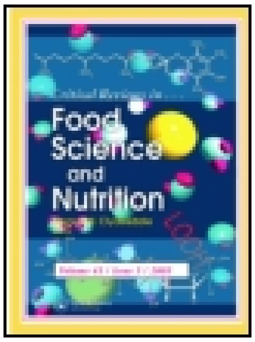

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: https://www.tandfonline.com/loi/bfsn20

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To cite this article: Sangamithra Asokapandian, Gabriela John Swamy & Haseena Hajjul (2019): Deep fat frying of foods: A critical review on process and product parameters, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2019.1688761

To link to this article: https://doi.org/10.1080/10408398.2019.1688761

Published online: 15 Nov 2019.

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2019.1688761

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REVIEW

Deep fat frying of foods: A critical review on process and product parameters

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ABSTRACT

Deep fat frying process involves submerging a food in extremely hot oil until a safe minimum internal temperature is attained. Deep fried foods are hot and crispy on the outside and cooked safely in the center. Deep frying is very fast and, when performed properly, destroys bacteria. When water/moisture in food encounters very hot oil water vaporizes instantaneously turning into super-heated steam. It expands quickly and creates the crispy texture. Though this process has been used traditionally, the mechanism has not been described in literature and it does have downsides. The paper discusses the pretreatment methods, frying oil, frying characteristics and product quality along with the advantages and disadvantages of the process.

KEYWORDS

Frying; fried foods; moisture loss; oil; oil uptake; pretreatments

Introduction

Deep fat frying is one of the conventional and most common unit operations involved in the preparation of variety of fried foods such as potato chips, French fries, extruded snacks, fish sticks, donuts and fried chicken products (Moreira 2007; Erickson 2015). This method involves cooking food by immersing it in hot edible oil or fat at a temperature higher than the boiling point of water (Farkas and Hubbard 2000) and yields product with a unique flavor-texture combination. The oil acts as an effective medium for transfer of energy from the heat source to the food. It is a rapid process in which simultaneous heat and mass transfers can be used as a drying operation. Deep-fat frying is a rapid process with simultaneous heat and mass transfer and it is also a complex process due to two mass transfer operations which takes place in opposite directions between the material (product) and heating medium (oil) when being fried. For example, starch products, water and few soluble materials escape from the product and oil enters into the food (Blumenthal and Stier 1991). Also during frying, the material undergoes physical and chemical transformation at a high temperature range of about 140–180 °C. The soft and moist interior along with the crispy porous outer crust and rich aroma in fried foods increases the palatability. Frying also provides dehydration to cooking, with starch gelatinization, protein denaturation, aromatizing and coloring through Maillard reactions and finally uptakes oil. These reactions are strongly coupled due to the transformation by adapting and optimizing the process parameters (Vitrac, Trystram, and Raoult-Wack 2000; Porta et al. 2012).

At present scenario, fat uptake is considered to be the major critical point of deep-fat frying because of the obesity prevailing in developed and in developing countries where meals high in fat and sugar are the cheapest (Bhurosy and Jeewon 2014). Mechanisms of oil uptake during deep fat frying is a complex phenomenon resulting from interactions between oil and product that undergo many physical, chemical, and structural changes during frying. Hence the quality and quantity of oil uptake have to be carefully controlled. Also the consumer fears have started to arise towards acrylamide, a possible carcinogen which has been detected in fried and baked foods when exposed to high temperatures (Baskar and Aiswarya 2018). The presence of acrylamide in food as a major threat due to its ability to induce cancer and heritable mutations in laboratory animals (Gianni et al. 2007; Kumar, Das, and Teoh 2018). Also during frying, toxic compounds may appear in the oil bath as a consequence of deterioration of oil due to heat, oxygen and water (Gertz 2005). These compounds alter the physical and chemical properties of oil and favors oil uptake. The foremost step is to improve the frying process by lowering and controlling the final fat content of the fried products which can be made possible by either modifying the frying medium, frying techniques, surface properties or application of coatings or by using optimum temperature and frying time, proper shaking and draining (Mellema 2003). Hydrocolloids have been successfully used in batter and breading systems to reduce fat absorption during deep-fat frying so that healthier low fat coated food products could be created (Kurek, Ščetar, and Galić 2017).

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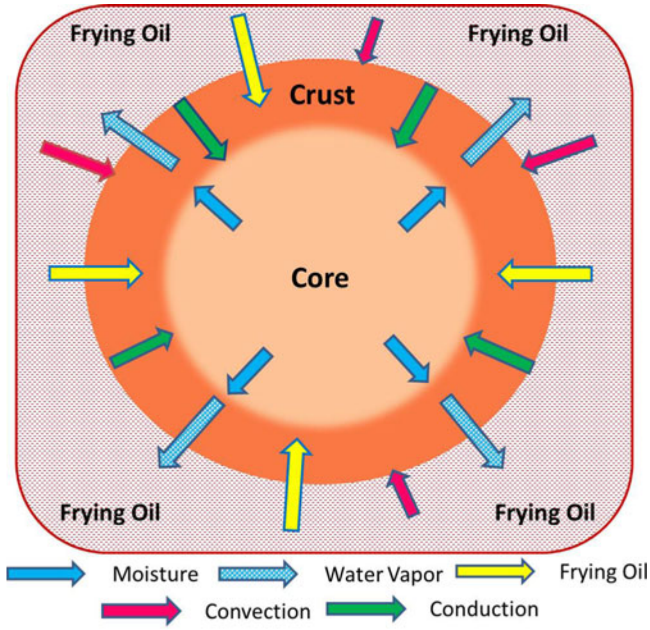

Figure 1. Heat transfer and mass transfer mechanism during deep fat frying.

Mechanism of deep fat frying

Deep fat frying is a complex process with simultaneous heat and mass transfer between the product and frying oil. The moisture loss, oil uptake and crust formation occurs in the surface region of deep fried products. The evaporation of water is rapid initially during frying. This process is restricted by the formation of the thick crust; so that pressure starts building up inside the product due to the accumulation of excess vapor and this result in the formation of cracks in the crust. Then these cracks act as conduits for the entry of oil into the product (Ziaiifar et al. 2008; Oke et al. 2018). Figure 1 represents heat transfer and mass transfer during deep fat frying.

