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Effects of Different Drying Methods on Drying Characteristics and Quality of Small White Apricot (*Prunus armeniaca* L.)

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Abstract: This study examined the effects of hot air drying (HAD), infrared radiation drying (IRD), microwave vacuum drying (MVD), freeze drying (FD), and freeze drying combined with microwave vacuum drying (FD-MVD) on the drying kinetics, color, rehydration ratio, titratable acidity, and vitamin C content of small white apricots (*Prunus armeniaca* L.). Results showed drying times of 12.5 h (IRD), 14.1 h (FD), 16 h (HAD), 0.53 h (MVD), and 6.15 h (FD-MVD). FD-MVD significantly outperformed MVD, HAD, and IRD in color, vitamin C, titratable acidity, and rehydration, though was slightly inferior to FD. Microstructural analysis revealed that FD-MVD preserved the most uniform pore structure, better maintaining apricots' original appearance. In contrast, IRD and HAD caused severe surface shriveling, compromising quality. In conclusion, FD-MVD emerges as a promising drying method to enhance apricot quality and market competitiveness in food processing.

Keywords: dried small white apricot; drying methods; physicochemical property; microstructure; nutritional value

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1. Introduction

In China, apricot cultivation is widely distributed throughout the country, while the main place of origin is Xinjiang, with more than 120 varieties, occupying an important position in China's forestry and fruit industry [1]. The small white apricot (*Prunus armeniaca* L.), belonging to the Rosaceae family, is extensively cultivated in the Kuche and Luntai counties of Xinjiang, China [2]. The fruit exhibits an ovoid shape, possesses a light yellow surface devoid of tomentum, and contains yellow-white flesh that is both sweet and sour, imparting a distinctive aroma and flavor [3]. It contains remarkable nutritional value, being high in carotenoids, vitamin C, carbohydrates, iron, potassium, minerals, and other essential elements [4,5]. Because of its excellent nutritional content and sweet-sour flavor, the small white apricot is popular and often consumed as a fresh food.

Apricots are classified as respiratory climacteric fruits, undergoing a rapid softening process post-harvest during periods of heightened respiration [6]. The harvesting of apricots predominantly occurs during summer, and their fruit water content can reach 80% or higher [7]. Consequently, apricot fruits are prone to quality issues such as browning and rotting soon after harvest, resulting in a significantly reduced shelf life [8]. Furthermore, as storage duration increases, there is a decrease in the sugar content, organic acid content, and flavor of apricot fruits [9]. This significant reduction greatly impacts the quality and nutritional value of apricots as fresh food. In the Xinjiang region, for example, the vast terrain frequently causes mechanical damage, crushing, and bumping of fresh fruits during harvesting and transportation. Such damages present substantial obstacles to marketing fresh apricots, leading to an annual loss of around 11% [10]. Therefore, addressing the reduction in apricot fruit waste has become an urgent priority. The dichotomy between high yields and limited shelf life poses significant constraints on the growth of the apricot industry in Xinjiang.

Drying serves as an effective post-harvest processing strategy that inhibits microbial growth by decreasing moisture content. Consequently, this method preserves the nutrient composition of the material, enhances storage and transportation convenience, and significantly minimizes losses [11]. Nonetheless, the advancement of apricot fruit drying technology has been sluggish, currently relying primarily on natural and hot air drying methods [12]. Consequently, the processing level of small white dried apricot products remains inadequate, characterized by limited product diversity, low technological sophistication, and an inability to meet the requirements of industrialized production. At present, the methods applied in the drying of fruits and vegetables are natural drying (ND), hot air drying (HAD), microwave vacuum drying (MVD), freeze drying (FD), etc.; freeze drying (FD) is a relatively effective way to maintain the original nutrients of food, but the drying time is long and energy consumption is high [13]. Infrared radiation drying (IRD) is a method in which the infrared radiation can directly pass through the surface of the material, from the inside to the outside to start the heating characteristics, but there are problems with it, such as low drying efficiency and uneven heat distribution [14]. Hot air drying is a low-cost drying method, but the material is exposed to hot air for a long time, making the drying quality poor [15]. Microwave vacuum drying has the characteristics of rapid drying, but the heating is not uniform, which easily causes the material to be scorched [16]. To date, there has been a noteworthy lack of research on the effects of different drying procedures on the drying kinetics, physicochemical qualities, and microstructural changes in little white apricots.

Hence, the aims of this study were twofold: (i) to explore the impact of various drying techniques, including hot air drying, infrared radiation drying, freeze drying, microwave vacuum drying, and freeze drying combined with microwave vacuum drying (FD-MVD), on the drying attributes and quality of small white apricots; (ii) to utilize scanning electron microscopy (SEM) to microscopically investigate how different drying methods affect the microstructure of small white apricots.

