Effects of processing conditions on the quality of vacuum-fried carrot chips

Shyi-Liang Shyu,1 Lung-Bin Hau2 and Lucy Sun Hwang2∗

1Graduate Institute of Food Science, National Chiayi University, Chiayi 600, Taiwan
2Graduate Institute of Food Science and Technology, National Taiwan University, Taipei 106, Taiwan

Abstract: The effects of pretreatment and vacuum frying conditions on the quality of fried carrot chips were studied. The moisture and oil contents of fried carrot chips were significantly (*p* < 0.05) reduced when blanched carrot slices were pretreated by immersion in fructose solution and freezing prior to vacuum frying. Furthermore, more uniform porosity was observed on the vertical cross-section of carrot chips when examined by scanning electron microscopy. During vacuum frying, the moisture content, colour and breaking force of carrot chips decreased while the oil content increased with increasing frying temperature and time. However, there was no apparent change in Hunter ΔE with time when the frying temperature was below 100 °C and the frying time was below 25 min. Results of this study suggest that vacuum frying at moderate temperature (90–100 °C) for 20 min can produce carrot chips with lower moisture and oil contents as well as good colour and crispy texture.

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Keywords: vacuum frying; carrot chips; processing conditions; scanning electron microscope

INTRODUCTION

Dehydration is one of the major processes in food preservation. The reduction in weight and bulk of dehydrated products and the increase in shelf stability can all reduce product storage and distribution costs.1 Some of the more common drying methods for vegetables and fruits are air drying, solar drying, vacuum drying and freeze-drying.2 Moisture removal by deep-fat frying is an alternative dehydration method. Fried foods are generally processed under atmospheric pressure at elevated temperature. Surface darkening may occur before the food is fully cooked.3

Deep-fat frying under vacuum (vacuum frying) can overcome the disadvantages of regular deep-fat frying, since the food is heated under reduced pressure in a closed system, which lowers the boiling point of water in the food. Moisture can be removed from the fried food rapidly once the oil temperature reaches the boiling point of water. The colour and flavour can be better preserved in vacuum-fried food, because the food is heated at lower temperature and oxygen content.4 Dehydrated food produced by vacuum frying can thus have crispy texture, good colour and flavour5 and good retention of nutrients.6 Vacuum frying also has less adverse effects on oil quality.7,8

It is generally recognised that the highest quality dehydrated vegetables and fruits are produced by freeze-drying, which can maintain their original flavour and colour.9 This operation, however, is energy- and time-consuming.10 Therefore how to produce high-quality dehydrated vegetables and fruits in a short time is an important issue for food processors. Vacuum frying may be a good alternative for the production of dehydrated fruit and vegetable slices. The objective of this study was to investigate the influence of raw material pretreatment methods and vacuum frying conditions on the quality of carrot chips.

MATERIALS AND METHODS

Materials

Carrots and palm oil were purchased from a local market in Taiwan. The palm oil had been imported from Malaysia. Whole carrots (Daucus carota L) were packaged in polyethylene (PE) bags and stored at 0 °C prior to use.

Processing overview of vacuum-fried carrot chips

The flow diagram for the processing of vacuum-fried carrot chips is shown in Fig 1. Washed, peeled and drained carrots were cut into 2 mm thick slices with a slicer (OMAS model VS250, Italy). The carrot slices, which contained 890 g kg⁻¹ moisture, were subjected to different pretreatments before being vacuum-fried.
Pretreatment of carrot slices

Pretreatment of carrot slices prior to vacuum frying included blanching, immersion in sugar solution and freezing. In our earlier study with apple chips it was found that the quality of vacuum-fried apple chips was greatly influenced by pretreatment methods such as immersion in sugar solution and freezing. In this study the blanching condition was kept at 95 °C for 2 min and the immersion and freezing methods were investigated. The procedures of the four different pretreatments (A, B, C and D) are shown in Table 1: (A) blanched carrot slices were immersed in 500 g kg⁻¹ fructose solution at 50 °C for various time intervals (1, 30, 60 and 180 min) and then fried; (B) blanched carrot slices were immersed in fructose solution, frozen at −30 °C overnight and then fried; (C) blanched carrot slices were immersed in fructose solution, frozen, thawed and then fried; (D) blanched carrot slices were frozen, thawed and then immersed in fructose solution before vacuum frying.

Vacuum frying conditions

Carrot slices were blanched in water at 95 °C for 2 min and immersed in 500 g kg⁻¹ fructose solution at 50 °C for 30 min. Drained slices were stored at −30 °C overnight prior to vacuum frying. About 36 kg of palm oil was poured into a vacuum fryer (Horng Yun Steel Factory, Yon Lin, Taiwan). A 400 g batch of carrot slices was fried under vacuum (98.66 kPa) at various temperatures (70, 90, 100 and 110 °C) for different amounts of time (5, 10, 15, 20, 25 and 30 min). After frying, the fried carrot chips were centrifuged at 600 × g for 30 min to remove the frying oil and then packed in PE bags and stored at −30 °C before analysis.

