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Review - Food/Feed Science and Technology

Vacuum Frying: A Promising Technique to Deliver Nutritive Snack Foods

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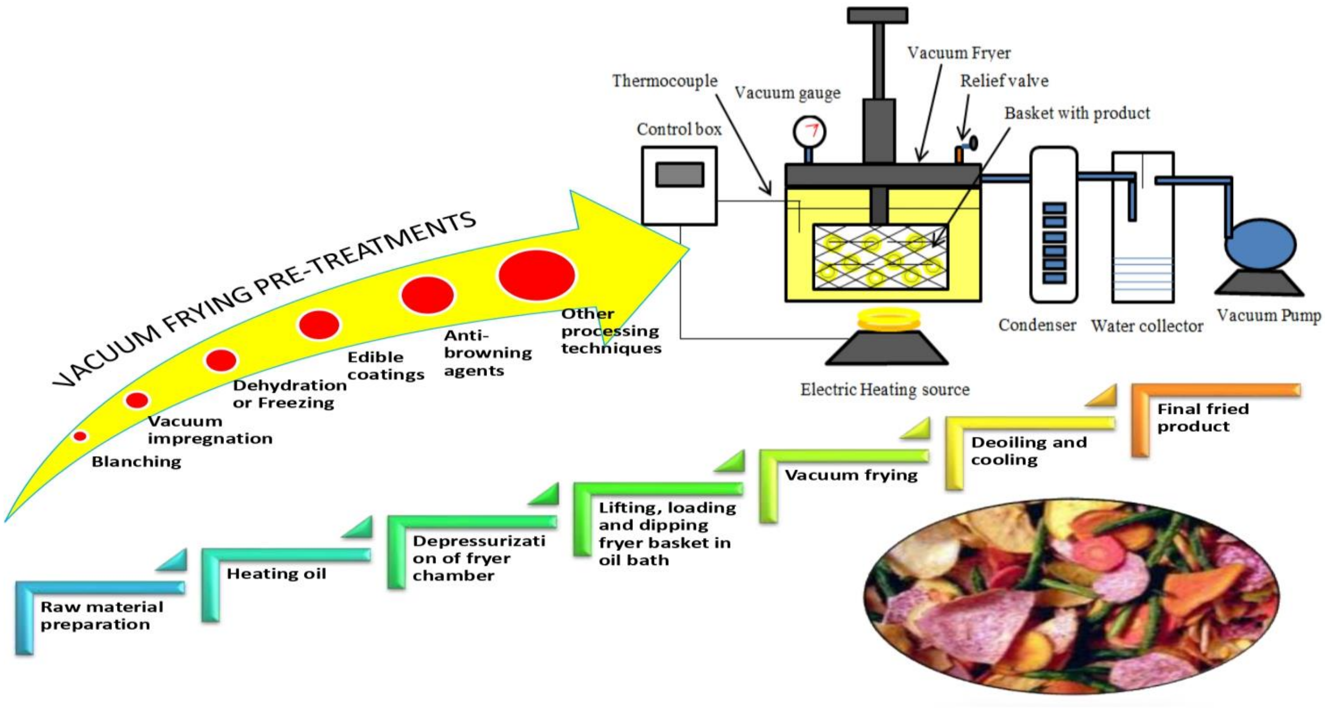
HIGHLIGHTS

- Typical vacuum frying equipment and operation.
- Product and process parameters.
- Pre-treatments before frying fruits and vegetables.
- Applications of vacuum frying in foods.

Abstract: The ubiquitous presence of fried foods in our diet necessitates the upgradation of techniques to override the ill effects of conventional frying. Vacuum frying, employing frying at low pressure and temperature has recently attracted research due to its excellent food frying capabilities with minimal damage to nutritional as well as sensorial quality. The objective of this review paper is to highlight the basics of vacuum frying technology, provide information about quality of vacuum fried products, parameters affecting the frying process, and interventions to improve the products quality. Prospects of vacuum frying technology to develop products with lower oil content using certain pre-treatments to foods such as partial drying, freezing, hydrocolloids etc. are included. With proper deployment and overcoming of the research gaps, vacuum frying technology can be used effectively as a food processing technique both in small as well as large-scale production industries.

Keywords: Vacuum frying; Maillard browning; Acrylamide; Hydrocolloids; Crisps.

