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Research Article

Effect of Hot-Water Blanching Pretreatment on Drying Characteristics and Product Qualities for the Novel Integrated Freeze-Drying of Apple Slices

Hai-ou Wang,[1,2] **Qing-quan Fu**,[1] **Shou-jiang Chen**,[1] **Zhi-chao Hu**,[2,3] **and Huan-xiong Xie**[2,3]

[1]*School of Food Science, Nanjing Xiaozhuang University, Nanjing 211171, China*
[2]*Key Laboratory of Modern Agricultural Equipment, Ministry of Agriculture, Nanjing 210014, China*
[3]*Nanjing Research Institute for Agricultural Mechanization, Ministry of Agriculture, Nanjing 210014, China*

Correspondence should be addressed to Hai-ou Wang; who1978@163.com

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The effect of hot-water blanching (HWB) on drying characteristics and product qualities of dried apple slices with the novel integrated freeze-drying (NIFD) process was investigated by comparing with 3 different FD methods. Compared with the NIFD process without HWB pretreatment (VF-FD), the NIFD process with HWB pretreatment (HWB-VF-FD) resulted in a significantly higher mass loss and more sufficient freezing in vacuum-frozen samples, significantly higher rehydration ratio (RR), higher shrinkage ratio (SR), smaller Vitamin C (V_C) content and lower hardness and better apparent shape in freeze-dried samples, and fewer change to the color of the dried or rehydrated samples ($p < 0.05$). Compared with the conventional FD process with HWB pretreatment (HWB-PF-FD), HWB-VF-FD cost significantly less processing time and FD time and obtained significantly higher RR ($p < 0.05$), almost the equivalent SR, V_C content, and hardness, and similar appearance in dried samples. The microstructure of apple cell tissues was analyzed by transmission electron microscopy and scanning electron microscopy to interpret the above differences in drying characteristics and product qualities. The results suggested that the NIFD process of apple slices with HWB pretreatment was a promising alternative method to decrease drying time, achieve similar product quality, and simplify the process steps of the conventional FD technology.

1. Introduction

Vacuum freeze-drying (FD) has been considered as one of the best methods for obtaining dehydrated foods with high quality. During FD, the whole dehydrating process is accomplished in the state of high vacuum and low temperature, which almost retains the original color, shape, smell, and nutritional ingredients in fresh materials [1–3]. An industrial-scale FD process for most fruits and vegetables generally consists of 4 main stages, including pretreating, freezing, freeze-drying (primary drying and secondary drying), and packaging. During pretreating in practice, the materials (especially fruits and vegetables) are usually conducted in the sequence steps including selecting, washing, slicing, blanching, quickly cooling, draining residual water, and filling trays. The materials are then transferred into freezing unit and FD unit. In conventional freeze-drying (CFD) processing line, all the individual steps require independent equipment or facility. For example, materials after blanching should be quickly cooled with cold running water, drained with vibratory or centrifugal equipment, frozen with fluidized bed freezer or cold storage, and then dried in vacuum freeze dryer. The CFD process technology is characterized by many disadvantages including complicated process steps, large space occupation, huge equipment investment, frequent materials transferring, long drying time, and high production cost [1, 4]. It was

reported that the production cost of FD was as much as 200–500% higher than that of hot air drying, which greatly reduced economic competitiveness of FD products [5].

In an effort to reduce drying time, researchers attempted to combine FD with other drying methods including vacuum drying, microwave drying, and osmotic drying, and they had achieved good effect in the laboratories [4, 6]. Litvin et al. showed that a considerable saving in FD time and similar quality parameters including color, dimensions, and rehydration ratio were achieved in dried carrot slices which were dried by combining freeze drying with a short microwave treatment and air or vacuum drying [7]. Wang et al. found that salt and/or sucrose osmotic pretreatment prior to microwave freeze-drying resulted in dried products of good quality with shorter processing time as compared with untreated samples [8]. Microwave was used as the heating source to heat the raw materials in FD, which had attracted much attention during the last decades [4]. In order to simplify the food FD processes and shorten the drying time, we proposed a novel integrated freeze-drying (NIFD) processing technology based on the principle of vacuum cooling and vacuum freeze dryer [9, 10]. More specifically, the post-blanching steps in the CFD process including quick cooling, draining, and freezing were replaced with the only step of vacuum freezing, which was conducted in the same vacuum freeze dryer. The step of vacuum freezing is a coupling process of water fast-evaporating and quick-freezing in a closed environment at low pressure, which can remove all the residual water on the material surface and partial internal water in the tissue resulting in rapid reduction of material temperature. The only step of vacuum freezing in the NIFD process can meet the requirements of the steps of cooling, draining, and freezing in the CFD process, which can save the prime-investment and space occupation of the corresponding facilities and equipment and simplify the assembly line and the operation process. Moreover, the water loss during vacuum freezing can reduce the subsequent sublimation load and the FD time. And some experiments of fruits and vegetables including apple were performed by this NIFD processing technology [9, 10]. The above expected effect was achieved. However, further investigation should be carried out on the product quality especially how to maximally retain the original shape of freeze-dried samples.

It is well known that blanching is an important processing step during commercial drying of vegetables and fruits [11]. The use of hot-water blanching (HWB) as a pretreatment is usually carried out to inactivate enzymes and remove air from intercellular space of fruits and vegetables in order to prevent off color and flavor changes during drying [12–14]. And some existent literatures revealed that blanching pretreatment can enhance mass transport in the tissue and affect the drying behavior of fruits and vegetables [15–19]. Apple is one of the most popular fruits worldwide in our life. FD apple slices products are available throughout the world market. However, to our knowledge there are no available reports on the studies on the NIFD processing technology of apple slices pretreated with HWB.

The main objectives of the current study are to evaluate the effect of HWB on the drying characteristics and product qualities of apple slices dried with the NIFD process, including mass loss and frozen temperature of apple samples at the end of freezing treatment, freezing time, freeze-drying time, rehydration ratio (RR), shrinkage ratio (SR), Vitamin C (V_C) content, color, texture, and microstructure of FD apple slice. This study aimed to provide basic knowledge for improving the effect of this NIFD processing and promoting its practical application in fruits and vegetables.

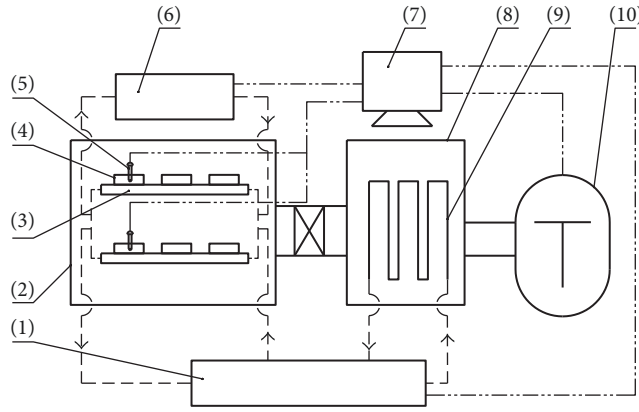


Figure 1: Schematic of the vacuum freeze dryer used. (1) Refrigeration machine; (2) freeze-drying chamber; (3) cooling/heating plate; (4) apple slice samples; (5) thermocouple temperature sensors; (6) heating machine; (7) control system; (8) cold trap; (9) refrigeration coils; (10) vacuum pump.

