically involve the use of cooking equipment such as open pans or deep fryers and sufficient oil to cook the food. These methods typically involve using a deep- or shallow-frying technique, where food is cooked in oil at high temperatures (Aydinkaptan et al., 2017). Deep frying involves immersing the food completely in hot oil, which allows for uniform heat transfer and frying. Shallow frying, on the other hand, only uses a thin layer of oil between the food and the cooking surface, resulting in nonuniform frying (İlter et al., 2023). Deep frying allows for more uniform heat transfer and frying, resulting in a crisp and evenly cooked exterior. It promotes the formation of a desirable texture and color in the fried food. However, deep frying also increases the risk of oil degradation due to the prolonged exposure to high temperatures (Asokapandian et al., 2020). The continuous circulation of hot oil around the food facilitates the transfer of heat and moisture, leading to more significant changes in the food's physicochemical and structural properties (Lima et al., 2024). On the other hand, the limited oil volume used in shallow frying might lead to less efficient heat transfer and a less uniform cooking process. Consequently, the fried food may have a different texture and less desirable appearance compared to deep-fried foods. However, shallow frying can be advantageous in terms of reduced oil consumption and potentially lower oil degradation. This approach ensures that the oil is utilized only once, reducing the potential detrimental effects of repeated frying on both the oil and the food (Garcimartín et al., 2020). To minimize the degradation of oil during frying, it is important to use proper frying methods and to frequently change the oil. The continuous use of oil in TF can lead to the accumulation of degradation products, further impacting the quality and safety of the fried food. The degradation of oil during frying is a complex process that is influenced by a variety of factors, including the frying temperature, heating time, frying method, oil/fat composition, and the presence of additives (Aydinkaptan et al., 2017). The rate of oil degradation is also affected by the interaction of these factors. The degradation of oil during frying can lead to the formation of harmful compounds, such as free fatty acids (FFAs), aldehydes, ketones, and volatile organic compounds. They can also pose a health risk, as some of them have been linked to the development of chronic diseases, such as heart disease and cancer.

TF methods may vary across different cultures and cuisines, but they generally follow similar principles. The oil is heated to a specific temperature, usually between 160 and 190°C, and the food is submerged in the hot oil until it reaches the desired level of doneness. The frying time can vary depending on the type and size of the food being fried. However, it is worth noting that TF methods are associated with certain challenges and limitations. The high temperatures used in TF can lead to the degradation of food components, such as proteins, lipids, and carbohydrates, resulting in the formation of undesirable compounds that may affect the quality of the fried food, such as off-flavors and colors (Devi, Zhang, & Mujumdar, 2021). It is important to note that the frying process can cause changes in both the food and the frying oil, with some food and oil compounds being lost and potentially toxic compounds being formed (Al Faruq et al., 2022). The frying process triggers a range of chemical reactions within the composition of food, including the oil oxidation reaction, the Maillard reaction, and the oxidative degradation protein, which subsequently generate harmful substances in products like heterocyclic amines (HAs), acrylamide, polycyclic aromatic hydrocarbons (PAHs), and trans fatty acids (TFAs). One such group of compounds, PAHs, has been identified as a potential health risk associated with the consumption of fried foods. PAHs are a group of organic compounds that are formed during the incomplete combustion of organic materials, such as oil and fat, at high temperatures (Xu et al., 2023). These compounds are of concern due to their potential carcinogenic and mutagenic properties, posing health risks upon consumption. PAHs can form during the frying process, particularly when food comes into direct contact with a heat source, such as hot oil. Oil smoke is the primary contributor of PAHs in both kitchen and indoor environments (Siddique et al., 2021). The formation of PAHs was influenced by various factors such as the type of frying, the oil used for frying, the temperature and duration of frying, the composition of the food being fried, and the presence of antioxidants (Xu et al., 2023). In a study conducted by Siddique et al. (2021), the effects of three different frying methods on the formation of PAHs in fried rabbit meat were compared. The results revealed that only fluorene was detected in all samples, with the highest fluorene content observed in the group treated with deep-frying (160 mL oils, 90°C, 4 min), followed by stir-frying (5 mL oil, 120°C, 8 min) and pan-frying (PF) (no oil added, 90°C, 8 min). Ge et al. (2021) conducted a study comparing the impact of deep-frying (using 200 mL of rapeseed oil [RO] at 226–228°C for 5 min) and PF (using 50 mL of oil at 226–228°C for 3 min) on the formation of PAHs in fried beef, pork, chicken, and duck, revealing that, with the exception of beef, the PAH content in deep-fried samples was higher than that in pan-fried samples. Another toxic compound that can occur in frying is acrylamide. Acrylamide, a potentially carcinogenic compound, can form in starchy foods when they are fried at high temperatures. Another group is HAs, which are produced when amino acids and creatine react at high temperatures (Olalekan Adeyeye & Ashaolu, 2021). HAs have been linked to various adverse health effects, including carcinogenicity. The presence of potentially toxic compounds in fried foods is a significant concern that has driven the exploration of new frying techniques. Understanding the formation and potential health risks associated with these compounds is crucial for the development of new frying techniques that minimize their presence and ensure food safety. The quality and stability of frying oils and the resulting fried foods are influenced by a complex interplay of factors, including temperature, oil or food composition, and method of frying.

The growing consumer awareness of health has led to research into healthier fried foods with reduced oil content and improved frying medium stability while maintaining food quality and safety. Alternative frying technologies such as vacuum frying (VF), ultrasound-assisted frying (USF), microwave frying (MWF), and their combinations have been explored as potential alternatives to the traditional method. These technologies have shown promise in producing fried foods with lower total oil content (TOC) and reduced levels of potentially toxic substances. These novel frying techniques have the potential to reduce oil uptake and/or improve frying medium stability. VF is one of the earliest and most mature alternative frying methods (Wang et al., 2021). Unlike TF methods, which involve frying in atmospheric pressure, VF occurs in a low-pressure environment. This technique involves reducing the pressure inside the frying chamber, which subsequently lowers the boiling point of the frying oil. The lower boiling point helps to minimize the degradation of heat-sensitive compounds in the food. Although VF may involve longer processing times and result in higher fat content compared to the traditional method, it is considered a healthier frying technique due to its ability to minimize frying medium damage by operating at lower temperatures and in the absence of oxygen (Devi, Zhang, & Mujumdar, 2021). In a study by Bedoya et al. (2018), the application of VF was shown to be effective in reducing the peroxide value (PV) of oil after frying potato snacks compared to conventional frying (CF). These results suggest that VF can be used to reduce the oxidation of oil during frying, which can lead to improved product quality and shelf life. The VF method does present some trade-offs compared to the TF method. Although VF can result in longer processing times and higher oil content due to the absence of oxygen and lower frying temperature, it is important to note that VF can also lead to improved oil and product quality (Devi, Zhang, & Mujumdar, 2021). This suggests that although VF may offer benefits in terms of oil and food quality, it may also present challenges in terms of processing efficiency and oil content. As such, a comprehensive evaluation of VF in comparison to TF methods is necessary to fully understand its impact on both product quality and health considerations. Furthermore, it is important to acknowledge the potential for VF to produce products with subpar quality. This highlights the need for further exploration and optimization of VF, potentially through the integration of complementary technologies such as ultrasound (US) and microwave (MW), to enhance the overall quality of VF products. By addressing these potential limitations and exploring synergistic approaches, the aim is to maximize the benefits of VF while mitigating any drawbacks related to product quality.

In the realm of novel frying technologies, US and MW techniques stand out as innovative methods with distinct advantages over conventional approaches. MW heating is a dielectric heating process in which the rapid rotation of polar molecules under the change of electric field transfers heat from the interior to the exterior of the material (Faruq, Zhang, & Fan, 2019). This unique heating mechanism allows for efficient and uniform cooking of food products, contributing to improved processing efficiency and reduced frying time. For example, in a study Zhou et al. (2022), MW-assisted frying has been shown to reduce the frying time by 30%–40% compared to deep-oil frying, while maintaining equivalent product quality attributes in terms of oil content, color, and texture. Additionally, post-frying conditions, such as a 60-s MW heating after frying, have been found to reduce the oil content by 18%–23% and produce fried products with better quality attributes (Zhou et al., 2022). On the other hand, the US waves create microscopic cavitation bubbles in the food, which can break down cell walls and release trapped moisture (Sun et al., 2019). This results in faster cooking times and more evenly cooked food. The benefits of US treatment before frying include producing high-quality fried food products with healthier attributes, better appearance, more natural color, and reduced frying time (Qiu et al., 2018). The use of high-intensity US in the pretreatment of food, such as potato chips, has been shown to significantly reduce color change, resulting in brighter products by inactivating enzymes like polyphenol oxidase (Habuš et al., 2021). This process contributes to the production of high-quality fried food products. US-MW–assisted VF (USMWVF) synergistically enhances the quality attributes of fried products (Su et al., 2022). MW can penetrate the food and heat it from the inside out, whereas US waves can break down the cell walls of the food, allowing moisture to evaporate more quickly. This results in faster cooking

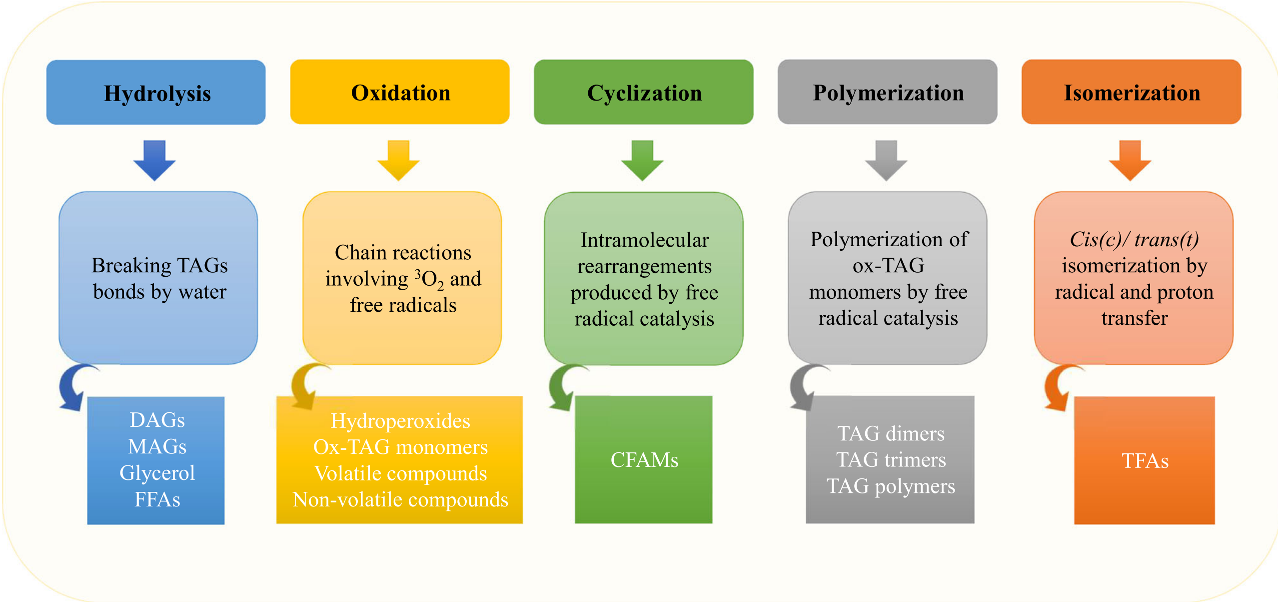

FIGURE 1 Main reactions produced during oil frying and major compounds formed. CFAMs, cyclic fatty acid monomers; DAGs, diacylglycerols; FFAs, free fatty acids; MAGs, monoacylglycerols; Ox-TAG, oxidized triacylglycerol; TAGs, triacylglycerols; TFAs, *trans* fatty acids.

times and more evenly cooked food. In a study, it was shown that low-frequency US pretreatment in a water/oil medium simulated system improved the processing efficiency and quality of MW-assisted vacuum-fried (MWVF) potato chips (Su et al., 2020).

This comprehensive review presents the USF and MW-assisted frying process and the frying process in hybrid technologies, focusing on the latest findings on the quality of oils and fried foods. It is emphasized that the incorporation of MW and US technologies into the frying process of foods is beneficial in terms of obtaining high-quality products with minimal oil degradation. These innovative techniques have the potential to deliver safer and more stable fried foods with lower fat content, thus contributing to improving consumer dietary habits and reducing production costs.

2 | CHEMICAL TRANSFORMATIONS IN OIL DURING FRYING

2.1 | Reactions in frying oil

In the course of frying, a succession of intricate changes and reactions occur in the used oil, including hydrolysis, oxidation, cyclization, and polymerization. These reactions are responsible for the formation of different compounds (Figure 1), some of which are considered potential health risk factors and are used as quality indicators for frying oils (Xu et al., 2019).