Heat transfer

Both conduction and convection modes of heat transfer are possible during deep fat frying (Sinha and Bhargav 2015). The magnitude of heat transfer greatly depends upon specific heat, density, thermal diffusivity and thermal conductivity. Heat transfer through conduction occurs within the food whereas, convective heat transfer occurs between the food and frying oil. Evaporation of water is rapid at the initial stages of frying and the water which escapes from the product reaches the surface. The escaped water comes in contact with frying oil and form bubbles which transfer vigorously throughout the oil thus creating turbulence in the oil. Thus the bubbling water at the surface influences heat transfer coefficient through increased turbulence. The amount of water vapor bubbles escaping from the food decreases with increased frying time due to decreased amount of remaining moisture within the product. Heat transfer during deep-fat frying can be divided into four phases (Farkas 1994; Sinha and Bhargav 2015).

Initial heating phase: The product temperature increases to the boiling point of water during the first few seconds of frying. It is the stage just before the vaporization of the moisture in the product begins. This phase is also considered to be very short and very negligible amount of water is lost from the product.

- Surface boiling phase: During this phase, surface moisture begins to evaporate and forms a crust at the surface of the product. Also an increase in surface heat transfer coefficient occurs during this phase.
- Falling rate phase: The stage where the evaporation of bulk moisture takes place and the moisture from the core region moves towards the outer portion of the food. Also physico-thermal changes like protein denaturation, starch gelatinization, internal cooking of food, thickening of crust takes place during this phase. This phase is considered to be the longest phase and during this period, the center core of the product approaches the boiling temperature of water.
- Bubble end point: This is the final stage of frying, where the moisture removal rates and the escaping water vapor bubble from the surface of the product also takes place gradually.

Mass transfer

During frying, two types of mass transfer such as moisture transfer and oil transfer takes place. As soon as the frying process starts and also when the frying oil temperature is low, the moisture transfer occurs in form of liquid movement. The liquid mode of moisture transfer is slower than the vapor mode (Mallikarjunan, Ngadi, and Chinnan 2009). The moisture loss from the product is considered as a diffusion controlled process and it can be explained by Fick's second law of diffusion. Initially moisture transfer occurs from the product surface and later at the interface between the dry layer and wet layer of the product (Levine 1990). The driving force for the moisture transfer is due the diffusion gradient between the dry layer and the wet layer of the product and also due to the pressure gradient created by the evaporation of the inner moisture. As frying proceeds, due to the decrease in moisture content, the amount of moisture loss from the product also decreases. The rate of moisture loss is rapid during the first 60 seconds of frying and later it reduces considerably and finally reaches a constant at the end of frying (Lalam et al. 2013).

The moisture loss during deep fat frying can be categorized into three different periods (Vitrac, Trystram, and Raoult-Wack 2000).

- Heating of the product to the boiling point of water along with evaporation of superficial moisture content
- Evaporation of free or capillary water at a temperature near boiling point of water
- Finally increase in product temperature to the frying oil temperature along with reduced drying rates. At the frying temperature, no driving force is available for further evaporation and is solely initiated by a high temperature which continues to occur

Another mass transfer that occurs during frying is the transfer of frying medium (oil) into the product. Oil absorption into a product is highly influenced by temperature of oil, frying period, surface moisture content, surface area of product, and pressure during frying (Innawong 2001). Oil uptake could be characterized by two phenomenon, moisture replacement and absorption during cooling of fried products. The amount of oil absorbed is directly proportional to the amount of moisture lost from the product. Higher frying temperature generally reduces oil uptake because of the reduction in the overall residence time in the frying medium.

As per Saguy and Pinthus (1995), the mechanism of moisture loss and oil absorption during deep fat frying can be categorized into the following stages:

- High temperature during frying generates "explosive" boiling of the water contained in the product which bursts cell walls and forms capillary pores and voids
- Oil is absorbed into the product through these pores and voids.
- The amount of oil absorbed increases with reduction in internal pressure due to moisture loss and subsequent cooling. It was also reported that the oil that enters the voids left by the moisture loss could hold the capillaries open by keeping the structure from shrinking or collapsing. The entry of frying oil through the capillary pores happen during the first 20s of frying

It was also found that as a result of adhesion and capillary action, oil absorption occurs mainly during cooling process after frying. Studies on deep fat frying of tortilla chips showed that 20% of the total oil content was absorbed by the chips during frying whereas, about 80% of the total oil content remained at the surface. During cooling of fried product, about 64% of the total oil content was absorbed by the chips and only 36% remained at the surface (Moreira, Sun, and Chen 1997). During frying some of the moisture inside the product gets converted into steam and causes pressure gradient. As long as the steam is generated, it literally prevents the frying oil from filling the voids. Hence during cooling, the internal pressure decreases due to condensation and thus creates a vacuum effect which pulls the oil into the product (Pedreschi 2012).

Factors affecting the oil uptake during frying of foods

Product parameters

Size, shape and surface of product

The shape and size of a food highly influences the quantity of oil uptake during frying. Being a surface phenomenon, oil uptake is negatively correlated with the product thickness as most of the frying oil remains on the surface. Guillaumin (1983) reported a significant increase in oil uptake when the product thickness was reduced. For instance, French fries absorb less oil than potato chips because of a smaller surface/volume ratio which implies a linear relationship between product surface area and oil content (Gamble and Rice 1988; Lusas and Rooney 2001; Krokida et al. 2001a). The penetration of oil into the product is limited to approximately 1 mm (Saguy et al. 1997). The structural properties of the food also had an impact on the oil uptake because most of the frying oil penetrates the food through the capillary pores in the crust. The privileged location for oil absorption is the broken cells during cutting. As the cut surface has more roughness and contact with oil, it increases the absorption of oil (Saguy and Pinthus 1995; Ziaiifar 2008). Use of good quality blades for cutting can therefore reduce the surface roughness and thus lowers the oil uptake.