Analytical methods

Total sugars of carrot slices were determined according to the AOAC method. Moisture content of carrot chips was measured in a vacuum oven by drying at 70 °C. Ground samples (5 g) were dried to constant weight. Moisture content was calculated from the weight difference between the original and dried samples and expressed as % of original sample. Oil content of carrot chips was determined gravimetrically by Soxhlet extraction.

Carrot chips, prepared by different pretreatment methods, were examined by scanning electron microscopy (SEM). Samples were defatted and freeze-dried and the vertical cross-section of the samples was sputter coated with gold and examined with a JSM-6300 scanning electron microscope (JEOL, Tokyo, Japan).

The surface colour of carrot chips was measured with a colorimeter (Nippon Denshoku 90 colour difference meter, Tokyo, Japan) and expressed as Hunter L (lightness), a (redness) and b (yellowness) values. The colorimeter was standardised using a white tile (Y = 95.43, X = 93.49, Z = 113.21). Colour difference (Hunter ΔE) was calculated according to the equation

$$ΔE = [(L - L_{ref})^2 + (a - a_{ref})^2 + (b - b_{ref})^2]^{1/2}$$

The colour of fresh carrot slices was used as reference. A TA-XT2 texture analyser (Stable Micro Systems Co Ltd, Godalming, Surrey, UK) was used to determine breaking force. Each carrot chip was placed across the bridge of a 2 ft (61 cm) long piece of 3/4 in (19 mm) aluminium channel and the probe (No P/0.5S) was brought down in the middle of the bridge. All numerical results were expressed in grams.

Statistical analysis

All data were obtained by triplicate analyses and were analysed using the SAS software package. Analyses of variance were performed by the ANOVA procedure. Significant differences between means were determined by Duncan’s multiple range test.
RESULTS AND DISCUSSION

Influence of pretreatment methods on quality of carrot chips

Moisture and oil contents

The effect of pretreatment methods on the moisture and oil contents of fried carrot chips is shown in Table 2. It is clear that the total sugar content in carrot slices increased with increasing immersion time. When blanched carrot slices were immersed in 500 g kg\(^{-1}\) fructose solution at 50°C for 30 min, total sugars reached 346 g kg\(^{-1}\) in carrot slices after immersion. When the immersion time was more than 60 min, there was no significant (p > 0.05) increase in total sugar content. Therefore a 30 min immersion time was chosen in the following studies. Moisture content of the fried carrot chips was found to be influenced by the pretreatment method employed. As shown in Table 2, method A yielded carrot chips with the highest moisture content, while method B gave the lowest moisture content, regardless of the immersion time. It is evident that freezing the carrot slices before frying without thawing can reduce the moisture content in the fried carrot chips most effectively.

Oil content of the fried carrot chips decreased with increasing immersion time in sugar solution for all four pretreatments under investigation (Table 2). When carrot slices were immersed in sugar solution, water would be removed from the cells of the carrot slices by osmotic pressure. In addition, water would also be vaporised during vacuum frying and might leave behind pores in the carrot slices. Subsequently the pores would be filled with solute (fructose), leading to lower oil uptake, so the oil content in the fried slices was reduced. Among the four different pretreatment methods, method A was found to yield chips with the lowest oil content, but the moisture content was the highest. Furthermore, the fried carrot chips made from method B had a lower oil content than those made from methods C and D (the two methods with thawing pretreatment). Therefore pretreatment method B can produce carrot chips with low moisture and oil contents. This result indicated that thawing the frozen carrot slices prior to frying would lead to higher moisture and oil contents in the fried chips.

Electron microscopic examination of the vertical cross-section of the fried carrot chips was employed to reveal the effect of pretreatment method on the interior structure of the chips. Figure 2a shows that carrot chips prepared without immersion in fructose solution and without freezing prior to vacuum frying appear to have a shrinkage in the structure. The vertical cross-section of the carrot chips showed uneven porosity and extensive shrinkage. Carrot chips prepared without the freezing step (pretreatment method A) possess the highest moisture content among the various pretreatments. This might be caused by the fact that, during vacuum frying, the surface water of carrot slices was evaporated more rapidly than when carrot slices were under frozen condition, resulting in surface shrinkage which prevented the diffusion of water from the interior to the surface of carrot slices. In addition, the rate of heat transfer between cells in carrot slices was different owing to the surface shrinkage. When the oil temperature reached the boiling point of water, the free and/or loosely bound water remaining inside the chip was vaporised suddenly, leaving behind the larger pores.