2. Materials and Methods

2.1. Materials and Samples. Commercial Fuji apples were purchased from a local supermarket (Nanjing, China) and stored at ambient temperature (20°C) until experimental use. The apples with similar dimension were chosen and washed with tap water and hand peeled, cored with a knife, and then cut into slices with about a dimension of 30 mm × 30 mm × 5 mm. The initial moisture content of these apple samples was measured as 86.56 ± 0.59% (w.b.).

2.2. Vacuum Freeze Dryer. In our experiments, the processing steps of the freezing and the freeze-drying of samples were carried out in a laboratory-scale vacuum freeze dryer (SCIENTZ-50F, Ningbo Scientz Biotechnology Co., Ltd., Ningbo, China) which was shown schematically in Figure 1. This equipment consists of a freeze-drying chamber where food samples are put on the cooling/heating plates to perform the freezing and drying steps. During freezing or freeze-drying, the temperature of the cooling/heating plates is controlled by the refrigeration machine or the heating machine; the temperature of food samples is monitored by using the thermocouple sensors. The refrigeration machine also provides refrigerating output to the clod trap to condense the water vapor generated from food samples. The vacuum condition is maintained by the vacuum pump.

2.3. Blanching Treatments. The HWB pretreatment of apple slices was conducted for 1 min in 90°C distilled water that was

heated by an electric heaters, which can inhibit the enzyme activity and retain good color for the fresh slices [20, 21].

2.4. Freezing Treatments. In this study, two different freezing methods were carried out in the vacuum freeze dryer: one was the vacuum freezing (VF) performed under vacuum condition and the other one was the plate freezing (PF) performed under atmospheric pressure condition. When performing the VF treatment, the refrigeration machine was started half an hour earlier to reduce the cold trap temperature below −50°C. The prepared apple samples were then put into the trays on the cooling/heating plates which were not controlled with either heating function or cooling function. The ambient pressure in the freeze-drying chamber was continuously reduced after starting the vacuum pump; then the liquid water evaporating and freezing happened in apple samples. The water vapor flowed into the clod trap and was condensed on the refrigeration coils. The VF treatment was sustained for 30 min and the samples were frozen finally. In case of the PF treatment, the cooling/heating plates temperature was kept around −40°C for 3 h to reduce the temperature of the center of apple slices below −30°C, which was carried out under atmospheric pressure without turning on the vacuum pump and the refrigeration in the clod trap.

2.5. Freeze-Drying Process. The above frozen apple slices were subsequently conducted in-place FD process on the plates in the vacuum freeze dryer. The plate's temperature throughout the FD process was controlled according to the preset automatic heating procedure of temperature-duration time: maintaining the plate's temperature at −20°C for 1 hour (h), then followed by −10°C for 1 h, 0°C for 1 h, 10°C for 2 h, 20°C for 2 h, and 30°C for 2 h, and finally maintaining the plate's temperature at 40°C until the drying end point. Meanwhile, the center temperature of the apple slices was monitored in real time by the control system. It was verified by the early FD experiments using this heating procedure that the moisture content of the dried samples reached about 5% (w.b.) when the center temperature of the apple slices increased to 35 ± 0.5°C, which was determined as the drying end point.

2.6. Three Different Processing Methods. The prepared apple slices samples in Section 2.1 were divided into three groups to perform three different processing methods. There were 50 slices of apple in each group.

2.6.1. VF-FD Method. Apple slices without HWB pretreatment were put into the vacuum freeze dryer to perform the VF treatment and FD process.

2.6.2. HWB-VF-FD Method. Apple slices were pretreated with HWB and then were quickly transferred into the vacuum freeze dryer to perform the VF treatment and FD process.

2.6.3. HWB-PF-FD Method. Apple slices were pretreated with HWB, then were quickly cooled to room temperature using tap water, drained the residual water by air blasting for 15 min with an electric fan at 60 watts power, and were subsequently performed with the PF treatment. This method was an CFD process.

2.7. Analytical Methods

2.7.1. Mass Loss and Temperature of Frozen Samples. At the end of the freezing treatments in the above three processing methods, mass loss of apple slice was calculated by using the following formula:

$$\mathrm{ML} = \frac{m_0 - m_1}{m_0} \times 100\%, \tag{1}$$

where ML (%) is the percentage of mass loss in the apple slice during freezing and m_0 (g) and m_1 (g) are the weight of the apple slice before and after the VF treatment, respectively.

During the VF treatment, the temperature of the geometric center of the apple slice was measured with the thermocouple temperature sensors of the SCIENTZ-50F freeze dryer to determine the temperature variation of apple samples. The measurements of mass loss and frozen temperature were carried out in triplicate for each processing method and the average values were taken for analysis.

2.7.2. Processing Time and FD Time Analysis. The processing time of the individual processing method consisted of two sections: freezing time and FD time. The freezing time in VF-FD and HWB-VF-FD was 30 min, and that in HWB-PF-FD was 3 h. The FD time was determined by the drying terminal temperature of 35 ± 0.5°C in apple slice center. The measurements were carried out in triplicate and the averages are reported.

2.7.3. Rehydration Ratio (RR) Analysis. Rehydration experiments were performed by immersing a weighed amount of dried samples (about 1 g) into a distilled water bath at a controlled temperature of 25°C for 30 min. Then the samples were removed and drained over a mesh for 30 seconds (s) and quickly blotted with the paper towels gently in order to eliminate the surface water and then reweighed. Each rehydration experiment was carried out in triplicate and the averages are reported. The RR was calculated according to the following formula:

$$\mathrm{RR} = \frac{M_r}{M_d} \times 100\%, \tag{2}$$

where RR (%) is the percentage of rehydration ratio of FD samples (%) and M_d and M_r are the mass of the apple sample before and after rehydration tests, respectively (g).

2.7.4. Shrinkage Ratio (SR) Analysis. The sample volume was determined by the volumetric displacement method using glass beads with a diameter in the range (0.105–0.210 mm) as a replacement medium [13, 22]. The measurements were conducted 5 times for the same apple slice sample and the average values were taken for analysis. The SR of the dried sample was calculated as follows:

$$\mathrm{SR} = \frac{V_d}{V_0} \times 100\%, \tag{3}$$

where SR is the percentage of shrinkage ratio of the FD sample (%) and V_0 and V_d are the volume of the sample (cm^3) before freezing and after drying, respectively.

2.7.5. Vitamin C Content Analysis. The V_C content was determined by using the 2,6-dichloroindophenol titration method [23].

2.7.6. Color Analysis. Color measurements of freeze-dried samples and rehydrated samples were carried out by using a colorimeter (NH310, Shenzhen 3nh Technology Co., Ltd., Shenzhen, China). The coordinates of the color CIE-L^* (lightness), a^* (redness), and b^* (yellowness) of the skin of apple slice samples were obtained by reflection. The total color difference (ΔE) was used to characterize the variation of in products color during processing by applying the following equation:

$$\Delta E = \sqrt{\left(L_0{}^* - L^*\right)^2 + \left(a_0{}^* - a^*\right)^2 + \left(b_0{}^* - b^*\right)^2}, \quad (4)$$

where $L_0{}^*$, $a_0{}^*$, and $b_0{}^*$ were the color readings of fresh samples. The measurements were carried out on 5 apple slice samples for each FD method and the average values were taken for analysis.