Composition of product

The initial composition of the product is also an important parameter influences the amount of oil uptake in fried products. The main factor that influence oil uptake during frying is the initial moisture and solid content in the product. The products such as plantain cylinders, French fries exhibit intermediary water content and also indicates product with high initial moisture content leads to higher oil uptake in fried products. This might be due to the correlation between water loss and oil uptake (Yamsaengsung and Moreira 2002). It was observed that the increase in initial moisture content of the masa flour significantly increased the final oil content of tortilla chips. The author also inferred that pore size distribution developed during frying was the main cause for oil absorption during cooling. Highly porous structure of fried product was mainly due to extensive moisture loss or high level of initial moisture content. The quantity of oil absorbed was related to particle size distribution in the dry masa flour during production of tortilla chips. Coarse masa flour produced tortilla chips with lower oil content than fine masa flour. The coarse particles allow the escape of water through fissures produced and thus restricts oil absorption (Gomez et al. 1987; Moreira, Sun, and Chen 1997). Product with high dry matter content produce fried product of low fat content. This was observed when French fries made from potato with high dry matter (>24%) shows 9% less oil content than made from potato with low dry matter (around 19.5%). The starch in tubers with high dry matter content tends to form granular texture when fried whereas, it tends to break apart during boiling (Lulai and Orr 1979; Lisinska and Leszczynski 1989). Addition of any leavening agents in the product also influences the oil uptake. Such results were observed during frying of battered squid. The reason for the increased oil uptake might be due to the formation of gas in the product which could be held by the oil on frying (Llorca et al. 2003).

Frying oil parameters

Oil type

Deep fat frying can be performed using wide range of fats and oils such as vegetable oils, animal fats, hydrogenated fats or a mixture thereof. The selected frying oil should

Table 1. Effect of oil quality on characteristics of fried potato and fat uptake (Blumenthal and Stier 1991).

Oil stages	Potato characteristics	Oil quality
Break in	White, raw un-gelatinized interior, no cooked odor, no crisp in surface, no oil uptake	Fresh oil, no surfactant, heat is not being transferred to food
Fresh	Slight darkening of surface, partially gelatinized interior, slight crisp in surface, slight oil uptake	Degree of surfactant increases
Optimum	Golden brown color, fully cooked at center, crisp in surface, rigid surfaces	Optimum level of oil absorption
Degraded	Darkened surface, case hardened surface, excess oil uptake	Oil starts to degrade, more surfactant formed
Runaway	Darkened surface, case hardened surface, excess oil uptake, collapsed wall with hollow center	Off odor, off flavor

possess good frying stability, fluidity, bland flavor, low tendency to foam or form smoke, low tendency to gum, oxidative stability of the oil in the fried food during storage, and affordable cost (Kochhar 1999). Vegetable oils, sunflower oil, peanut oil, soybean oil, safflower oil, canola oil and corn oil are commonly used for frying. Peanut oil and canola oil are ideal for use in deep fryers because of their high smoke points. Peanut oil is used widely as it is low in saturated fat and high in polyunsaturated and monounsaturated fats. Therefore, it is a healthier substitute to other frying fats like shortening and lard (Hosseini et al. 2016). Though it is made from peanuts, not all peanut oil is considered an allergen. Highly refined peanut oil is safe for consumers with peanut allergies, while cold-pressed, expelled, and extruded peanut oils are considered allergens. As per Food Allergen Labeling And Consumer Protection Act, highly refined oil such peanut and soybean are exempted from allergen foods (FDA 2006).

A study was conducted to observe the impact of eight different frying oils on fat absorption of French fries by Kita and Lisińska (2005). Higher oil absorption was observed in unsaturated fatty acid, whereas saturated fatty acids provide a greater stability in frying applications (Sanibal and Mancini-Filho 2004). The rate of oxidation was also found to increase with increased unsaturation in frying oils. For example, corn oil with less unsaturated fatty acid was found to be a better frying medium than soybean or canola oils with more unsaturated fatty acids (Warner and Nelsen 1996). It has been also reported that unsaturated cotton seed oil absorbs less oil than palm oil. The contradictions may be due to the oil viscosity which could also be related to fat absorption (Vitrac, Trystram, and Raoult-Wack 2000). The higher viscosity and/or lower surface tension of the frying oil could adhere to the product's surfaces thus making it difficult to remove from surface or less likely to penetrate through crust pores. Thus higher the oil viscosity, the slower is the oil migration. The initial oil viscosity of frying oil depends on the oil type, temperature and oil quality. Viscosity of oil decreases with a decreasing temperature following the Arrhenius equation (Tseng, Moreira, and Sun 1996; Moreira, Sun, and Chen 1997; Vitrac, Trystram, and Raoult-Wack 2000).

Degree of oil refinement

Crude oil is refined to eliminate undesirable minor components that make oils unpleasant to consumers, while causing the least probable damage to the neutral oil as well as least refining loss. The constituents to be removed are all those glyceride and non-glyceride compounds that are detrimental to the flavor, color, stability and safety of the refined oils. They are primarily phosphoacylglycerols, free fatty acids, pigments, volatiles and contaminants. Conversely, not all the minor compounds in fats and oils are unwanted. For instance, phytosterols have nutritional interest while tocopherols with vitamin E activity protect the oil against oxidation. Therefore, to reach the maximum oil quality all the steps of the refining process should be carried out with the minimum losses of desirable compounds. The more refined an oil, the higher the smoke point. That is because refining removes the impurities that can cause the oil to smoke (America's Test Kitchen 2016). A simple rule of thumb is that the lighter the color of the oil, the higher its smoke point.

Quality of frying oil

The frying medium is selected based on price, quality, flavor, oxidation susceptibility, availability and functionality. The composition of oil influences oil uptake, type of by products and residues absorbed by deep-fat fried foods. Oil absorption and degradation of the oil doesn't show a linear relationship but increases with frying time. It was found that the oil extracted from the fried food contains higher amount of polymers than the oil remaining in the fryer. It was reported that the interfacial tension between the product and frying oil decreased with increase in rate of degradation of oil. Blumenthal and Stier (1991) described frying fat quality during frying of potato crisp, which showed a distinct pattern of degradation in five phases of oil (Table 1).

