Frying Technology and Starchy Food

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Frying is commonly used by consumers, restaurants, and industries around the globe to cook and process foods. Compared to other food processing methods, frying has several potential advantages, including reduced processing times and the creation of foods with desirable sensory attributes. Frying is often used to prepare starchy foods. After ingestion, the starch and fat in these foods are hydrolyzed by enzymes in the human digestive tract, thereby providing an important source of energy (glucose and fatty acids) for the human body. Conversely, overconsumption of fried starchy foods can induce overweight, obesity, and other chronic diseases. Moreover, frying can generate toxic reaction products that can damage people's health. Consequently, there is interest in developing alternative frying technologies that reduce the levels of nutritionally undesirable components in fried foods, such as vacuum, microwave, air, and radiant frying methods.

Keywords: vacuum frying ; microwave vacuum frying ; air frying ; food quality

1. Introduction

Deep frying is a widely used cooking process, which has been applied to prepare various kinds of foods with unique textures, flavors, and appearances since ancient times [1]. Frying typically involves cooking foods at relatively high temperatures for short times using a liquid oil as a heating medium [2]. During frying, mass and heat transfer processes occur simultaneously: heat and oil move into the food, while moisture moves out [3]. The high frying temperatures used, typically mean than only short times (0.5 to 5 min) are required to fully cook foods [4]. Moreover, frying can kill microorganisms in food more effectively than many other cooking methods, and the high fat and low water content of the fried food produced is not conducive to the growth and reproduction of microorganisms. The absorption of oil during frying increases its calorie content, which may be undesirable from a nutritional perspective [5]. Moreover, the relatively high temperatures involved during frying can lead to the chemical degradation of some heat-labile food components.

Starch is an important source of energy in the human diet. It also plays an important role as a functional ingredient in the food and pharmaceutical industries [6][7][8]. Cereal starch currently accounts for more than 80% of the total global starch market [9] and it is often used in the production of fried starchy foods. Starch is the main component in many fried foods, such as potato chips, French fries, instant noodles, and coating flours. During frying, the oil content increases by an amount that depends on the initial composition and structure of the food product. A large amount of oil is absorbed by starch granules, with most of it being located near their surfaces [10]. The structure and physicochemical properties of starch are affected by the heat and mass transfer processes during frying, thus changing the final quality of starch-based foods [11]. However, little information is currently available on the changes in properties of starch that occur when it is heated in oils at the high temperatures used during frying [12].

A growing number of people are concerned about food- and nutrition-related issues due to the increasing prevalence of diet-related chronic diseases in many countries. Foods typically absorb a large amount of oil during frying, leading to around 30 to 50% fat in the final product [13]. Excessive fat intake, especially the saturated- and trans-fats often used during industrial frying to avoid oxidation, leads to obesity and some chronic diseases, such as cardiovascular and cerebrovascular diseases, and several types of cancers [14]. Besides, the high temperatures used during frying can generate potentially harmful substances. For example, fried foods containing starch and protein, such as French fries and potato chips, are the main source of acrylamide in many people's diet, which may be a human carcinogen [15]. This toxic substance is generated as the result of the Maillard reaction between amino acids (mainly asparagine) and reducing sugars (mainly glucose) at high temperatures [16]. The concentration of acrylamide formed depends on several factors, including food type, moisture content, and frying conditions. Moreover, the type of frying oil, especially the composition, is very important for the final quality and safety of fried foods. Fatty acid composition, and advantages and disadvantages of different edible oils are shown in **Table 1**. Unsaturated fats are susceptible to lipid oxidation during frying, which can also lead to the generation of toxic reaction products. Extra Virgin Olive Oil (EVOO) is mainly composed of triglycerides, with relatively high concentration of oleic acid, monounsaturated fatty acid and low polyunsaturated fatty acid amounts, which makes it more stable at higher temperatures than other edible oils with high polyunsaturated fatty acid amounts [17][18]. In other words, EVOO is more stable during oxidation and heating than other edible oils [19]. According to the results obtained by Napolitano et al. [20], the more polyphenols in olive oil used for fried potatoes, the less acrylamide is formed. This is in agreement with the study of Friedman and Levin [21], who reported that antioxidants can reduce the level of acrylamide in heated foods. Although soybean oil contains high levels of polyunsaturated fatty acids, and is therefore highly susceptible to oxidation, it is still widely used in starch-based fried foods due to its low price [22]. Liu et al. [23] speculates that fried foods may absorb harmful compounds from frying oils during the cooking process, especially when foods are fried for prolonged periods. The type of oil also affects the formation of acrylamide. According to the results reported by Gertz and Klostermann [24], when French fries are fried in palm oil, levels of acrylamide are higher in French fries than in rapeseed oil. Becalski [25] revealed that the acrylamide content of the sample fried with olive oil is higher than that of the sample fried with corn oil.

