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# Applications of Novel Frying Technologies in Food Processing: Advantages, Limitations, and Industrial Challenges

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## ABSTRACT

Frying is one of the most widely used food processing methods employed by consumers, restaurants, and the food industry worldwide to produce products with distinctive sensory characteristics. The most common approach is deep frying, which, despite its high popularity, is associated with high oil absorption and the formation of carcinogenic compounds such as acrylamide. Regular consumption of deep-fried foods may increase the risk of cardiovascular diseases, diabetes, hypertension, cancer, and obesity. In recent years, novel processing methods including hot air frying, vacuum frying, microwave frying, and hybrid technologies have been developed. These approaches have been introduced as healthier alternatives to deep frying and are capable of reducing oil uptake while maintaining desirable sensory properties. Moreover, they contribute to improving the nutritional quality and overall health attributes of fried products. Consequently, the production of a new generation of healthier fried foods has become feasible. In this review, the operating mechanisms, advantages, and limitations of these novel frying methods in the food industry are discussed. Finally, a comparative framework based on energy consumption, product quality, consumer acceptance, and industrial scalability is presented to identify existing research gaps and provide new insights into food frying technologies.

## 1- Introduction

Frying is a dehydration and cooking process in which simultaneous heat and mass transfer occur, leading to the development of distinctive sensory attributes in food products, such as aroma, flavor, and color [1]. It is one of the most widely used unit operations in the food industry, involving the processing of food in hot oil at relatively high temperatures (160–190°C). Many desirable characteristics of fried foods arise from the formation of a composite structure consisting of a dry, porous outer layer (crust) and a moist, cooked interior (core). During frying, various physical and chemical phenomena occur, including starch gelatinization, protein denaturation, Maillard browning reactions, moisture evaporation, oil uptake, and the eventual formation of a surface crust. These processes play a decisive role in the interaction between food and frying oil [2]. Oil absorption is considered a complex phenomenon that, as illustrated in Figure 1, can be explained through simultaneous heat and mass transfer mechanisms [3]. Frying also contributes to food preservation and safety, as thermal processing destroys microorganisms, inactivates enzymes, and reduces surface water activity [4]. The quality of fried foods is strongly dependent on the frying oil used. Degraded oil negatively affects flavor, texture, and overall product quality. As oil oxidation and degradation progress during frying, more reactive compounds accumulate at the surface, enhancing food–oil interactions. This leads to excessive drying of the product, darkening of color, and loss of nutritional value [5].

Over the past four decades, the use of deep-fat frying has increased significantly due to its rapid preparation time. However, its health implications and the development of alternative technologies have gained increasing attention from both consumers and researchers [6]. The health concerns associated with deep-fried foods are mainly related to their high oil content, which may reach up to 45% [7]. High oil intake is associated with an increased risk of cardiovascular diseases [8], diabetes [9], hypertension, cancer, and obesity [10]. Several factors influence oil uptake during frying (Figure 2) [11]. These include oil viscosity [12], frying temperature and time [13], pre-frying treatments [14], food microstructure [15], and post-frying oil removal methods [16]. Increasing frying temperature can reduce oil uptake by enhancing moisture evaporation and shortening processing time [17]. Higher oil viscosity is generally associated with increased oil absorption both at the surface and within the food matrix during the cooling stage [18,19]. After removal from the frying medium, the food temperature decreases below 100°C, leading to condensation of internal steam and a reduction in internal pressure. This pressure drop creates a suction effect that facilitates oil uptake [14]. Surface collapse during cooling further promotes oil penetration into the food structure [20]. Pre-cooking treatments can reduce oil absorption by modifying the internal structure and compacting the food matrix [21]. Hydrocolloid coatings, due to their barrier properties and high water-binding capacity, reduce moisture loss and oil uptake during frying [22]. Food moisture content and composition also play a key role in oil absorption. A linear relationship between the kinetic constant of moisture loss and oil uptake has been reported, confirming the influence of dehydration on oil absorption reduction [23].

During deep frying, oil is exposed to high temperatures and oxygen, which can trigger complex chemical reactions such as oxidation, polymerization, and hydrolysis. As a result, harmful compounds such as acrylamide, total polar compounds, and other toxic substances may be formed during frying (Figure 3) [24]. Zhang et al. (2016) reported that polar compounds include oxidation products, hydrolysis products, triglycerides, and oxidized sterols, whereas non-polar compounds include cyclic compounds, trans isomers, and oxygen-containing compounds such as heterocyclic amines [25]. Recent studies have shown that the safety of frying oils is mainly related to the level of total polar compounds (TPC) [26]. Concerns regarding acrylamide formation in fried foods have increased due to evidence of its adverse health effects. Acrylamide formation is highly temperature-dependent and increases significantly with rising frying temperatures. When carbohydrate-rich foods containing the amino acid asparagine are heated at high temperatures, significant amounts of the carcinogenic compound acrylamide are produced, posing potential health risks [27]. Pedreschi et al. (2004) reported that acrylamide content in potato chips was approximately 500 µg/kg after 7 minutes of frying at 150°C, whereas it reached about 4500 µg/kg after 3.5 minutes of frying at 190°C [28].