2.1.1 | Hydrolysis reactions in frying oils

Hydrolysis reactions involve the breakdown of triacylglycerols (TAGs) into diacylglycerols (DAGs), monoacylglycerols (MAGs), glycerol, and FFAs (Meenu et al., 2022; Velasco et al., 2009). These hydrolytic reactions in oil are primarily triggered by the presence of moisture. Water molecules, acting as weak nucleophiles, can attack the ester bonds of TAGs, which are subsequently protonated and exhibit strong electrophilicity. This leads to the formation of hydrolytic byproducts mentioned above (i.e., DAGs, MAGs, glycerol, and FFAs) (Oke et al., 2018). TAG hydrolysis takes place within the oil phase at the oil–water interface and progresses through three stages. This process is reversible and facilitated by high temperatures (150–190°C) and various catalysts (Choe & Min, 2007). The reaction rate varies across the three stages of hydrolysis, with the first and last stages occurring at slow rates, whereas the intermediate step proceeds rapidly.

For nonenzymatic hydrolysis, determining the sequence of ester bond cleavage in the TAG molecule poses a challenge. This difficulty arises from factors such as the position and number of unsaturations, the length and steric hindrance of the aliphatic chains, moisture content, temperature, and other undisclosed factors (Zhang et al., 2012). Notwithstanding, it is well-established that the primary products of TAG hydrolysis in frying oils are FFAs, which show a linear increase with frying time. In contrast, DAGs and MAGs remain relatively constant throughout frying after undergoing an initial increase, with DAGs predominating over MAGs (Xu et al., 2019). On the other hand, glycerol vaporizes at temperatures exceeding 150°C, leading to its low concentration in frying oils. Therefore, the content of FFAs is commonly used as an indicator to assess the quality of frying oil and can be correlated with the extent of hydrolysis (Zhang et al., 2012).

In relation to the toxicity of the compounds produced during hydrolysis reactions, both DAGs, MAGs, glycerol, and FFAs do not inherently pose risks. This is because they are identical to the products of TAGs hydrolysis during digestion by pancreatic lipases within the body (Mu & Høy, 2004). Furthermore, the sensory implications of these compounds resulting from TAG hydrolysis are negligible. Despite FFAs being characterized by strong flavor attributes, they are highly reactive and readily volatilize, dissipating from the oil through steam generated during food frying (Perkins, 2007).

2.1.2 | Oxidation reactions in frying oils

The oxidation process experienced by oils begins with the double bonds of fatty acids. This process leads to the formation of lipid hydroperoxides, which are the primary products of lipid oxidation (Choe & Min, 2006). These compounds are highly reactive and readily transform into secondary oxidation products (Ahmed et al., 2016). Nevertheless, the initial formation of hydroperoxides in oils varies depending on the type of reaction mechanism involved. Specifically, four main oxidation pathways are recognized: autoxidation, photooxidation, enzymatic oxidation, and thermal oxidation (Echegaray et al., 2022). During the frying process, thermal oxidation emerges as the predominant oxidation reaction due to the application of high temperatures (above 150°C) (Choe & Min, 2007; Momchilova et al., 2012). In practical terms, thermal oxidation occurs similarly to autoxidation, but at a faster rate. Thermal oxidation begins with the atmospheric triplet oxygen ($^3O_2$) attacking the allylic position of the lipid, resulting in the formation of hydroperoxides, which quickly convert into other more stable compounds (Bruheim, 2009). This process unfolds in three phases: initiation, propagation, and termination. The initial step is marked by the removal of a hydrogen atom from a fatty acid due to the applied temperatures. The resulting alkyl radical initiates a free radical chain reaction (Lee et al., 2004). Moreover, the alkyl radical can react with $^3O_2$ to form a peroxyl radical. This last radical is capable of liberating hydrogen atoms from other unsaturated lipid molecules, leading to the production of hydroperoxides and other radicals (such as alkoxyl and hydroxyl radicals). These substances continue to react with additional unsaturated fatty acids (UFAs). Eventually, free radicals coming from the propagation phase react with each other or with other substances to form more stable non-radical species, thereby terminating the oxidation reactions (Echegaray et al., 2022; Matthäus, 2010).

The chemistry underlying the oxidation mechanisms that occur during frying is highly intricate. This complexity arises from the simultaneous occurrence of oxidation and thermal decomposition reactions, which are generated through various different and intricate pathways (Choe & Min, 2006; Köckritz & Martin, 2008). As temperature increases, the solubility of oxygen in the oil drops dramatically, but oxidation reactions occur more rapidly. Consequently, the formation of hydroperoxides is notably accelerated. However, their decomposition can be even faster, leading to a decrease in the amount of these compounds in the frying oil, tending toward zero. Additionally, as oxygen pressure decreases, initiation reactions become more important. This results in an increased concentration of alkyl radicals relative to peroxyl radicals, leading to the formation of polymeric substances. These mechanisms take place within the unsaturated fatty acyl groups attached to the glyceridic backbone, leading to the generation of stable end products such as monomeric, dimeric, and higher oligomeric TAGs, including oxidized TAG (ox-TAG) monomers (Chen et al., 2011; Dobarganes & Márquez-Ruiz, 2007). These ox-TAG monomers can account for up to 10% of used frying oils (Berdeaux et al., 2009). Moreover, oxidation reactions can lead to the formation of volatile compounds such as acids, alcohols, aldehydes, esters, ketones, lactones, and low molecular weight short-chain hydrocarbons (Choe & Min, 2006). Typical volatile compounds present in used frying oils are 1-pentanol; 1-octen-3-ol; hexanal; octanal; furfuryl alcohol; (E)-2-heptenal; 5-methylfurfural; 2-pentylfuran; (E)-2-octenal; nonanal; (E)-2-nonenal; hexadecanoic acid; and pyrazines (Zhang et al., 2012). The presence of these compounds enables the assessment of oil oxidation using chromatographic techniques. Additionally, the oxidation state can be determined through the analysis of primary compounds (hydroperoxides) and secondary oxidation compounds. This is achieved by conducting the PV test and assessing the p-anisidine value (AV), which, respectively, indicates the presence of compounds generated during the initial and subsequent stages of oxidation. By combining both results, the total oxidation value (TOTOX) is obtained, providing a comprehensive assessment of the oil's oxidation state and quality (Echegaray et al., 2022).

The oxidation occurring during frying results in a depletion of the nutritional value of the oil. UFAs, including essential fatty acids, are particularly vulnerable to degradation compared to saturated fatty acids (SFAs). Furthermore, these reactions lead to a reduction in bioactive compounds with antioxidant properties. Moreover, the toxicological implications of the oxidation of frying oil are of paramount concern, as many secondary oxidation compounds formed during lipid oxidation are considered hazardous to human health. Some of these concerning compounds include short-chain volatile aldehydes such as acetaldehyde, formaldehyde, malondialdehyde, propanal, and 2-propenal (Grootveld et al., 2020; Insecticide Resistance Action Committee [IRAC], 2014; Kanner, 2007; Vieira et al., 2017). Additionally, ox-TAG monomers and nonvolatile hydroxylated α,β-unsaturated aldehydes such as 4-hydroxy-2-trans-hexenal, 4-hydroxy-2-trans-octenal, 4-hydroxy-2-trans-nonenal, and 4-hydroxy-2-trans-decenal have been identified in frying oils. These compounds have negative effects on health (Khor et al., 2019; Liu et al., 2018; Ma et al., 2020).

In addition to the mentioned compounds, it is important to consider heat-induced toxic compounds PAHs and heterocyclic amines (HAs) renowned for their potential carcinogenic and mutagenic effects on human health (Lai et al., 2024; Li et al., 2016). The formation of these compounds in frying oils primarily stems from oxidation reactions, although they can also be generated through the thermal decomposition of organic compounds and other intricate reactions. For example, in the study of Lai et al. (2024), the levels of PAHs and HAs in fried crispy pork spare ribs (CPS) were measured after deep-frying in soybean oils (SBOs) and palm oils. A greater amount of PAHs were found in deep-fried CPS at 150°C for 12 min than at 190°C for 6 min in SBO due to its higher unsaturation degree compared to palm oil. The findings suggested that higher unsaturation degree alongside prolonged frying duration had a greater impact on PAH development in CPS. However, the degree of oil unsaturation had a lesser impact on the production of HA production. Likewise, in the earlier investigation of Lai et al. (2023), highly unsaturated sesame oil had higher PAH and HA levels in pork fiber compared to more saturated lard. Therefore, selecting the appropriate oil and processing conditions is essential to minimize HA and PAH formation during frying. Fortunately, the addition of antioxidants (Gong et al., 2018), phenolic compounds (Guzel et al., 2024), flavonoids (Huynh et al., 2024), and proanthocyanidins (Gao et al., 2024) to the oil can potentially decrease the formation of PAHs and HAs.

On the other hand, the development of volatile compounds through oil oxidation significantly impacts its oduor, flavor, color, and texture, thus influencing the sensory quality of heated oils. The presence of volatile compounds in both oil and fried products can be desirable, contributing pleasant aromas, or undesirable, resulting in rancid odors (Perkins, 2007). Notably, volatile aldehydes play a crucial role from both perspectives, as they can greatly influence consumer acceptance due to their low perception threshold (Zamuz et al., 2020). Compounds such as alkanals, 2-alkenals; trans, trans-2,4-alkadienals; pentanal; and hexanal are often regarded as indicators of off-flavors in oil (Van Ruth et al., 2000). Moreover, the presence of aldehydes like 2,4,7-decatrienal and ketones such as 1-penten-3-one and 1-octen-3-one have been associated with fish-related off-flavors after heat application, whereas 2,4-decadienal is considered a significant contributor to the flavors of deep-fried products due to its pleasant aroma (Matthäus, 2010).

2.1.3 | Cyclization reactions in frying oils

Cyclization reactions lead to the creation of cyclic organic compounds by closing linear or branched molecular structures. When oils are heated above 200°C, these reactions give rise to cyclic fatty acid monomers (CFAMs). CFAMs result from alterations in double bonds within the aliphatic chain, which may belong to TAG or a decomposed fatty acid. CFAMs found in frying oils typically manifest as five- or six-membered ring structures with a carboxyl-containing carbon chain and a hydrocarbon chain, resulting in a diverse array of cyclopentyl, cyclopentenyl, cyclohexyl, and cyclohexenyl fatty acids (Zhang et al., 2012). The most widely accepted mechanism for CFAM formation in fried oil involves intramolecular rearrangements produced by free radical catalysis with hydroperoxides serving as initiators. However, further research is needed to fully understand the cyclic products generated during oil degradation at high temperatures.

The concentrations of CFAMs typically found in heated oils are generally low, ranging from 0.01% to 0.66% (Cherif et al., 2019). However, from a nutritional standpoint, studies have indicated that the ingestion of CFAMs can disrupt fatty acid metabolism (Christie & Dobson, 2000). More recently, even at low doses, the consumption of CFAMs has been associated with an increase in pro-atherogenic markers and has been shown to have pro-inflammatory and pro-oxidative effects. Additionally, CFAMs have been implicated in the accumulation of TAG in the liver and the induction of hepatomegaly in animal models (Mboma, Leblanc, Angers et al., 2018; Mboma, Leblanc, Wan et al., 2018).

2.1.4 | Polymerization reactions in frying oils

During frying, TAG molecules undergo polymerization reactions, specifically oxidized polymerization and thermal polymerization, resulting in the formation of complex polymers. These polymers contain carbon–carbon (–C–C–), carbon–oxygen–carbon (–C–O–C–), and carbon–oxygen–oxygen–carbon (–C–O–O–C–) bonds, classified as dimers, trimers, and oligomers of TAGs, collectively referred to as TAG polymers. The polymerization reactions occur differently depending on the presence or absence of oxygen. In the absence of this molecule, polymerization proceeds via –C–C– bonds, forming polymers without additional oxygen atoms through free radical chain reaction or Diels–Alder reaction (Zhang et al., 2012). Nevertheless, in the presence of oxygen, it participates in the formation of ox-TAG monomers, which undergo polymerization through –C–C–, –C–O–C–, and –C–O–O–C– linkages catalyzed by free radicals. In these reactions, one, two, or more additional oxygen atoms may be incorporated into the molecules as bridging oxygen in dimers, trimers, or oligomers (Byrdwell & Neff, 2004). This process serves as the termination step of lipid oxidation reactions. The allyl radical produced during oxidation readily combines with an alkoxy radical to produce oxodimers, whereas two molecules of peroxy radicals can join to form a peroxy dimer. Consequently, TAG polymer structures contain carbonyl, epoxy, hydroxy, and hydroperoxy groups (Choe & Min, 2007). The variety of products formed in the polymerization of TAGs depends largely on the fatty acids present in the oil. These products can be classified based on the presence of additional oxygen into nonpolar TAG polymers, which include dehydrodimers, noncyclic dimers, cyclic dimers, and polar TAG polymers, comprising diverse and often indeterminate groups of substances (Zhang et al., 2015).