Table 1. Fatty acid composition, advantages and disadvantages of different edible oils.

Edible Oil	Concn (g/100 g of Fat)	Advantages	Disadvantages	Ref.
Soybean oil	C18:1, oleic acid: 25.76 ± 0.21 C18:2, linoleic acid: 51.04 ± 1.26 C16:0, palmitic acid: 11.02 ± 0.03	The content of vitamin E is rich; The output of the world is high and the price is cheap.	The high content of polyunsaturated fatty acids makes it easy to oxidize, and regarding rancidity, it smells like fishy beans.	[26]
Rapeseed oil	C18:1, oleic acid: 57.7 ± 0.10 C18:2, linoleic acid: 19.0 ± 0.03 C16:0, palmitic acid: 4.74 ± 0.01	It has high content of monounsaturated fatty acids.	The price is relatively high.	[27]
Sunflower oil	C18:1, oleic acid: 26.1 ± 0.06 C18:2, linoleic acid: 58.5 ± 0.10 C16:0, palmitic acid: 6.44 ± 0.03	It is rich in vitamin E and chlorogenic acid with antioxidant activity.	The content of polyunsaturated fatty acids is high and it is easy to oxidize and deteriorate.	[27]

Edible Oil	Concn (g/100 g of Fat)	Advantages	Disadvantages	Ref.
Peanut oil	C18:1, oleic acid: 41.07 ± 0.43 C18:2, linoleic acid: 40.01 ± 0.62 C16:0, palmitic acid: 11.63 ± 0.03	It has unique peanut flavour and high thermal stability; It can be fried for a short time.	There may be a small number of phospholipids, so frying makes it easy to foam, or even overflow the pan.	[26]
Peanut oil	C18:1, oleic acid: 41.07 ± 0.43 C18:2, linoleic acid: 40.01 ± 0.62 C16:0, palmitic acid: 11.63 ± 0.03	It has unique peanut flavour and high thermal stability; It can be fried for a short time.	There may be a small number of phospholipids, so frying makes it easy to foam, or even overflow the pan.	[26] [28]

Due to concerns about the potentially negative health effects of frying, both pre-frying and post-frying techniques have been developed to reduce the oil absorption of fried samples [29][30]. Other studies have shown that the content of amylose in starch samples also has an effect on the oil absorption of starch fried foods, and the higher the content of amylose, the lower the oil absorption of potatoes [31]. The efficacy of a number of innovative frying technologies have been investigated. These technologies may be able to produce fried foods with lower total oil content and reduced levels of potentially toxic substances, while still maintaining desirable quality attributes, thereby leading to a new generation of healthier and delicious fried foods.

To achieve this goal, researchers have been carrying out research to improve the effectiveness of a variety of frying technologies that were developed recently or in the past [32]. For example, vacuum frying, which originated around 60 years ago, can be used to fry foods in the absence of air [33]. Some researchers have combined microwave and ultrasonic methods with vacuum frying to further improve the quality of the fried foods produced [34]. In addition, other technologies that use different heat-transfer mediums or heating sources to fry foods have also been investigated, including air frying [35], spray frying [36], radiant frying [37], oil–water mixed frying [38], and electric field frying [39]. Different frying methods lead to different product characteristics and have different suitabilities for large-scale industrial production of fried products. The overall characteristics and applications of some novel frying techniques are summarized in **Table 2**. In this paper, we review several of the most promising new frying technologies available, focusing on the application to cooking starchy foods. In particular, we present their operating principles and discuss their effects on product quality and safety. Moreover, we discuss their current limitations and their potential for commercial development. In future, it is likely that one or more of these technologies may at least partially replace traditional frying methods and produce better-quality foods in the future.