Increasing consumer awareness regarding the impact of diet on human health has stimulated further research into the development of nutritious and safe fried foods [29]. Consequently, the food industry has focused on developing and improving alternative frying methods aimed at producing fried products with lower oil uptake and healthier profiles, while maintaining sensory and organoleptic properties similar to those obtained through conventional deep-fat frying [30,31]. The use of coating agents in food formulation to reduce oil absorption may exhibit variable effects due to the heterogeneity of raw materials and, in some cases, may adversely affect the sensory properties of the final product [32]. Therefore, the development of innovative processing techniques or the optimization of existing frying methods has become increasingly important in the food industry. Modifications in frying techniques and optimization of key processing parameters such as time and temperature represent major strategies for reducing oil uptake and improving product quality. These factors have a significant impact on both oil absorption and the reduction of toxic compound formation [33]. Accordingly, several emerging frying technologies have been developed, including hot air frying, vacuum frying, microwave-assisted frying, and hybrid systems. These technologies are considered healthier alternatives to conventional deep-fat frying and have gained strategic importance in the production of fried foods. Table 1 provides a general comparison of these methods in terms of energy consumption, product quality (oil uptake, nutrient retention, and sensory attributes), consumer acceptance, and industrial scalability. In this review, several novel frying technologies were examined, with a particular focus on their industrial applications in the food sector. The underlying principles of these technologies were described, and their effects on product quality as well as their potential for commercial development were evaluated.

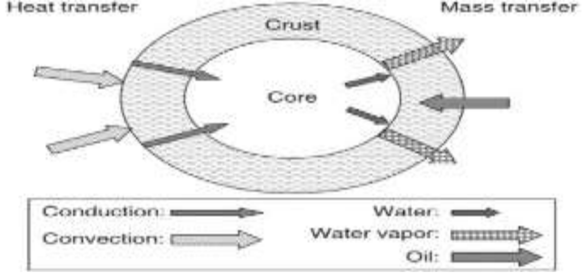

**Figure 1.** Schematic diagram of simultaneous heat transfer (left-hand side) and mass transfer (right-hand side) during deep-fat frying [3].

**Figure 2.** Factors that influence oil absorption in foods during deep-frying [11].

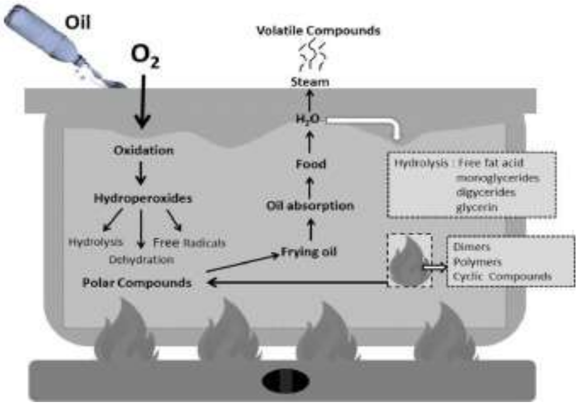

**Figure 3.** Diagram of changes occurring during the frying process [24].

**Table 1.** Comparison of novel frying techniques

| Criteria | Air frying (AF) | Vacuum frying (VF) | Microwave-vacuum frying (MVF) | Radiant frying (RF) |
|---|---|---|---|---|
| Product quality | Reducing the amount of acrylamide and polar compounds,<br>Very low in fat | Low fat content,<br>Smooth and uniform, microstructure | Low moisture content,<br>Reduced damage to food nutrients,<br>Similar taste to ordinary French fries | Lighter in color,<br>Less oil and more moisture than the deep fat frying products |
| Energy consumption | 70% energy savings | Increased energy consumption due to longer frying time | Reduced energy consumption due to shorter frying time | Reduced processing time and improved energy use, leading to cost-effective operation |

| | | | | |
|---|---|---|---|---|
| Consumer acceptance | Sensory evaluation shows that the color of air fried products can be similar to deep-fat-fried product, but the texture is harder and mouthfeel and appearance are drier | VF successfully enhances the textural properties at optimum process parameters which are in accordance with consumer acceptance | Sensory evaluation shows that MVF can be an attractive alternative to deep-fat frying | Sensory evaluation indicates comparable taste to deep fat frying |
| Industrialization potential | Research on home fryers is ongoing, while their industrial use and impact still require further study. | The efficiency of VF is not high; microwave-assisted frying improves process efficiency and facilitates industrial-scale production | High equipment cost and complex operation limit large-scale production | Automation and monitoring systems enhance the reliability and scalability of radiant frying |
| Reference | [24, 34, 35, 36] | [37, 38] | [39, 40] | [41, 42] |

## Hot Air Frying

Hot air frying has recently been introduced as an innovative alternative to conventional deep-fat frying, as it produces fried products with significantly reduced oil content. Compared to other frying technologies that have been extensively studied over several decades, research on hot air frying remains relatively limited, mainly because it is a comparatively new technology that has only been in use for approximately the past decade. However, since around 2020, the number of scientific publications in this field has increased markedly, and this upward trend is expected to continue in the coming years. In hot air frying systems, instead of immersing the food in oil, the product is dehydrated through direct contact with a stream of hot air containing dispersed fine oil droplets within the frying chamber, and a crust gradually forms on the product surface [43]. Figure 4 illustrates a hot air frying system, which typically consists of a fan, an electric resistance heating element, a hot air generation unit, and a sample chamber [44]. These systems provide relatively uniform heat transfer between the hot air and the food product being processed [45], resulting in more homogeneous quality changes throughout the product structure [34]. Hot air frying yields products with very low oil content and moisture levels comparable to those obtained through deep-fat frying [43]. In addition, hot air frying reduces oil consumption and improves environmental performance. Products prepared using this method may contain up to 80% less oil compared to deep-fat fried counterparts [46], while also achieving approximately 70% energy savings and reducing wastewater generation associated with frying operations [24]. The difference in final oil uptake between hot air frying and deep-fat frying is mainly attributed to the frying medium. In deep-fat frying, food is immersed in a large volume of hot oil, whereas in hot air frying, only a dispersed oil mist is present in the air phase [34].

Truel et al. (2015) reported that oil uptake in hot air fried potato chips ranged from 0.37 to 1.12 g per 100 g of fat-free dry matter, whereas in deep-fat fried chips it ranged between 5.63 and 13.77 g per 100 g of fat-free dry matter [34].