2.7.7. Hardness Analysis. Hardness of FD apple samples were measured by using a texture analyzer (TA.XTplus, Stable Micro Systems Ltd., Surrey, UK). The cylinder penetrometer probe (5 mm diameter) was passed through the sample with the test parameters set as follows: 2 mm/s of prespeed and postspeed, 2 mm/s of test speed, and 10 g trigger. In the penetration test, hardness was defined as the maximum force (N) required for puncturing the apple slice. The measurements were performed 5 times for samples in each method treatment and the average values were reported.

2.7.8. Transmission Electron Microscopy Analysis. Transmission electron microscopy, TEM (Model JEM-1400; JEOL Inc., Tokyo, Japan), was used to analyze the internal structure of apple slices before and after HWB pretreatment referring to the method in Jiang's research report [24]. Samples of apple tissue were cut into 2 mm × 1 mm pieces, fixed in 3.5% glutaral phosphate buffer, flushed with 0.1 mol/L PBS (pH 7.2), fixed in 1% osmium acid (OsO4), and flushed again in 0.1 mol/L PBS. The samples were then dehydrated in graded ethanol solutions of 35%, 45%, 60%, 70%, 85%, 95%, and 100% (v/v), followed by propylene oxide. The samples were then embedded in Spurr resin and polymerized for 8 h at 20°C. The samples were then pruned and cut into thin slices by using an LKB ultramicrotome. Finally, the samples were double-stained using uranyl acetate and lead citrate. Micrographs were taken at 20000x and 40000x magnification. All the microstructural examinations were performed at 25°C.

2.7.9. Scanning Electron Microscopy Analysis. Cross-sectional observed samples for scanning electron microscopy (SEM) analyses were obtained by naturally fracturing the freeze-dried samples with the aiding of instant freezing by liquid nitrogen. The observed samples were placed on one surface of a two-sided adhesive tape that was fixed to the sample support. Then, they were sputtered immediately (CPD-030; BAL-TEC Company, Liechtenstein). Finally, the specimen fragments were mounted on aluminium stubs, coated with gold under vacuum conditions, and then observed on a scanning electron microscope (EVO-LS10, Cambridge, Germany) for outer surface using an accelerating voltage of 10 kV. In addition, apparent photographs of freeze-dried samples were taken with a camera to compare with the SEM photographs.

In every processing method, 5 SEM images were taken from the dried apple samples to analyze the pores network structure. To quantify the difference in the structure of dried samples, the porosity in the structure was determined. Firstly, the SEM images were turned into gray level and binarized by using an automatic image processing method based on the gray level difference between adjacent pixels, which was performed using Matlab code (Mathworks, Inc., version 7.0.1 Release 14, USA). Then, measurements of pores area (obtained from binarized images) were carried out by the Image Pro-Plus software (Media Cybernetics, Inc., Version 4.0, USA). The porosity of the dried sample was calculated as follows:

$$\mathrm{PR} = \frac{S_p}{S_0} \times 100\%, \quad (5)$$

where PR is the percentage of porosity of the FD sample (%), S_p is the sum of the area of all pores in the image (μm^2), and S_0 is the whole area of the image (μm^2).

2.7.10. Statistical Analysis. Statistical analysis of variance (ANOVA) was performed by using SPSS 20.0 software (IBM, Chicago, IL, USA). Tests of significant differences between means were determined by Tukey's HSD test at a significance level of 0.05 ($p < 0.05$).

3. Results and Discussion

3.1. Mass Loss and Frozen Temperature at the End of Freezing Treatment. Mass loss and frozen temperature of apple samples at the end of freezing treatment in the three processing methods were shown in Figure 2. Mass loss was an inevitable phenomenon for either the VF treatment or the PF treatment. The highest mass loss value at the end of freezing treatment occurred in HWB-VF-FD 32.38%, followed by VF-FD 22.5% and HWB-PF-FD 5.19%, showing significant difference. It was found that mass loss of apple samples at the end of the VF treatment are much higher than that in the PF treatment because they were caused by completely different action principles. During the VF treatment, water on the surface and in the tissue of apple slices evaporated quickly due to exposing to specific vacuum conditions, which resulted in an apparent mass loss and a rapid decrease in the materials temperature [25, 26]. The water evaporation in apple samples during the VF treatment was an intensive and short process of self-dehydration, while no intensive water evaporation happened in the PF treatment because it was performed at atmospheric pressure by using mechanical refrigeration and heat conduction. When apple samples were frozen during the PF

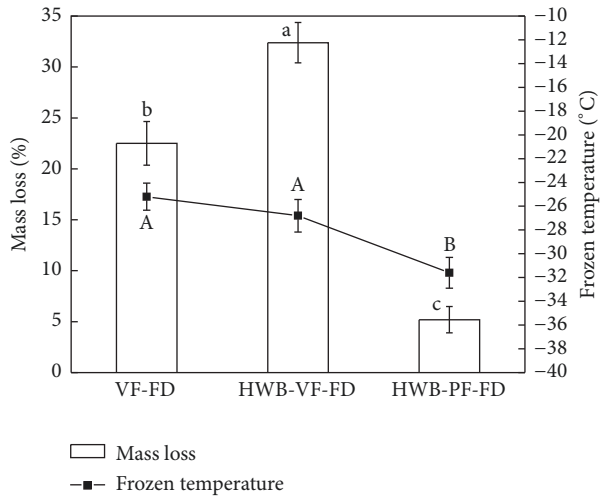


Figure 2: Mass loss and frozen temperature of apple samples at the end of freezing treatment in 3 freeze-drying methods. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process. *Note*. Different letters on the same bar or line indicate significant differences at $p = 0.05$ by Tukey's HSD test.

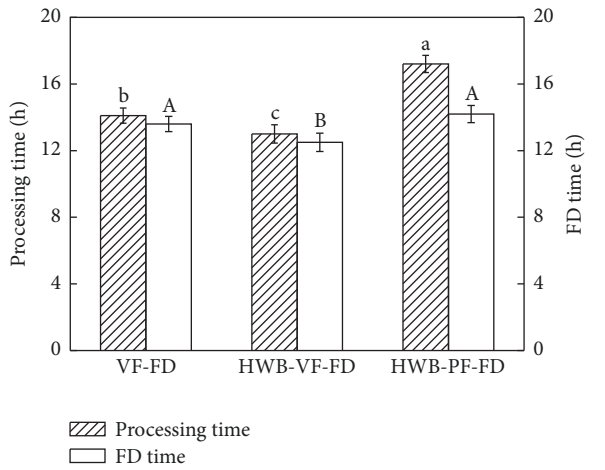


Figure 3: Processing time and FD time in 3 freeze-drying methods. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process. *Note*. Different letters on the same bars indicate significant differences at $p = 0.05$ by Tukey's HSD test.

treatment, a small amount of dehydration also occurred due to the superficial ice sublimation caused by the vapor pressure-temperature environmental interaction [27, 28].

Mass loss of VF treatment in HWB-VF-FD was increased by 43.91% in contrast to that in VF-FD; this significant difference was caused by HWB pretreatment. It can be attributed to the fact that short-time action of high-temperature blanching generally produces profound changes to the cell microstructure including protoplasm coagulation, water loss and shrinkage of intercellular spaces, plasmolysis, increase in permeability or even disruption of cell membranes, and decrease in bound or hydrophilic capacity of extracellular and intracellular water [29–31], which definitely contributed to faster water-evaporating speed and higher mass loss in HWB-VF-FD.