GRAPHICAL ABSTRACT



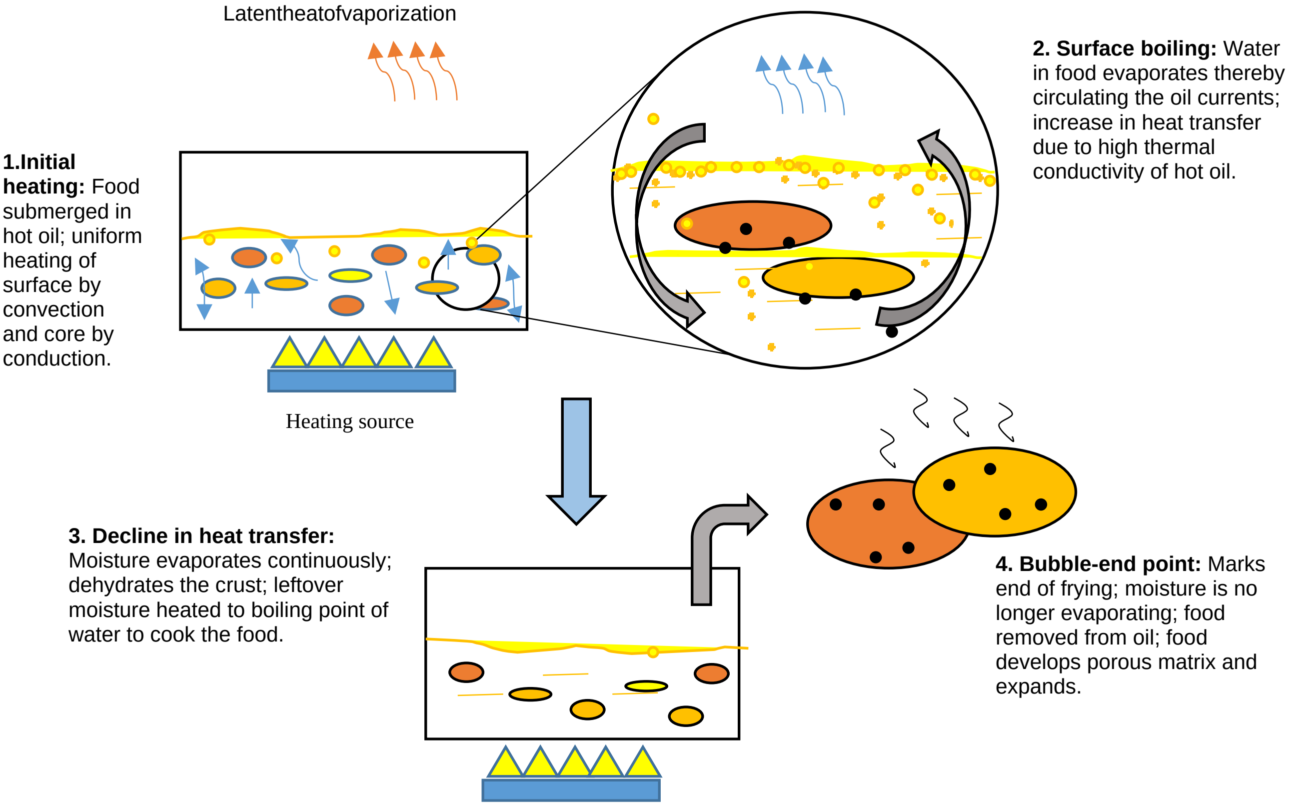
INTRODUCTION

Frying is one of the ancient, traditional methods of food preparation used to create food with distinctively appetizing taste and texture. Frying remains one of the most popular unit operations to process food. The immense popularity may be attributed to desirable sensory attributes, while being relatively fast and easy to operate. The shelf-life enhancement is attributed to thermal destruction of microorganisms and enzymes, in addition to reduction of water activity on the food surface. A lot of technological potential exists for design, improvement and innovation on different parameters involved in frying of food.

Frying is a process where food is completely submerged or partially submerged in hot oil at temperatures reaching 150-200ºC. The different surfaces of food experience different frying temperatures with the highest temperatures attained by peripheral surfaces while the core (rich in water) experiences around 100ºC during frying with temperature gradients ranging from 60-80 ºC.

The rate of heat transfer is affected by the composition of food and its heat and mass transfer properties which include thermal conductivity, diffusivity, density, specific heat etc. Upon heating (frying of food), these characteristics are dramatically altered [1]. Simultaneous heat and mass transfer modify the food, leading to formation of crust while retaining the juiciness of the food and preserving flavor while cooking. This dehydration forms a crust that further limits oil absorption. The main reaction responsible for the appealing golden-brown color while frying is the Maillard reaction that polymerizes sugar and proteins with the removal of moisture. Maillard reaction proceeds with the formation, condensation, polymerization, degradation, cyclization etc. associated with the development of peculiar colour and aroma. The brown colour imparted to foods is mainly attributed to melanoidins, which are structurally complex pigments formed during high temperature processing of sugars and amino acids. Although the contribution of these pigments is small, their contribution is cumulative.

During industrial frying process, the heat transfer efficiency, initially by conduction and then continuous transfer by convection are involved. Convective heat transfer causes the more heated oil in proximity of the heating element to replace the oil at the surface of food being fried which is cooled by heat losses and evaporation of moisture.



1.Initial heating: Food submerged in hot oil; uniform heating of surface by convection and core by conduction.

2. Surface boiling: Water in food evaporates thereby circulating the oil currents; increase in heat transfer due to high thermal conductivity of hot oil.

3. Decline in heat transfer: Moisture evaporates continuously; dehydrates the crust; leftover moisture heated to boiling point of water to cook the food.

4. Bubble-end point: Marks end of frying; moisture is no longer evaporating; food removed from oil; food develops porous matrix and expands.

Figure 1. Mechanism of frying

The exact mechanism of frying is still being studied, but the main theory behind the textural and flavor properties of a product is explained in four major steps (Figure 1). The first step is initial heating where the food is submerged completely in the hot oil till its surface reaches the boiling point of water. Uniform heating of food surface occurs by convection, but the inner core portion is heated and cooked by conduction where heat diffuses from surface to core. It is followed by surface boiling where water inside the food evaporates due to the presence of hot oil in food surroundings. This in turn circulates the frying oil currents thereby increasing the rate of heat transfer, keeping the oil from being soaked by the crust or surface of the food. Cooking oils have thermal conductivity higher than that of air, therefore close contact of hot oil with the food surface or coating or dough provides rapid heat transfer.

The third step of frying process is a decline in heat transfer in which moisture evaporates continuously and dehydrates the crust; it conducts less heat to the remaining food. The leftover moisture inside the food gets heated slowly to the boiling point of water, which cooks the food. Lastly, the bubble-end stage marks the last phase in frying where moisture is no longer evaporating, and therefore the food may be removed from the oil.