Hot air frying has also been reported to reduce acrylamide content by approximately 90% compared to deep-fat frying [47]. Acrylamide is widely formed in fried foods through Maillard reactions [48] and is known for its neurotoxic, genotoxic, and carcinogenic properties [49]. The reduction of acrylamide formation in hot air frying is mainly attributed to the use of lower processing temperatures. Therefore, concerns regarding high oil content and the formation of harmful compounds in deep-fat fried foods have significantly contributed to the development and adoption of hot air frying systems.

From a textural and visual perspective, notable differences exist between deep-fat fried and hot air fried products, which are primarily related to differences in oil uptake and heat and moisture transfer mechanisms. Hot air fried products generally exhibit a puffed and drier appearance, whereas deep-fat fried products tend to have a greasier mouthfeel. The microstructure of hot air fried foods is typically more compact and uniform, while deep-fat fried products exhibit larger pores, higher surface roughness, and more structural irregularities due to greater thermal damage [50]. Scanning electron microscopy (SEM) and differential scanning calorimetry (DSC) analyses have indicated that a key difference between hot air fried and deep-fat fried products lies in the extent of starch gelatinization, which is more pronounced in deep-fat frying. This phenomenon is visually manifested as a thicker and drier crust. The underlying reason is the rapid exposure of the product surface to high temperatures in deep-fat frying, which leads to intense surface moisture evaporation and prevents complete starch gelatinization. In contrast, in hot air frying, moisture evaporation occurs more gradually, resulting in a thinner, more uniform crust with fewer structural irregularities, thereby producing noticeable differences in texture [34]. Color, as one of the most important quality attributes influencing consumer acceptance, is generally darker in deep-fat fried products compared to hot air fried ones. This is attributed to greater moisture loss and enhanced Maillard reactions [51]. Although high-temperature, short-time deep-fat frying can help control color development, it may also influence overall product safety and quality [52]. Rahman et al. (2017) reported that hot air frying leads to reduced product darkening compared to deep-fat frying, resulting in lighter-colored final products [53].

Zaghi et al. (2019) reported that hot air frying has the potential to produce products with sensory attributes (color and flavor) comparable to those obtained by deep-fat frying, while significantly reducing oil content and the formation of polar compounds such as polymers, dimers, free fatty acids, and acrylamide. These compounds are associated with metabolic disorders, impaired absorption of essential lipids, and cancer development [24].

One of the main disadvantages of hot air frying compared to deep-fat frying is the slower dehydration rate [34]. This limitation is primarily attributed to the higher heat transfer efficiency in the liquid phase (oil) compared to the gaseous phase (air). Fang et al. (2021) reported that during deep-fat frying, the moisture content of the product decreased from approximately 69% to 2% within 6 minutes, whereas in hot air frying, a similar reduction required about 10 minutes [37].

To optimize the hot air frying process, several approaches have been proposed, including increasing processing temperature and developing hybrid frying systems. These strategies aim to enhance process efficiency, reduce processing time, and facilitate the industrial scalability of this technology.

Based on the literature review, research on hot air frying of foods remains limited, with most studies focusing on starchy products such as potatoes. Therefore, further investigations on a broader range of food systems, including meat and aquatic products that are widely consumed globally, are strongly recommended.

In a recent study, Maroufpour et al. (2025a, 2025b) investigated hot air frying and deep-fat frying of shrimp. They reported that oil content in deep-fat fried shrimp increased linearly during processing time, indicating substantial oil uptake in this product, whereas hot air frying effectively limited oil absorption. Moreover, in the hot air frying system, the temperature evolution at the core of the product was more controlled, which may contribute to improved product safety and help prevent the degradation of valuable bioactive compounds in shrimp, thereby reducing nutritional losses [36,54].

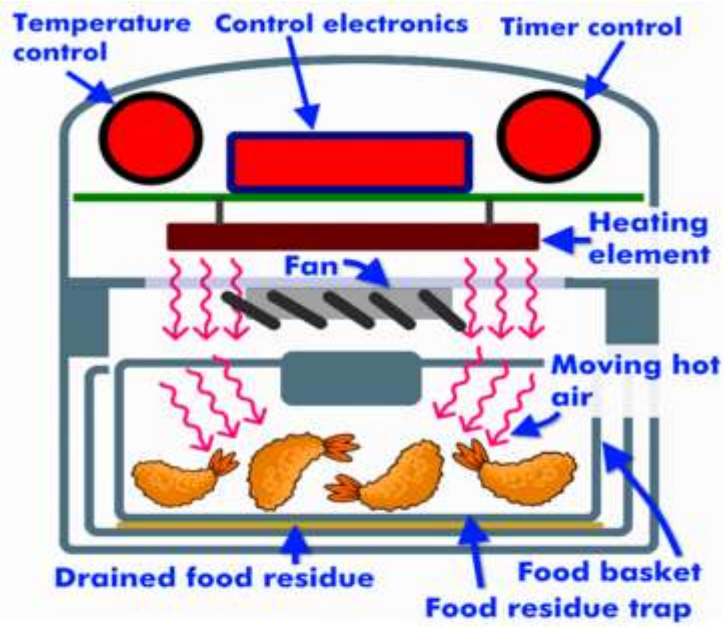

**Figure 4.** Schematic diagram of air-frying equipment showing its operating principle and main components [44].

## Microwave Frying

Microwave frying is a thermal processing technique in which non-ionizing electromagnetic waves, ranging between infrared and radio waves (wavelengths from 1 mm to 1 m and frequencies between 300 MHz and 300 GHz), are used to heat food materials. This radiation is typically generated by a magnetron, which converts electrical energy into electromagnetic energy. A microwave frying system, consisting of a step-up transformer, waveguide, applicator, and oil chamber, is illustrated in Figure 5 [55]. In this system, microwave energy is amplified by the transformer, transmitted through the waveguide into the applicator, and subsequently induces heating within the food, enabling the frying process.