Frying parameters

Frying temperature

Frying temperature is one of the most important parameter which is monitored during frying in order to ensure good quality of fried foods. Deviation in frying temperature is associated with oil degradation, increased formation of surfactants, darkening of product and oil uptake. During deep-fat frying of potato, the high moisture product was exposed to heat for a short period resulting in gelatinization of starch followed by a rapid dehydration period to a final moisture content of about 2% (Ufheil and Escher 1996). Researchers have reported contrasting results regarding the influence of frying temperature on oil uptake. Gamble, Rice, and Selman

Table 2. Effect of blanching on oil uptake during frying.

Product	Blanching parameters	Observations	Reference
Potato	• Hot water blanching, 85 °C for 3.5 min	• Blanched slices absorbed more oil than control slices • Blanched and subsequently dried slices absorbed less oil than control	Pedreschi et al. (2005)
Potato strips	• Blanching in 0.5% aqueous solution of calcium chloride at 85 °C for 5 min	• Blanched sample reduces oil uptake by 27.38% compared to unblanched potato strips • Stabilized tissue structure against frying due to blanching in calcium chloride solution	Ali, Abdel-Razek, and Kamil (2012)
Potato	• Hot water blanching at 85 °C for 3.5 min followed by soaking in 20 g/L NaCl solutions at 25 °C for 5 min	• Reduced oil uptake than edible film coated samples	Durán et al. (2007)
Potato	• Hot water blanching at 65 °C for 5 min, 1:60 w/v	• Significant reduction in oil uptake when blanching was done with high-pressure treatment • Reduced oil uptake could be due to breakdown in cellular structure a thermal blanching	Al-Khusaibi and Niranjan (2012)
Taro (*Colocasia esculenta*) chips	• Hot water blanching at 85 °C for 3 min	• Reduced oil uptake up to 80% in blanched samples	Paz-Gamboa et al. (2015)
Yam slices	• Hot water blanching at 60, 70, and 80 °C for 1–5 min, 1:20 w/v	• Samples blanched at 70 °C at 5 min for 50s frying time resulted in lower oil content in fried chips than unblanched samples • Reduced oil uptake could be due to gelatinization of starch • Optimum blanching conditions: temperature of 70–75 °C, blanching time of 4–5 min	Sobukola et al. (2008)

(1987) had reported that moisture loss and oil uptake were independent of frying temperature. On the contrary, Orthoefer and Cooper (1996) noticed higher oil uptake at lower frying temperature. This might be due to the reason that at lower frying temperature the residence time for the product tends to be high which improved the oil absorption. Also higher frying temperature triggered the dehydration process and the immediate crust formation acted as a barrier for oil absorption which prevented the escape of moisture from food product and subsequently hinder the oil uptake. Similar results were reported by Pedreschi and Moyano (2005) and Kita and Lisińska (2005). It was also studied that at frying temperatures of between 150 and 180 °C, no significant oil absorption was observed but found that increasing frying temperature leads to a decreasing of oil uptake (Varela 1988). In a study on deep fat frying of carrot chips, an increase in frying temperature darkened the color and decreased the carotenoid contents (Sulaeman et al. 2001).

Frying time

The frying time and temperature affects the amount of heat transferred to the product and thus both are closely related. If the frying time exceeds the optimum at constant temperature, the product tends to have higher oil absorption. It was found that the oil content was twice the square root of frying time during frying of potato (Gamble, Rice, and Selman 1987). Oil uptake was found to increase with increase with frying time in both coated and uncoated foods until it reaches equilibrium (Krokida and Maroulis 2000). During the frying of instant fried noodles, increased frying time increases the porosity of crust which in turn resulted in higher oil uptake (Gulia and Khatkar 2013).

Pre-frying treatments

Blanching

Blanching in hot water lowers the reducing sugars and asparagine levels of cut potatoes before frying. Also, blanching has been reported as a pretreatment which could improve the color and texture of the chips and reduce their oil uptake by gelatinization of the surface (Califano and Calvelo 1988). Reduced oil uptake was reported by authors when low temperature blanching for long time (55–70 °C, 15–60 min) before frying activates pectin esterase enzyme and these reactions decreased the porosity and in turn oil uptake is reduced (Aguilera and Gloria 1997). On contrary to this, high temperature and short time (97 °C, 2 min) blanching of potato strips before frying resulted in higher oil content than fresh products, which was not accepted by the consumer (Alvarez, Morillo, and Canet 2000). Table 2 represents the effect of blanching pretreatment on uptake on oil content during frying of foods. Rimac-Brnčić et al. (2004) studied the impact of blanching of potato strips in water and solutions of calcium chloride or citric acid on the oil absorption in fried strips. Water blanched potato strips had the highest values for oil content. Samples blanched in citric acid solution resulted in lowest values (13–15%) compared to samples blanched in calcium chloride solution (27–28%). Reaction between calcium and native pectin of potato tissue was observed in calcium chloride blanched

Table 3. Effect of pre drying on oil uptake during frying.

