1. Overview

Frying is one of the most practiced cooking methods in the world. Frying is considered a dry method of cooking as the process does not involve water. In frying process, high temperature and the high heat conduction of oil, food is cooked with preserved and even enhanced nutritional values and minimized quality losses. Food frying technology can extend the shelf life of fruits and vegetables and frying oil enhances the flavors of the products, however, improper frying oil can have harmful effects on consumer health.

Vacuum frying, on the other hand, operates at relatively lower temperatures (e.g., 130°C). Apart from high quality retention in the final product obtained by vacuum frying, the main difference of the two techniques is the investment cost and operational cost. For deep frying home appliances can be used, however, in order to do commercial production on mass scale, additional care must be given for keeping the process hygienic and the materials used should conform to the principles of Good Manufacturing Practices (GMPs). For vacuum frying specially designed machines and equipment are needed. Both frying techniques have different benefits and disadvantages, therefore, investors should carefully consider the required properties of raw materials and desired characteristics of final product to avoid any investment waste.

Figure 1 Gas vacuum fryer with basket lifting to remove frying oil
Description of vacuum frying

When frying is carried out at below atmospheric pressure, boiling point of water reduces; hence, higher temperatures are not required to remove moisture from the food. The deteriorating effect on food due to heat would be less. Following is the brief account of governing theories:
1. Water evaporation under vacuum

Boiling point of water is 100°C at atmospheric pressure. Evaporation of water at this temperature occurred together with loss of some food nutrients. Under vacuum water is boiled and evaporated at lower temperature even at 0°C so that nutrients loss is reduced especially for heat sensitive nutrients. Table 1 shows the boiling point of water at different pressure levels.

2. Heat transfer

For hot air dryers heat is transferred by convection using hot air as a medium. Air has relatively lower heat transfer coefficient. Contrast to air, frying under vacuum condition, vegetable oil has higher heat transfer coefficient. Therefore shorter time is required to reduce moisture content.

3. Frying temperature

Automatic temperature control system, when used, provides a mechanism by which moisture is reduced while food temperature is controlled by the system. Constant temperature of food results in uniformity of product quality.

Table 1 Boiling point of water at different pressure levels

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Pressure (inHg)</th>
<th>Pressure (mmHg)</th>
<th>Pressure (mBar)</th>
<th>Boiling Temperature (°C)</th>
<th>Air Specific Volume (m³/kg)</th>
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<tbody>
<tr>
<td>101.33</td>
<td>30.0</td>
<td>760.0</td>
<td>1013.0</td>
<td>100</td>
<td>1.7</td>
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<tr>
<td>84.55</td>
<td>25.0</td>
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<td>70.14</td>
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<td>701.2</td>
<td>90</td>
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<td>57.83</td>
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<td>433.7</td>
<td>578.1</td>
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<td>65</td>
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<td>4.6</td>
<td>6.1</td>
<td>0.01</td>
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</tr>
</tbody>
</table>

Advantages of vacuum frying

Vacuum fried products has low moisture content (<6%) and low water activity (a_w<0.3) (Tawong, 2000; Piamkhla, 2004; Wongsuwan and Laosuksuwan, 2006) so it has long shelf life. Under vacuum condition frying temperature is constant and not higher than 100°C and frying time is not longer than 2 hours. Obviously, vacuum frying is energy efficient process. The products are crispy and retain original color, taste and odor as of the natural foods. Likewise vacuum frying is beneficial to some fruits or vegetables with intense odor such as durian. Vacuum fried durian is less objectionable and more convenient to carry when compared with fresh durian.

Vacuum frying can be used to fry high sugar fruits and fresh vegetable in order to produce various kinds of snacks. Sugar is burnt before water is removed from the fruits. The products still have high moisture content. Vegetables have high moisture content around 85%. During water removes cell structure is collapse with the loss of integrity so that the products are not crispy. If frying until crispiness is obtained, the products are burnt. Coating fruits and vegetables with flour paste before frying provides crispy products. But the products have short shelf life and are not suitable for commercial production as it requires certain time-to-shelve before consumption.

Disadvantages of vacuum frying

In vacuum frying, vegetable oil is used as heat transfer medium. Oil is possibly absorbed by foods, therefore, there will be oil remaining in fried products making them undesirable and may raise health concern among consumers. There are many research works which has described techniques to reduce oil absorption during vacuum frying. Pre-coating with guar gum is one of the recommended techniques. Banana coated with guar gum before frying under vacuum has lower oil content of 8% compared to vacuum fried banana without guar gum pre-coating, which has 12% oil content (Wongsuwan and Laosuksuwan, 2006). Oil absorption, however, varies with chemical properties of raw materials. Different pretreatment techniques and processes will be applied to produce good quality of vacuum fried products.