Problems with Conventional Frying Systems

The conventional (atmospheric) frying is a unit operation that is employed in production of crisps with desirable taste and color. The frying system consists of an oil bath being heated in atmospheric conditions. The frying temperatures reach up to 190ºC resulting in thermal and oxidative reactions which not only impair the nutritional and functional quality but undermine sensorial quality of foods. Although most prevalent, the traditional frying technology has several other drawbacks such as low energy utilization and improper processing efficiency [2]. Formation of acrolein and acrylamide in oils and foods subjected to temperatures above 120ºC is a major cause of concern. Therefore, traditional frying systems have been upgraded in the form of vacuum frying, which utilizes the vacuum environment for frying foods at lower temperatures, thereby developing healthier fried foods.

VACUUM FRYING

The process of vacuum frying is carried out at pressures largely below atmospheric levels. It can be considered as an alternative way to atmospheric frying for the improvement of the quality of fruits and vegetables. Vacuum frying lowers the frying temperature and thus slows down the rancidity in oils in comparison to atmospheric fried products [3]. Vacuum frying has several benefits with its low temperatures (<100ºC), reduced pressure and minimal exposure to environmental factors such as oxygen making it favorable for developing snacks from fresh fruits and vegetables. In a comparative study, wheat starch and gluten-based snacks were fried under both conventional and vacuum frying. Crosa and coauthors [4] reported that vacuum fried snacks contained approximately 27% lower fat content with lighter color as compared to atmospheric frying. High-quality dried products with better flavor and color due to reduced oxidation, shorter processing times, and lower frying temperatures can be obtained with vacuum frying, providing a good alternative to conventional frying. Since the temperature of frying is low, vacuum frying significantly reduces the degradation of frying oil and food components especially vitamins and pigments as compared to conventional frying.

Details: Vacuum fryer

The vacuum frying system consists of four parts, namely: a) *vacuum frying chamber* b) *refrigerated condenser* c) *vacuum pump* d) *Electric heating source* (Figure 2). The frying chamber is an airtight vessel fitted with oil heating device and a frying basket that is adjustable to oil by a lift rod. The spinner motor which is used for centrifuging the product to remove surface oil is connected to the lift rod. The evolved steam as the result of frying is trapped and condensed on the cold surface by the refrigerated condenser. The refrigerated condensers are better recommended for efficiency than water-cooled condensers due to rapid heat exchange. The low pressure required for the process is aided by the vacuum pump; it also helps in getting rid of non-condensable gases. The equipment can be used in a batch process or semi-continuous process [5]. The batch process used mainly for research purposes often doesn't have provision for centrifugation i.e. spinner rotor is absent. The industrial fryer with high capacity usually has several heat exchangers to maintain oil temperature constant and an oil filter to maintain oil quality. The oil uptake mechanism is still not understood in vacuum frying. The frying basket is loaded with the product and lid is closed to depressurize the chamber. The basket is immersed in pre-heated oil bath for a required period. The basket is then lifted, and pressure valve is opened. This pressurizing of oil tank back to atmospheric pressure results in sudden increase in pressure around the product making the vapours inside the pores to condense, which means that oil absorption may precede cooling. The diffusion of air into the porous structure maybe caused by low pressure atmosphere, thereby obstructing oil passage and consequently resulting in lower oil absorption. The study is also supported by experiments where vacuum fried crisps contained less than half oil compared to crisps fried under atmospheric conditions [6].

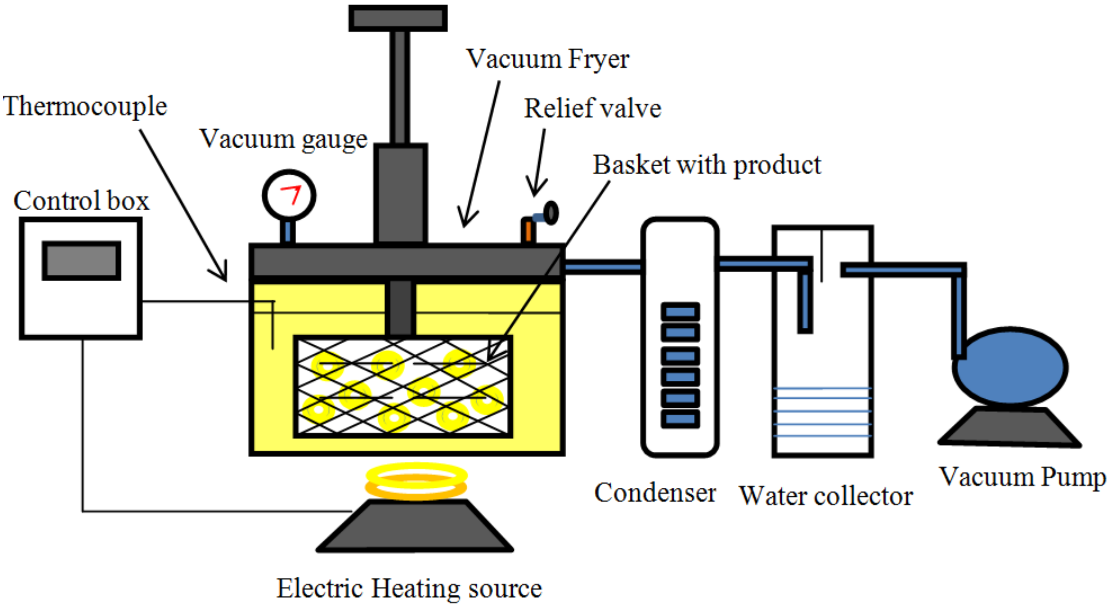


Figure 2. Typical vacuum frying equipment

Advantages of Vacuum Frying

Vacuum frying is achievable at a lower temperature than conventional frying, therefore nutritional quality is better (better retention of phytochemicals and essential nutrients), lesser oil degradation, enhanced color than conventional frying [7]. Another important advantage of vacuum frying over conventional (atmospheric frying) is that products are fried at 160-190ºC in conventional frying, and moisture inside evaporates approximately at 100ºC which indeed depends upon the composition of the dissolved solutes. On the other hand, under vacuum, frying temperatures can be as low as 60ºC while achieving boiling point at as low as 35-40ºC. The pressure gradient between vacuum pressure of fryer and the internal pressure of the product results in the reduction of surface oil in the end of frying process which limits the amount of oil absorbed in products [8]. The lower frying temperatures also reduced 94% of acrylamide formation in potato crisps [7].