Polymerization reactions significantly impact the sensory attributes of oil, leading to undesirable outcomes such as darkening of color and increased viscosity. In practice, the formation of TAG polymers often serves as a key indicator for determining when frying oil should be discarded (Zhang et al., 2012), with these products serving as important indices of oil quality (Khor et al., 2019).

2.1.5 | Isomerization reactions in frying oils

During the frying process of edible oils rich in UFAs, reactions involving the breaking, displacement, and formation of double bonds between carbons (C = C) can result in the generation of *trans* configurations. This leads to the presence of TFAs in frying oils, characterized by UFAs containing nonconjugated C = C bonds in the *trans* configuration (Guo et al., 2017). Moreover, during the formation of cyclic compounds, some products undergo *cis (c)/trans(t)* isomerization (Zhang et al., 2012). The synthesis of TFAs primarily involves the *c/t* isomerization of UFAs. Initially, these fatty acids undergo isomerization to produce mono-*trans* isomers, which then further isomerize to form double-*trans* isomers and ultimately lead to the formation of multi-*trans* isomers (Guo et al., 2023). Although the isomerization reactions induced by heating are complex and less understood compared to those induced by catalysts like metals, current knowledge suggests that they follow mechanisms involving free radical isomerization and proton transfer isomerization through various pathways (Tsuzuki et al., 2010). Specifically, TFAs can be synthesized by direct isomerization, hydrogen extraction isomerization, proton transfer isomerization, catalytic hydroisomerization, and oxidation-induced isomerization (Goldbach et al., 2015; Guo et al., 2023). These processes yield different *trans* isomers such as C18:1*t*; C18:2-9*t*,12*c*, C18:2-9*c*,12*t*, and C18:2-9*t*,12*t*; and C18:3-9*t*,12*c*,15*c*, C18:3-9*c*,12*t*,15*c*, C18:3-9*c*,12*c*,15*t*, C18:3-9*t*,12*c*,15*t*, C18:3-9*c*,12*t*,15*t*, C18:3-9*t*,12*t*,15*c*, C18:3-9*t*,12*t*,15*t*, derived from the isomerization reactions of oleic, linoleic, and linolenic fatty acids, respectively.

Although heat can induce *c/t* isomerization reactions, the presence of TFAs in frying oil is typically low and may even be negligible in daily dietary intake from compounds formed during frying (Tsuzuki et al., 2010). Nevertheless, special attention is warranted for these substances due to their implications on human health. Excessive intake of TFAs has been linked to deaths from coronary disease, as well as an increase in mortality (World Health Organization [WHO], 2018).

2.2 | Factors influencing reactions in frying oil

The reactions that take place during frying are influenced by a variety of factors, ranging from frying process conditions such as temperature and time to the characteristics of the oil and the foods being cooked. Exposure time and temperature during frying are generally associated with increased hydrolysis reactions, which are augmented at temperatures between 150 and 190°C, resulting in an increase in DAGs and FFAs content (Xu et al., 2019). Similarly, elevated temperatures (above 150°C) have been correlated with increased formation of oxidation compounds such as ox-TAGs in different vegetable oils subjected to heating treatments (Giuffrè et al., 2020), whereas cyclization reactions have been observed at temperatures exceeding 200°C (Cherif et al., 2019). Moreover, polymerization reactions may occur at low temperatures, typically around 110°C (Gertz et al., 2014); meanwhile, the effect of frying temperature has been shown to be limited in reactions related to isomerization (Cherif & Slama, 2022). Additionally, intermittent heating during frying (i.e., frying cycles) has been observed to significantly worsen oil quality by increasing FFAs and PV and the appearance of polymeric substances (Sadawarte &

Annapure, 2023; Zubairi et al., 2022). On the other hand, the composition of the oil significantly affects the degradation reactions during frying. Notably, one of the critical factors is its fatty acid composition, as UFAs are more prone to oxidative processes and may be more susceptible to the formation of toxic compounds (Gómez-Cortés et al., 2015; Li et al., 2013). It has been observed that oils richer in SFAs, such as palm oil, demonstrate greater oxidative stability and lower formation of toxic compounds compared to oils with higher UFAs content, such as high oleic peanut, sunflower (SFO), and ROs (Xu et al., 2020). However, there is controversy as other studies have found opposing trends (Aladedunye & Przybylski, 2014). Furthermore, oils with short-chain, UFAs are more susceptible to hydrolytic alterations due to higher water solubility compared to oils with long-chain, highly SFAs. The TAG structure also plays a crucial role in reactions such as cyclization, where the Sn-2 position of C18 polyunsaturated fatty acids (PUFAs) in the TAG molecule has been found to favor cyclization reactions at frying temperatures (Martin et al., 1998). Additionally, high concentrations of DAGs, MAGs, and FFAs, high water content, and the presence of chlorophylls, lipoxygenases, and metals in the oil favor oxidation reactions, although their influence at frying temperatures could be negligible at times. Conversely, the presence of phospholipids (especially phosphatidylcholine, phosphatidylethanolamine, phosphatidylinositol, phosphatidylserine, and phosphatidic acid) and antioxidant compounds (such as phenolic substances) can act as oxidation-protective agents, and they can improve the stability of oils rich in UFA (Echegaray et al., 2022).

The composition of the food being fried is also relevant to the quality of the oil after frying (Li et al., 2019). During the frying process, heat and mass transfer occur between the food and the oil simultaneously. Depending on the nature of the food (e.g., bakery products, fish, meat, and vegetables), different compounds such as water, fat, proteins, sugars, and salt can be transferred to the oil, influencing the rate of reactions (Juárez et al., 2011). Indeed, it has been observed that water content in food can exacerbate oil deterioration by accelerating lipid hydrolysis at high temperatures. Furthermore, it increases the rate of oxidation reactions and the formation of TFAs (Choe & Min, 2007; Chu & Luo, 1994; Nieva-Echevarría et al., 2016).

Moreover, combining different types of oil (oil blends) can be used to improve oil stability. Additionally, antioxidant and antifoaming additives are commonly used to enhance the quality of frying oil, with tert-butylhydroquinone (TBHQ), butylated hydroxyanisole, butylated hydroxytoluene, and dimethylpolysiloxane being the most commonly used antioxidants and antifoaming agents, respectively (Orthoefer & List, 2007).

3 | INNOVATIONS IN THE FRYING PROCESS

Due to the nutritional and toxicological implications of frying, as well as the sensory quality of the products obtained through this process (Figure 2), the search for new alternatives that allow for providing nutritious and tasty fried foods is becoming increasingly interesting. Thus, with the aim of obtaining higher quality fried foods, US and MW technologies are recently being used to improve the frying process (Devi, Zhang, & Mujumdar, 2021; Zhang, Zhang, & Adhikari, 2020).

3.1 | Ultrasound-assisted frying (USF)

US are mechanical waves that possess high frequency. This type of wave is originated from equipment that contains a generator that transforms electrical energy into alternating current, a transducer that changes the oscillation voltage from power source to mechanical vibration, and a probe that emits sound waves into the medium which in the case of US fryer equipment will be the oil employed in frying (Pinton et al., 2021; Zhang, Zhang, Wang et al., 2020). The usual range of US intensity utilized by these equipment is between 10 and 1000 W/cm^2, corresponding to frequencies of 16–100 kHz (Zhang, Zhang, Wang et al., 2020), although normally, US is considered from 20 kHz (Gómez-Salazar et al., 2021). The application of US causes a series of intricate phenomena in liquid state, which occur synergistically. Among these phenomena are acoustic cavitation and streaming, agitation, atomization, heating, mechanical oscillations, and sponge effect, with acoustic cavitation (i.e., the formation and sudden explosion of vapor bubbles) being the most important mechanism. Because of the constant compression and rarefaction generated during the formation of vapor bubbles, the US causes internal physical forces in the media, such as shear forces, shock waves, and turbulence, as well as generates high local pressures and temperatures (Gonzalez-Gonzalez et al., 2020).

The mechanical vibration energy produced by the US contributes to forming an effective agitation and flow (Chemat et al., 2011) that accelerates convection and heat conduction from the oil to the food. This, accompanied by the various modifications produced by US in food matrices, can lead to different benefits in the frying process compared to CF (Table 1). Despite this, the current use of US during frying (as the only method) is scarce as this technique is more often used as a pretreatment before frying (Jaggan et al., 2022; Mohammadalinejhad & Dehghannya, 2018; Oloruntoba et al., 2022; Ren et al., 2022) or in combination with other technologies (Devi et al., 2018; Devi, Zhang, & Mujumdar, 2021; Mojaharul Islam et al., 2019).

TABLE 1 General advantages and drawbacks of ultrasound-assisted frying (USF), microwaved frying (MWF), and hybrid frying technologies.

Frying method	General advantages	Drawbacks
Ultrasound-assisted frying (USF)	- Commonly, improves the benefits achieved by conventional frying (CF) - Decreases frying time - Enhances cooking yield - Favors the appearance of a crunchy external layer in the food - Improves the formation of desired volatile compounds - Increases the content of certain free amino acids related to the overall desired flavor - Favors the formation of flavor precursor nucleotides	- Increases lipid oxidation of the fried product - Not always produce a significant reduction in the fat content of fried foods - High initial investment cost for industrial equipment
Microwaved frying (MWF)	- Commonly, improves the benefits achieved by conventional frying (CF) - Reduces frying times - Increases the heat transfer coefficient during frying - Increments the rate of moisture removal - Minimizes the absorption of oil by food - Reduces oil consumption during frying - Produces a golden color and a crunchy texture - Reduces acrylamide build-up - Food with organoleptic characteristics like conventional frying (CF) or better	- May cause overheating and burns at certain points depending on penetrating power - Requires homogeneity of the food to be fried for a good heat distribution - The oil can undergo metamorphism during frying - High initial investment cost for industrial equipment
Microwave-assisted vacuum frying (MWVF)	- Normally, improves the benefits achieved by vacuum frying (VF) - Softer frying temperatures - Reduces frying times - Reduces energy consumption - Improves heat transfer - Increases heating speed - Minimizes dehydration time - Retains heat-sensitive nutritional ingredients - Reduces the amount of oil absorbed by food - Decreases oil consumption during frying - Reduces the formation of toxic compounds - Improves sensory attributes (color, flavor, texture, etc.)	- High initial investment cost for industrial equipment
Ultrasound-microwave assisted vacuum frying (USMWVF)	- Normally, improves the benefits achieved by MWF and VF - Softer frying temperatures - Reduces frying times - Reduces energy consumption - Improves heat transfer - Increases heating speed - Minimizes dehydration time - Retains heat-sensitive nutritional ingredients - Reduces the amount of oil absorbed by food - Decreases oil consumption during frying - Reduces the formation of toxic compounds - Improves sensory attributes (color, flavor, texture, etc.)	- High initial investment cost for industrial equipment

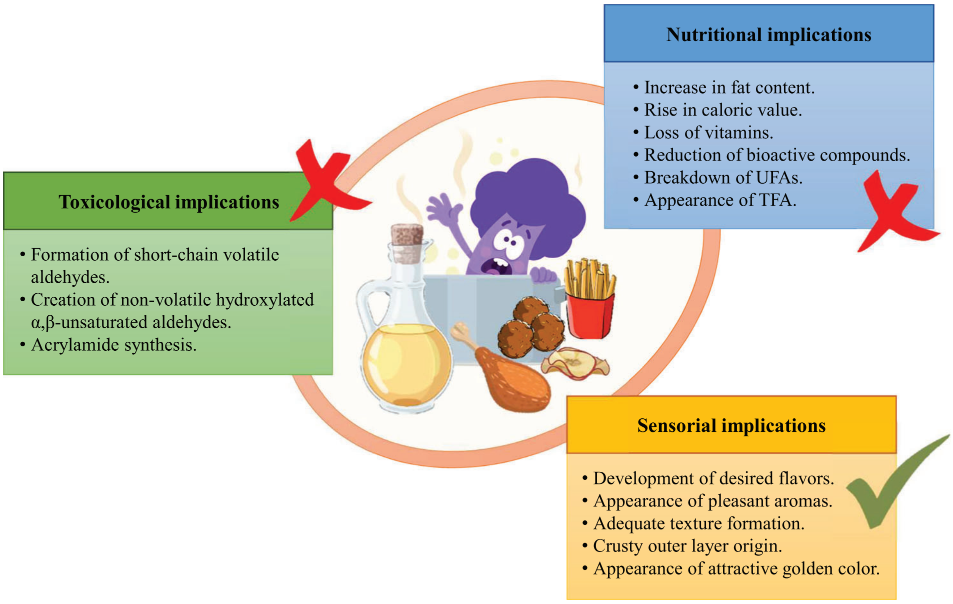

FIGURE 2 Nutritional, toxicological, and sensory implications of conventional frying (CF). TAF, *trans* fatty acids; UFAs, unsaturated fatty acids.