The use of microwaves in food heating and processing has been increasingly adopted due to its ability to accelerate processing time while maintaining product quality. Microwave heating occurs through the excitation of molecular vibrations via dipolar rotation and ionic polarization mechanisms in dielectric materials [56]. Among these, dipolar rotation is considered the dominant mechanism responsible for dielectric heating during microwave processing [57]. Unlike deep-fat frying, where heat is transferred from the surface to the interior via conduction and convection, microwave frying generates heat volumetrically through rapid rotation of polar molecules within the electromagnetic field [58]. The rapid motion of polar molecules and ions within the food matrix generates internal heat, resulting in fast and uniform heating of the product [59]. Due to relatively high internal pressure caused by steam generation during microwave exposure, heat transfer occurs rapidly, leading to quick dehydration of the food matrix [40].

Microwave frying offers several advantages over conventional deep-fat frying, including reduced energy consumption, shorter processing times, unique microstructural characteristics, and improved retention of nutritional quality [60].

Despite these advantages, one of the major limitations of microwave frying is non-uniform heat distribution and the formation of hot spots. Microwave electromagnetic fields are not uniformly distributed within the cooking chamber, resulting in localized overheating in some regions while others remain undercooked. Consequently, this leads to non-uniform color and texture in the final product. For this reason, microwave processing is more commonly applied as a pre-treatment rather than a standalone frying method in many studies and industrial applications. Microwave pre-treatment has a significant impact on reducing product moisture content and, consequently, oil uptake during frying, as moisture content is a key factor influencing oil absorption. During frying, water inside the food is converted into steam and escapes from the matrix; this process generates internal pressure, which contributes to oil penetration through a suction effect once the product is removed from the frying medium [61]. Therefore, reducing moisture content prior to deep-fat frying can effectively decrease oil uptake. Compared to conventional deep-fat frying, microwave-assisted processing can reduce oil absorption within a shorter processing time. Several studies conducted on products such as eggplant, chicken, and potatoes have reported that microwave pre-treatment reduces moisture content and results in products with significantly lower oil uptake [62]. In addition, microwave pre-treatment, due to substantial moisture removal, may lead to product shrinkage and structural collapse prior to frying [63]. Sansano et al. (2018) compared the quality parameters of microwave-fried and deep-fat fried potatoes. Their results showed that microwave processing increased the dehydration rate and significantly reduced the time required to reach comparable moisture levels compared to deep-fat frying. Moreover, microwave-assisted frying reduced both acrylamide formation and oil uptake in the final product [64].

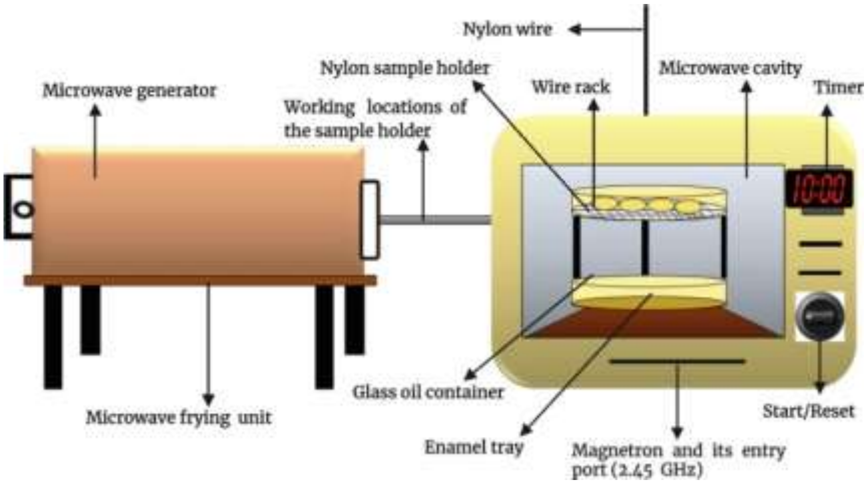

**Figure 5.** A schematic diagram of the microwave frying system [55].

## Vacuum Frying

Vacuum frying is an advanced processing technique and a suitable alternative to conventional deep-fat frying in the food industry. It was first patented by Yan (1989) to overcome the limitations of traditional atmospheric frying, which often leads to excessive oil uptake and rapid oxidation of frying oils [65]. Figure 6 illustrates a vacuum frying system, which typically consists of three main components: a vacuum frying chamber, a condenser, and a high-capacity vacuum pump [66]. In this system, prior to frying, the required low-pressure environment is established using a vacuum pump to maintain the system under reduced pressure conditions. The food is then heated during processing, leading to moisture evaporation. The generated vapor is transported through a vacuum line to a condensation unit, where it is collected and removed from the system. One of the most notable advantages of vacuum frying is the oil removal step, which can reduce surface oil content in fried foods by approximately 87%, resulting in higher-quality products compared to deep-fat frying [67]. Dueik et al. (2010) evaluated the performance of vacuum frying using carrot slices. Their results showed that oil uptake in vacuum-fried carrots was 50.5% lower than in deep-fat fried samples, while approximately 90% of carotenoids were retained, contributing to improved color stability [68].

In vacuum frying, food is processed at relatively low temperatures under reduced pressure (below atmospheric pressure, approximately 6.65 kPa) and in the presence of limited oxygen. This condition lowers the boiling point of both oil and moisture, enabling frying at lower temperatures compared to conventional deep-fat frying. The reduction in temperature and oxygen availability helps inhibit oil oxidation and minimizes the formation of harmful compounds such as acrylamide and furan [69]. Vacuum-fried products are therefore considered safer than conventionally deep-fat fried products due to significantly reduced or negligible acrylamide formation, and they may also exhibit improved shelf-life stability [31]. Belkova et al. (2018) reported that acrylamide content in deep-fat fried products reached 1000 µg/kg, whereas in vacuum-fried potatoes it did not exceed 250 µg/kg, indicating the production of healthier fried foods under vacuum conditions [69].