A. Factors Affecting the Frying Process

Composition of the raw material:

Initial solid content influences oil uptake during frying because of the proportional relationship between moisture loss and oil uptake, so it becomes a factor that influences the frying process. Indeed, higher initial water content gives a product with higher oil absorption.

Dimension and surface of material:

Oil uptake is influenced by the dimensions and surface structure which is linked to the permeability of the surface and not the volume. The adherence of fat on the surface of food results in increased fat content of that product. A significant increase in fat content of potato slices when thickness was increased from 0.8 to 1.2 mm could be due to the longer frying time required by thicker food [9]. An increasing surface area to volume ratio of simulated potato strips affected the moisture and oil content positively. Another case in point, French fries absorb less oil than crisps due to smaller surface area to volume ratio [10].

Oil Type:

The type of oil used for frying influences the oil uptake in more than one way. Unsaturated oil such as cottonseed oil is less absorbed as compared to palm oil because the former has lower viscosity during cooling and drains easily [11]. The higher amounts of unsaturated fatty acids in frying oil result inhigher fat absorption [12]. These contradictory studies could be simplified by considering the influential role of oil's viscosity in the fat absorption mechanism [13].

Frying time and Temperature:

Frying oil and temperature are the two most important factors which directly influence physical and chemical changes such as moisture loss, fat uptake and overall quality of fried products [13]. High oil temperatures enable rapid heat transfer resulting in rapid browning and a short frying time. Therefore, processing a large amount of raw food in hot oil has deleterious effects on product quality and overall process efficiency. Millin and coauthors [14] observed that increasing temperature and decreasing the frying time results in lower moisture content and high oil content. Baumann and Escher [9] on the other hand confirmed that lower frying temperature (150ºC) leads to prolonged frying time resulting in high fat content while a higher temperature (180ºC) leads to the rapid development of tougher crust in shorter time with lower oil absorption. Teruel and coauthors [9] also determined upto 35% decrease in fat content was observed when temperature was increased from 150 to 190ºC using a 3-D mathematical model to simulate a domestic deep fryer.

Process Variables:

Vacuum frying process is characterized by vacuum pressure and a suitable time-temperature combination and a general flow for vacuum frying is given in Figure 3. These parameters are adjusted according to the characteristics of fruits to produce their vacuum fried products.

Time-Temperature

The time-temperature conditions of vacuum frying play a major role with respect to product quality characteristics [6]. The study of potato crisps showed a linear nature of oil absorption and moisture loss. The highest oil absorption or conversely maximum moisture loss was obtained at 144ºC with vacuum pressure of 3.115 kPa, though these conditions did not affect the texture or color at the end of frying [15]. In apricots, β-carotene content increased upon increasing temperature from 70 to 90ºC, thus showing increased accessibility of β-carotene by the oil which enters the sample [16], but this could also be due to higher solids content in higher frying temperatures samples. The increase in frying temperature from 90 to 110ºC was found to increase the oil content due to faster moisture loss from the apple matrix [17]. Enhancement in oil absorption in apple crisps is caused by an increase in temperatures from 95-115ºC can be associated with tissue degradation. While removal of water from matrix damages cells, make surface hydrophobic and thus results in oil absorption at damaged sites [18]. There was an insignificant increase in oil content of plantain with an increase in temperature from 112 to 113ºC and time from 3 to 9 min [19]. Vitamins retention is also affected by the temperature of frying. An increase in frying temperature from 80º to 100 ºC decreased the vitamin C retention in gold kiwifruit [21]. Jackfruit fried at lower frying temperatures better retained the bioactive components such as flavonoids, phenolics and carotenoids better and therefore, high-quality jackfruit crisps were obtained if fried under vacuum at 90ºC [22]. It was however reported that vacuum frying of carrot showed the similar carotenoids retention and color as that of atmospheric frying [23].

Vacuum Pressure

Another vital processing parameter is the pressure: a decrease in pressures (13.14 to 26.54kPa) of frying results in faster moisture removal thereby reducing the penetration rate of oil into the pores of plant tissue [19]. However, lower pressure (40 to 60 Pa) deteriorated the textural quality and led to darker color in mango [24]. Reducing the pressure of potato crisps during frying to 1.33 kPa reduced the saturation temperature of water which resulted in continuous moisture loss. This prevented the surface oil from penetrating the structure and release from surface, thereby minimizing the oil oxidation and better retention of polyunsaturated fatty acids