Product	Pre drying parameters	Observations	Reference
French fries	Pre drying to 10, 15 and 20% Weight loss	• Reduced oil uptake at 20% weight loss than 10 and 15 % • 20% weight loss had negative effect on crispness of French fries	van Loon et al. (2007)
Chickpea flour-based snack	Dried in cross flow convective hot air drier	• The moisture of snack decreased from 0.39 kg/kg db to 0.10 kg/kg db • Drying up to 40 min resulted in a reduced oil uptake to 54% • Reduced oil uptake – pre drying may be due to compactness (reduced porosity) or increase in solid content	Debnath, Bhat, and Rastogi (2003)
French fries	Air dryer, 70 °C ± 0.2 °C, 20, 40, 60, 90, 120 mins	• Frying rate decreased with increase in pre drying duration • Pre drying decreased the oil content of French fries	Krokida et al. (2001b)
French fries	Convective drying (CD), 70 °C and Vacuum-microwave drying (VM), 480 W, 4–6 kPa	• VM pre drying absorbed less fat than pre-dried with the CD • The distribution of water is uniform in VM pre-drying than CD	Tajner-Czopek, Figiel, and Carbonell-Barrachina (2008)
Yam slices	Convective hot-air drying, 60, 70 and 80 °C for 1–5 min	• Oil content of chips decreased with increase in pre drying time • Increase in pre drying temperature at any time resulted in better crispness	Sobukola et al. (2010)
Potato chips	Air recirculation oven, 60 °C, 10, 20, 30 mins	• Pre-drying reduced the oil uptake during frying • Less water was displaced during the frying resulted in lower absorption oil.	Cruz et al. (2018)
Potato strips	Tray dryer, 80 °C, 8 and 15 mins	• Pre drying for 15 min significantly decreased oil uptake • Pre drying generates an external crust during frying – increases resistance to oil absorption	Dehghannya, Naghavi, and Ghanbarzadeh (2016)
French fries	Pulse spouted microwave vacuum drying, 11 to 18 kPa, 10, 15, 20 W/g	• About 40% decrease of oil content when vacuum frying combined with microwave vacuum drying • Due to the synergy effect during the combination process	Quan et al. (2016)
Potato slices	Air dryer, 60 °C, 15, 30, 45, 60, 90 and 120 min	• Pre drying significantly decreased the oil content during frying • Decreased oil content in potato slices after frying was observed with increase in pre drying time	Capar and Yalcin (2017)

sample which was able to stabilize the tissue structure. Pectin substances on reaction with divalent ions of calcium form calcium pectate which increases the rigidity of lamella-cell wall as well as resistance to degradation by the frying process. Pedreschi and Moyano (2005) noted that blanched slices (85 °C, 3.5 min) absorbed more oil than control slices after frying. Fried control potato slices absorbed an average of 9% less oil than the corresponding blanched samples for the three temperatures tested, 120, 150 and 180 °C.

Pre-drying

Drying is the application of heat under controlled conditions to remove the moisture normally present in food by evaporation. The main purpose of dehydration is to extend the shelf life of foods by a reducing the water activity (Fellows 2009). However, drying prior to frying is used to decrease the initial moisture content of potatoes (typically to a content of 60% wet basis). Table 3 represents the effect of pre-fry drying treatment on uptake on oil content for different type of products. The availability of free moisture should be low during frying. Several studies showed that decreasing the initial moisture content of potato by air drying is an efficient way to reduce fat uptake in the final fried product. The pre-drying step decreased the oil content of French fries during frying (20 min), as the pre-drying time increases from 0 to 120 min (Krokida et al. 2001a). The effectiveness of this pre-drying treatment was mainly believed due to the reduction of the moisture content on its own. But in actual it is due the structural changes occurring at the surface of the product. Such changes produce an external crust with low permeability which increases the resistance to oil absorption during frying, thus reducing oil uptake.

Coating

The use of hydrocolloids plays a major role as edible coating to the product to be fried. They are the water soluble

Table 4. Examples of protein based coatings.

Ingredient	Formulation	Product	Fat reduction (%)	Reference
Soy protein	10% soy protein + 0.05% gellan gum film	Fried donut disks	55.12	Rayner et al. (2000
Corn Zein	14% corn zein + 2.8% glycerin film	Fried mashed potato balls	59	Mallikarjunan et al. (1997
Casein	3% sodium caseinate protein film	Potato chips	13.6	Aminlari, Ramezani, and Khalili (2005
Whey protein	3% whey protein film		4.8	
Albumin	3% albumin film		12.1	
Whey protein	10% whey protein post breading dip	Chicken	15	Brannan and Pettit (2015

polymers used in various food and beverage applications as emulsifying, thickening, gelling and stabilizing agents. During deep fat frying of foods, the hydrocolloids form a uniform coating over the surface of the product and avoid excess absorption of oil. Being highly hydrophilic, these hydrocolloids provide limited permeability to moisture, and provide barrier to oxygen and carbon dioxide and protect against lipid oxidation (Porta et al. 2012). Table 4 and Table 5 represent few of protein and non-protein based coatings used for deep fat fried foods respectively. According to Makinson et al. (1987), batter coated products absorbed less oil than uncoated fish sticks, while breading alone did not significantly change the total fat uptake of fish sticks. Presence of batter apparently resulted in the formation of a hard crust, which was impervious to the movement of water and fat. Hence, water loss and fat absorption were reduced during frying (Fillion and Henry 1998). Beneficial properties of coatings in reducing fat intake include thermogelling or cross-linking, low moisture permeability, and low moisture content. Coatings should have low moisture content because oil uptake is dependent on the moisture content of the surface of the fried food (Lamberg, Hallstroem, and Olsson 1990; Moreira, Sun, and Chen 1997).

The size of the fried product decreased significantly due to increased fat content of fries in a linear pattern due to higher surface area. Thin potato chips with rough surfaces had higher fat uptake than potato chips that were thicker and had smoother surfaces (Keller, Escher, and Solms 1986; Goñi et al. 1997). In general, products with a larger surface area have higher fat content compared to products with lower surface area. Low moisture permeability in coatings helps to reduce water loss and thus, reduces oil uptake. However, too much of this property may result in soggy foods. Thermogelling or crosslinking results in high gel strength and leads to lower water diffusivity. Thermogelling or crosslinking also promotes the formation of wide punctures with low capillary pressures (Mellema 2003)

Effect of frying on physico-chemical properties of fried foods

Moisture content

Generally, the oil absorption takes place as a result of the removal of moisture from the food products. It has been reported that if the fat uptake is high, then it is due to higher initial moisture content. If initial moisture content is lower, it would lessen the internal volume of the food that could be occupied by oil during frying and would also shorten the frying time. The food additives such as alginates and cellulose could play an important role in changing the amount of oil uptake and moisture loss (Duxbury 1989). Moisture exits the food products mainly through diffusion. The effective water diffusion through the crust is an important parameter which affects water evaporation and probably oil uptake. Oil uptake ratio (UR) was used to express the weight ratio between oil uptake and moisture loss (Pinthus, Weinberg, and Saguy 1993). This was found to be instrumental in assessing the effectiveness of reducing oil uptake during deep fat frying.