In order to obtain a successful FD performance, the fresh raw materials were required to be fully frozen and keep frozen temperature below their eutectic temperature. The eutectic temperature of the fresh apple in this study was determined as −22.6°C by the electric resistance method [32]. Frozen temperature of samples in VF-FD and HWB-VF-FD was around −26°C with no significant difference and that in HWB-PF-FD was around −32°C, which all can meet the requirements of the eutectic temperature.

Higher mass loss and more temperature decrease in HWB-VF-FD were more favorable for the NIFD process by considering the requirement of the fully freezing and the eutectic temperature of fresh samples as well as the least FD time as possible. Theoretically, the mass loss would be closely corresponding to the frozen temperature of samples complying with the principle of conservation of energy during the VF process. In other words, the higher mass loss, the lower frozen temperature. But no significant difference was observed between the frozen temperatures of the VF treatment in VF-FD and HWB-VF-FD. The reason may be inferred that the removed latent heat by mass loss (water evaporation) in the samples during the VF treatment came from the sensible heat for reducing samples temperature, the latent heat for forming ice crystals in the samples, the foreign heat transmitted from the plates, and the ambient chamber into the apple samples. Before the beginning of the VF treatment in VF-FD method, the temperature of apple samples and the material trays was around the room temperature (20°C) and the plate's temperature in the freeze-drying chamber was around 5°C due to the heat transferring from the cold trap. Before the beginning of the VF treatment in HWB-VF-FD method, the temperature of apple samples and the material trays was around 50°C without precooling treatment and the plate's temperature was also around 5°C. At the end of the VF treatment, the temperature of apple samples, the material trays, and the plates was all around or close to the frozen temperature −26°C. The removed heat either from the material trays or from the plates due to the temperature difference before and after the VF treatment was absorbed mostly by the latent heat of water evaporation from apple samples. So the energy of water evaporation was not only dedicated to the cooling and freezing of apple samples. The inevitable foreign heat transmission might undermine the apparent difference of frozen temperature of apple samples caused by different mass loss.

3.2. Processing Time and FD Time. It is well known that FD is a drying method with high production cost. And the drying time is regarded as one of the main economic indicators of freeze-dried food processing. As shown in Figure 3, HWB-VF-FD cost the shortest FD time and processing time, then

followed by VF-FD and HWB-PF-FD. There was no significant difference between FD time in VF-FD and HWB-PF-FD. But FD time in HWB-PF-FD was significantly longer than that in HWB-VF-FD, which was caused by huge difference in mass loss of apple samples after VF and PF. In other words, the moisture content of samples after VF was much lower than that after PF. And the processing time in HWB-PF-FD was significantly higher than the other two methods. In particular, HWB-VF-FD method reduced 24.42% of the processing time compared with the conventional HWB-PF-FD method, showing an evident economic advantage of the NIFD process. The processing time was the sum of freezing time and FD time. The freezing time of the VF and PF treatment was set as 0.5 h and 3 h, respectively. 2.5 h difference in the freezing time of the two freezing methods probably contributed to the main difference in the processing time. It also can be concluded that HWB pretreatment in the NIFD process (HWB-VF-FD) can shorten FD time and processing time. The similar results had been reported in some available research publications [13, 33, 34]. The reason why blanching pretreatment can accelerate the drying process might be attributed to the fact that high-temperature blanching can relax tissue structure, enhance cell membranes permeability, and reduce water hydrophilic capacity, facilitating faster and more vapor transmission during VF treatment and FD process.

3.3. Rehydration Ratio (RR) and Shrinkage Ratio (SR). The higher values of RR and SR are desired for better quality of FD products. As shown in Figure 4, RR of freeze-dried samples in HWB-VF-FD were obviously higher than that in VF-FD and HWB-PF-FD, showing that the freeze-dried samples with the treatment of HWB and VF were easier to recover nearly to the fresh state by rehydrating. The possible reason was that better porous structure and higher cell membranes permeability were formed in the dried samples in HWB-VF-FD.

There was no significant difference between SR in HWB-VF-FD and HWB-PF-FD. But SR in VF-FD was significantly smaller than the others, which indicated that more shrinkage happened in the tissue of freeze-dried samples. By comparing RR and SR in the two NIFD process (VF-FD and HWB-VF-FD), we can conclude that HWB pretreatment resulted in a significant enhancement on the FD properties of apple slices. The NIFD process of HWB-VF-FD can even acquire a higher RR value and an equivalent SR value in contrast with those in the CFD process of HWB-PF-FD.

3.4. V_C Content. Figure 5 showed the V_C content of freeze-dried samples in the three methods. V_C content in VF-FD was evidently higher than HWB-VF-FD and HWB-PF-FD. It can be concluded that HWB pretreatment was the main factor accounting for the difference in V_C contents, while the freezing method was not. It had been reported that V_C loss was found to occur during the blanching process, which was probably caused by high-temperature thermal degradation, leaching of V_C into the blanch water and involving V_C in the ascorbic acid oxidation [33, 35]. Therefore, HWB pretreatment was not favorable for the V_C retention either in the NIFD process or in the CFD process.

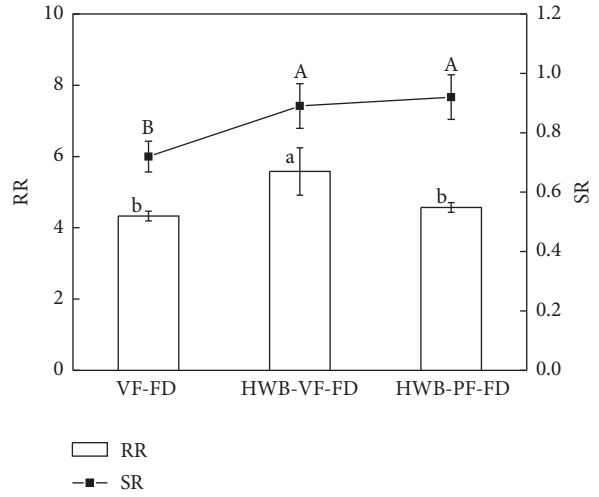


Figure 4: Rehydration ratio and shrinkage ratio of freeze-dried samples in 3 freeze-drying methods. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process. *Note*. Different letters on the same bar or line indicate significant differences at $p = 0.05$ by Tukey's HSD test.

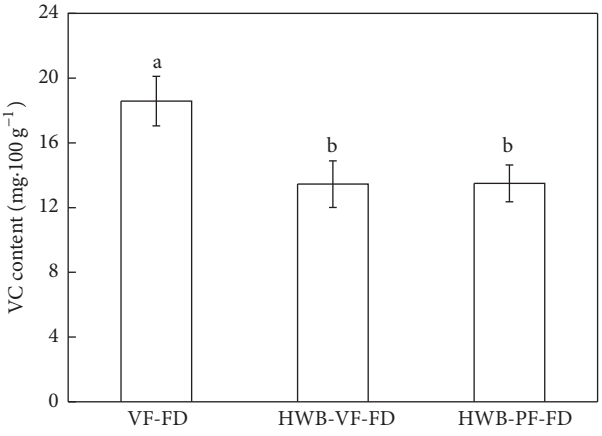


Figure 5: Vitamin C content of freeze-dried samples in 3 freeze-drying methods. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process. *Note*. Different letters on the same bar indicate significant differences at $p = 0.05$ by Tukey's HSD test.