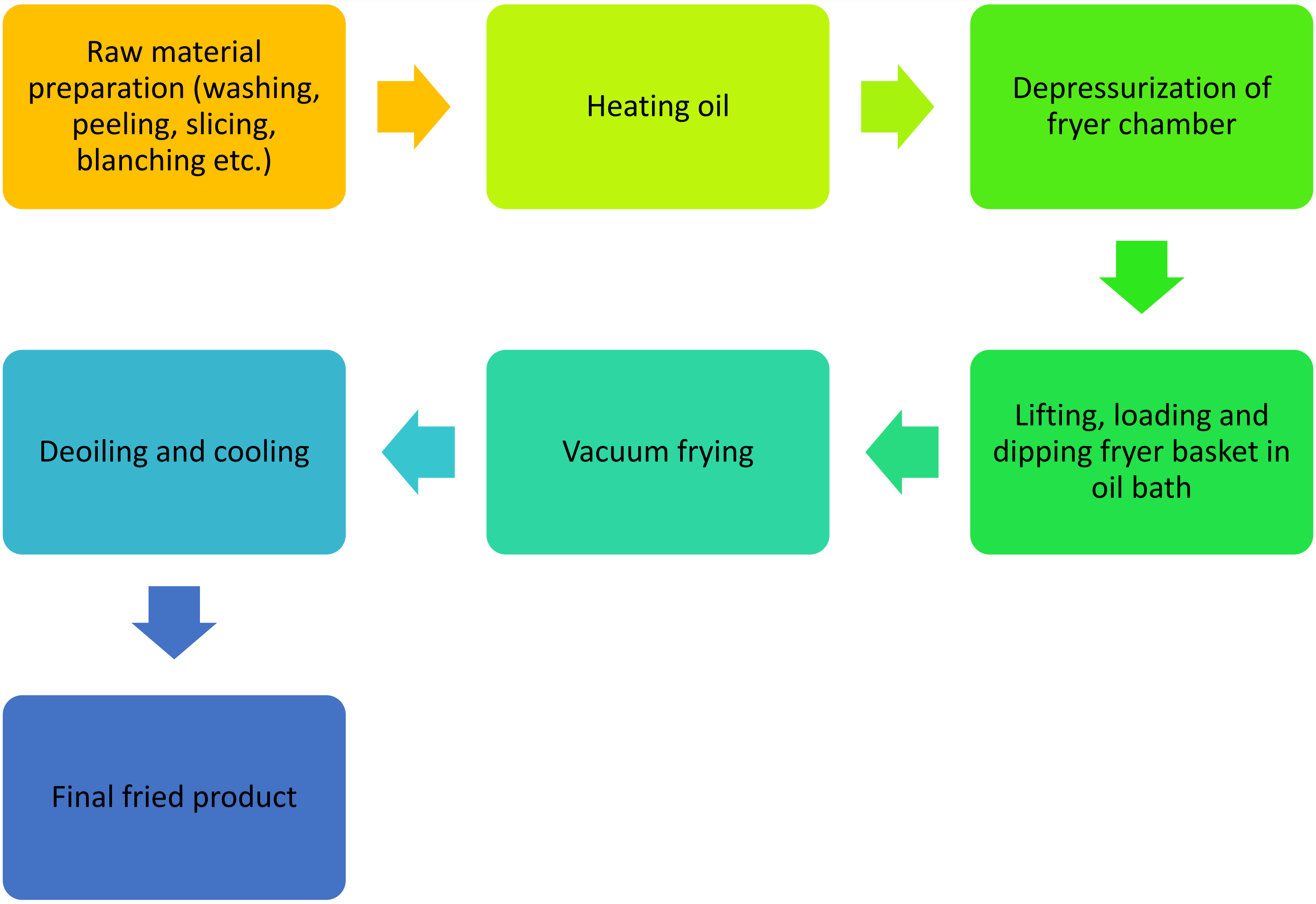


Figure 3. General flow diagram for process of vacuum frying

B. Vacuum Frying Pre-treatments

Various pre-treatments have been employed to prepare food for vacuum frying operations to enhance the quality attributes and appeal (Figure 4).

Blanching

Browning inhibition through inactivation of the catalytic action of polyphenol oxidase (PPO) caused by blanching also results from enhancement of water in issue, porosity of thetissue [25]. Significant water soluble bioactive loss does not support blanching as a promising pretreatment of vacuum frying of fruit matrix. This brief heat treatment not only inactivates browning-associated enzymes but also modifies the surface texture and porosity of tissues. The effect, however, varies from commodity to commodity. In jackfruit, mango, and yam crisps researchers had the same observation while vacuum fried [26-28].