Vacuum frying also enhances product quality by preserving nutrients, color, flavor, and texture due to reduced processing temperatures and limited oxygen exposure. The absence of oxygen during frying suppresses undesirable chemical reactions such as oxidation and enzymatic browning. As a result, nutritional compounds and natural color pigments are better preserved, and the final products exhibit a more natural flavor compared to deep-fat fried counterparts [70]. Vacuum-fried products can achieve the desired level of dehydration without excessive burning or darkening.

Texture is a critical factor in consumer acceptance of fried foods, and vacuum frying can provide a desirable melt-in-the-mouth sensation similar to deep-fat frying, while offering the advantage of being a healthier processing method [71].

Garayo and Moreira (2002) reported that vacuum fryers are capable of producing fried products with approximately 30% less oil while maintaining similar texture and color attributes to those obtained by conventional deep-fat frying [7].

Studies have demonstrated that the reduction in frying temperature under vacuum conditions decreases oil oxidation and oil uptake, thereby leading to healthier final products. In vacuum frying, the use of lower temperature and reduced pressure shortens the cooling stage of the product; consequently, there is less opportunity for oil penetration and moisture–oil exchange. This significantly contributes to reduced oil absorption in the final product [72].

Bedoya et al. (2018) showed that vacuum frying leads to a lower peroxide value in frying oil compared to deep-fat frying. These results indicate that vacuum frying can effectively reduce oil oxidation during processing, thereby improving product quality and extending shelf life [73].

Yamsaengsung and Rungsee (2003) reported that vacuum frying has a significant effect on reducing oil uptake. Moreover, vacuum-fried products exhibited greater shrinkage and a lighter, more natural color compared to atmospheric deep-fat fried products [74]. Fang et al. (2021), in a study comparing deep-fat frying, hot air frying, and vacuum frying of fish, reported that hot air fried and vacuum-fried samples had lower oil uptake (9.8% and 27.7%, respectively) and exhibited more uniform and smoother microstructures compared to deep-fat fried samples. In contrast, deep-fat frying, due to high temperature and rapid mass transfer, resulted in a highly porous, irregular, and heterogeneous microstructure, along with pronounced browning reactions [37].

Akinpelu et al. (2014), in a study on optimization of vacuum frying conditions for desirable quality attributes, identified optimal processing conditions at 133°C, a vacuum pressure of 9.91 cm Hg, and a frying time of 6 minutes [75].

The main limitation of vacuum frying is that, due to the lower processing temperature, the time required to achieve desirable crispness may be prolonged. In addition, vacuum systems and pressure control equipment are associated with high operational costs and require precise design to control pressure, temperature, and processing time [38]. Therefore, the potential of vacuum frying can be further enhanced by combining it with other emerging technologies, enabling its application at both small-scale and industrial production levels.

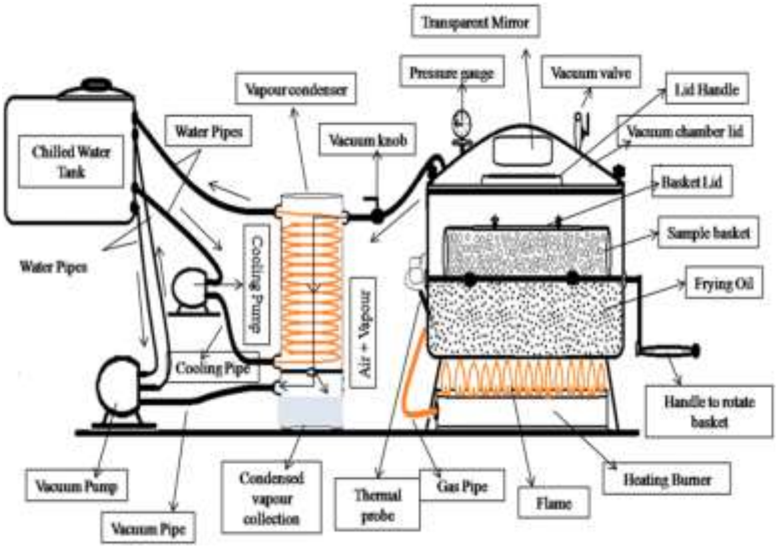

**Figure 6.** A schematic diagram of the vacuum frying system for industrial production [66].

## Hybrid Methods

The combination of advantageous features from different frying technologies can improve product uniformity, reduce processing time, enhance thermal efficiency, decrease oil uptake, minimize the formation of harmful compounds such as acrylamide, and lower overall energy consumption. However, these benefits are often accompanied by increased process complexity, more sophisticated control requirements, and higher equipment costs at the industrial scale.

## Microwave-Vacuum Frying (MVF)

Hybrid process design has been widely investigated as a strategy to enhance processing efficiency and optimize frying time. Non-uniform heating, color degradation, and excessive moisture loss are among the common limitations associated with microwave processing [76]. Therefore, to improve product quality and process efficiency, microwave heating has been combined with vacuum frying, resulting in microwave–vacuum frying (MVF). The integration of these two technologies, as illustrated in Figure 7 [77], has led to the development of an advanced frying system that enables faster heating rates and shorter frying times, thereby reducing energy consumption. In addition, this approach minimizes dehydration time and reduces oil uptake in the final product [78]. These advantages have been confirmed in several studies, making MVF a promising technique for improving frying processes and enhancing the quality of fried products [77]. In recent years, this method has gained increasing attention due to its high heating efficiency, improved uniformity, relatively simple operation, and reduced energy demand. In MVF systems, microwave energy is applied to heat the food material under vacuum conditions, thereby overcoming several limitations associated with conventional deep-fat frying [79].