Freezing of carrot slices prior to vacuum frying resulted in lower moisture content (Table 2) and a porous sponge-like structure of the fried carrot chips (Figs 2b–2e). This could be due to the fast heat transfer between frozen cells and the fact that water can evaporate rapidly from ice crystal state under vacuum condition. Increasing the immersion time of carrot slices in fructose solution to 60 min resulted in more uniform porosity of the fried carrot chips, as can be seen on the vertical cross-section of carrot chips examined by SEM (Figs 2b–2e). When carrot slices were frozen, thawed, immersed in fructose solution and then fried (pretreatment method D), it resulted in uneven porosity and excessive shrinkage in the structure of fried carrot chips, as shown in Fig 2f.

<table>
<thead>
<tr>
<th>Immersion time (min)</th>
<th>Total sugars in carrot slice after immersion (g kg(^{-1}))</th>
<th>Moisture content (g kg(^{-1}))</th>
<th>Oil content (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretreatment method</td>
<td>Pretreatment method</td>
<td>Pretreatment method</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>0</td>
<td>32 ± 1d</td>
<td>65 ± 5e</td>
<td>22 ± 1f</td>
</tr>
<tr>
<td>1</td>
<td>133 ± 3c</td>
<td>70 ± 2e</td>
<td>24 ± 1h</td>
</tr>
<tr>
<td>30</td>
<td>346 ± 10b</td>
<td>91 ± 6e</td>
<td>42 ± 1f</td>
</tr>
<tr>
<td>60</td>
<td>362 ± 8ab</td>
<td>100 ± 5e</td>
<td>47 ± 2g</td>
</tr>
<tr>
<td>180</td>
<td>381 ± 5a</td>
<td>106 ± 2e</td>
<td>57 ± 1g</td>
</tr>
</tbody>
</table>

a Pretreatment methods are described in Table 1.

b The frying condition was 90°C for 10 min under vacuum (98.66 kPa).

c Carrot slices were immersed in 500 g kg\(^{-1}\) fructose solution at 50°C for different time intervals.

d All data were obtained by triplicate analyses and expressed as mean ± standard deviation.

Table 2. Effect of different pretreatment methods on moisture and oil contents of vacuum-fried carrot chips

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Figure 2. Scanning electron micrographs of vertical cross-section of vacuum-fried carrot chips prepared by different pretreatment methods: a, pretreatment A with 0 min immersion time; b, pretreatment B with 0 min immersion time; c, pretreatment B with 1 min immersion time; d, pretreatment B with 30 min immersion time; e, pretreatment B with 60 min immersion time; f, pretreatment D with 60 min immersion time.

Similar to the situation of pretreatment method A, this shrinkage also resulted in higher moisture content as compared with pretreatment method B (Table 2). These results clearly indicated that the best pretreatment method was immersing carrot slices in fructose solution and freezing prior to frying (pretreatment B). It could produce fried carrot chips with low moisture and oil contents as well as more uniform porosity and less surface shrinkage. This is in agreement with the observation reported by Jayaraman et al,\textsuperscript{17} who found that immersion of cauliflower in salt and sucrose solution prior to dehydration could reduce shrinkage and retain the integrity of cell walls.

Effects of vacuum frying temperature and time on quality of carrot chips

Moisture and oil contents

When carrot slices were fried at 70°C, the moisture content of carrot chips was significantly ($p < 0.05$) decreased with increasing frying time, as shown in Table 3. After frying at 70°C for 30 min, the moisture content of carrot chips was still above 60 g kg$^{-1}$. More than 30 min of frying time was needed in order to decrease the moisture content to below 60 g kg$^{-1}$. When carrot slices were fried at temperatures above 100°C, however, the moisture content of carrot chips showed a rapid decrease in the first 10 min to 20 g kg$^{-1}$ or below. Loss of moisture during frying exhibited a classical drying profile. The slow decrease in moisture content after 10 min of frying was similar to the falling rate period of drying. During this stage the moisture in the raw material was slowly removed by capillary action. In vacuum frying, food is heated under reduced pressure in a closed system, which can lower the boiling point of water. At an absolute pressure of 2.64 kPa during vacuum frying, the boiling point of water is about 22.1°C.\textsuperscript{1} Therefore the unbound water in the fried food can be quickly removed when the oil temperature reaches the boiling point of water.

It is also evident from Table 3 that, when carrot slices were fried at low temperature (70°C), the oil
content of carrot chips was significantly ($p < 0.05$) increased with increasing frying time from 5 to 30 min. When the frying temperature was above 90 °C, however, the oil contents of carrot chips increased rapidly with increasing frying time in the first 15 min and thereafter the increase was quite moderate. When the slice was placed in hot oil, water evaporated quickly from the surface of the slice, resulting in a diffusion gradient for moisture. The moisture in the inner area of the slice was thus driven out as steam, creating a pressure gradient. As this continued, the areas surrounding the moisture escape sites could be dried out and lose their hydrophilicity, oil could then adhere to the slice and enter the porous areas. The amount of oil entering the slice has been shown to be directly proportional to the amount of moisture lost. From the results of these frying experiments it is clear that the moisture content of carrot chips decreased while the oil content increased with increasing frying temperature and time.