However, in an opening study by Wang et al. (2019), they have shown that USF (200–600 W, 20 kHz, at 120–160°C, for 8–16 min) in meatballs can be proposed as a method that provides good quality fried products as well as a good way to help to reduce cooking times compared to CF (immersion in oil at 120–160°C, for 8–16 min). Specifically, these authors reported that the use of US improved the water retention capacity of meatballs (and therefore cooking yield) due to that US contributed to the rapid formation of a crispy crust on the outside of the food while also favoring the immobilization of free water, making water loss more difficult. Concurrently, the use of US reduced the hardness of this meat product as cavitation can affect the myofibrillar structure of the meat by producing high shear and pressure (Dolatowski et al., 2007). Moreover, the use of US during frying modified the color of the meatballs, increasing the lightness (L^*) values and decreasing the redness (a^*) parameter. Despite these changes, a sensory analysis revealed that the meatballs had a higher quality when frying with US (with the conditions set at 160°C and 12 min). Further, in meatballs, Zhang, Zhang, Wang et al. (2020) displayed that USF (200–800 W, 160°C, for 12 min) could help improve the meatballs flavor compared to a CF (160°C for 12 min) as US accelerated oxidation of FFAs into desired volatile compounds and increase the concentration of certain free amino acids (namely, Ala, Cys, Glu, Gly, Ser, and Tyr). At the same time, powers up to 400 W had a positive effect on nucleotides origin. On the contrary, the US treatment increased the lipid oxidation of fried products because the high pressure and temperature generated in the cavitation zone can favor these chemical reactions (Lorenzo et al., 2015).

For their part, Ostermeier et al. (2021) investigated the employ of USF (1000 W, at 150°C, during 3 min) in potato chips and compared it with different procedures (CF, CF with pulsed electric field [PEF] pretreatment, and combined USF with a PEF pretreatment). Thus, they observed that the use of US during frying affected the cooking process, resulting in higher volumes of bubbles produced and an increase in heat and mass transfer that affected the removal of water. In addition, this study observed that the reduction in the fat content of potato chips was produced with the combination of PEF and USF, as the exclusive use of USF did not produce a significant diminution.

3.2 | Microwave frying (MWF)

MW is a form of nonionizing electromagnetic radiation which is located at frequencies ranging from 0.3 to 300 GHz, encompassing wavelengths from 1 mm to 1 m. This radiation is usually generated by a magnetron and/or solid-state MW generator, responsible for transforming electrical energy into electromagnetic energy. The MW equipment also possesses a step-up transformer, a waveguide, an applicator, and an oven cavity, which in the case of MWF processes, must include an oil container (Orsat et al., 2017; Zhou et al., 2022). The most commonly used frequencies in this equipment for the food industry are 915 and 2450 MHz (Puligundla, 2013). Under these conditions, the MW causes molecular movement by migration of ionic particles or by the rotation of dipolar particles through the migration of solutes and vibrating, and through the alignment of polarized molecules in the electromagnetic field, respectively (Kutlu et al., 2022). When food is heated by MW, water molecules and other charged particles constantly rotate and couple with electromagnetic field throughout the food. This particle vibration leads to collisions between them, converting kinetic energy into heat and resulting in a homogeneous distribution of temperature in the nourishment (unlike CF treatments where heat transfers from the outside to the inside) (Vadivambal & Jayas, 2010). To understand the behavior of foodstuff during MW heating, the dielectric constant (ε') and dielectric loss factor (ε'') are employed, which are defined as the MW energy generated capable of storing in the food and the amount of energy generated that the food can absorb and convert into heat, respectively. Thus, the relationship between these factors ($\tan\delta = \varepsilon'/\varepsilon''$) allows for expressing the transformation of electromagnetic energy into thermal energy due to dielectric losses (Ellison et al., 2017). Additionally, as the food heats up from the inside, the outside also cooks due to the temperature of the oil, creating a crispy outer layer similar to that created with CF (Zhang, Zhang, & Adhikari, 2020).

MWF can be especially favorable for the frying of samples that present meager heat penetration up to the interior of the food matrix as it provides products with improved quality in nutritional, toxicological, and organoleptic terms, whereas it can help reduce production costs at an industrial level (Table 1). Specifically, various studies have shown that MWF reduces the absorption of oil by the product to be fried. An early study showed that the application of MWF (power level of 400–700 W, at 170°C, for 120–180 s) during the cocking of potato slices reduced the amount of oil absorbed by the food matrix in comparison with a traditional immersion frying (170°C, during 270 s) (Oztop et al., 2007). In a similar way, Parikh and Takhar (2016) reported that the MWF (power level of 1500 W, frequency of 2.45 GHz, at 177–193°C, during 90 s) reduced the fat content in French potatoes, but only at temperatures above 180°C. The decrease in the absorption of oil by the food matrix produced by the MW could be related to the high rate of evaporation of the water content with respect to the low rate of oil diffusion achieved in the food, which also helps to reduce frying times (Oztop et al., 2007). Despite this trend, a recent study carried out by Zhou et al. (2022) stated that MWF (power level of 800 W, frequency of 2.45 GHz, 5.85 GHz, or their combination, at 180°C, for 30–120 s) led to higher oil absorption also in French potatoes compared to CF (conditions not specified), which was related to the greater formation of pores originated in MWF in the outer rind of the potato, where the oil can be lodged.

Regarding the toxicological improvements achieved in MWF compared to TF, many studies have shown a reduction in acrylamide formation when MW technology was applied to this culinary process. This reduction can be mainly due to the protective effect exerted by the flow of water steam produced in the food during MWF, which drags both the acrylamide formed and the precursor substances of its origination (Sansano et al., 2018). In this line, Barutcu et al. (2009) observed a reduction of up to 34.5% in the formation of acrylamide in chicken batter (different batter formulations of soy, chickpea, and rice flour) using MWF (power level of 365 W, at 180°C, during 30–120 s) compared to TF (immersion in oil at 180°C, for 5 min). In an identical manner, in French fries, Sansano et al. (2018) achieved a reduction between 37% and 83% in acrylamide concentration using MWF (315–600 W, during 1–10 min) compared to CF (immersion in oil at 180°C, for 8 min). Furthermore, these authors found that acrylamide reduction increased with the power level used during MW.

On the other hand, the organoleptic characteristics obtained in different foods fried by MWF have been assessed as similar to conventional fried products, without the reduction in absorbed fat detrimental to parameters such as color or texture (Parikh & Takhar, 2016; Sansano et al., 2018), even sometimes the results for sensory attributes were reported as better (Devi, Zhang, Ju et al., 2021; Oztop et al., 2007; Parikh & Takhar, 2016; Schiffmann, 2017).

3.3 | Hybrid frying technologies

As stated in the previous sections, USF and MWF have several advantages over CF. However, its use is also subject to some drawbacks (Table 1) that could limit its utilization in the industry. For this reason, combinations of US and MW have emerged with VF, another frying technique developed to improve CF. VF is an approach that allows operating with a lesser amount of oxygen and reduced pressures (below 6.65 kPa), which helps to decrease the boiling point of water and oil and consequently permits working at milder temperatures (90–115°C) (Zhang, Zhang, & Adhikari, 2020). In this way, VF helps prevent lipid oxidation, decreases nutrient loss, reduces the formation of toxic compounds, maintains the quality of frying oil for longer, and minimizes the food oil absorption (Belkova et al., 2018; Devi, Zhang, Ju et al., 2021; Sobukola et al., 2013). Nonetheless, VF is a rather slow process (Manzoor, Masoodi, Rashid et al., 2023).

Given the characteristics of USF, MWF, and VF, their combination can improve the deficits of each technology separately (Table 1). Thus, the inclusion of VF can help to avoid oxidation reactions and enhance the homogeneous heat transfer of USF and MWF, whereas frying times of VF are reduced thanks to the two later. Consequently, the joining of these three techniques has given rise to hybrid frying methods. Specifically, the combinations used for frying different foods have been those that unify US or MW and VF or those that combine both US and MW with VF, leading to US-assisted vacuum fried (USVF), MWVF, and USMWVF, respectively. Of all these combinations to our knowledge, the least used is that of USVF (Devi, Zhang, Ju et al., 2021; Sosa-Morales et al., 2022), so in the following, we will focus on MWVF and USMWVF.

3.3.1 | Microwave-assisted vacuum frying (MWVF)

The union of MW technology with VF conditions has led to the development of a new frying technique that achieves fast heating speeds and shorter frying times, thus reducing specific energy consumption. At the same time, MWVF minimizes dehydration time and the amount of oil absorbed by the product. These advantages have been discovered in various works. An example is an early study conducted by Su et al. (2016), where it was revealed that potato chips produced by MWVF (12–20 W/g, 0.075–0.085 MPa, 100–120°C, 2–10 min) reduced the oil content compared to those produced exclusively by VF (0.075–0.085 MPa; 100–120°C; 2–10 min). In addition to this nutritional improvement, the use of MW enhanced the water evaporation rate, originating crisper chips with a better natural color, while preserving the cell structure and cell wall integrity of the fried potatoes. In this way, the MWVF-treated chips were healthier and with enhanced color and texture. A more recent study showed similar beneficial effects in MWVF-treated apple slices (800–1000 W, 0.01 MPa, 95°C, 4–14 min) compared to VF-treated apple slices (0.01 MPa, 95°C, 4–14 min) (Al Faruq et al., 2018). In this research, MW power was observed to significantly increase moisture evaporation rate, reduce fruit oil uptake while increasing crispness, and provide a more desirable yellow color compared to VF-treated apple slices. As a result, the MWVF technology provided low-temperature snacks that retained natural flavor, color, and heat-sensitive nutritional ingredients. In fresh bananas, it was also determined that the use of MWVF (2.45 GHz, 2 kPa, 95°C, 5–10 min) was beneficial to produce high-quality chips in less time than VF (2 kPa, 95°C, for 75 min). Specifically, the use of MWVF for 10 min, combined with VF for 40 min, reduced frying time by 33% (from 75 to 50 min), simultaneously achieving improvements in the quality and sensory characteristics of the banana chips. Even this enhancement was not only obtained compared to VF-treated banana chips but also compared to a commercial product.

MWVF has not exclusively been applied to vegetable products but has also been employed in fish frying. Concretely, Shi et al. (2019) utilized MWVF (800–1000 W, 0.085 MPa, 90°C, 6–36 min) in bighead carp fish fillets with promising results. They observed that the MWVF technology significantly increased the water evaporation rate with respect to the VF (0.085 MPa, 90°C, 6–36 min). In addition, the 800 and 900 W power levels provided fish fillets with lower oil content compared to VF-treated fillets, whereas the 1000 W power level resulted in fish fillets with a higher L^* value, and with the highest sensory evaluation score (at 24 min of frying).

3.3.2 | Ultrasound-*microwave*-assisted *vacuum frying (USMWVF)*

Several research studies have displayed that the combination of US, MW, and VF technology provides a synergistic effect in enhancing the quality attributes of fried products compared to USF, VF, and MWVF methods. In the USMWVF technology, the sponge effect produced by the US originates a larger vapor pressure around the frying food, which, combined with the MW power and the vacuum pressure, prevents the oil from being absorbed into the final nourishment (Al Faruq et al., 2022). Moreover, the synergistic effects of US and MW help to maintain the physicochemical characteristics and quality of the oil in relation to CF (Sun et al., 2019). In white button mushroom fried, an investigation conducted by Devi, Zhang, and Mujumdar (2021) showed that the simultaneous use of US (300–600) and MW (1000 W) during VF (0.015 MPa; 90°C; 2–14 min) (meaning, the use of the USMWVF hybrid frying technique) had a positive influence on the properties of mushrooms chips with a clear potential for consumer acceptance. When using US, the samples presented a more expanded and less distorted microstructure, which accelerated the frying speed and reduced processing times. Furthermore, the mushroom chips treated with the maximum power of US (600 W) absorbed less oil, maintained the protein content, total phenolic compounds, and total flavonoid content to a greater extent, and preserved the original color of the sample. In another previous study by Devi et al. (2018), they observed that the use of USMWVF technology (US power of 800–1000 W; MW power of 1000 W; 1 kPa; 80–90°C; 3–14 min), in the same matrix food, reduced the oil content between 16% and 20% compared to mushroom chips treated by VF (1 kPa; 80–90°C; 3–14 min) and MWVF (1000 W; 1 kPa; 80 –90°C; 3–14 min) when the USMWVF conditions used were set at 90°C and 1000 W of US power. Furthermore, regardless of the US potency used, mushroom chips obtained by USMWVF had the best color, texture, and structure quality attributes. In an identical manner, Huang et al. (2018) reported that pumpkin chips manufactured by USMWVF (US power of

300–600 W; MW power of 600–1000 W; 0.14 MPa; 90°C; 15 min) displayed a minor moisture amount and oil absorption; meanwhile, superior retention of cellular structure and texture (i.e., crispness) was superior compared to VF and MWVF-treated mushroom chips. Nevertheless, the color of the pumpkin chips produced by USMWVF was not affected.