3.5. Color. Color data of freeze-dried and rehydrated samples was shown in Table 1. Among the color parameters, L^*

Table 1: Color difference of freeze-dried and rehydrated samples in 3 freeze-drying methods.

	L^*	a^*	b^*	ΔE
Fresh sample	74.56 ± 0.92	6.72 ± 1.26	21.24 ± 2.20	
Freeze-dried sample				
VF-FD	81.98 ± 2.68^{ab}	7.07 ± 1.89^{a}	29.84 ± 1.92^{a}	11.36 ± 0.76^{a}
HWB-VF-FD	82.89 ± 0.47^{a}	1.83 ± 0.57^{b}	18.07 ± 1.51^{c}	10.16 ± 0.86^{a}
HWB-PF-FD	78.85 ± 2.11^{b}	8.33 ± 0.61^{a}	25.04 ± 1.42^{b}	5.95 ± 0.45^{b}
Rehydrated sample				
VF-FD	56.01 ± 1.37^{b}	14.34 ± 0.31^{a}	30.47 ± 0.75^{a}	22.08 ± 0.68^{a}
HWB-VF-FD	63.41 ± 2.59^{a}	3.41 ± 1.70^{c}	21.00 ± 1.04^{c}	11.63 ± 1.07^{c}
HWB-PF-FD	58.24 ± 2.61^{b}	9.55 ± 1.94^{b}	24.00 ± 2.54^{b}	16.79 ± 1.15^{b}

VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process. *Note*. Different letters on the same columns indicate significant differences at $p = 0.05$ by Tukey's HSD test.

expresses the brightness of sample, a higher value of L^* means brighter color; a^* and b^* with decreasing value indicate red to green and yellow to blue, respectively; ΔE shows the color change compared to the original fresh samples.

In case of freeze-dried samples, HWB-VF-FD presented a brighter appearance than HWB-PF-FD based on both visual evaluation and instrumental testing. Instrumentally, L^* value in HWB-VF-FD was higher than that in HWB-PF-FD. Compared with the fresh samples, the dried samples in HWB-VF-FD became slightly more green and blue, and dried samples in VF-FD and HWB-PF-FD became slightly more red and yellow judging from the values of a^* and b^*. The comprehensive parameter ΔE was calculated with the lowest value in HWB-VF-FD and the highest value in VF-FD.

In case of the rehydrated samples, the L^* value in HWB-VF-FD was significantly higher, and ΔE was significantly lower than the two others. Actually, the rehydrated samples in VF-FD appeared visually to be darker in color than that in HWB-VF-FD. The color of rehydrated samples in HWB-VF-FD was most approximate to the fresh samples. The reason why the color difference occurred was very complicated and might be attributed to the comprehensive difference in porosity, density, and other physical properties, activity of oxidation or residual-enzyme browning, and so on. A bright and white appearance of product in HWB-VF-FD is naturally more popular with customers whether for freeze-dried samples or for rehydrated samples.

3.6. Hardness. Hardness (force at fracture) is viewed as one of the important textural properties for dried food products. Fracture of dried food products is a complex phenomenon that depends largely on the components and the microstructure of food materials [36]. As shown in Figure 6, dried samples in VF-FD were measured with significantly higher hardness values than those in HWB-VF-FD and HWB-PF-FD. The fact that blanching pretreatment can lead to some soluble solid loss in fruits tissue had been verified by some available research literatures [37, 38]. In particular, the leaching of soluble solid during blanching would also reduce rigidity to the cell wall in the tissue and the hardness of dried samples [39, 40]. Additionally, high-temperature blanching

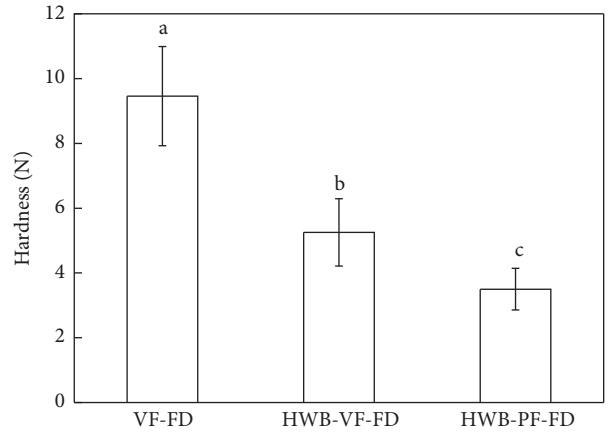


Figure 6: Hardness of freeze-dried samples in 3 freeze-drying methods. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process. *Note*. Different letters on the same bar indicate significant differences at $p = 0.05$ by Tukey's HSD test.

itself can relax and soften the apple tissue and undermine the mechanics properties of porous structure in freeze-dried apple slices [40], which can also contribute to the hardness reduction of dried samples in HWB-VF-FD and HWB-PF-FD. In VF-FD, the most compact and denser porous structure might be formed due to its highest SR of freeze-dried samples (see Figure 4). Thus the highest fracture force in VF-FD (see Figure 6) was reasonably to be expected by considering the microstructure shrinkage as well as the influence of HWB pretreatment.

3.7. TEM Analysis. Representative TEM micrographs of cell wall and membrane in apple slices before and after HWB pretreatment are shown in Figure 7. It was found that HWB pretreatment resulted in evident changes to cell tissue. Before HWB pretreatment, cell wall and membrane were tightly

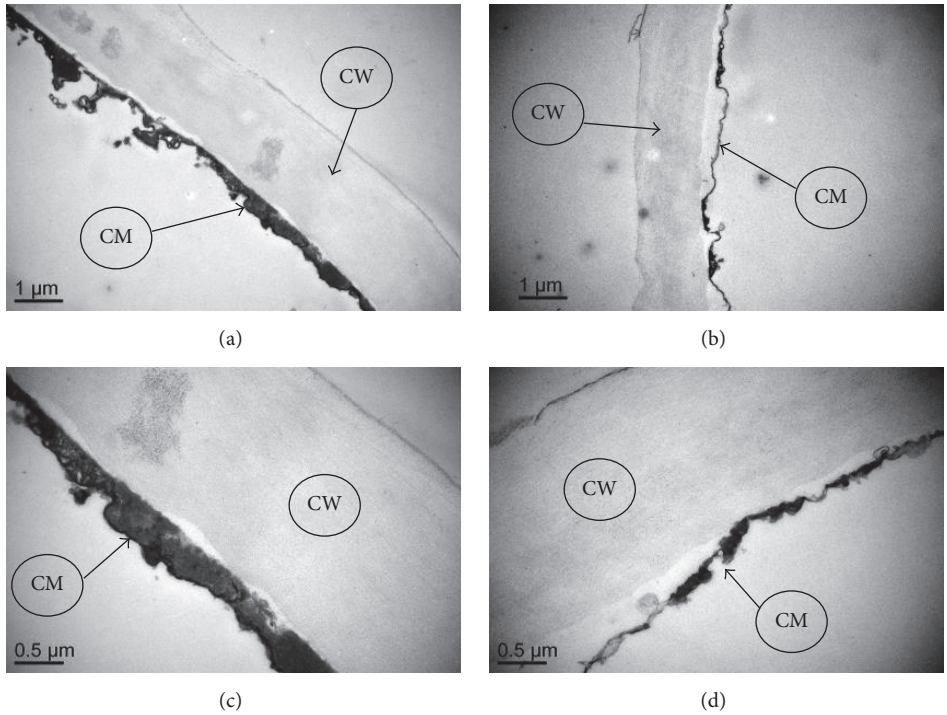


Figure 7: Microphotographs from TEM of cell wall and membrane in apple slices before and after hot-water blanching. (a) Before hot-water blanching at 20000x magnification; (b) after hot-water blanching at 20000x magnification; (c) before hot-water blanching at 40000x magnification; (d) after hot-water blanching at 40000x magnification; CW: cell wall; CM: cell membrane.