Oil content

According to Keller, Escher, and Solms (1986), oil deposit on French fries was strictly limited to the surface and outermost layers of cells the product during frying. No oil diffusion towards the center was observed even after prolonged frying. It was inferred that oil absorption from the surface occurs during the post-frying cooling step. When the food is quickly removed from the fryer and while the temperature is continuously rising, only 15% of the oil is absorbed into the food, while the remaining located on the surface itself. Gamble, Rice, and Selman (1987) used microwaves, hot air (49° and 105 °C), and freeze-drying before frying to study the final oil content of potato chips. Microwave drying led to 20% reduction whereas hot air drying led to a reduction of 38–41% in final oil content. Hot air drying did not produce large areas that were oil-free, but eliminated moisture in a more regular pattern than microwave drying, resulting in an even drying effect. Due to increased freeze drying time, it increased the final oil content of potato chips.

Lamberg, Hallstroem, and Olsson (1990) also observed that an increased initial surface moisture content of potato chips resulted in an increased oil content in the chips. During frying, oil enters the product through damaged areas on the chip's surface, which has lost their hydrophilic nature. Vapor developed in the chips escapes through the areas of weakness in cellular adhesion. Kawas and Moreira (2001) found that tortilla chips fried in oil with a high temperature had higher internal oil content during frying and cooling, probably since the pressure gradient inside the pores was greater once the chips were immersed in the oil. Pore size distribution developed during frying of tortilla chips was observed to be the main cause for oil absorption during cooling. Pore space developed in the tortilla chips trapped more air during frying, resulting in higher capillary pressure during cooling and, therefore, higher internal oil content. The higher initial moisture content of tortilla chips resulted in higher internal oil absorption during frying and cooling. Frying oil partially replaces the internal water which evaporates as the cells are dehydrated. Oil absorption is

Table 5. Examples of non-protein based coatings.

Ingredient	Formulation	Product	Fat reduction (%)	Reference
Cellulose	2% in batter	Fried falafel balls	8.5	Pinthus, Weinberg, and Saguy (1993)
Methylcellulose (MC)	1% in batter	Fried falafel balls	46.4	Pinthus, Weinberg, and Saguy (1993)
	2% in batter	Fried, breaded, and marinated chicken strips	6.5	Holownia et al. (2000)
	1% MC + 0.75% sorbitol coating solution	Fried wheat dough balls	29.9	Suárez et al. (2008)
	2% MC + 0.2% polyethylene glycol film	Fried mashed potato balls	83.6	Mallikarjunan et al. (1997)
Carboxy-methylcellulose	0.25–2% in batter	Deep-fat fried foods	9.8–3.0	Annapure, Singhal, and Kulkarni (1999)
	0.25–1% in batter	Fried papad	1.7–19.5	Patil, Singhal, and Kulkarni (2001)
	2% in tortilla chips	Tortilla chips	5–40	Esturk, Kayacier, and Singh (2000)
Hydroxypropyl-methylcellulose (HPMC)	0.25–2% in batter	Deep-fat fried foods	12.6–7.8	Annapure, Singhal, and Kulkarni (1999)
	2% in batter	Fried breaded marinated chicken strips	4.8	Holownia et al. (2000)
	0.25–1% in batter	Fried papad	17.2–2.4	Patil, Singhal, and Kulkarni (2001)
	2.2% HPMC + 0.5% polyethylene glycol film	Fried chicken balls	Up to 33.7	Balasubramaniam et al. (1997)
	2% HPMC + 0.2% polyethylene glycol film	Fried mashed potato balls	31.4	Mallikarjunan et al. (1997)
Xanthan gum	0.25–2% in batter	Deep-fat fried foods	8.4–4.4	Annapure, Singhal, and Kulkarni (1999)
Guar gum	0.25–2% in batter	Deep-fat fried foods	9.7–8.2	Annapure, Singhal, and Kulkarni (1999)
	0.25–1% in batter	Fried papad	9.7–22.0	Patil, Singhal, and Kulkarni (2001)
Locust bean gum	0.25–2% in batter	Deep-fat fried foods	3.4–4.8	Annapure, Singhal, and Kulkarni (1999)
Carrageenan	0.25–2% in batter	Deep-fat fried foods	3.4–15.7	Annapure, Singhal, and Kulkarni (1999)
	0.25–1% in batter	Fried papad	2.8–12.0	Patil, Singhal, and Kulkarni (2001)

primarily a surface phenomenon introduced by a balance between adhesion and oil drainage on removal of the food from the hot oil (Ufheil and Escher 1996). During frying of tortilla chip it was observed that most of the oil penetrates into the product during the post-frying cooling period. In other words, only 20% of the oil is absorbed during the immersion period, whereas 64% of the total oil content is absorbed during post-frying cooling (Moreira, Sun, and Chen 1997). Increased oil temperature, higher moisture content and decreased slice thickness contributes to higher oil uptake in the final product (Baumann and Escher 1995). Degree of starch gelatinization also influences the final oil content in tortilla chips. Freeze-drying of the samples prior to frying led to no gelatinization of starch. On the other hand, tortilla chips treated with steam before frying causes the starch granules to swell, resulting in lower oil content (Kawas and Moreira 2001). Soaking potato strips in sodium chloride solution before frying has been reported to reduce the oil uptake in French fries (Bunger, Moyano, and Rioseco 2003).