In financial terms, investment cost of vacuum frying process is much higher than that of deep frying. This is because vacuum frying technique is basically designed for large scale industry. There is a lack of design of vacuum fryer for small scale production. Small scale producers such as grower group, small community enterprise, and cooperatives find it hard to afford vacuum frying machines and equipment without financial support from government. In Thailand investment for vacuum drying is from two groups of producers as grower groups who are supported by government and private companies who either has new business or has already produced fried products. High investment cost is a considerable disadvantage in implementing vacuum frying in small scale production.
Application of vacuum frying

A locally developed vacuum fryer has been designed for the raw materials commonly available in Thailand especially tropical fruits and vegetables. The vacuum fryer was tested in laboratory scale and later scaled up at industrial level production. Many vacuum fried products are introduced in the markets such as ripe banana, ripe jackfruit, ripe durian, ripe mango, pineapple, pumpkin, taro, yam, carrot, baby corn, okra, garlic, multiplier onion, seasoned and fresh shrimp and squid.

Recommended raw materials for deep and vacuum frying

Selection of fruits for vacuum frying

Ripe fruits, which have high sugar content, are popularly fried under vacuum because it is not possibly fried at atmospheric pressure. Selection of fruits suitable for vacuum frying is based on the followings;

1. Variety
   Chemical and physical properties of fruits are varied by varieties. These properties affect the quality of the fried products. Trimming can eliminate this problem. Thin flesh jackfruits can be fried as lumps of pulp whereas thick flesh jackfruits should be chopped to small pieces before frying. Thickness of the raw materials affects vacuum frying. Crispy and soft texture of vacuum fried jackfruits is obtained together with uniformity of the moisture content when raw material thickness is efficiently controlled.
2. **Ripeness**
Vacuum frying is effectively used to fry high sugar fruits so that fried products have sweet taste. Fruit subjected to vacuum frying should not have any astringent taste. Fruits should be ripe but not be too ripe because high sugar content induces high absorption of oil during frying. Likewise ripe fruits should not have too soft texture due to breaking of fruits to small pieces occurs from quick evaporation of water during vacuum frying. Vacuum frying of too ripe durian gives small pieces of fried products.

3. **Taste**
Vacuum frying is the process of evaporating of water at low temperature in order to maintain natural taste and minimize nutrient losses. Original taste of the fruits should be considered for raw material selection. Stronger taste of fried products is observed when compared to the taste of raw materials. This is due to very little excreting saliva during eating fried products, therefore, strong taste from high concentration of taste components is observed. Vacuum fried pineapple has very sour taste when made from sour pineapple. Also too sweet ripe fruits should not be selected as raw materials for vacuum frying.

4. **Moisture content**
Usually it is difficult to fry high moisture fruits. Much water has to be removed during frying. Fruits will be burnt before they are dried and shrinkage will occur during water evaporation. Freezing of high moisture raw materials before vacuum frying such as longans, lychees is recommended in order to perform water evaporation at lower temperature.

5. **Raw materials that are not qualified for fresh consumption**
Fruits, which are not qualified to sell as fresh fruits such as too big or too small, not smooth in surface or have defects, are selected for vacuum frying. Unqualified fruits are cheap. They must be washed, peeled, and trimmed to remove defects and uneatable parts before vacuum frying. Defects are not detected in fried fruit products. Therefore vacuum frying should be applied for fresh fruit industry, packing house and grower groups to reduce waste because they can use unqualified raw material for processing.

6. **Seasonal fruits**
Some fruits are seasonally grown and harvested. Domestic and export markets cannot absorb the entire production yield. Excess fruit during the season lowers its price. This is an important problem of developing agricultural countries. Frying can be applied to extend the shelf life of the seasonal fruits.

7. **Raw material by-products waste during processing**
In fruit and vegetable industry, a huge lot of fruits and vegetables are wasted from trimming. These parts are in good quality but their sizes and shapes do not meet the processing standards. Vacuum frying help enhance commercial value addition of the wastes.
**Vacuum frying for fruits**

Fruits may be harvested as unripe fruits. A controlled ripening process is required before vacuum frying. Freezing is a recommended pretreatment in order to obtain crispy vacuum fried products. Example of vacuum frying process for pineapple is shown in Figure 5.

![Flowchart of vacuum frying of pineapple](image)

Figure 5 Flowchart of vacuum frying of pineapple
Figure 6 Vacuum fried ripe banana

Figure 7 Vacuum fried-sliced and tidbit pineapple
Figure 8 Vacuum fried-sliced mango

Figure 9 Vacuum fired jackfruit

Figure 10 Vacuum fried durian
Procedure for quality control

Many factors in terms of raw material frying load, raw material properties, raw material size, frying temperature, frying time, oil casting speed and casting time affect qualities of fried products. Therefore qualities of vacuum fried products should be controlled using record sheet. Example of good record sheet for vacuum frying is shown in Table 2. This designed table can be used as a document for quality control in order to produce uniform and qualified fried products, which meet safety regulations and quality standards. Every data recorded by the operators is important factor affecting quality changes and production losses. At the same time supervisor can use this record sheet to monitor the operators.