Another matrix such as fried edamame has also been successfully produced by the USMWVF process (US power of 600 W; MW power of 1000 W; 2 kPa; 80–100°C; 3–18 min) (Islam et al., 2019) as the use of this hybrid frying technology allowed obtaining fried products with a better nutritional profile, namely, with a lower oil content, and a higher concentration of chlorophylls and vitamin C. In addition, the edamame fried by USMWVF provided a snack with improved color and crispness.

4 | QUALITY OF FRYING OILS AND FOOD PRODUCTS DURING ULTRASOUND-ASSISTED FRYING (USF) AND MICROWAVE FRYING (MWF) PROCESSES

The quality and stability of frying oils play key roles in determining the flavor, safety, and shelf life of fried foods. TF methods (DF, PF, and CF) frequently use high temperatures and long cooking times, which can cause oil degradation and the formation of harmful compounds. In this context, some of the representative studies are given in Table 2. Particularly, US and MW-assisted hybrid frying processes have drawn interest as novel alternatives to TF methods (Su, Zhang, Zhang et al., 2018). Both MW and US are used to improve energy and frying efficiency, heat and mass transfer, texture, and color retention by reducing oil absorption, acrylamide formation, and oil oxidation. With the combination of USMWVF, high-quality, visually appealing, low-oil-containing, healthier, and crispier food products can be produced (Al Faruq, Zhang, & Adhikari, 2019; Chitrakar et al., 2019; Devi et al., 2020).

In fried foods, carbohydrates, proteins, and lipids undergo physical, chemical, and structural changes such as lipid oxidation, protein denaturation, and Maillard or browning reactions (Devi et al., 2020). In particular, the oxidation of lipids during frying can result in toxic, low-quality, and unsafe food products that pose a threat to health (Liu et al., 2023). Oil thermal stability is influenced not only by frying temperature but also by mass transfer between food and oil, the presence of antioxidants, composition of fatty acids, and the type of fried food (Crosa et al., 2014). Due to the simultaneous heat and mass transfer (oil, moisture, salt, sugar, antioxidants, and bioactive compounds) that occur during frying, the composition and quality of the final product are significantly affected by the toxic oxidation products. In contrast, antioxidants can transfer from food to frying oil, delaying lipid oxidation, and preventing TFA formation (Manzoor, Masoodi, & Rashid, 2023).

Manzoor, Masoodi, and Rashid (2023) investigated the oxidation effect of DF (180°C) on fish, chicken, peas, and potatoes using SBO and mustard oils (MO). The results showed that the thermal oxidative stability of MO was higher than that of SBO. This was explained by the high unsaturation degree of SBO, which also resulted in more TFA production. TFA formation was correlated to lipid oxidation (acid value, PV, and AV), and frying time. Depending on the type of food, fat-rich foods (fish) are highly prone to lipid oxidation than protein (chicken), carbohydrate (potato), and vegetables (beans), respectively. The levels of both primary (acid value and PV) and secondary (AV, TOTOX, and thiobarbituric acid reactive substances) lipid oxidation products were higher in the fish group. Vegetables have a significant number of antioxidants that may slow the rate of lipid oxidation. However, chlorophylls may act like prooxidants, which can increase lipid oxidation and free radical formation. When it comes to protein-rich foods, protein can form complexes with oxidation products such as aldehydes and free radicals, potentially resulting in underestimation.

The initial moisture content of the food played a crucial role in TFA formation, especially in high-moisture foods like fish and chicken. These high-moisture foods have the potential to originate elevated levels of TFA as a result of the hydrolysis in the trans-isomerization of the double bonds of UFAs. Similarly, fish fillets were fried in SFO and extra virgin olive oil (EVOO) at 170°C using PF and MWF methods (Nieva-Echevarría et al., 2016). Despite the absence of primary oxidation products (e.g., FFA, hydroperoxides, and conjugated dienes), greater quantities of toxic aldehydes were observed in SFO during PF. Furthermore, PF had a greater thermo-oxidation effect in fish fillets than MWF, and EVOO was found to be safer than SFO due to the absence of aldehydes during MWF. As a result, the presence of polyunsaturated acyl groups in SFO, acyl groups in fish lipids, and frying time all played crucial roles in oil oxidation. In a different investigation, VF and TF techniques were employed to fry potato chips in SFO and high-oleic acid SFO oil (HOSFO) (Crosa et al., 2014). According to findings, VF-treated SFO had higher oxidative stability over HOSFO, with lower AV. In the case of synthetic antioxidant addition (tertiary butyl hydroquinone, TBHQ) to SFO, antioxidants, α-tocopherol, and PUFAs remained at higher levels in the SFO during VF. With the application of 10 days of VF, the frying temperature was lower (130°C) and without air compared to TF (180°C) counterparts, resulting in lower free acid, PV, AV,

TABLE 2 Effects on stability and quality of frying oils and the quality characteristics of foods using microwave (MW), ultrasound (US), and hybrid techniques.