Table 2. Brief on new frying techniques.

Frying Techniques	Characteristics	Applications	Ref.
Vacuum frying (VF)	Low fat content Smooth and uniform microstructure Longer frying time	The efficiency of vacuum frying technology is not high, so microwave and ultrasonic assisted frying can greatly improve the frying efficiency, which is conducive to the expansion of industrial production. However, the equipment is expensive, and the operation and assembly are complex, so it is still difficult to carry out large-scale mass production.	[40]
Microwave vacuum frying (MVF)	Low moisture content Reducing the damage of food nutrients Similar taste of ordinary French fries		[41] [42] [43]
Ultrasound combined microwave vacuum frying (UMVF)	Increasing evaporation rate compared with VF and MVF Improving texture (crispness) and color, greatly shortening the frying time		[44] [45]
Air frying (AF)	Reducing the amount of acrylamide and polar compounds Very low in fat Longer processing time Low degree of starch gelatinization Bad taste compared to traditional fried products	There is no need to add extra oil when frying food, resulting in very low oil content in the final product. This makes it suitable for middle-aged and elderly people with cardiovascular and cerebrovascular diseases, such as hypertension or hyperlipidemia. The price is low and has entered thousands of households. However, its low frying efficiency is not suitable for industrial production.	[35] [46]
Oil-water mixed frying (OWF)	Delaying the oxidation and polymerization degradation of oil No obvious change on the water content compared with conventional frying Similar in color, smell and flavor of conventional frying	OWF has less decline in color, smell, flavor, and overall acceptability, which can produce healthier and better fried meat products. It is suggested that measures should be taken to slow down the hydrolysis rate of oil in the process of oil–water mixed frying in the future.	[38]

Frying Techniques	Characteristics	Applications	Ref.
Spray frying	Low fat content Better color of products (lighter)	In order to improve the spray frying process, various parameters need to be optimized.	[36]
Radiant frying	Lighter in color Less oil and more moisture than the immersion fried products	Sensory evaluation personnel believe that the fried products taste no different from ordinary products, indicating that the fried products can be used as a feasible alternative to oil immersion frying.	[47]
Electric field frying (EFF)	Delaying the oil degradation during frying Lower moisture content Smaller structural damage	This technology can reduce the cost of industrial production, and future work will focus on the mechanism of electric field on fried products to improve the equipment.	[39]

2. Vacuum Frying

Deep-frying is a high-temperature short-time heating process that is widely used to prepare starchy foods. The foods produced using this method have a golden color, crispy texture, and unique flavor profile, which is extremely popular with many people. Vacuum frying is a new food processing technology developed in the late 1960s and early 1970s that is carried out under pressures well below atmospheric levels. Compared with conventional frying, vacuum frying has several advantages: (1) the oil absorption rate is decreased [48]; (2) the formation of harmful substances (such as acrylamide) during frying is reduced due to the lower temperatures and pressures used [49]; (3) the nutritional quality of the food is better preserved [50]. For these reasons, vacuum frying is often used in the dehydration and drying of fruits and vegetables [51]. Vacuum frying has a wide range of applicability, which is mainly used in fruits (e.g., apples, bananas, strawberries), vegetables (e.g., carrots, tomatoes, potatoes, onions), and dried fruits and nuts (e.g., dates, peanuts).

3. Microwave Vacuum Frying

As discussed in the previous section, there has been great interest in the production of vacuum-fried products because of their enhanced color, texture, and nutritional attributes. However, researchers have shown that the potential of vacuum frying can be further improved by combining it with other technologies [52]. In particular, there has been interest in the development of microwave vacuum frying (MVF), which uses a microwave oven to heat foods placed in a vacuum [53].

During MVF, a microwave is used as a heating source to overcome the shortcomings of traditional vacuum frying [41]. Compared with other frying methods, the main advantage of MVF is that it is a faster dehydration method, which can produce fried fruit and vegetable products with lower oil content, better texture and flavor, less harmful substances, and higher overall quality attributes [54]. These benefits are mainly a result of the reduced heating times required when a microwave is used to heat the samples rather than a normal oven.