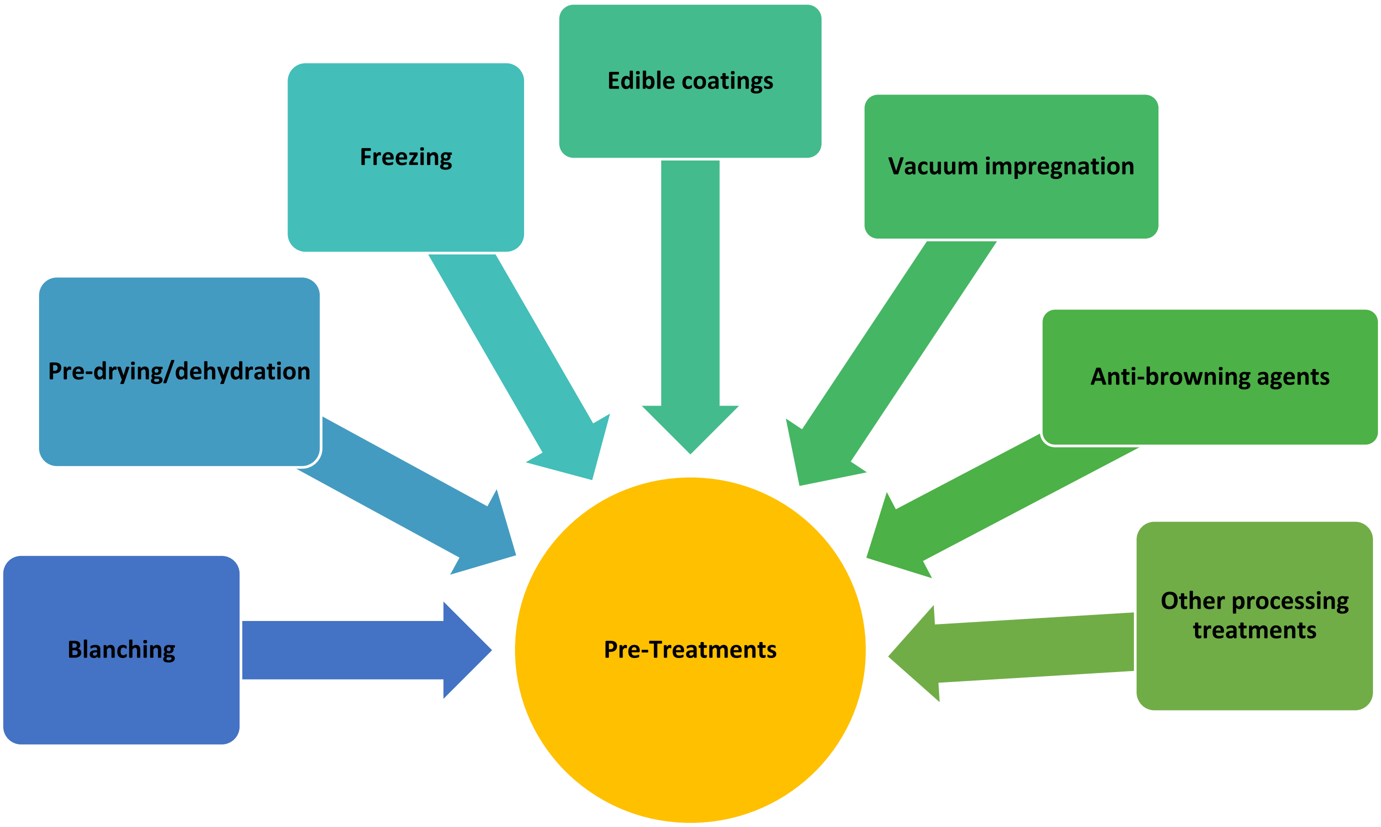


Figure 4. Pre-treatments of frying

Pre-drying/ Dehydration

A few strategies such as pre-drying with hot air and osmotic dehydration are used to reduce the initial moisture content of fruit. Hot air-drying at 80ºC, when used as pre-treatment, resulted in similar color of preserved apple slice to that of raw slice with its final moisture content of 64% (wb). Further, the enzymatic browning and non-enzymatic browning were inhibited by high-temperature treatment and this color preservation corresponded to lower water activity after hot air drying [18]. Mango crisps when subjected to osmotic dehydration with 40-65% maltodextrin, had lower initial moisture content which resulted in a shorter final frying time. They also explained that water loss during osmotic dehydration with 40-65% maltodextrin for 5 hours reduced the oil content in mango crisps [29]. Pre-drying of potato crisps by vacuum infrared radiation reduced the oil content in microwave-assisted vacuum frying products from 22.38 to 13.49 g oil/100g dry solid [30].

Table 1. Fat reduction techniques applied in fried foods and their effect on quality attributes.

Food	Fat reduction techniques	Effect on quality attributes	References
Banana crisps	Coating solutions containing (0.5, 0.75, 1.0% w/w and glycerol (1.96, 3.85 or 5.66% w/w)	Guar gum (1.0%) and glycerol (5.6%) showed lowest oil content with 33.02% oil reduction compared to uncoated sample and 15.19% oil reduction compared to sample coated with guar gum alone. Coated crisps showed highest fracturability and hardness with slight color change and good sensorial acceptability.	[56]
Jackfruit crisps	Hydrocolloid pre-treatments like pectin, carboxymethyl cellulose (CMC), gum Arabic, and sodium alginate	2% gum arabic treatment showed maximum reduction in oil uptake.	[26]
Potato crisps	Guar gum of 1% (w/w) and glycerol 8% (w/w)	Reduction of oil absorption by 34.8%	[59]
Potato pellet	Whey protein Isolate coatings (1;3;5;7%) and Glycerin	49.9% reduction in fat uptake at 5% WPI level	[57]
Crisps	Soya protein Isolate coatings (2;6;10;14%) and Glycerin	54.4% reduction in fat uptake at 10% SPI level	[58]
Apricot slices	Frying temperature of 100 ^{0}C, frying time of 72.5 min and MD level of 70% used	Moisture content of vacuum-fried apricot slices decreased with increasing frying temperature and frying time; oil content decreased with decreasing frying temperature and frying time; β-carotene content increased with high frying temperature at lower MD level.	[16]

Freezing

The application of freezing prior to frying also preserves the raw materials. Large ice crystals formed during slow freezing may however lead to cell wall damage and leaching of water upon thawing. The moisture content of vacuum fried carrot subjected to-20ºC blast freezing was lower as compared to overnight freezing pre-treatment, followed by non-frozen sample. For achieving the benefits of freezing pre-treatment, the water present in the matrix should be evaporated in the fryer without thawing [31]. Freezing the apple slices at -30ºC overnight before vacuum frying resulted in a porous sponge-like matrix upon frying [32] and is a common industrial practice. The fast heat transfer to frozen tissues lead the ice crystals to sublime under vacuum conditions which left pores in the food matrix through which moisture loss is accelerated and resulted in lower final moisture content. Different fruits, however, have different susceptibility to freezing. It depends on the variation in adaptation and resistance of cell walls and membranes to phase changes during the freezing process.

Vacuum impregnation

Vacuum impregnation is a valuable technique to enhance the solids and pigment content. It introduced antioxidant properties of beetroot extract directly into porous structure of potato slice matrix [33]. Agents such as citric acid, tartaric acid, L-cysteine, and L-ascorbic acid may also be used for pre-treating the food slices before frying. Various combinations having synergistic effect werescreened, like tartaric acid-ascorbic acid, cysteine-citric acid, and calcium chloride-ascorbic acid but use of 1% L-cysteine-citric acid in vacuum fried banana showed the highest preference overall. These agents have been applied to reduce enzymatic as well as non-enzymatic browning in fruits. The sucrose solution of 50 ºBrix and temperature range of 10-50ºC showed high solid gain in apple samples with temperature that had significant effect on water loss during subsequent frying [34].