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Fried chips						
Apple chips (AC)	Palm oil (PO)	Ultrasound dielectric pretreatment (US) Vacuum frying (VF)	US: (1) 150, 250, and 400 W, <30°C, 20 min (2) 400 W, <30°C, 10, 20, and 30 min VF: 150°C, 0.095 MPa	US: 400 W, 30 min + VF conditions	—US significantly changed the dielectric properties of apple slices and retained color by improving the quality of AC —With increasing US power and time, the moisture and oil content of AC decreased —US decreased acid value (AV), peroxide value (PV) and improved the antioxidant properties of AC. In US-treated samples, the AV and PV of the oil were delayed by 2 days compared to the untreated ones —The oil uptake of treated AC (31.40–34.43 g oil/100 g dry solid) were lower than that of untreated AC (35.07 g oil/100 g dry solid) for a 10 min VC frying	Shen et al. (2018)
Apple slices (AS)	Soybean oil (SBO)	Microwave vacuum frying (MWVF), ultrasound-microwave assisted vacuum frying (USMWVF)	US: 600 W (28 kHz) MW: 800 and 1000 W VF: 90°C, 0.01 MPa, 6, 8, 10, 12, 14, and 16 min MWVF: MW + VF USMWVF: US + MW + F	USMWVF US:600 W, MW: 800–1000 W + VF conditions, 16 min	USMWVF —Increased the moisture evaporation rate —Shortened the frying time —Increased the textural crispiness —Produced a more desirable yellow color of AS —Oil uptake was similar to that of MWVF —Maillard reaction products were lower than that of MWVF —Moisture content of AS varied as: MWVF-800 W > USMWVF-800 W > MWVF-1000 W > USMWVF-1000 W —Oil uptake of AS varied as follows: USMWVF-1000 W > MWVF-1000 W > USMWVF-800 W > MWVF-800 W —The best crispiness was obtained for USMWVF (1000 W, 16 min) —The brightest color was obtained for: L^* (USMWVF 800 W); a^* (MWVF 1000 W) b^* (USMWVF 1000 W)	Al Faruq et al. (2019)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Apple slices (AS)	Soybean oil (SBO)	Ultrasonic (US) and ethanol (EtOH) pretreatment followed by deep frying (USEtOHDF)	Untreated: Without ultrasound (US) and ethanol pretreatment Water + US: US (300 W,40 kHz) in water for 30 min Ethanol treatment: immersion in 95% ethanol for 30 min US + ethanol: US (40 kHz) + 95% ethanol for 30 min DF (160°C for 2, 4, 6, 8, 10, and 12 min)	USEtOHDF: 300 W, 40 kHz + 95% ethanol, 30 min +DF (160°C, 6 min)	—The cavitation effect of US increased with ethanol application —The combined application of US and ethanol pretreatment increased antioxidant capacity, total phenolics, flavonoids, permeability, heat transfer, and AS water loss —95% ethanol and US + ethanol pretreatment generated more pores in AS and reduced oil uptake of AS by 34.5% and 28.2%, respectively	J. Gao et al. (2021)
Banana bracts (BB)	Palm olein oil (POO)	Vacuum frying (VF)	VF: 580 kPa, 100, 110, and 120°C, 10, 15, and 20 min, followed by centrifugation at 600, 1200, and 1800 rpm for 1, 3, and 5 min	VF: 86.65 kPa, 100°C, 20 min, followed by centrifuga-tion at 1800 rpm for 5 min	—Peroxide value (PV) (1.58 ± 0.01 mEq/kg) of BB was less than 30 mEq/kg —VF-treated BB resulted in the lowest fat, less broken pieces, and low moisture while retaining its phenolic composition and antioxidant activity	Wichaphon et al. (2023)
Banana slices (BS)	Palm oil (PO)	Ultrasound (US) in infrared frying (IF) (USIF)	US: 40 kHz, 600 W, 800 W, and 1000 W IF: 2, 4, 6, 8, and 10 min, 140 °C, with the infrared radiation power of 3000 W	USIF-1000 W, 10 min	—US treatment resulted in a tinner crust in BS with a delayed crust formation —US reduced oil uptake (by 1.5%–9.4%) of BS —Oil uptake: IF > USIF-600 W > USIF-800 W > USIF-1000 W —Porosity of BS: IF > USIF-800 W > USIF-600 W > USIF-1000 W —USIF reduced the pore volume of BS —USIF increased the resistant starch content and changed the starch structure, resulting in more starch–lipid complexes	Sun et al. (2024)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Chinese yam (*Dioscorea polystachya*) (CY)	Sunflower oil (SFO)	Ultrasound (US) Microwave (MW) Vacuum frying (VF) Ultrasound-microwave assisted vacuum frying (USMWVF)	US: 300 and 600 W MW: 1800, 2400, and 3000 W VF: 90°C, 10 kPa, for 12, 14, 16, and 18 min	USMWVF (US: 600 W, MW: 3000 W, VF: 90°C, 10 kPa, for 12 min)	—With the synergistic effect of USMWV, low-fat fried CY was produced with better color retention (L^* 77.01 ± 1.21) —USMWV reduced the frying time (18–12 min) and oil uptake (40.29%) —Oil content: US600-MW3000 < US600-MW2400 < US600-MW1800 —More disrupted and porous structure (better texture and quality) was obtained with USMWV	Chitrakar et al. (2019)
Edamame	Soybean oil (SBO)	Vacuum frying (VF), microwave frying (MWF) Vacuum frying assisted by ultrasound (US) and microwave frying (USMWVF)	VF: 10 ± 2 kPa MWF: 1000 W 2450 MHz, 10 ± 2 kPa; 80, 90, and 100°C US: 600 W and 28 kHz Frying time: 3, 6, 9, 12, 15, and 18 min	USMWVF (MW:1000 W, US: 600 W, VF: 10 ± 2 kPa, 100°C, 12 min)	—Oil uptake reduction: USMWVF > MWVF > VF —USMWVF reduced oil uptake and frying time, increased moisture loss kinetics ($2.014–3.823 \times 10^{-9}$ m^2/s), and improved the crispiness, quality (with the highest vitamin C and chlorophyll retention), and color preservation of edamame —USMWVF increased production efficiency by lowering energy consumption (28%–39%) and water use	Mojaharul Islam et al. (2019)
Fish, chicken, peas, and potato chips	Soybean oil (SBO) Mustard oil (MO)	Deep-frying (DF)	DF: 180°C, heated for 5 h, with 10 frying cycles/day, for 5 days	Peas in MO with 1 round/half hour DFF	—Thermal oxidative stability: MO > SBO; beans > potato > chicken > fish —Trans fatty acid (TFA): SBO > MO, related to lipid oxidation —Peas fried in MO have the highest thermal stability with the lowest TFA formation (2.29%) —Fish fillets fried in SBO have the highest TFA content (5.48%) —The oxidative stability of frying oils in terms of acid value, peroxide value, and *p*-anisidine value corresponded to the synthesis of TFA for both SBO and MO —TFA formation and lipid oxidation shows the following trend; fat > protein > carbohydrate > vegetable-based foods —Increased frying time results in higher TFA concentrations (0.87%–2.41%), followed by trans18:3 (0.38%–1.70%) and trans18:2 (0.22%–1.37%), with trans18:2 generated at a faster rate comparably	Manzoor et al. (2023)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Mushroom chips (MC)	Soybean oil (SBO)	Vacuum frying (VF), microwave-assisted vacuum frying (MWVF), ultrasound-assisted vacuum frying (USVF) Microwave combined with ultrasound VF (USMWVF)	Frying temperature (90°C), vacuum pressure (0.01 MPa), ultrasound (600 W, 28 kHz) Microwave (2450 MHz, 3000 W) Frying time: 0, 2, 4, 6, 8, 10, 12, and 14 min	USMWVF (3000 W MW, 600 W US)	—USMWVF has resulted in the maximum moisture removal and reduction in oil uptake (by 27.6% compared to VFs) and frying time (from 14 to 10 min) with enhanced flavor attributes in MC —The fried chip's dielectric loss factor varied as follows: USMWVF > MWVF > USVF > VF	Devi et al. (2020)
Mushroom chips (MC)	Soybean oil (SBO)	Vacuum frying (VF), microwave vacuum frying (MWVF), ultrasound-assisted MWVF (USMWVF)	Frying temperature (90°C), vacuum pressure (0.015 MPa) Microwave (1000 W), 300 W ultrasound-assisted MWVF (300USMWVF), and 600 W ultrasound-assisted MWVF (600USMWVF)	600USMWVF	—600USMWVF gave the best results for color (higher L^* and b^* values, higher consumer acceptance), protein, total phenolics, and total flavonoids —600USMWVF treated MC had the lowest moisture and total oil content (decreased by 20% compared to VFs) —The synergism between US and MW treatments improved the oxidative stability (by decreasing peroxide, carbonyl, and acid values) of SBO by minimizing the loss of nutrients and bioactive compounds	Devi et al. (2021)
Mushroom *(Pleurotus eryngii)* chips (MC)	Palm oil (PO)	Ultrasound-microwave assisted vacuum frying (USMWVF)	US: 0 W, 300 W, 600 W; 15 min MWVF: 90°C, 10 kPa, 1000 W, 25 min	US: 600 W; 15 min + MWVF conditions	—USMWVF delayed the PO degradation and increased the water evaporation rate in a shorter frying time —US treatment at 600 W reduced the levels of peroxide, acid, carbonyl, and polar components compared to 300 W and the control —USMWVF increased PO quality by improving the color, viscosity, and dielectric properties of MC, with a minor effect on the fatty acid composition of PO —Low-field nuclear magnetic resonance (LF-NMR) was used to determine oil quality, and the results (viscosity, acid value, carbonyl value and polar component content, and the synthetic evaluation function) correlated with physicochemical properties —The LF-NMR relaxation time (T_{22}, T_{23}) decreased with increasing frying time, and the peak area ratio S_{21} increased	Sun et al. (2019)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Pear chips (PC)	Palmolein and Sesame oil blends (80:20, 70:30, 60:40, and 45:55 v/v)	Conventional frying (CF) Vacuum frying (VF)	CF: 175 ± 5°C, 4 min VF: 93 and 127°C, 2–7 min, 43–177 mbar	Flying temperature: 110°C Vacuum pressure: 74–98 mbar Frying time: 4–4.2 min, 60:40 palmolein and sesame oil blend	—VF improved the oxidative stability of the oil, resulting in better oil quality (VF > CF) —VF-treated oil had lower PV, free fatty acids (FFA), atherogenicity (IA), and thrombogenicity index (IT) (≤5.28, ≤2.84, ≤0.57, and ≤1.08, respectively) when compared to CF (10.83, 3.70, 0.59, and 1.11, respectively) —Oil intake of PC increased to 18.77%, 21.73%, and 25.18%, respectively, at 100, 110, and 120°C. For CF, it climbed to 44.83% at 175°C —VF-treated PC had lower *a** values in comparison to CF	Juvvi et al. (2020)
Potato starch chips (PSC)	Palm oil (PO) Rapeseed oil (RO)	Pretreatments: Potato starch slices (PSS), pre-steamed potato starch (SPS), steaming potato starch slices (SPSS), steaming and dried potato starch slices (SDPSS) + deep-frying (DF)	PSS: 170°C, 120 s SPS: 100°C, 5 min SPSS: 100°C, 5 min + DF in PO and RO at 170, 180, and 190°C; 60, 90, 120, 150, and 180 s	DF by PO; 120 s at 170, 180, and 190°C DF by RO; 90 s at 170, 180, and 190°C	—Potato starch was processed into the dough, sliced, and produced PSCs that were DF-fried and investigated for their starch–lipid complexes —The oils with longer chain lengths and a lower degree of unsaturation supported starch-lipid complex (PO > RO) —The maximum crystallinity (19.74%) was found in DF in PO (PO-SPSS > RO-SPSS) —Steaming pretreatment supported starch–lipid complex: SPSS > PSS, but the drying process in SDPSS underwent retrogradation, and resistant starch (RS3) in PSC was formed by inhibiting starch—lipid complexes —The results showed that frying conditions, including frying time, frying temperature, and the types of frying oil, significantly influenced the formation of starch-lipid complexes in SPSS —Starch–lipid complexes increased with prolonged frying time, but excessive frying time decomposed these complexes	Li et al. (2024)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Potato chips (PC)	Palm-free sunflower frying oil (PFSFO)	Ultrasound (US) pretreatment + deep frying (DF)	US pretreatment: 40 kHz, 100 W, 15 min at 4, 25, and 73°C, in water or brine (3% NaCI) Ultrasound-assisted frying system (USAFS): US (40 kHz, 50 W, 180°C, 90 s in 1 L of PFSFO	USB73-US (US pretreatment in 73°C brine (3% NaCI) followed by USAFS	—US pretreatment + USAFS of PC were investigated —USAFS significantly reduced oil uptake of PC due to pore formation, which was confirmed by microscopic images (SEM) —US pretreatment reduced enzyme activity (polyphenol oxidase) and free sugars, thereby color changes —USAFS yielded better quality and crispiness in PC with reduced moisture content —Synergistic combination of US pretreatment and USAFS (USB73-US) yielded the best PC with 32% oil reduction	Alikhani Chamgordani et al. (2024)
Potato chips (PC)	Sunflower oil (SFO) High-oleic acid sunflower oil (HOSFO)	(1) TBHQ (tertiary butyl hydroquinone) + SFO + vacuum frying (VF): TBHQ + SFOv (2) TBHQ + FSO + traditional frying (TF): TBHQ + SFOt (3) HOSFO + VF: HOSOv (4) HOSFO + TF: HOSFOt	VF: 130°C, 5 min at 40 mmHg TF: 180°C, 2 min at atmospheric pressure	VF: TBHQ + SFOv	—VF decreased the deterioration rate of SFO and increased the oxidative stability and usage time of the oil —Oxidative stability order of oil: VF > TF —TBHQ + SFOv had the highest antioxidant activity —Oil degradation of TBHQ + SFOv was monitored by measuring the free acidity (FFA: 0.073), peroxide (PV:4.2), *p*-anisidine (p-AV: 25.8), total polar compounds (TPC: 11.2), and oxidative stability (OE), which were far lower than the traditional counterparts —TBHQ + SFOv retained most of the polyunsaturated fatty acids —Alpha-tocopherol: reduction: HOSFOt (99%) > HOSFOv (97%) > TBHQ + SFOt (54%) > TBHQ + SFOv (5%), which can be related to the oxidative stability of SFO	Crosa et al. (2014)
Potato strips	Sunflower oil (SFO)	Deep frying (DF)	DF: 150, 170, and 190°C, 10 min	DF: 170°C, 10 min	—The free fatty acids and acrylamide content of SFO (blank sunflower oil, BSFO) and SFO with potato strips, SFOPS) significantly increased, while peroxide value, 2,2-diphenyl1-picrylhydrazyl free radical scavenging activity, and iodine value decreased with increased frying temperatures (150, 170, and 190°C) —Structure, shape, and cell wall integrity of potatoes remain stable at 170°C	Shabbir et al. (2020)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Frozen pre-fried potatoes (FPP)	Sunflower oil (SFO) Canola oil (CO) Commercial frying oil (palm oil, PO)	Deep-fat frying (DFF) Microwave-assisted frying (MAF)	DFF: 160 and 190°C, 4 min MAF (MW power levels: 600 and 900 W)	SFO MW application at higher power levels (600 W) provided fast, homogenous heating	—Trans fatty acid (TFA): PO > CO > SFO —TFA: DFF > MAF —SFO was the best oil for both DFF and MAF —Toughness of FPP: MAF > DFF —As the MW power increased, the moisture content decreased, and the total polar compounds (TPC) and oil uptake of FPP increased TPC Peroxide value: DFF > MAF; SFO > CO > PO $K_{232,}$ $K_{270,}$ and iodine value (IV): SFO > CO > PO Saponification value (SV) for 160 and 190°C: CO > SFO > PO; SV value for 600 W: SFO > PO > CO; SV for 900 W: SFO > CO > PO. Free fatty acid (FFA) value for 160°C: CO > SFO > PO; FFA for 190°C: CO > PO > SFO; FFA for 600 W: CO > PO > SFO, saturated fatty acid (SFA): PO > SFO > CO	Baltacıoğlu (2017)