Oil composition

Changes in composition of frying oil happen at elevated frying temperatures due to hydrolysis, oxidation, and polymerization reactions. These reactions are triggered by the presence of oxygen, moisture and excessive free radicals which in turn tends to decrease oil stability, increase foaming of oil reduce antioxidant content, darken color, decrease smoke point, and form products responsible for nutritional loss and loss of sensorial characteristics. These changes in oil during frying depends on temperature, the heating cycles, surface to volume and food to oil ratios, the fatty acid and the antioxidant composition of the oils (Melton et al. 1994; Quiles et al. 2002). The quality of frying oils was judged by determining properties such as acid value, peroxide value, and total polar components. Acid value indicates the measure of free fatty acids, which corresponds to the hydrolysis of triglycerides. Peroxide value indicates the extent of oxidation the oil has undergone. Total polar component (TPC) accounts for the non- volatile compounds produced during frying, is an indicator for the total alteration of the oil. TPC is formed during repeated usage of frying oil. TPC and acid value are used as a parameter to judge the quality of oil for further use. In India and in many European countries, the vegetable oil shall not be used when TPC is beyond 25% (Takeoka, Full, and Dao 1997; FSSAI 2011).

During the analysis of different oils after 101 cycles of frying of chicken nuggets, an increased peroxide value was noted with increase in frying time in soy bean oil, canola oil and lard. This was due to the increased initial oxidation and breakdown of hydroperoxides at elevated temperature. This paved way for the formation of secondary oxidation products during cooling. Also the acid value increased with increase in frying cycles from 1 to 101 (Park and Kim 2016). The heating of oil also bring about changes in fatty acid composition of frying oil. Reduction of PUFA and increment of SFA and MUFA were observed in oils after frying.

The effect of frying on composition of three edible oils such as virgin olive oil, olive oil and sunflower oil were studied and observed a significant decrease in the quantity of vitamin E in all three oils after 60 min of frying. Also the reduction in phenolics was seen which might be due to thermal destruction. The formation of TPC due to the breakdown products from frying oil was found to be high in sunflower oil than the other oils (Quiles et al. 2002). Similarly, on frying of potato in virgin olive oil, the total antioxidant activity of reduced to less than 250 μmol of Trolox/kg from an initial activity of 740 μmol/kg, during the first six frying process. At the end of the first frying process for 10 min at 180 °C, the concentration of the dihydroxyphenol components reduced to 50–60% of the original value, and only 10% of the initial components were present after six frying operations. The loss of antioxidants would allow the increase in the rate of formation of oxidized polar compounds in the oil, which was observed from the sixth frying operation onwards with increased concentration of polar compounds (Gómez-Alonso et al. 2003). In the same way, Winkler, Warner, and Glynn (2007) reported an increase in TPC ranged between 5.0 and 6.7% during continuous frying of potato in soybean oil, high oleic sunflower oil, corn oil, and hydrogenated soybean oil. Comparatively, TPC formation was less in hydrogenated soybean oil and high oleic sunflower oil due to their low amount of poly unsaturated fatty acids. Unsaturated fatty acids produced more polar compounds than saturated fatty acids.

Texture

Texture is an important quality of fried food products and it is the response to the structural change of products during thermal processing and cooking. Texture of a food product can be evaluated by instrumental analysis and sensory evaluation. Texture determination by instrumental examination is more accurate, simpler and is less time consuming (Kayacier and Singh 2003). Hardness is one of the parameters that can be identified from a texture profile curve, and is defined as the force at maximum compression during the first bite. The terms describing hardness include soft, firm and hard; the hardness of the chips was evaluated by obtaining the maximum force at compression (Steffe 1996). During texture evaluation in fried potato chips, Kita et al. (2015) reported that texture fried potato chips was highly influenced by the type of frying oil, oil temperature, dry matter content of fresh sample as well as by fat content of final product. It was inferred that the potato chips of 1.2 mm exhibited good texture when their hardness was between 25 and 30 and between 30 and 35 for 1.8 mm thick sample (Kita 2002). A frying temperature of less than 170 °C reduced the hardness of potato crisps whereas the decrease in temperature of rapeseed oil from 190 °C to 170 °C had no influence on the texture of crisps (Kita, Lisińska, and Gołubowska 2007). The softening of the middle lamella between cells, starch gelatinization of inner cells and dehydration, crust formation in fried potatoes is the result of changes in the original structure of the potato tissue after exposure to hot oil. The outer crust hardens progressively with accelerated temperature in case of French fries (Pedreschi, Aguilera, and Pyle 2001).

Color

Papadakis et al. (2000) reported that color is one of the most significant attributes in any food products. In the potato processing industry, probably the critical point of quality evaluation is the maintenance of the satisfactory color of chips. Color of fried potatoes is usually defined in the unit L*a*b* which is an international standard to measure color adopted by the International Commission on Illumination (CIE) in 1976. L*, a* and b* define the luminance or lightness (0 to 100), the degrees from green to red, and from blue to yellow (−120 to 120), respectively. Being, heterogeneously colored product, computer vision system is currently used to measure color of potato chips in L*a*b* units from RGB images (Pedreschi et al. 2006). Santis et al. (2007) determined that the process variables such as type of oil, temperature, time and pretreatments of the raw materials are expected to influence the color of the fried products. Lower frying temperatures generate less non-enzymatic browning in potato resulting in the lighter colored chips (Pedreschi et al. 2006). The color of the chip is the consequence of the non-enzymatic browning associated with the Maillard reaction during frying. It is the result of reaction of amino acids with the reducing sugars, mainly D-glucose, accumulated during low-temperature storage. Vacuum frying, which uses a lower oil temperature, can help decrease the effect of higher temperatures on the color of fried foods. Garayo and Moreira (2002) found a higher L* at a vacuum pressure of 3.115 kPa at 140 °C frying temperature. The production of lighter colored chips often requires some pretreatment of the sliced potatoes in processing. Blanching is one of the most important unit operations in vegetable processing helps control the color of the final product. The reducing sugars from the potato tissue leach out during blanching leading to lighter color and avoiding undesirable dark color in the potato slices after frying. It is difficult to control the color of the chips because it depends on other aspects apart from heating such as potato storage conditions, potato variety, and maturity of the tubers. Reducing and non-reducing sugars accumulate markedly in potatoes stored at low temperatures. Gould (1995) recommends storage temperature of potatoes for French fries (7 °C) and for chips (10 °C) at above 90% relative humidity. Excessive browning and the development of off-flavors due to extreme reducing sugar content are not acceptable for processed potato products.