During the frying process quality of frying oil should be constantly monitored. Frying oil should be changed frequently because changing in physicochemical properties of oil affects product quality and oil uptake during frying. In addition toxic compounds can be generated in deteriorated frying oil, which is harmful to consumer health. Evaluation of frying oils can perform as following methods.

- **Sensory evaluation**
  - Used frying oil exhibits definite smell and taste defects
  - Used frying oil shows an intensified formation of smoke and foam during frying
  - Intensified darkening, however, is not a measure of deterioration. Change of color is caused by the reaction of proteins with fat components or sugars

- **Quick tests**
  - Colorimetric procedures determine the amount of degradation products of fatty acids (carbonyl compounds) (Figure 11)
  - Color reaction aims to determine portion of polar compounds or the acid value
  - Redox reaction determines amount of oxidized fatty acids
  - Measuring of foam height, viscosity or dielectric properties

- **Analytical methods**
  - Physical methods include the determination of smoking point, viscosity, conductivity, dielectricity constant and the Lovibond color index
  - Chemical methods include the determination of free fatty acids (acid value) by acid-base titration, of polar compounds by means of chromatographic procedures, of polymer triacylglycerols and oxidized fatty acids

- **Codex Alimentarius**
  - Used frying oils are generally considered as deteriorated when they clearly exhibit objectionable smells or taste, e.g. strong mildew, strongly gritty, rancid, vanish, bitter
  - These sensory impressions are objectified through further analytical criteria like the polar compounds and polymer triacylglycerols
Table 2 Record sheet for vacuum fryer

<table>
<thead>
<tr>
<th>Batch No.</th>
<th>Raw material Types</th>
<th>Raw material load</th>
<th>Raw material Shape</th>
<th>Frying temperature</th>
<th>Frying time (begin)</th>
<th>Frying time (end)</th>
<th>Time of unloading oil</th>
<th>Oil casting time (begin)</th>
<th>Oil casting time (end)</th>
<th>Casting speed</th>
<th>Oil casting time (end)</th>
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</table>
Quality, Safety and storage

Among the important qualities of deep and vacuum fried products are nutrition values, consumer acceptability and safety of frying oil. These qualities can be controlled by selection of proper raw materials. One of properties that affect consumer acceptance is crispiness of fried products. Crispiness of deep fried product changes rapidly after frying because it is mainly composed of sugar and readily absorbs moisture. Whereas crispness of vacuum fried product does not change much because it is composed of starch, which absorbs less moisture after frying. Beside of types of raw material thickness affects product crispiness. Thin slices are needed in order to obtain soft crispy and dried texture after frying. Producers should change frying oil when it is oxidized and not safe for consumers. Particular care should be for deep fried products, which is fried at high temperature and continually exposed to air during frying.

Vacuum fried product is much susceptible to spoilage during storage especially in tropical and humid conditions. It can readily absorb moisture from storage environments. Therefore, producers should separately pack fried products that have different moisture content because, in the same packaging, moisture can move out from high moisture product and be absorbed by low moisture product. Then product crispiness decreases and consumer will reject the products. Quality of fried products changes when storing at high temperature such as shop standing in open space or in cars and containers parking in the sun. This also causes loss of product crispiness.

Therefore producers should follow the below guidelines in order to control the qualities of fried products.

- Producers should use control sheet presented in Table 2 to control frying operation and also responsible operators.
- After frying producers should remove high moisture fried product by pressing and observing soft texture and then bring that product to fry once more to obtain low moisture content and desire crispiness.

Figure 11 Paper used for determination of free fatty acid content in oil
- For storing fried products prior to packing producers should use closed containers that can prevent moisture transfer and store products under shade at low temperature. The best storing method is packing in double polypropylene (PP) plastic bags and then putting in closed plastic bucket.
- For retail packaging producers should use closed containers that can prevent moisture transfer such as aluminum foil bag, aluminum foil bag in paper box, paper can coated inside with aluminum foil and metal can.

Shelf life of fried product is not less than 6 months when producers follow the above guidelines. Long shelf life can be obtained when using nitrogen gas packaging. From the study of Piamkhla (2004) shelf life of vacuum fried ripe banana is 6 months when packing in plastic bag and can that flushed with nitrogen or putting moisture absorbent.

Figure 12 Storing of vacuum fried banana in double polypropylene plastic bag prior to pack in retail bag and distribute to market

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Wongsuwan, J., Laosuksuwan, C. 2006. Oil uptake reduction of fruit chips in vacuum frying. Project study, Food Engineering Department, Faculty of Engineering, Kasetsart University (Kamphaengsaen Campus) (In Thai).