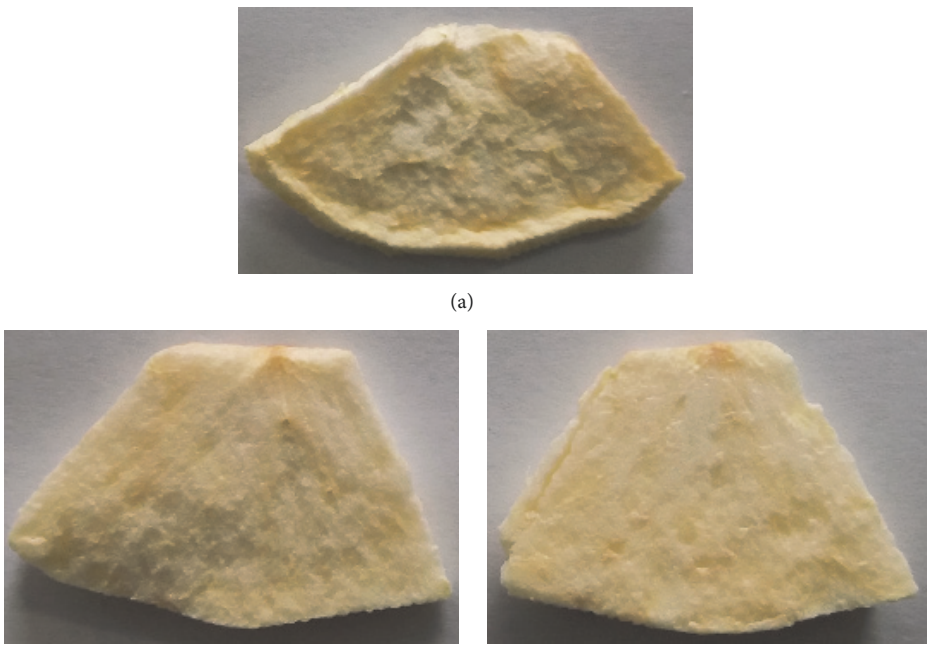
bonded with each other, and the cell membrane was thick, intact, and continuous in shape and dimension. After HWB pretreatment, cell membrane was partly detached from cell wall and became thinner and partially broken, which can contribute to the results of the dehydration and softening in cell tissue, the increase of cell membrane permeability, and the decrease in tissue hardness. In some sense, all the changes in cell tissue caused by HWB pretreatment can account for the higher mass loss, shorter FD time, higher SR and RR, and smaller hardness of the freeze-dried samples in HWB-VF-FD.

3.8. SEM Analysis. Representative apparent photographs and SEM micrographs of freeze-dried samples in the three methods were shown in Figures 8 and 9, respectively. Retaining the original shape of the materials is an essential requirement for FD products. In Figure 8, a significant shrinkage and collapse phenomenon was observed in the freeze-dried samples in VF-FD (Figure 8(a)), whose volume was much smaller than the others, while HWB-VF-FD obtained a flat and full appearance in the samples which was almost the same as that in HWB-PF-FD (Figures 8(a) and 8(b)), showing a good performance of retaining the original shape of fresh materials.

In Figure 9, it can be found that the honeycomb network was formed in the tissues of all the samples. VF-FD samples formed the smallest pores and appeared to be the most compact and dense (Figure 9(a)). HWB-VF-FD samples showed a network size with larger pores (Figure 9(b)). HWB-PF-FD samples appeared to be of a network size with the largest pores (Figure 9(c)). The porosity of freeze-dried samples in the three methods was shown as Figure 10. There was significant difference among the porosity of samples in the three methods. HWB-PF-FD samples had the highest porosity, followed by HWB-VF-FD samples and VF-FD samples. The results of the porosity measurement were consistent with the observation results of SEM images in Figure 9, which identified that the VF-FD samples had a dense structure.

The pores of the tissue in SEM images were associated with the size and location of ice crystals [27]. It is well known that ice crystal size is closely related to the freezing rate. Compared with the PF treatment in HWB-PF-FD, the VF treatment in VF-FD and HWB-VF-FD was performed with a much faster freezing rate, resulting in smaller ice crystals in the frozen tissue and forming smaller pores in the dried tissue after ice sublimation. Besides, microvolume distribution of water in the apple tissue during the VF treatment can directly influence the size of ice crystal and the network pores. About 30% water was removed from apple samples during the VF treatment in VF-FD and HWB-VF-FD, which inevitably reduced the water microvolume distribution in the cell tissue and also formed smaller ice crystals and network pores in contrast to that in HWB-VF-FD.

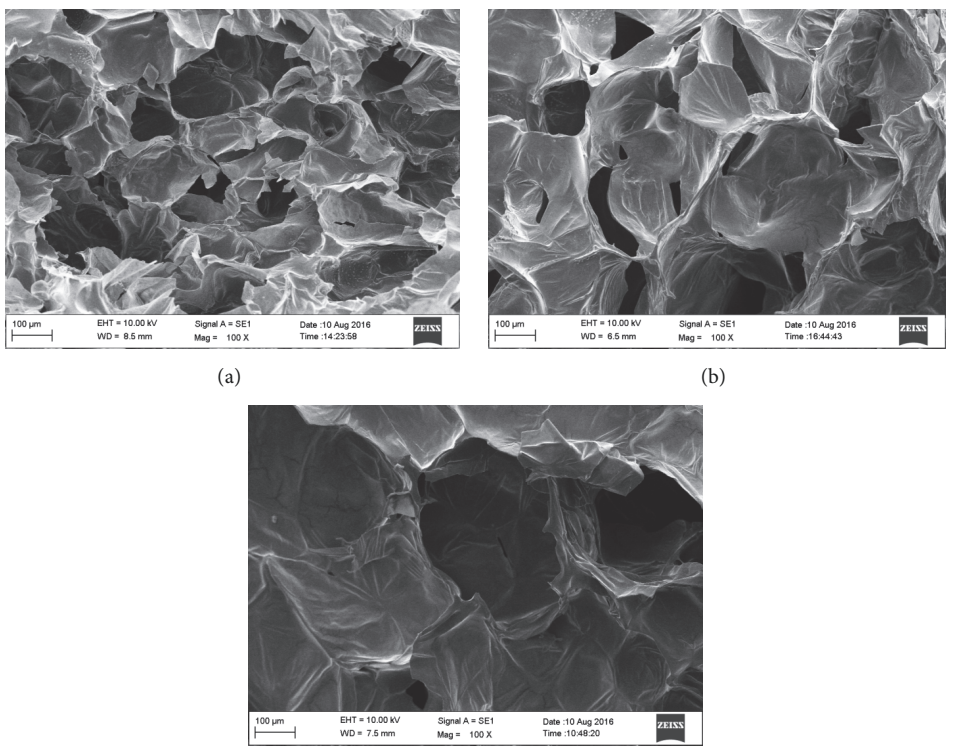
On the other hand, the shape of the honeycomb network was also influenced by HWB pretreatment in the NIFD process. Pores in the samples of VF-FD presented much more shrinkage and collapse than the others, which conform to the results of apparent photographs in Figure 8. Krokida et



(a)

(b) (c)

Figure 8: Apparent photographs of freeze-dried samples with 3 freeze-drying methods. (a) VF-FD; (b) HWB-VF-FD; (c) HWB-PF-FD. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process.