**Colour**

The effects of vacuum frying temperature and time on the colour of carrot chips are shown in Fig 3. There was no significant ($p > 0.05$) change in $L$ value during frying at lower temperatures (70–90 °C) and for shorter times (5–15 min). When carrot slices were fried at 100 °C for up to 15 min, the $L$ value decreased significantly ($p < 0.05$). This could be due to the lower moisture content in the carrot chips. A similar phenomenon was observed for the $a$ and $b$ values, which apparently decreased as the frying temperature increased to 100 °C and higher. It is assumed that heating could cause degradation of carotenoids in carrot slices, because carotenoids are unstable at temperatures above 100 °C. The change in colour difference value (Hunter $\Delta E$) of carrot chips during vacuum frying is shown in Fig 4(A). There was no apparent change in Hunter $\Delta E$ with time when the frying temperature was below 100 °C and the frying time was below 25 min. However, when the frying temperature was raised to 110 °C, Hunter $\Delta E$ of carrot chips increased markedly with increasing frying time.

**Table 3. Effect of vacuum frying temperature and time on moisture and oil contents of fried carrot chips**

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>70</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>Moisture content (g kg$^{-1}$)</td>
<td>358 ± 1a</td>
<td>77 ± 1a</td>
<td>48 ± 2a</td>
<td>29 ± 1a</td>
<td>52 ± 1l</td>
<td>111 ± 2j</td>
</tr>
<tr>
<td>Oil content (g kg$^{-1}$)</td>
<td>5 ± 1k</td>
<td>70 ± 1k</td>
<td>124 ± 3i</td>
<td>128 ± 6k</td>
<td>145 ± 6i</td>
<td>87 ± 1j</td>
</tr>
</tbody>
</table>

$a$ Carrot slices were immersed in 500 g kg$^{-1}$ fructose solution at 50 °C for 30 min and then frozen and vacuum fried.

$b$ All data were obtained by triplicate analyses and expressed as mean ± standard deviation.

$c$ Data in the same column with different letters are significantly different ($P < 0.05$).
time (Fig 4(B)). After frying at 100 °C, chips decreased with increasing frying temperature and crispness. When carrot slices were fried at 70 °C for 20–25 min, the texture of the carrot chips was too soft to be measured owing to the high moisture content (Table 3). The breaking force was therefore measured for samples obtained at frying temperatures above 5–30 min, the texture of the carrot chips was too soft to be measured by SEM. The breaking force of carrot chips decreased as the frying temperature. During vacuum frying, the colour and breaking force of carrot chips decreased as the frying temperature and time increased. However, when the frying temperature was raised to 110 °C, Hunter ΔE of carrot chips increased markedly with increasing frying time. From the results of this study it is suggested that the optimal vacuum frying conditions are an oil temperature of 90–100 °C and a frying time of 20–25 min.

**ACKNOWLEDGEMENT**
This work was supported by the National Science Council, Republic of China under grant NSC 85–2313–B–021–007.

![Figure 4](image-url)

**Figure 4.** Effects of vacuum frying temperature and time on (A) ΔE and (B) breaking force of fried carrot chips.

**Breaking force**
Breaking force was used to represent the crispness of fried carrot chips in this study. A carrot chip with a lower breaking force value is considered to have higher crispness. When carrot slices were fried at 70 °C for 5–30 min, the texture of the carrot chips was too soft to be measured owing to the high moisture content (Table 3). The breaking force was therefore measured for samples obtained at frying temperatures above 70 °C. Results showed that the breaking force of carrot chips decreased with increasing frying temperature and time (Fig 4(B)). After frying at 100 °C for 20 min, the breaking force of carrot chips was decreased to below 600 g (Fig 4(B)).

**CONCLUSIONS**
The moisture and oil contents of fried carrot chips were significantly \( p < 0.05 \) decreased when carrot slices were immersed in fructose solution for 30 min, frozen and then vacuum fried. Both uniform porosity and integral texture were observed when the vertical cross-section of carrot chips was examined by SEM. Both moisture and oil contents of carrot chips were found to be affected by the vacuum frying time and temperature. During vacuum frying, the colour and breaking force of carrot chips decreased as the frying temperature and time increased. However, when the frying temperature was raised to 110 °C, Hunter ΔE of carrot chips increased markedly with increasing frying time. From the results of this study it is suggested that the optimal vacuum frying conditions are an oil temperature of 90–100 °C and a frying time of 20–25 min.

**REFERENCES**