4. Air Frying

Air frying directs hot air containing oil droplets around raw food materials to cook them. The main objective of this kind of frying is to promote the uniform contact between the food and the oil droplets within the hot air stream, which reduces the total amount of oil required to achieve effective cooking. Air frying may therefore lead to final products with greatly reduced fat and calorie contents.

As a result, this technique not only brings great health benefits, but also has environmental advantages, such as reducing fuel consumption and emissions. However, due to the limitations of the physical form of the oil used to promote heat transfer, some physical properties of the final products may be adversely affected, including texture, color, flavor, and moisture content [55].

5. Others

5.1. Water–Oil Mixed Frying

Water–oil mixed frying is another innovative frying technology that has advantages over conventional deep-fat frying for certain foods. In this approach, the food residue falls into water, which prevents it from depositing in the oil and being fried repeatedly. The water–oil mixing technology reduces the occurrence of coking and carbonization of residues in oil, which slow-downs the increase in turbidity of frying oils and reduces the deterioration of their quality [56].

In the water–oil mixed deep-frying process, oil and water are added to the same open container, and the oil with relatively low density occupies the upper half of the container, while the water with higher relative density occupies the lower half. An electric heating pipe is placed horizontally in the oil layer of the container. The food is located in the oil layer during frying. A horizontal cooler is installed at the oil–water interface and a forced circulating fan is installed to cool the water, so that the temperature at the oil–water boundary is controlled at 55 °C. The food residue from the fried food falls from the high-temperature oil layer and accumulates in the lower-temperature water layer at the bottom. At the same time, the oil contained in the residue is separated through the water layer and then returned to the oil layer, and the residue falling into the water can be discharged with the water. Ma et al. [38] studied the effect of water–oil mixed frying on soybean oil and chicken. Compared with traditional frying, water–oil mixed frying not only delayed the oxidative deterioration of the soybean oil, but also reduced the production of acrylamide in the chicken.

5.2. Spray Frying

In spray frying, a heated oil is sprayed on the sample. Udomkun et al. [36] reported that the moisture content of spray-fried rice crackers was around 18% higher than those of deep-fried samples, while oil uptake was about 32% lower. These researchers also found that the moisture loss and oil uptake increased as the spraying rate was increased. Spray-frying produced rice crackers that had a more attractive color but worse textural properties than those produced by deep frying. This may be one reason why there is currently a lack of information regarding this technique at both research and commercial scales. To improve the spray-frying process, aspects such as frying temperature, frying time, spraying rate, and spinning speed should be optimized.

5.3. Radiant Frying

Radiant frying is accomplished by using high-temperature radiant emitters that mimic the heat flux profile which foods typically experience during deep-fat frying. Through adjustment of power settings, emitter-sample geometry, and product exposure time, operators can match the radiant heat flux profile to that of oil immersion frying. Nelson et al. [47] reported that radiant fried chicken patties had 16% less fat and 19% more water than those produced by conventional deep fat frying. However, the crispiness and appearance of the products produced by radiant frying were not satisfying according to a sensory analysis: the color of the radiant fried samples was 11% deeper than the deep-fried ones, and they were not as crispy.

5.4. Ultrasonic-Microwave-Assisted Vacuum Frying (UMVF)

Ultrasonic-microwave-assisted vacuum frying systems combine an ultrasound source, a microwave source, and a heating system in a vacuum frying system. The microwave source promotes even heating throughout the vacuum chamber, while a series of ultrasonic sources located at the bottom of the frying container are used to ensure thorough mixing. The operating principles of this kind of innovative frying device are shown schematically in **Figure 4**.