(a) (b)

(c)

Figure 9: Microphotographs (at 100 magnification) from SEM of freeze-dried samples with 3 freeze-drying methods. (a) VF-FD; (b) HWB-VF-FD; (c) HWB-PF-FD. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process.

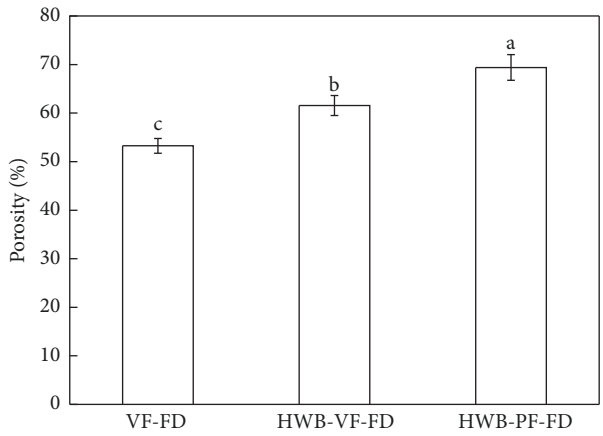


Figure 10: Porosity of freeze-dried samples in 3 freeze-drying methods. VF-FD: apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-VF-FD: apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process; HWB-PF-FD: apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process. *Note*. Different letters on the same bar indicate significant differences at $p = 0.05$ by Tukey's HSD test.

al. showed that serious shrinkage of FD products was often caused by the appearance of the overmuch unfrozen water due to the insufficient freezing treatment of materials and the ice melting in samples during FD process because of unsuitable heating speed [41]. Mass loss during the VF treatment in VF-FD was significantly smaller than HWB-VF-FD because of the HWB pretreatment. It can be inferred that ice melting and collapsing occurred during the FD process because of the incomplete freezing status caused by insufficient mass loss during the VF treatment. VF-FD samples had the lowest SR value and the highest hardness value mainly due to its smallest pores size and porosity, most compact and densest structure of the honeycomb network formed during the VF treatment and the subsequent FD process. So, the NIFD process of VF-FD without HWB cannot be viewed as a successful one especially due to its serious shrinkage and collapse appearance.

4. Conclusions

By comparing the 3 different FD processing methods, we can conclude that HWB pretreatment in the NIFD progress of HWB-VF-FD resulted in lots of changes to the product qualities in contrast to VF-FD, including higher mass loss, shorter FD time, higher SR and RR, lower Vc content, smaller hardness, better apparent colors, and shape in freeze-dried samples, which were desired or acceptable for a successful FD process (except the quality index of V_C content). Compared with the CFD process in HWB-PF-FD, the NIFD process of HWB-VF-FD achieved similar or better product quality and, moreover, showed a considerable time-saving advantage. The observation of apple sample's microstructure was conducted by TEM and SEM, which can account for the above differences in product qualities.

Abbreviations

FD:	Freeze-drying
NIFD:	Novel integrated freeze-drying
CFD:	Conventional freeze-drying
HWB:	Hot-water blanching
VF-FD:	Apple samples without hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process
HWB-VF-FD:	Apple samples with hot-water pretreatment were performed with vacuum freezing treatment and freeze-drying process
HWB-PF-FD:	Apple samples with hot-water pretreatment were performed with plate freezing treatment and freeze-drying process
V_C:	Vitamin C
VF:	Vacuum freezing
PF:	Plate freezing
RR:	Rehydration ratio
SR:	Shrinkage ratio
TEM:	Transmission electron microscopy
SEM:	Scanning electron microscopy.

Additional Points

Practical Application. Vacuum freeze-drying is one of the best methods for food drying. But in practice, conventional freeze-drying process is characterized by many disadvantages including complicated process steps, large space occupation, huge equipment investment, frequent materials transferring, long drying time, and high production cost, which greatly reduced economic competitiveness of FD products. Therefore the novel integrated freeze-drying processing technology was proposed. In this study, the effect of HWB on the drying characteristics and product qualities of apple slices dried with the novel progress. HWB pretreatment in the novel progress resulted in lots of desired or acceptable changes to the drying characteristics and product qualities such as FD time, rehydration ratio, shrinkage ratio, apparent colors, and shape. The NIFD process of HWB-VF-FD was suggested as a promising alternative method to decrease FD time, simplify the steps, and achieve similar product quality of the CFD process.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] C. Ratti, "Hot air and freeze-drying of high-value foods: a review," *Journal of Food Engineering*, vol. 49, no. 4, pp. 311–319, 2001.

[2] F. Shishehgarha, J. Makhlouf, and C. Ratti, "Freeze-drying characteristics of strawberries," *Drying Technology*, vol. 20, no. 1, pp. 131–145, 2002.

[3] L. G. Marques, A. M. Silveira, and J. T. Freire, "Freeze-drying characteristics of tropical fruits," *Drying Technology*, vol. 24, no. 4, pp. 457–463, 2006.

[4] M. Zhang, J. Tang, A. S. Mujumdar, and S. Wang, "Trends in microwave-related drying of fruits and vegetables," *Trends in Food Science & Technology*, vol. 17, no. 10, pp. 524–534, 2006.

[5] H. Jiang, M. Zhang, A. S. Mujumdar, and R.-X. Lim, "Comparison of drying characteristic and uniformity of banana cubes dried by pulse-spouted microwave vacuum drying, freeze drying and microwave freeze drying," *Journal of the Science of Food and Agriculture*, vol. 94, no. 9, pp. 1827–1834, 2014.

[6] S. V. Jangam, "An overview of recent developments and some R&D challenges related to drying of foods," *Drying Technology*, vol. 29, no. 12, pp. 1343–1357, 2011.

[7] S. Litvin, C. H. Mannheim, and J. Miltz, "Dehydration of carrots by a combination of freeze drying, microwave heating and air or vacuum drying," *Journal of Food Engineering*, vol. 36, no. 1-4, pp. 103–111, 1998.

[8] R. Wang, M. Zhang, and A. S. Mujumdar, "Effect of osmotic dehydration on microwave freeze-drying characteristics and quality of potato chips," *Drying Technology*, vol. 28, no. 6, pp. 798–806, 2010.

[9] H. Wang, Z. Hu, K. Tu, F. Wu, T. Zhong, and H. Xie, "Application of vacuum-cooling pretreatment to microwave freeze drying of carrot slices," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 27, no. 7, pp. 358–363, 2011.

[10] H. O. Wang, S. J. Chen, and W. Zhang, "An integrated equipment of radiation vacuum freeze-drying and its method," in *Chinese Patent No. 201510017464.8 , Beijing: State Intellectual Property Office of the P.R.C*, in Chinese, C, 2015.