French fried potatoes (FFP)	Sunflower oil (SFO)	Microwave frying (MWF) Deep-fat frying (DFF)	MWF: 180°C, 360 W (65 min), 600 W (33 min), and 900 W (25 min) DFF: 180°C, 3 min Frying time: 15 times/day for 5 days	DFF: 180°C, 3 min, 1 day	—MW (900 W) resulted in the highest values for viscosity (76.29 cp) and refractive index (1.4738) —TPC level exceeded 25% after the third day of MW at all power levels —Free fatty acid (FFA) levels during microwave cooking increased gradually from 0.157% to 0.320%–0.379% on day 5 —Polyunsaturated fatty acid loss was between 37% and 53% after MW treatment —MW treatment at 900 W decreased the oil (by 20%–33%) and moisture content (by 25%–33%) of FF compared to deep frying —MWF led to significantly more prolonged processing time and higher levels of SFO degradation than DFF at all power levels	Aydınkaptan and Mazı (2017)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
French fried potatoes (FFP)	Sunflower oil (SFO) Rapeseed oil (RO)	Pan-frying (PF) Microwave frying (MWF) Deep-fat frying (DFF)	PF: 180–200°C, 2, 7, 13, 23, 33, 43, and 50 min;160 g oil, 3 mm deep oil layer MWF: 1100 W, 2, 4, 6, 8, and 10 min; 5 g oil DFF: 180 ± 2°C, 2, 7, 13, 23, 33, 43, and 50 min; 950 g oil, 3 cm deep oil layer	DFF: 180 ± 2°C, 2–4 min	—Frying time: DFF > PF > MWF —Peroxide value: SFO > RO —Tocopherol content: DFF > MWF > PF; RO > SFO —As SFO contained higher levels of polyunsaturated fatty acids (linolenic acid), tocopherol degradation was higher —Oil degradation: MWF > PF > DFF —Peroxide value: SFO > RO, MWF > PF > DFF —Polymer content with PF after 20 min: SFO > RO —Cytotoxic γ-tocopheryl quinone (γ-TQ) formation: PF > MWF > DFF —A 50 min-PF of RO produced the most cytotoxic γ-TQ (22 mg/kg), then α-TQ and γ-TQ transferred (5–7 mg/kg) to FF. Then, 10 min-MWF produced 10 mg/kg of γ-tocopheryl quinone, whereas DFF produced only 6 mg/kg in RO —The quantity and type of oil substantially impacted the production of cytotoxic α- and γ-tocopheryl quinone	Kreps et al. (2017)
French fried potatoes (FFP)	Soybean oil (SBO)	Microwave frying (MWF)	MWF: 2.45 GHz, 5.85 GHz, both 2.45 GHz and 5.85 GHz, 800 W Post-MWF: 2.45 GHz, 5.85 GHz, both 2.45 GHz and 5.85 GHz, 400 W	MWF: 5.85 GHz, 400 W	—MWF led to a reduction in the frying time by 30%–40% —Increased water loss resulted in increased oil intake of FFP —Post-MWF at 5.85 GHz was better than 2.45 GHz in oil reduction, color, texture, and quality improvement —1 min post-MWF reduced the oil content by 18%–23%	Zhou et al. (2022)
Purple-fleshed sweet potato chips (PSPC)	Palm oil (PO)	Vacuum frying (VF), ultrasound vacuum frying (USVF), microwave-assisted vacuum frying (MWVF), ultrasound-microwave assisted vacuum frying (USMWVF)	VF (frying temperature: 90 °C, vacuum pressure 10 ± 2 kPa USVF (VF + US: 600 W) MWVF (VF + MW: 800 W) 1.USMWVF (VF + MW: 600 and 800 W, US: 600 W) 2.USMWVF (VF + US: 300 and 600 W, MW: 800 W)	USMWVF (VF + US: 600 W, MW: 800 W)	USMWVF (VF + US: 600 W, MW: 800 W) treated potatoes had the best drying efficiency and physical properties —USMWVF decreased moisture levels and minimized potato chips' frying time and oil uptake by 16%–34% —USMWVF reduced potato chips' water activity and shrinkage while increasing their crispiness —USMWVF retained almost 80% of total anthocyanin, resulting in a better-colored PSPC	Su, Zhang, Bhandari et al. (2018)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Potato chips (PC)	Palm oil (PO)	Deep-frying (DF)	DF:170°C for 0.5, 1.5, 2, 3, and 4 min, dough: oil ratio (1:50 g/mL) in 2 L of PO	DF 170°C, 1 min	—Potato-based doughs were prepared using wheat (WS), corn (CS), and tapioca (TS) starches —Wheat and corn starch addition significantly lowered the oil content of PC by 7.94% and 13.06%, respectively —Oil uptake of PC: TS > WS > CS —The decrease in oil absorption in PC was linked to the stronger starchy gel network in the dough, which resulted in a decelerated water evaporation rate and restricted dough expansion and porous structure during frying	Zhang et al. (2024)
Potato chips (PC)	Palm oil (PO)	Microwave-assisted vacuum frying (MWVF) Ultrasonic microwave-assisted vacuum frying (USMWVF)	MWVF: 90°C (14 min) and 100°C (10 min), MW: 3000 W, 10 kPa USMWVF: 90°C (10 min) and 100°C (8 min), US:600 W, MW:3000 W, 10 kPa	USMWVF: 90°C (10 min), US:600 W, MW:3000 W, 10 kPa	—USMWVF outperformed MWVF with its higher drying kinetics, reduced energy usage (by 20.4%–24.7%), shortened frying time (by 20%–28%), and improved textural quality in PC —USMWVF decreased oil uptake with its porous structure and improved the color and crispiness of PC	Su, Zhang, Zhang et al. (2018)
Pumpkin slices (PS)	Soybean oil (SBO)	Vacuum frying (VF), microwave-assisted vacuum frying (MWVF), ultrasound-assisted microwave vacuum frying (USMWVF)	VF: (90 °C, 0.14 MPa) MW powers: (600 W, 800 W, and 1000 W, 2450 MHz,90 °C) US powers: (0 W, 300 W, 600 W,28 kHz, 90 °C)	USMWVF: US:600 W, MW: 1000 W, 90 °C, VF: 0.14 MPa, 15 min	—USMWVF significantly reduced the moisture content of PS (USMWVF > MWVF > VF) —USMWVF-treated PS showed better crispiness, lower oil content, and no color change	Huang et al. (2018)
Pumpkin dough chips (PDC)	Sunflower oil (SFO)	Oven frying (OF)Microwave frying (MWF) Deep frying (DF)	OF: 180 ± 5°C, 2 min MWF: 360 W, 6 min (2.5 + 0.5 + 1.5 + 0.5 + 1 mi DF: 180 ± 2°C, 5 s	OF: 180 ± 5°C, 2 min	—The highest minerals were found in PDCs were K, Na, Ca, Mg, and Si —Panelists expressed a preference for OF PDCs over other types (OF > MWF > DF) —DF-reduced nutritional values (antioxidants and phenolics) and quality of PDCs, and the panelists found them oily —Oil content of PDCs: DF > MWF > OF	Çavuş et al. (2024)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Fried oils						
Extra virgin olive oil (EVOO)	Extra virgin olive oil (EVOO)	Microwave frying (MWF) Conventional frying (CF)	MWF: 150 and 500 W (200°C); 2.5, 5, 10, 15, 20, 25, and 30 min, 50 g oil CF: 200°C, 200 g oil	MWF: 150 W; 2.5, 5, 10, 15, 20, 25, and 30 min	—Oil degradation: MWF > CF —MWF at 500 W increased the oxidative deterioration of EVOO by increasing free acid and acrolein —Oxidation order of oil: CF-200°C > MWF-500 W > MWF-150 W —Loss of phenolic compounds and increase in specific extinction coefficients (K_{270}) follows as MWF-500 W > CF-200°C > MWF-150 W	Kishimoto (2019)
Rapeseed oil (RO)	Rapeseed oil (RO)	Microwave heating (MWH) Conventional heating (CH)	MH: 180 ± 2°C, 1900 W, 1–6 h CH: 180 ± 2°C, 1–6 h	MH: 180 ± 2°C, 1900 W, 1–6 h	—The degree of unsaturation and water content of RO significantly affected oxidation —γ-Tocopherol and polyphenols showed antioxidant activity and retarded oxidation of MWH-treated RO —RO samples were divided into three groups based on their oxidation indices. The average fatty acid content of saturated, monounsaturated, and polyunsaturated fatty acids was 5.99%, 66.41%, and 25.54%; 5.72%, 63.65%, and 28.68%; and 6.10%, 59.41%, and 32.44% in the oils from the categories 1, 2, and 3, respectively —Peroxide value (POV), *p*-anisidine value (*p*-AV), conjugated dienes (K_{232}), conjugated trienes (K_{270}), and oxidative stability (OSI) were determined for each class —OSI of category 1 showed that the oils subjected to MH showed higher oxidation stability —OSI of category 2 was similar —In category 3 RO, higher levels of hydroperoxides were produced during MH than during CH	Yan et al. (2023)
Sunflower oil (SFO)	Sunflower oil (SFO)	Microwave (MW): 360, 600, and 900 W	180°C, 3 min and cooling for 15 min, ×5 times repeating 5 day	Higher MW (600–900 W) power levels	—For all MW power levels, similar free fatty acid (0.28%–0.31% oleic acid), K_{232} (37.11–40.28), and peroxide values (10.35–11.09 meq O_2/kg) were detected —MW treatment at 360 W led to higher total polar material (57.5%), viscosity (119.4 cp), refractive index (1.4774), redness (4.2), and yellowness (70.0) and lower values of polyunsaturated fatty acids (linoleic acid) —Higher MW power levels are recommended for frying to increase oil quality, and it is a faster alternative to conventional frying because the same temperatures can be acquired in less time —Instead of the MW power level, the total heat exposure time may be the primary factor in oil degradation	Aydinkaptan et al. (2017)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Fried dough/bread						
Doughnuts	Vegetable oil (Kanola)	Deep fat frying (DFF) Hot air frying (HAF)	DF: 150, 165, and 180 °C; 3, 5, and 8 min HAF: 150, 165, and 180 °C; 4, 6, and 8 min	DFF, 180 °C, 3 min HAF, 180 °C, 4 min	—The extension of doughnut crust was generated around 100 °C —Crust formation was more temperature dependent in DFF than that of HAF —In DFF, crust formation was greater at high temperatures, whereas in HAF, it was higher at lower temperatures —The homogeneity of the air-fried doughnut's crust rose as the frying temperature dropped	Ghaitaranpour et al. (2018)
Leavened doughs	Sunflower oil (SFO)	Deep frying (DF)	DF: 160,180, and 200°C; 1, 3, and 5 min; 0%, 1%, and 2% salt content	160°C, 1 min, 1.97% salt content	—Total polar material content, polymer triglyceride content, viscosity, and a^* and b^* color values of oil samples were all significantly affected by frying temperature, frying time, and dough salt content. In contrast, dough salt content had no significant impact on the L^* color values and conjugated diene value of oil —The conjugated diene values in SFO: 0.67%–1.22% —Total polar materials in SFO: 3.3%–10.1% —Polymer triglycerides in SFO: 5.33%–9.27% —Viscosity of SFO: 44.03–54.85 cP —Color of SFO: L^*: 49.84–59.67 a^*: 5.50–4.81 b^*: 26.6–44.1	Turan et al. (2022)
Fried bread (FB) (Youtiao)	Peanut oil (PO)	Electrostatic frying (EF) Vacuum frying (VF) Deep-frying (DF)	EF: 180°C, 4 min VF: 120°C, 73.327 kPa, 4 min DF: 180°C, 4 min	DF: 180°C, 4 min	—EF, VF, and DF methods were applied on FB (Youtiao) —Potassium aluminum sulfate (PAS) addition reduced acrylamide by 79.88% in DF —EF and VF did not have acrylamide and oil content in FB —VF increased the pH of FB from 5.87 to 6.49 without PAS addition —PAS added FB in DF had higher flavor and appearance score and lower oil content (DF > EF) to see if there is any effect on acrylamide formation and oil content with and without potassium aluminum sulfate	Shyu et al. (2021)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Fried bread (FB) (Youtiao)	Soybean oil (SBO) Palm oil (PO)	Deep-frying (DF)	DF: 180°C, 140 s +Antioxidants; rosemary extract (RE), tea polyphenol (TP), antioxidant of bamboo (AOB), and tertiary butylhydroquinone (TBHQ) at 700, 400, 500, and 200 mg/kg, respectively	DF: 180°C, 140 s	—Antioxidants (60, 120, and 180 mg/kg) were added to SBO and PO —The acid value (AV), peroxide value (POV), and polar components (PCs) were measured to determine the antioxidant effect —Antioxidants had a larger inhibitory effect on oxygenated polycyclic aromatic hydrocarbons (OPAHs) than PAHs —TBHQ, RE, TP, and AOB reduced the total PAH and total OPAH concentrations by up to 30.30%, 23.47%, 11.38%, and 28.85% respectively, in SBO —TBHQ, RE, TP, and AOB reduced the total PAH and total OPAH concentrations by up to 38.94%, 27.56%, 9.45%, and 39.26%, respectively, in PO —A positive correlation was detected between OPAHs and POV for FBs fried in both SBO and PO —The synthetic antioxidant TBHQ performed the best in controlling PAHs and OPAHs, whereas AOB, a natural antioxidant, effectively decreased PAHs while also lowering FB quality degradation	Gong et al. (2018)
Fried fish and meat products						
Crispy pork spareribs (CPS)	Soybean oil (SBO) Palm oil (PO)	Deep frying (DF)	DF: 150°C/12 min and 190°C/6 min	DF: 190°C, 6 min in PO for PAHs DF: 150°C, 12 min in SO for HAs	—Polycyclic aromatic hydrocarbons (PAHs) and heterocyclic amines (HAs) in CPS were detected by GC–MS/MS and UPLC–MS/MS, respectively —Both HAs and PAHs increased in CPS in a temperature- and time-dependent manner, but the formation of PAHs was more susceptible than that of HAs —SO produced more total PAHs and less total HAs than PO, and vice versa, which can be related to variations in oil unsaturation and precursor (benzaldehyde, 2-cyclohexene-1-one, and trans,trans-2,4-decadienal) content —CPS cooked in SO and PO at 150°C/12 min or 190°C/6 min contained 7 HAs (20.34–25.97 μg/kg) and 12 PAHs (67.69–85.10 μg/kg)	Lai et al. (2024)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Fish fillets from gilthead sea bream (*Sparus aurata*) Fish fillets from European sea bass (*Dicentrarchus labrax*)	Sunflower oil (SFO) Extra virgin olive oil (EVOO)	Pan-frying (PF) Microwave frying (MWF)	PF: 170°C, 2.5 min each fillet side MWF: 900 W, 170°C, 2.5 min each fillet side	MWF: 900 W, 170°C	—MWF produces less degradation than PF, thus thermo-oxidation of oils: PF > MWF —No primary oxidation products were detected —Secondary oxidation products were found to be higher in SFO during PF of sea bass fish fillets —In terms of aldehyde production, EVOO was found to be safer than SFO for both PF and MWF —Trans-2-alkenals, alkanals, *cis*, *trans*- and trans,*trans*-2,4-alkadienals, *trans*-9,10-epoxystearate, and 1,2-diglycerides were detected for both PF and MWF	Nieva-Echevarría et al. (2016)
Fishball (FB) and plant-based fishball (PBF)	Sunflower oil (SFO)	Deep-fat frying (DFF) Air frying (AF)	DFF and AF (160°C, 0, 60, 120, 180, 240, 300, and 360 s)	AF: (160°C, 6 min)	—Moisture and heat transfer, DF > AF for PFB and FB —Oil uptake during DF: PFB > FB due to rougher and less uniform structure of PFB —Color change: DF > AF —AF significantly reduced the oil uptake of PFB —Texture and gel strength features of PFB and FB were similar	Ran et al. 2023
Air-fried fish fillets (AFFF)	–	Air frying (AF)	AF: 160°C, 15 min	AF: 160°C, 15 min	—Heterocyclic amine (HA) inhibition in AFFF: clove seed marinade (CSM) (43.98%) > tamarind seed marinade (TSM) (40.26%) > fenugreek seed marinade (FSM) (39.07%) > Acacia seed marinade (ASM) (37.99%), > black beans seed marinade (BSM) (29.95%) —Marinades showed a dose-dependent inhibition in HAs and lipid and protein oxidation —All marinades successfully reduced TBARS and carbonyl while retaining thiol content —There was a substantial correlation among TBARS, carbonyl, and HA levels	Ali Khan et al. (2024)
Fried meatballs (FM)	Soybean oil (SBO	Ultrasonic-assisted frying (UAF)	UAF: Ultrasound powers:0, 200, 400, 600, and 800 W; 12 min, 160°C, meatballs: oil (1:5)	UAF: 200 W, 12 min, 160°C	—UAF increased lipid oxidation by increasing free fatty acid oxidation and TBARS value —UAF increased flavor of meatballs together with free amino acids (glutamine, lysine, glycine, alanine, cysteine, serine, and tyrosine) —UAF within 400 W (particularly at 200 W) increased the nucleotides and volatile flavor compounds, which were confirmed by the electronic nose	Zhang, Zhang, Wang et al. (2020)