The primary advantage of MVF compared to other frying methods is its rapid dehydration rate. Microwave-assisted volumetric heating enables fast heat transfer, resulting in fried products with lower oil content, improved texture and flavor, reduced acrylamide formation, and higher overall quality [80]. These improvements are mainly attributed to shorter heating times compared to deep-fat frying. Moreover, MVF lowers the boiling point of water under vacuum conditions, allowing dehydration to occur at lower temperatures and in shorter times. This, in turn, reduces the rates of Maillard reactions, lipid oxidation, and enzymatic browning.

Figure 8 presents scanning electron microscopy (SEM) images and cross-sectional microstructures of mushroom chips processed by vacuum frying (Figure 8-a) and microwave–vacuum frying (Figure 8-b) [81]. The images indicate that MVF technology can produce products with improved health attributes, more uniform texture, better color, and lower fat content, thereby preserving both sensory and nutritional qualities.

Quan et al. (2014) compared MVF with vacuum frying for potato chips. Their results showed that MVF significantly reduced oil uptake compared to vacuum frying, while also improving crispness and color and reducing frying time [80].

According to Su et al. (2016), the quality of MVF products was significantly superior to that of vacuum-fried products. They reported that microwave-induced porosity enhanced crispness and improved textural properties. Additionally, oil uptake in MVF products was considerably lower. However, the authors also noted that the equipment required for this technology is expensive and its implementation is relatively complex [39].

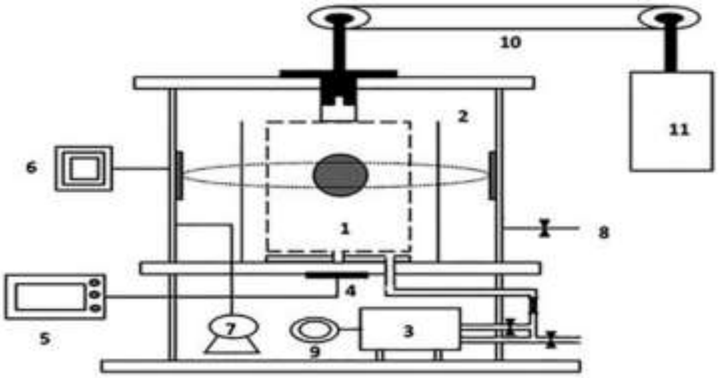

**Figure 7**. Schematic diagram of the microwave-vacuum frying equipment: (1) Frying chamber; (2) vacuum chamber; (3) oil tank; (4) temperature sensor; (5) controller; (6) microwave source; (7) vacuum pump; (8) valve for breaking vacuum; (9) circulation pump; (10) conveyor; and (11) electric motor [78].

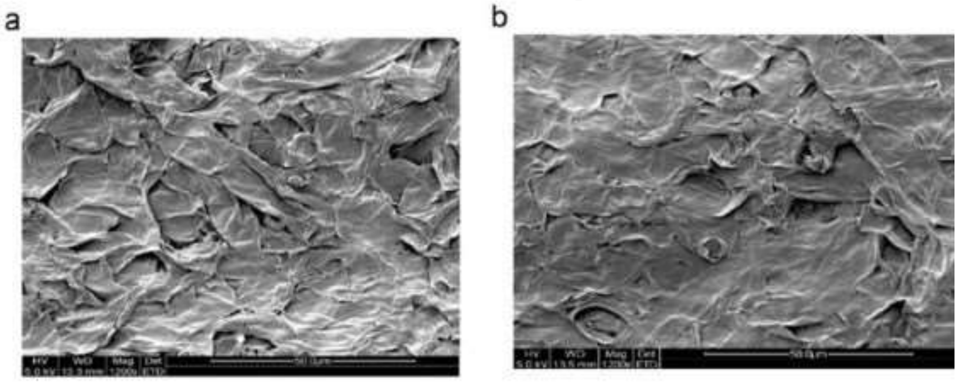

**Figure 8.** SEM images (×1200 magnification) of mushroom chips (8a: VF, 8b) [81].

## Infrared Frying

In hybrid processing systems, infrared radiation can be utilized as a low-cost, controllable, and industrially applicable heat source. In infrared-assisted frying systems, infrared radiation is combined with complementary frying methods to enhance both process efficiency and product quality. Infrared heating enables rapid surface heating, while secondary processes facilitate internal moisture removal. This combination accelerates the frying process while preserving the sensory and nutritional attributes of the final product. Infrared radiation is a part of the electromagnetic spectrum with wavelengths ranging from 0.78 to 1000 µm, positioned between visible light and radio waves. Based on wavelength, infrared radiation is classified into three regions: near-infrared (NIR), mid-infrared (MIR), and far-infrared (FIR) [82]. Each region exhibits distinct characteristics suitable for different thermal applications. Near-infrared radiation, with higher energy, penetrates deeper into materials; far-infrared radiation, with lower energy, provides surface heating suitable for gentle processing; and mid-infrared radiation offers a balance between surface and volumetric heating. Although microwave systems also rely on electromagnetic energy, infrared heating is generally more direct and efficient for surface heat transfer.

The mechanism of infrared frying involves direct absorption of infrared energy by the food surface. Infrared radiation excites water molecules, inducing molecular vibrations that facilitate rapid moisture evaporation from the surface, thereby enhancing frying efficiency. The performance of infrared frying is strongly influenced by the physical and chemical properties of the food, including moisture content, porosity, and thermal characteristics. High-moisture foods absorb infrared energy more effectively, leading to faster frying rates, while porous structures enhance vapor diffusion and accelerate moisture removal [83].