[11] A. A. Adedeji, T. K. Gachovska, M. O. Ngadi, and G. S. V. Raghavan, "Effect of pretreatments on drying characteristics of okra," *Drying Technology*, vol. 26, no. 10, pp. 1251–1256, 2008.

[12] C. Severini, A. Baiano, T. De Pilli, R. Romaniello, and A. Derossi, "Prevention of enzymatic browning in sliced potatoes by blanching in boiling saline solutions," *LWT- Food Science and Technology*, vol. 36, no. 7, pp. 657–665, 2003.

[13] Y. Wang, M. Zhang, A. S. Mujumdar, K. J. Mothibe, and S. M. Roknul Azam, "Effect of blanching on microwave freeze drying of stem lettuce cubes in a circular conduit drying chamber," *Journal of Food Engineering*, vol. 113, no. 2, pp. 177–185, 2012.

[14] M. González-Fésler, D. Salvatori, P. Gómez, and S. M. Alzamora, "Convective air drying of apples as affected by blanching and calcium impregnation," *Journal of Food Engineering*, vol. 87, no. 3, pp. 323–332, 2008.

[15] N. Sanjuán, G. Clemente, J. Bon, and A. Mulet, "The effect of blanching on the quality of dehydrated broccoli florets," *European Food Research and Technology*, vol. 213, no. 6, pp. 474–479, 2001.

[16] J. I. Maté, M. Zwietering, and K. Van't Riet, "The effect of blanching on the mechanical and rehydration properties of dried potato slices," *European Food Research and Technology*, vol. 209, no. 5, pp. 343–347, 1999.

[17] C. Severini, A. Baiano, T. De Pilli, B. F. Carbone, and A. Derossi, "Combined treatments of blanching and dehydration: study on potato cubes," *Journal of Food Engineering*, vol. 68, no. 3, pp. 289–296, 2005.

[18] S. Prakash, S. K. Jha, and N. Datta, "Performance evaluation of blanched carrots dried by three different driers," *Journal of Food Engineering*, vol. 62, no. 3, pp. 305–313, 2004.

[19] K. O. Falade and O. J. Solademi, "Modelling of air drying of fresh and blanched sweet potato slices," *International Journal of Food Science & Technology*, vol. 45, no. 2, pp. 278–288, 2010.

[20] T. Beveridge and S. E. Weintraub, "Effect of blanching pretreatment on color and texture of apple slices at various water activities," *Food Research International*, vol. 28, no. 1, pp. 83–86, 1995.

[21] I. Doymaz, "Effect of citric acid and blanching pre-treatments on drying and rehydration of Amasya red apples," *Food and Bioproducts Processing*, vol. 88, no. 2-3, pp. 124–132, 2010.

[22] R. Thuwapanichayanan, S. Prachayawarakorn, and S. Soponronnarit, "Drying characteristics and quality of banana foam mat," *Journal of Food Engineering*, vol. 86, no. 4, pp. 573–583, 2008.

[23] AOAC, *Official Methods of Analysis*, Association of Official Analytical Chemists, Washington, Wash, USA, 14th edition, 1984.

[24] N. Jiang, C. Liu, D. Li, and Y. Zhou, "Effect of blanching on the dielectric properties and microwave vacuum drying behavior of Agaricus bisporus slices," *Innovative Food Science and Emerging Technologies*, vol. 30, pp. 89–97, 2015.

[25] K. McDonald, D.-W. Sun, and T. Kenny, "Comparison of the quality of cooked beef products cooled by vacuum cooling and by conventional cooling," *LWT- Food Science and Technology*, vol. 33, no. 1, pp. 21–29, 2000.

[26] D. Sun and L. Zheng, "Vacuum cooling technology for the agri-food industry: past, present and future," *Journal of Food Engineering*, vol. 77, no. 2, pp. 203–214, 2006.

[27] Q. T. Pham, "Modelling heat and mass transfer in frozen foods: a review," *International Journal of Refrigeration*, vol. 29, no. 6, pp. 876–888, 2006.

[28] L. A. Campañone, V. O. Salvadori, and R. H. Mascheroni, "Weight loss during freezing and storage of unpackaged foods," *Journal of Food Engineering*, vol. 47, no. 2, pp. 69–79, 2001.

[29] S. M. Alzamora, M. A. Castro, S. L. Vidales et al., "The role of tissue microstructure in the textural characteristics of minimally processed fruits," *Minimally Processed Fruits and Vegetables*, pp. 153–171, 2000.

[30] A. Nieto, D. Salvatori, M. A. Castro, and S. M. Alzamora, "Air drying behavior of apples as affected by blanching and glucose impregnation," *Journal of Food Engineering*, vol. 36, no. 1-4, pp. 63–79, 1998.

[31] A. Nieto, M. A. Castro, and S. M. Alzamora, "Kinetics of moisture transfer during air drying of blanched and/or osmotically dehydrated mango," *Journal of Food Engineering*, vol. 50, no. 3, pp. 175–185, 2001.

[32] Q. Cui, Y. Guo, and Z. Cheng, "Measurement of the eutectic point and melting point of the freeze-dried materials based on electric resistance method," *Transactions of the Chinese Society of Agricultural Machinery*, vol. 39, no. 5, pp. 65–69, 2008.

[33] T. M. Lin, T. D. Durance, and C. H. Scaman, "Characterization of vacuum microwave, air and freeze dried carrot slices," *Food Research International*, vol. 31, no. 2, pp. 111–117, 1998.

[34] R. Moreira, A. Figueiredo, and A. Sereno, "Shrinkage of apple disks during drying by warm air convection and freeze drying," *Drying Technology*, vol. 18, no. 1-2, pp. 279–294, 2000.

[35] Y. Wu, J. H. Qi, M. Q. Huang et al., "Analysis of substrates and products of non-enzymatic browning in Chinese chestnut," *Chinese Agricultural Science Bulletin*, vol. 28, no. 30, pp. 267–271, 2012 (Chinese).

[36] N. C. Acevedo, V. Briones, P. Buera, and J. M. Aguilera, "Microstructure affects the rate of chemical, physical and color changes during storage of dried apple discs," *Journal of Food Engineering*, vol. 85, no. 2, pp. 222–231, 2008.

[37] S. Mizrahi, "Leaching of soluble solids during blanching of vegetables by ohmic heating," *Journal of Food Engineering*, vol. 29, no. 2, pp. 153–166, 1996.

[38] C. Arroqui, T. R. Rumsey, A. Lopez, and P. Virseda, "Losses by diffusion of ascorbic acid during recycled water blanching of potato tissue," *Journal of Food Engineering*, vol. 52, no. 1, pp. 25–30, 2002.

[39] G. Romano, M. Nagle, D. Argyropoulos, and J. Müller, "Laser light backscattering to monitor moisture content, soluble solid content and hardness of apple tissue during drying," *Journal of Food Engineering*, vol. 104, no. 4, pp. 657–662, 2011.

[40] P. P. Lewicki, "Effect of pre-drying treatment, drying and rehydration on plant tissue properties: a review," *International Journal of Food Properties*, vol. 1, no. 1, pp. 1–22, 1998.

[41] M. K. Krokida, V. T. Karathanos, and Z. B. Maroulis, "Effect of freeze-drying conditions on shrinkage and porosity of dehydrated agricultural products," *Journal of Food Engineering*, vol. 35, no. 4, pp. 369–380, 1998.