(Continues)

TABLE 2 (Continued)

Product type	Frying oils	Frying methods	Process conditions	Optimal conditions	Findings	Reference
Fried meatballs (FM)	Soybean oil (SBO)	Ultrasonic-assisted frying (UAF)	Ultrasound powers: 0, 200, 400, 600, and 800 W, 20 kHz; 8, 12 and 16 min; 120, 140, and 160°C	UAF: 200 W, 8 min, 120°C	—UAF reduced frying time and UAF-FM had improved sensory characteristics —UAF improved the quality and color (L^* values) of FM —UAF treatment increased the moisture retention by the cross-linking of myofibrils in FM —UAF increased the cooking yield from 82.58% to 85.50%	Wang et al. (2019)
Fried meatballs (FM)	Sunflower oil (SFO)	Deep frying (DF)	DF: 150 and 190°C, 3 min + 0%, 0.25%, 0.5%, and 1% of Reishi mushroom extract (RME)	DF: 150°C, 3 min with 0.25%RME addition	—RME was added or surface-spreading (0%, 0.25%, 0.5%, and 1%) to meatballs to investigate its effect on heterocyclic aromatic amines (HAAs) formation —Addition > spreading; adding RME inhibited lipid oxidation more effectively —At 150°C, 3 min, adding 0.25% and 0.5% of RME mitigated the HAAs by 76.2% and 77.7%, respectively —The presence of phenolic compounds and antioxidant capabilities in RME was linked to reducing HAAs in FM	Guzel et al. (2024)
Fried chicken meatballs (FCM) and tofu	Soybean oil (SBO)	Deep frying (DF) Polymeric proanthocyanidins (PPAs) and ultrasound-assisted acid-catalyzed/catechin nucleophilic depolymerized proanthocyanidins (UAPAs) from Chinese quince proanthocyanidins (CQPs)	DF: 180°C, 6 min + PA and UAPA (0.05%, 0.1%, and 0.15%)	DF: 180°C, 6 min + PA and UAPA (0.15%)	—Adding PA and UAPA resulted in a dose-dependent reduction of heterocyclic amines (HAs) in chicken meatballs and tofu —PA and UAPA were more effective in inhibiting HAs in the exterior crust than in the interior of the FCM —PA and UAPA incorporation reduced lipid oxidation in FCM and tofu The addition of 0.15% UAPA to FCM reduced HAs by 57.84% —PPA and UAPA strongly inhibited HAs in chicken meatballs compared to fried tofu	Gao et al. (2024)

and total polar compounds in SFO. In different studies, palmolein and sesame oil mix (60:40, v/v) treated with VF had lower PV, FFA, atherogenicity, and thrombogenicity index, indicating a higher quality oil (Juvvi et al., 2020). Moreover, the presence of water deteriorated oil oxidation and increased the generation of reactive free radicals due to polar interactions. In this regard, the oxidative stabilities of different RO samples were investigated during MWF (Yan et al., 2023). According to findings, unsaturation degree and water content of RO promoted the oxidation by reducing phenolic, tocopherols, antioxidant, and bioactive compounds during MWF.

Likewise, Kreps et al. (2017) examined how deep-fat frying (DFF) (180–200°C), MWF (1100 W), and PF (180°C) affected oxidative stability and the breakdown of tocopherols to generate tocopheryl quinones (TQ) and cytotoxic γ-TQ in French fried potatoes. DFF was found to be safer than PF and MWF, respectively, with its short frying time and formation of these toxic compounds. Oil degradation and PV were higher in MWF, followed by PF and DFF. When compared to RO, higher PV was observed for SFO during PF. As SFO contained higher levels of PUFAs (linolenic acid), tocopherol degradation was found to be higher. Thus, tocopherol content remained high in a 2–4 min-DFF by forming 6 mg/kg of γ-TQ in RO, implying high oxidative stability. However, a 10 min-MWF formed 8 mg/kg of γ-TQ. For its part, 50 min-PF in RO, 22 mg/kg of γ-TQ were produced, and 5–7 mg/kg of which permeated the French fries. It is therefore important to monitor the formation of toxic compounds in the oil during frying, which can be absorbed by the fried food (Kreps et al., 2017). In another study, MWF (150–500 W) CF (200°C) was applied to EVOO to evaluate the oxidative degradation parameters (Kishimoto, 2019). Oil degradation was higher in MWF (500 W) by the formation of free acid and acrolein content; this was followed by CF and MWF (150 W). Because hydroperoxides are unstable at high temperatures, the PV is not a reliable oxidation indicator. They suggested to use specific extinction coefficient at 270 nm (K_{270}), which indicated the presence of carbonyl compounds, with a higher value indicating more oxidative stability.

Oil uptake during frying is one of the key quality characteristics of food. The frying method and temperature, components of frying oils, the frying conditions, type, size, composition, and shape of the food material, moisture content, the surface roughness, the porosity, the cooling process, and the chemical interactions between them can all have an impact on how much oil is absorbed during frying (Devi et al., 2020; Juvvi et al., 2020; Su, Zhang, Bhandari et al., 2018). The TOC of fried food can be divided into two fractions: (1) surface oil (SO), where the oil adheres to the surface of the fried food during frying, and (2) structural oil (STO), where the oil penetrates into the inner structure of the food. For example, Devi et al. (2020) found that the TOC of USMWVF-treated mushroom chips (in SBO) was 32.4%, which was lower than that of VF-treated counterparts (38.8%). The SO of potato chips followed a decreasing path with increasing frying time, whereas the STO values increased with increasing time, but the USMWVF had the lowest value for all conditions. Because US treatment increased mass transfer rate and reduced processing time, energy consumption, and oil pick up due to microstructural changes in the mushroom tissue (Devi et al., 2020), supporting this, a study by Juvvi et al. (2020) demonstrated that subjecting pear chips to a 4-min VF process not only resulted in reduced oil absorption but also facilitated rapid moisture evaporation. A similar trend was also observed for USMWVF-treated potato chips (Baltacıoğlu, 2017; Su, Zhang, Bhandari et al., 2018), mushroom chips (Devi, Zhang, & Mujumdar, 2021), edamame (Mojaharul Islam et al., 2019), and Chinese yam (Chitrakar et al., 2019).

However, in some cases, depending on the food, oil absorption was found to be higher under certain circumstances. For example, USMWVF (US 600 W; MW 1000 W) resulted in higher oil uptake than MWVF (MW 1000 W). The reason for this is that when the US treatment was applied to apple slices, a greater number of microscopic channels were formed during moisture evaporation, allowing hotter SBO to penetrate into the apple tissue during frying. This study indicated that US treatment and its power levels have specific results for each food product. In addition, final oil uptake increased at higher MW power levels (USMWVF-1000 W > MWVF-1000 W > USMWVF-800 W > MWVF-800 W). The phenomenon was explained by the increased escape of water, followed by the entry of frying oil into the remaining pores (Al Faruq et al., 2019). Conversely, Su, Zhang, Bhandari et al. (2018) found that the oil content of the purple-fleshed potato decreased as the MW power level increased (800 W) in the hybrid frying process USMWVF (US 600; MW 800). Higher power levels of MW and US combined with VF formed a more porous and disrupted microstructure, resulting in faster frying, mass transfer, and less oil absorption (Su, Zhang, Bhandari et al., 2018). Similar results were also obtained by Devi, Zhang, and Mujumdar (2021), and after treating mushroom chips with USMWVF (US 600 W; MW1000 W), the cavitation effect formed cracked, more expanded microscopic holes within the cell surface, resulting in a reduced frying rate and time with better color retention (total phenolics and total flavonoid content) and consumer acceptance. Furthermore, this type of synergism between US and MW treatments improved the oxidative stability (by lowering PV and carbonyl and acid values) of SBO during frying.

The studies showed that USF and MWF processes hold promise for improving the quality and stability of frying oils and fried foods compared to CF. However, further research is required to fully understand the complex nature of these impacts and their application across different food products and process circumstances.

5 | ADVANTAGES AND CHALLENGES OF ULTRASOUND-ASSISTED FRYING (USF) AND MICROWAVE FRYING (MWF) OVER TRADITIONAL TECHNIQUES

USF and MWF are effective methods to improve the quality of fried products. US pretreatment accelerates mass transfer, reduces oil uptake, and improves texture properties during frying. MWF results in higher thermal efficiency, shorter drying time, and better final quality compared to CF. However, further studies are required to understand the mechanism and interaction of these technologies with different food matrices (Pankaj & Keener, 2017). Exploring and optimizing these technologies can lead to the production of healthier and safer fried products. For example, nonuniform heating and oil deterioration at high temperatures are the main challenges of MWF (Pankaj & Keener, 2017). However, these challenges can be overcome by using proper equipment and operating conditions. Aydinkaptan et al. (2017) have shown that MWF leads to significantly higher change in the oil quality than immersion frying and was dependent on the MW power level. Additionally, it is important to consider the cost and energy efficiency of these technologies before they can be widely adopted. By optimizing these technologies, it is possible to produce healthier and more sustainable fried foods that can be enjoyed by people of all ages. This could have a significant impact on public health and the environment. However, the optimization of these technologies for large-scale commercial applications is a complex and challenging task. This is due to the need to balance the competing factors of food quality, safety, and cost. Additionally, further research is needed to improve the flavor, texture, and overall sensory experience of foods prepared using alternative frying methods. Most studies on frying technology have focused on the technical aspects of the process, and there is limited data on consumer acceptance of fried products. This is a critical gap, as consumer acceptance is essential for the commercialization of any new food technology. A consumer-based sensory evaluation of fried snacks would provide valuable insights into the factors that influence consumer acceptance of these products. This information could then be used to optimize the frying process and to develop products that are more appealing to consumers.

6 | CONCLUSIONS AND FURTHER PROSPECTIVE

The production of high-quality fried foods while preserving the properties of frying oil remains a significant challenge despite the implementation of various innovative frying processes. This review summarizes research on innovative frying processes that aim to achieve these goals. The review suggests that the limitations of traditional oil frying can be overcome by adopting new frying technologies such as VF, USF, MWF, and their combinations. However, it is important to note that although extensive studies have proposed various ideas and advancements in frying methods, producing food products with minimal fat content and optimal nutritional and sensory properties remains a complex goal. The challenge lies in achieving a balance among sensory attributes, safety, and nutritional quality in fried foods. Future investigations should focus on developing new frying technologies that can meet these requirements while also being economically and environmentally sustainable. By addressing these research areas, scientists and industry professionals can work toward creating innovative frying technologies that produce healthier, safer, and more palatable fried products. This will contribute to the advancement of the field and provide consumers with improved options for enjoying fried foods. However, further research is needed to optimize these technologies and to compare their relative advantages and disadvantages for large-scale commercial applications. This will pave the way for a new generation of high-quality and healthier fried products, which can contribute to reducing the prevalence of diet-related chronic diseases.

AUTHOR CONTRIBUTIONS

Aysun Yurdunuseven Yildiz: Investigation; writing—original draft; writing—review and editing. **Noemí Echegaray and Sebahat Öztekin**: Investigation; writing—original draft; writing—review and editing. **José Manuel Lorenzo**: Conceptualization; writing—review and editing; supervision.

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest related to this manuscript.

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