Infrared frying is considered a precise and distinctive technique widely used for process optimization and the design of hybrid systems. This technology enables rapid and uniform energy transfer through electromagnetic radiation, while preserving sensory and nutritional qualities such as color, flavor, and vitamins, and ensuring microbial safety, particularly for high-value products [84]. Furthermore, its alignment with energy efficiency goals and environmental sustainability (e.g., reduced greenhouse gas emissions) strengthens its role in modern food processing and helps overcome limitations of conventional methods [85,86]. Sabbaghi and Nguyen (2025) reported that infrared technology reduces processing time and improves energy efficiency, enabling more economical operation without compromising final product quality [42]. However, consumer acceptance data for infrared-assisted frying remain limited, and most studies have been conducted at laboratory or pilot scale. At the industrial level, further research and development are still required for full-scale implementation.

Recent technological advances, including hybrid systems combining infrared radiation with vacuum frying, hot air frying, or microwave processing (Figure 9) [87], have improved process efficiency and expanded application potential. These innovations highlight the transformative potential of infrared-based frying technologies in the food industry [88].

Compared to hot air frying, infrared heating significantly reduces processing time by providing direct and targeted energy transfer to the food surface and promoting more uniform heating, thereby overcoming the limitations associated with the low heat transfer efficiency of air as a gaseous medium [89].

In microwave frying systems, heat is generated volumetrically within the food through electromagnetic waves, reducing processing time compared to hot air frying; however, microwave heating may cause hot spots and non-uniform moisture distribution. Infrared radiation, by providing more uniform surface heating, improves moisture removal uniformity and helps maintain structural integrity of the product [90].

Vacuum frying is conducted under reduced pressure and is suitable for heat-sensitive products, as it minimizes thermal degradation and nutrient losses. However, it typically requires longer processing times and higher energy consumption. The integration of infrared radiation with vacuum systems as a hybrid approach effectively mitigates these limitations by enhancing process speed and energy efficiency [91]. In such systems, infrared radiation promotes rapid energy transfer and crust formation, while vacuum conditions lower the boiling point of water, facilitating moisture removal at lower temperatures and preserving heat-sensitive compounds, thereby improving sensory quality. Additionally, increasing infrared power and reducing pressure further enhance process efficiency and reduce frying time [92]. The interaction between infrared power, vacuum level, and processing time plays a crucial role in determining final product quality and oil uptake. Proper optimization of these parameters enables the production of fried products with desirable sensory properties and reduced fat content. Overall, infrared-assisted vacuum frying, through the combination of multiple heat transfer mechanisms, pressure reduction, and precise process control, offers strong potential for producing low-oil, high-quality fried foods and represents a promising alternative to conventional deep-fat frying.

Nelson et al. (2013) evaluated the efficiency of infrared frying and reported that products fried using this method exhibited a lighter color, contained on average 16% less oil, and retained 19% more moisture compared to conventionally deep-fat fried products [41].

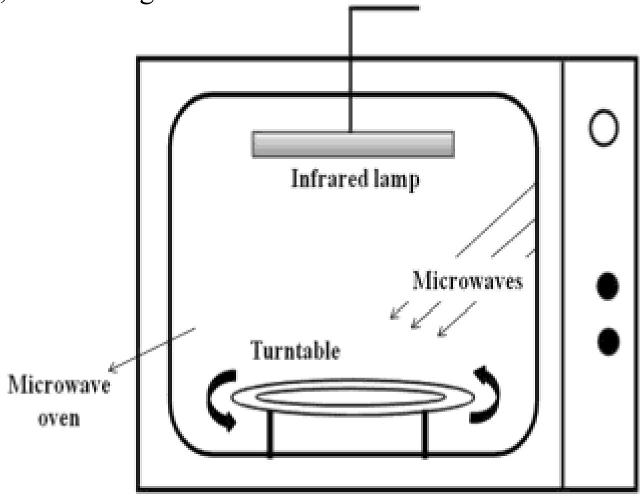

**Fig. 9.** A schematic diagram of the microwave infrared frying system [87].

## Challenges in Sensory Evaluation of Products Produced by Novel Frying Methods

Sensory evaluation is one of the most critical criteria for determining the success of emerging frying technologies, as improvements in nutritional quality and reductions in oil uptake are only meaningful if sensory acceptance is maintained or enhanced. Sensory attributes such as color, texture, crispness, flavor, and overall acceptability play a decisive role in the commercial success of fried products [7]. Sensory studies have indicated that novel frying methods can achieve substantial reductions in oil uptake while still producing acceptable sensory quality aligned with consumer preferences.

Based on sensory evaluations, the color of hot air fried products does not differ significantly from that of deep-fat fried samples, a finding that is consistent with instrumental color measurements. However, in terms of texture and mouthfeel, hot air fried products typically exhibit a harder texture, a drier appearance, and a less greasy mouthfeel compared to deep-fat fried counterparts [35]. These differences are mainly attributed to changes in crust structure and product microstructure, where hot air fried products contain more void spaces and smaller cells, whereas these spaces are largely filled with oil in deep-fat frying [34,35]. Despite these differences, hot air frying can still achieve satisfactory flavor and overall acceptability when processing conditions are properly optimized, making it a healthier alternative associated with reduced oil uptake. Vacuum frying and microwave–vacuum frying also demonstrate similar advantages. Due to lower processing temperatures and reduced oil absorption, these methods help preserve heat-sensitive compounds and improve textural and color attributes of the final product [38]. Furthermore, microwave–vacuum frying can produce desirable sensory qualities while simultaneously reducing processing time and oil uptake, making it an attractive alternative to conventional deep-fat frying [35]. Nevertheless, available data on sensory evaluation and consumer acceptance remain limited, highlighting the need for further research. Recent studies have reported that although novel frying technologies are effective in reducing oil uptake, they still face sensory challenges. Reduced crispness, altered flavor perception, and non-uniform color development are among the common limitations, largely arising from differences in heat and mass transfer mechanisms compared to deep-fat frying [55]. Hybrid frying systems, by improving heat and mass transfer and accelerating crust formation, have shown significant potential to overcome these limitations and enhance sensory acceptance. However, current evidence suggests that the sensory success of novel frying technologies depends strongly on precise optimization of processing parameters and the integration of sensory evaluation with physicochemical analyses. The development of hybrid technologies, with simultaneous emphasis on health improvement and sensory quality preservation, can play a crucial role in increasing consumer acceptance through optimized processing conditions.