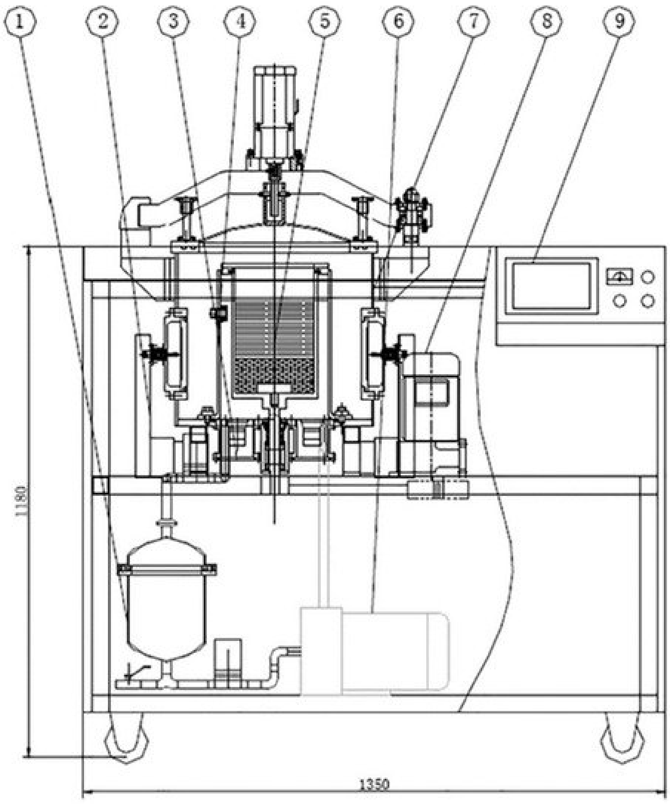

Figure 4. Schematic diagram of the combined ultrasonic-microwave-assisted vacuum frying (USMVF) instrument: (1) Oil tank; (2) microwave source and heating system; (3) ultrasound source and vacuum pressure balance system; (4) vacuum chamber; (5) frying chamber; (6) circulation pump; (7) electric cabin door system; (8) blending and centrifugation system; and (9) controller and operation panel [45].

High-energy ultrasonic waves (20–100 kHz) create a series of compressions and rarefactions that can break-up and mix the fluids they are passing through. In addition, cavitation, microstreaming, and channeling effects can promote mass transfer and evaporation processes [57], which can accelerate dehydration processes.

Compared to microwave vacuum frying (MVF), UMVF can significantly improve the water evaporation rate, shorten the frying time, increase the texture quality, and produce a better final color, although the final oil absorption of UMVF is similar to that of MVF, as no reduction of oil content was observed. It has been reported that the combined application of ultrasound and microwave energy had a significant effect on the energy utilization rate and quality index of vacuum-fried potato chips, while shortening frying times by 36 to 55% [45]. In addition, the Maillard reaction products produced by UMVF were less than those produced by MVF. The additional energy provided by the ultrasonic waves decreases the frying temperature required, thereby reducing the formation of harmful substances (such as acrylamide) and improving food quality (color and flavor). From the industrial point of view, UMVF could save energy and extend the shelf life of fried products. Faruq et al. found that the dehydration rate of fruits and vegetables decreases markedly and the entire dehydration process is enhanced during UMVF, giving a more efficient way to produce snacks from fruits and vegetables [58]. UMVF therefore appears to be more effective than microwave vacuum frying. However, it is worth noting that the ultrasonic waves generated by the machine when it is working may pose a threat to the health of the operators and affect their hearing and attention [59]. Therefore, it is necessary to ensure the sound insulation of the instrument, although it will increase the price.

5.5. Electric Field Frying (EFF)

Electric field frying (EFF) utilizes high-frequency, low-voltage electric fields to promote the dehydration of foods during frying. EFF does not act directly on the food, but on the frying oil, thereby doing little damage to the food tissue. Studies have shown that the total polar compound content, acid value, viscosity, and color-deepening rate of frying oil increased more slowly when an electric field was applied. The time taken for the total polar compound content of the oil to exceed 27% and the acid value to exceed 5 mg KOH/g, was 32 h for EFF treatment and 28 h for conventional deep frying. The darkening of frying oil reflects the degree of deterioration. Compared with deep-fried oil, the EFF oil had a lighter color and higher transparency at the same frying time, which is indicative of a reduction in the oil deterioration rate during frying. According to Yang et al. [39], fried shrimps prepared using EFF had a higher water content, lower oil content, less microstructure damage, and more uniform oil distribution than those produced by conventional deep-frying. The holes and fractures in the fried shrimp produced by EFF were less, and the final structure was more compact. This kind of structure is not conducive to the absorption and retention of oil, thereby leading to a lower final oil content [60].

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