Degree of shrinkage and expansion

Shrinkage of biological materials during frying takes place simultaneously with moisture diffusion and thus may affect the mechanism between the moisture removal rate and oil-uptake rate. Mittelman, Mizrahi, and Berk (1984) realized that the crust of potato chips started to form as soon as the potatoes were immersed in the hot oil. Water vapor escaped uniformly through the entire surface as very small bubbles during the first stage of the process. As frying continues, the crust becomes thicker, thus creating resistance to the escape of water vapor and reducing the rate of evaporation. During frying of sweet potato, it shrinks in the radial direction and expands in the axial direction during frying (Taiwo, Baik, and Farinu 2007). Most diameter shrinkage of tortilla chips (9%) occurred at a slow rate during the first 5 seconds of frying. after 30 s of frying; the thickness of chips increased by only 10% and remained the same until the end of frying. the puffiness of chips increased to 72% during first 20 s and continued to increase until it reached 100%. Initially shrinkage of chips was due to the rapid evaporation of moisture during frying and the thickness increased as a result of crust formation, and gas expansion on the surface caused some bubbles which resulted in vapor expansion inside the chips pores (Kawas and Moreira 2001). Similar results were observed during frying of yellow fleshed cassava root slices. Higher frying temperatures resulted in a higher mass diffusivity and greater moisture loss which led to higher shrinkage of cassava slices. Rigid surface formed during deep frying led to reduction in volume shrinkage at higher frying times (Oyedeji et al. 2016). A linear relationship was observed between the shrinkage and moisture loss during deep fat frying of chicken breast (Kassama and Ngadi 2016).

Microstructural changes during frying

The main microstructural changes produced during frying are starch gelatinization and protein denaturation (Prabhasankar et al. 2003). Porosity of the food crust during frying is considered as a major contributor to the surface roughness, which in turn affects the oil uptake. During deep fat frying, when the meat is submerged into the oil, water vapor chooses different paths of evacuation, and these paths serve as conduits for oil intrusion (Aguilera and Stanley 1999). The porosity and pore sizes of fried food tend to decrease with the frying time. This may be attributed to the physicochemical changes like protein gelation, muscle shrinkage due to intense heating. The decrease in porosity with the increase in frying time may be due to the fact that the oil absorbed into the food matrix crystallizes to form a composite structure with the muscle fibers, which results in the destruction of the pores. Deterioration of the collagen connective tissue due to heat causes the shrinkage, swelling, denaturation, gelation and agglomeration of protein in addition to moisture loss and oil uptake during DFF contribute to the pore structure modification (Kassama and Ngadi 2004).

The gelatinization of the starch granules results in the development of the microstructure during frying (Aguilera and Gloria-Hernandez 2000). By using fast freezing and cryosectioning after frying, Aguilera and Gloria (1997) observed three different microstructural layers in the potato: Outer crust layer formed by the damaged cells after frying, middle layer formed by the shrunken cells after the evaporation of water vapor from the food, and inner core which has fully hydrated cells and is intact in nature. The core of the fried chips showed non-deformed cells with starch granules, whereas, the scanning electron microscopy image showed mechanical damage of cells on the outer surface. This was due to the damage to the cells due to cutting process. Also it was revealed that the swelling of starch granules mainly occurred in the core region, as a result of hydration and gelatinization (Teruel et al. 2015). A significant difference in pore structure between coated and uncoated chips was observed. Potato chips coated with guar gum and glycerol look smoother than those of uncoated product, consequently preventing oil penetration into the potato tissue during frying process. It was observed that the coated samples showed reduction in cell volume which was due to partial hindrance to the oil to enter into the passages (Yu et al. 2016).

Packaging and shelf life of fried foods

It was understood that the deep fat fried foods absorbs oil which is not only nutritionally important but has its influence on the calories, flavor, and shelf life of the product. During deep fat frying, the product in the presence of oxygen and water exposes to high temperature frying oil. During these conditions, oils go through thermal oxidation, hydrolysis and polymerization and the resulting products that are decomposed affect the quality of frying oils and foods. Balev et al. (2011) reported that packaging plays a very important role of safeguarding food products from outside influences and damage. Marsh and Bugusu (2007) proved that food packaging can avoid product deterioration, retain the effects of processing in a beneficial manner, extend shelf-life and increase the quality and safety of food. In this situation, packaging is critical in maintaining the quality of the product while providing protection from microbial and chemical contamination, as well as from oxygen, water vapor and light. Due to the alterations that are bound to happen, crisps quality attributes that need attention during storage include peroxide, free fatty acids, fat oxidation, flavor alteration and moisture build up (Ogunsola and Omojola 2008). Moisture gain in the products might be due to storage conditions and packaging material. It was found when deep fried rice and legume based products are packed in pouches of CPP and stored at temperature of $29 \pm 2.0\,^{\circ}C$ and relative humidity of $67 \pm 2.5\%$, a linear increase in moisture gain, FFA and PV was observed. The maximum shelf life of the products was 24 days under the storage conditions studied (Tiwari et al. 2011). During storage of potato crisps, various kinds of off-flavor volatile compounds have been shown to develop and their concentrations increase. Since storage conditions influence the final quality of the product strongly, they are of utmost importance (Laine et al. 2006).

Conclusion

Deep fat frying is one of the conventional and popular food preparation methods especially in snack industries. Deep fat fried foods are liked by people of all ages. But consuming deep fat fried foods has issues like high fat content and also offers high calories than non-fried counterparts. The major concern due to the consumption of fried foods is the risk of obesity which in turn cardio vascular health issues. Wider ranges of physical, chemical, and nutritional changes are observed in foods during deep fat frying. Many of these changes are functions of oil temperature and quality, product moisture content and composition/structure, and product residence time in the fryer. Many investigations have been done on reducing the oil uptake by blanching, pre-drying and coatings. Also during this method, compounds such as trans-fat acid and acrylamide are produced which are major threat to public health. It is therefore highly imperative to identify and assess their effects on human health and also find ways to reduce the oil uptake and production of such compounds without comprising the taste of fried foods during frying.

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