Other Processing Techniques

Osmotic dehydration and ultrasound are some of the pre-treatment techniques that can be applied to samples before frying to enhance their acceptability. Mango slices were fried following osmotic dehydration duration of 45, 60 and 70 min with maltodextrin concentrations of 40, 50 and 65 ºBrix at temperatures of 22 and40ºC. The best crisps were obtained from fruits given osmotic treatment of 60 min at 65 ºBrix and vacuum fried at 120ºC [30]. Ultrasound pre-treatment also improved the quality of fried food products. Sweet potato slices subjected to ultrasound at 150, 300, and 450 W for 20 min. Crispier fried sweet potato crisps with reduced moisture content and oil uptake of fried potato crisps were obtained with stronger ultrasound power and longer processing time [35]. A better texture and appearance of sweet potato crisps was obtained in the frying process carried out in two stages, i.e. frying at atmospheric pressure for 1 min and then 2 min in vacuum [56]. Centrifugation step post frying reduced the fat content by up to 60% as compared to traditional sweet potato crisps. There was a 15% reduction in oil content of sweet potato crisps with double stage frying process as compared to frying in single stage.

Changes in Physico-Chemical Properties after Vacuum frying

Color

The development of color takes place when a sufficiently dry state has been achieved by food during frying. Evaporation of moisture provides a dry surface for the interaction of hot oil which favors color development. Maillard reaction and caramelization (non-enzymatic browning) are two main reactions responsible for food color during frying. The reaction between amino acids and reducing sugars and among sugar molecules itself leads to non-enzymatic browning of foods during high-temperature frying. Browning is also associated with interactions between ascorbic acid, dehydro-ascorbic acid, and other reaction products. It is also measured with a* (red-green chromaticity) which increases considerably in atmospheric frying, but these are not significant in vacuum frying [36]. Apart from this, the rate of heat transfer also influences the development of color [37]. Ripe mango has significantly higher sugar content, so the darker color was expected to be dominating, but this was not the case. Therefore, it suggested that besides frying time and temperature, other mechanisms could play roles in the color change [38]. Low frying temperature (<100ºC) and absence of air prevent the browning of foods during vacuum frying [36]. The high temperature of cooking results in a dependent group of reactions involving reducing sugars, ascorbic acid, and free amino acids with other elements. Development of brown pigments like melanoidins and toxic components such as hydroxyl-methylfurfural (HMF), acrylamide and heterocyclic amines takes place contributing to the color of final fried products [20].The effects of frying time and temperatures on crispness and browning index of vacuum fried kiwifruit crisps was studied by Diamante and coauthors [21].The color of kiwifruit crisps increased with frying temperature while browning index increased with increase in both frying temperature and time.

Flavor

Vacuum fried fruits and vegetables like sweet potato, green beans and mango retain their natural attributes in vacuum frying due to low oxidation and exceptionally low frying temperatures [39]. Carrot crisps when vacuum fried showed a lower intensity of bitter taste, aftertaste and roasted aroma with high intensity of natural taste compared with traditionally fried ones [23]. The organoleptic appeal of vacuum fried jackfruit was affected with the application of hydrocolloids as pre-treatment. Alginate and gum Arabic significantly reduced the flavor of jackfruit crisps. An increase in hydrocolloids concentration further decreased the overall flavor and taste attributes of crisps [40]. For vacuum fried shiitake mushroom crisps, Ren and coauthors [41] reported that pre-treatments (i.e. blanching, blanching+osmotic, blanching+osmotic+coating and blanching+osmotic+freezing) did not result in any major difference of flavor.

Texture

A study deduced a relation of moisture content of papaya slices with firmness of vacuum fried papaya crisps. A change in processing conditions such as the thickness of slices (2-4 mm), temperature (80-100ºC) and time (20-40 min) affected the textural attributes and final moisture content of vacuum fried papaya crisps. Upon frying, food is subjected to a variety of changes such as shrinkage, puffing and hardness. The final texture of fruit and vegetable snack is greatly influenced by the composition of raw materials and the stage of ripening. Further pre-treatment with hydrocolloids (in vacuum fried jackfruit crisps) increased the breaking force in proportion to concentration [42].

Fat content

Several studies have been carried out to reduce the fat uptake in final food products upon frying such as use of hydrocolloid coatings due to their thermos-gelling properties etc. (Table 1). The traditional frying has oil uptake confined to its surface region only while competing between drainage and suction phenomenon on heated food crust [18]. The final oil content of conventional fried potato crisps is 35-45% [20]. The pressurization and cooling phase during vacuum frying exacerbates the oil absorption by the product. These steps increased the pressure inside pores by vapor condensation thereby forcing oil to seep into product pore spaces through channels of capillary formed by evaporation of moisture [39]. Vacuum fried apple crisps recorded 50% reduction in oil uptake in comparison to traditionally fried ones even as constant thermal driving force (ΔT=60°C) was applied to both batches [18]. Therefore, the concept of equivalent thermal driving force was found to be equally effective for comparison of traditional and vacuum frying. On vacuum frying sweet potato and green beans 24% and 16% less oil uptake respectively, while 4% and 6% more oil uptake by vacuum fried mango and blue potato, respectively was recordedas compared to conventional frying [43]. Thus, product characteristics as well as texture development during frying also influence the final oil uptake. The oil quality degradation during atmospheric and vacuum frying was studied [4]. Oil stability was increased significantly in vacuum frying as compared to conventional process.