## Industrial Challenges in Novel Frying Methods

Among alternative frying technologies, only vacuum frying has achieved substantial commercial adoption within the food industry. The most significant limitation of vacuum frying is its high initial capital investment and limited accessibility for small-scale production systems, which represents a major barrier for entrepreneurs and small industries in adopting this technology [93]. Hot air frying and infrared frying have also shown promising potential; however, current research has primarily focused on domestic-scale equipment. Investigation of their performance and applicability at industrial scale remains an emerging research area that requires further studies to better understand their mechanisms and interactions with different food matrices [82]. One of the main challenges of microwave frying is non-uniform heating and oil oxidation at elevated temperatures [82]. Nevertheless, these limitations can be mitigated through appropriate equipment design and optimized operating conditions. Hybrid frying processes have received increasing attention as novel alternatives to conventional deep-fat frying. These technologies improve energy efficiency and process performance, while simultaneously reducing oil uptake and acrylamide formation, thereby enhancing texture, color, and overall product quality. However, considerations related to cost, energy efficiency, and process optimization remain critical prior to large-scale industrial implementation. In addition, further research is required to evaluate the sensory properties of foods produced by alternative frying methods. Most existing studies on frying technologies have focused primarily on process engineering aspects, while limited data are available regarding consumer acceptance of fried products. This represents a significant research gap, as consumer acceptance is essential for the successful commercialization of any new food processing technology. Sensory evaluation based on consumer perception can provide valuable insights into the factors influencing product acceptance. Such knowledge can contribute to process optimization and support the development of more appealing fried products tailored to consumer preferences.

## Conclusion

In this review, several alternative and healthier frying technologies, including hot air frying, microwave frying, vacuum frying, and hybrid frying systems, were discussed. These emerging frying methods have substantially addressed the food industry's demands for reduced oil uptake, improved healthiness, and the preservation of sensory attributes. However, research on hot air frying in different food matrices remains limited. Therefore, further studies on a wider range of food products are strongly recommended. Regarding microwave frying, the key limitation of non-uniform heating and hot spot formation—which negatively affects sensory quality and consumer acceptance—can be effectively mitigated by combining microwave heating with vacuum frying, resulting in more uniform and rapid heat transfer. In addition, the potential of vacuum frying can be further enhanced through integration with other technologies, making it applicable both at small-scale production and industrial levels. In fact, hybrid frying technologies present a broad and promising future for the food industry and can significantly improve the performance of alternative frying systems compared to conventional deep-fat frying.

Nevertheless, the production of fried foods with low oil content while maintaining high nutritional and organoleptic quality remains a major challenge in frying processes. Future research should focus on further optimization of novel frying technologies and systematic comparison of their advantages and limitations for large-scale industrial applications. Moreover, with advances in equipment design and precise process control, these technologies are expected to be widely implemented in the food industry. These developments may lead to the creation of a new generation of healthier fried products with high quality, which could contribute to mitigating the increasing prevalence of diet-related chronic diseases.

## Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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## Author Contributions

All authors contributed to the study design, data analysis, manuscript preparation, and approval of the final version of the manuscript. Bahareh Maroufpour: Literature collection, preparation of the original manuscript draft, and manuscript revision. Aman Mohammad Ziaiifar: Project supervision and manuscript revision. Hassan Sabbaghi: Manuscript structuring, manuscript revision, and finalization of the content.

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**مقاله علمی_پژوهشی**

# کاربرد فناوری‌های نوین سرخ‌کردن در فرآوری مواد غذایی: مزایا، محدودیت‌ها و چالش‌های صنعتی

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**چکیده**

سرخ‌کردن یکی از روش‌های پرکاربرد فرآوری مواد غذایی است که توسط مصرف‌کنندگان، رستوران‌ها و صنایع غذایی برای تولید محصولاتی با ویژگی‌های حسی منحصربه‌فرد در سراسر جهان مورد استفاده قرار می‌گیرد. رایج‌ترین روش آن، سرخ‌کردن عمیق است که علی‌رغم محبوبیت بالا، با جذب زیاد روغن و تشکیل ترکیبات سرطان‌زا مانند آکریل‌آمید همراه می‌باشد. مصرف مداوم این محصولات می‌تواند خطر ابتلا به بیماری‌های قلبی‌عروقی، دیابت، فشار خون، سرطان و چاقی مفرط را افزایش دهد. در سال‌های اخیر، روش‌های نوین فرآوری شامل سرخ‌کردن با هوای داغ، سرخ‌کردن تحت خلأ، سرخ‌کردن با مایکروویو و فناوری‌های هیبریدی توسعه یافته‌اند. این روش‌ها به‌عنوان جایگزین‌های سالم‌تر برای سرخ‌کردن عمیق مطرح شده‌اند و می‌توانند ضمن حفظ ویژگی‌های حسی مطلوب، میزان جذب روغن را کاهش دهند و کیفیت تغذیه‌ای و سلامت محصولات را بهبود بخشند. در نتیجه، امکان تولید نسل جدیدی از محصولات سرخ‌شده سالم‌تر فراهم شده است. در این مرور، مکانیسم عملکرد، مزایا و محدودیت‌های هر یک از این روش‌های نوین در صنعت غذا مورد بررسی قرار می‌گیرد. در نهایت، با ارائه یک چارچوب مقایسه‌ای شامل مصرف انرژی، کیفیت محصول، پذیرش مصرف‌کننده و قابلیت صنعتی‌سازی، شکاف‌های تحقیقاتی موجود شناسایی شده و دیدگاهی نوین در حوزه سرخ‌کردن مواد غذایی ارائه می‌شود.