Acrylamide content

Acrylamides are Class 2 carcinogenic compounds formed when food rich in carbohydrates is fried at high temperatures through Maillard reaction pathway [44]. Potatoes are more prone to acrylamide formation since they are rich in amino acids, particularly asparagine responsible for acrylamide generation. As per Daniali and coauthors [47], highest amount of acrylamide formation is linked to asparagine (5987.5 µg/ kg) and lowest is from phenylalanine (9.25 µg/ kg). Acrylamides are formed generally at the end of frying or heating process when product moisture levels are sufficiently low [45]. Hydrolysis of sucrose present in food releases D-glucose and D-fructose which may contribute to acrylamide formation. The type of oil and additives like silicones (legally permitted in Europe as additive E900) present in them also increase the rate of acrylamide formation. Vacuum frying is itself a suppressor of acrylamide generation. Accordingly, the European Commission issued ‘Indicative Values’ for the presence of acrylamide in food for potato crisps and French fries as750 and 500 µg/kg, respectively. These indicative values are not regulatory limits or safety thresholds per se. Acrylamide and its metabolite glycidamide are genotoxic and carcinogenic. Since any level of exposure to a genotoxic substance could potentially damage DNA and lead to cancer, therefore, tolerable daily intake (TDI) of acrylamide in food can’t be set.

The formation of acrylamide has been found to increase linearly over frying time, while its relationship with frying temperature is not linear, although frying at temperatures over 175 °C significantly increased acrylamide levels [46]. Acrylamide content of 735-4386 µg/kg has been reported for atmospheric frying of potatoes [46] as compared to 183-244 µg/kg for vacuum fried potatoes [48]. A reduction of 58% in acrylamide content has been reported in comparison to conventional frying of potato crisps [36]. Pre-treatment of samples prior to frying can be an excellent choice to reduce acrylamide up to 98%in vacuum fried potato crisps [48] such as calcium and sodium salts dip during blanching [49, 50]. Kita and coauthors [12] reported that dipping in acetic acid solution and post drying treatment could decrease acrylamide content by 90%. Seasonal variability in acrylamide levels has been reported, highest being observed when potatoes were being used from storage, and lowest when potatoes were freshly harvested.

Raw material characteristics affecting the quality of crisps

Quality of vacuum fried crisps depends widely on variety, nature and stage of ripeness of fruits and vegetables that are used for frying [21]. Food matrix like molecular interactions, chemical composition, and structural organization affects the processed food quality [51, 52]. Mariscal and Bouchon [18] reported correlation between apple crisps' quality parameters (moisture, color, oil content, breaking force) and processing conditions (pre-treatment, time & temperature and frying method).

The maturity of banana and jackfruit bulbs was taken as a factor affecting the quality of vacuum-fried crisps [26, 56]. With increasing ripeness, the sugar content of banana increased, significantly influencing sensory as well as textural properties of crisps. Color changes in unripe mango crisps were more susceptible to temperature and time [38]. Case hardening decreased with the progression of ripeness while the sensory acceptability increased with increase in ripeness. The maturity level significantly influenced the overall quality of crisps when processed under similar vacuum frying conditions. The vacuum fried banana crisps resulted in browning defects due to exposure of raw slices to air before frying. The degree of ripeness in fruits also determines the oil uptake by the fruit and vegetable. The raw fruit took less time for vacuum frying resulting in products which were less flavorful in comparison to the ripe ones where the fried product was soft. Ripe fruit required longer time for frying but was more flavorful because of maturity associated release of volatiles [40].

Commercial Availability of Vacuum Fried Products

Vegetable crisps (also referred to as veggie crisps) are prepared by frying, deep frying, dehydration, or baking. In the United States, vegetable crisps are often produced in bulk with many brands marketing them to consumers. The major market players for veggie crisps are Bradds LLC, Calbee, Zweifel, Snikiddy, Frito-lay, Bare snacks. Indian brands such as TBH, Chopinz, Bagrry's, Jacme etc. account for a big proportion of vacuum fried crisps in Indian markets. According to Grand View Research Inc., the global market for fruit and vegetable crisps is expected to reach USD 78.4 billion by 2028 with a CAGR of 6.4% from 2021 to 2028. There is a shift in consumer interest from conventional fried snacks to healthier snacking options to bridge the prevailing nutritional gap.

CONCLUSION

Frying is a multifaceted process involving mass and momentum transfer with the occurrence of heat in food which modifies physical and chemical states of food. It is a popular processing operation to produce attractive foods in a relatively quick way with desirable sensory properties and a longer shelf life. Many vacuum fried products are available in the market with varieties of fruits and vegetables being displayed on shelves. The product characteristics and process parameters in vacuum frying play a vital role in the final quality of fried foods. The size and surface characteristics of food material, composition of food material, oil type, frying temperature, frying time and vacuum pressure influences the nutrient retention in final fried products. The fat content of fried foods is most important and draws the concerns of consumers in the market. Many studies on fat reduction strategies and pre-treatments have been developed to make fried foods healthier to eat. The potential carcinogenic compounds formed in foods during Maillard browning of starch rich foods is another reason for modifying the frying methods to reduce their generation in foods.

The limitation of vacuum frying operation is high initial investment and cost of machinery which is a big hurdle faced by small organization, low key manufacturers and entrepreneurs. Besides, a small-scale food processing operation is not available thereby making it even more expensive to afford. The fruit and vegetable crisps market is ever-growing industry with the advent of modern fryers, but studies are still needed to explore potential of modern processing treatments (microwave, pulsed electric field, ultrasound, etc.) in becoming an integral part of frying operation i.e. hybrid frying systems on industrial level. Moreover, the application of vacuum frying on traditional food materials needs to be studied. There is also a scope of modeling the fundamental process of vacuum frying including the parameters and changes that take place during the process.

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Conflicts of Interest: "The authors declare no conflict of interest."

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