2. Materials and Methods

2.1. Materials

Eight or nine fresh ripe small white apricots with yellowish or all-yellow surfaces were hand-picked in March 2023 in Kuche city to ensure similar size, no mechanical damage, and no pests or diseases. They were transported by car to the agricultural products drying laboratory of Shihezi University using ice packs at low temperature for about 12 h. They were then stored in a 4 °C refrigerator and drying experiments started immediately. Ten randomly sampled small white apricot fruits were measured for average size with digital vernier calipers and for average weight with an electronic balance. Moisture content of small white apricot fruits was determined by drying them in a hot air drying oven at 105 °C until constant weight [17]. The average weight of a single fruit was 15.86 ± 1.25 g, the longitudinal diameter of the fruit was 28.25 ± 0.16 mm, the transverse diameter of the fruit was 27.68 ± 0.48 mm, and the lateral diameter of the fruit was 26.93 ± 0.47 mm. The initial wet basis moisture content of fresh small white apricot fruits was 81.82 ± 0.75%. Before the start of each set of drying tests, 100 ± 1 g of small white apricots were weighed, and drying was stopped after the moisture content of the wet base reached a state of 10%. Before the beginning of the experiment, small white apricots were cut in half and cored.

2.2. Instrumentation and Equipment

We adopted a DHG-9070A electric constant temperature blast drying oven for the determination of moisture content and the hot air drying test (Shanghai Yihuan Scientific Instrument Co., Ltd., Shanghai, China, power 1550 W); infrared radiation drying using short- and medium-wave infrared oven (Shengtaike Co., Ltd., Taizhou, China, power 0~2 kW); vacuum freeze drying by vacuum freeze dryer (Germany Christ vacuum freeze dryer Co., Ltd.); RWBZ-08S Microwave vacuum drying oven for microwave vacuum drying (Nanjing Suenrui Drying Equipment Co., Ltd., Nanjing, China, power 800 W); KQ-5200DE CNC ultrasonic cleaner for ultrasonic operation during quality analysis (Kunshan Ultrasonic Instrument Co., Ltd., Kunshan, China, power 800 W); CR-400 colorimeter for color measurement (Konica Minolta, Japan); SU8010 Field Emission Scanning Electron Microscope for Surface Microstructure Observation (Hitachi, Ltd.); FW100 High-speed universal pulverizer for the preparation of samples into powders (Tianjin Taiste Instrument Co., Ltd., Tianjin, China); and an Electronic Balance for determining the weight of samples and reagents (Shanghai Zhuojing Ltd., Shanghai, China, accuracy 0.0001 g).

2.3. Test Method

2.3.1. Drying Experiment

Before starting the test, turn on the dryer and set the relevant parameters to run for 30 min to obtain a stable state. The specific parameter settings for different drying methods are shown in Table 1 below. Moisture content during drying is achieved by rapid removal from the drying box at regular intervals and weighing. In this, the hot air drying is performed by taking out the samples every half an hour for weighing and putting them back. Among them, hot air drying and infrared radiation drying were each performed for 30 min by removing the samples, weighing them, and putting them back. The microwave vacuum drying interval was 2 min. Freeze drying was performed for 30 min. The combined drying conditions were 30 min for the freezing phase and 2 min for the microwave vacuum phase.

Table 1. Drying method and dryer parameter setting.

Drying Methods	Parameter Setting
HAD	Temperature 50 °C, air flow velocity 2.2 m/s
IRD	Infrared radiation temperature 50 °C, heating power 6.75 W/g
FD	Cold trap temperature −40 °C, heating plate temperature 60 °C, drying chamber pressure 12 Pa
MVD	Microwave temperature 50 °C, heating power 5 W/g, drying chamber pressure 1325 Pa
FD-MVD	Cold trap temperature −40 °C, microwave temperature 42 °C, power 4 W/g, conversion point wet base moisture content of 61%, MVD drying chamber pressure 1325 Pa, FD drying chamber pressure 12 Pa

2.3.2. Drying Kinetics

The dry basis moisture content, moisture ratio, and drying rate of small white apricots under different drying methods were mainly calculated using the following formula:

(1) Dry basis moisture content [18]

$$M_t = \frac{G_t - G_d}{G_d} \tag{1}$$

where M_t is the dry basis moisture content at any drying moment, %; G_t is the mass of small white apricots at any drying moment, g; G_d is the mass of small white apricots dry matter, g.

(2) Moisture ratio (MR)

The dry moisture ratio of small white apricots was calculated according to Equation (2) [19].

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{2}$$

Since the equilibrium moisture content of small white apricots M_e is much less than M_0 and M_t, and can be approximated as 0, Equation (2) can be simplified as follows [20]:

$$MR = \frac{M_t}{M_0} \tag{3}$$

(3) Drying rate (DR)

Calculate the drying rate of small white apricots under different drying conditions according to Equation (4) [21].

$$DR = \frac{M_{t1} - M_{t2}}{t_2 - t_1} \tag{4}$$

where DR denotes the drying rate, g/(g·h); t_1 and t_2 represent different moments in the drying process of small white apricots, respectively; M_{t1} and M_{t2} denote the moisture content at the moments of t_1 and t_2, respectively, during the drying process of small white apricots, expressed on a dry basis, g/g.

2.3.3. Rehydration Ratio

The method of Geng et al. for determining the rehydration ratio of sea buckthorn was adopted and improved for determining the rehydration ratio of small white apricots [22]. For each group, 5 g of dried sample was weighed and placed in a 5 mL beaker, transferred to a water bath at 80 °C for immersion, and weighed at 30 min intervals; each time it was taken out, the surface moisture of the sample was drained with filter paper and weighed until the sample stopped absorbing water and the weight remained the same when it was stopped. The Rehydration Ratio (RR) was calculated as follows.

$$RR = \frac{m_r}{m_d} \tag{5}$$

where m_d is the weight of the sample before rehydration, g; m_r is the weight of the sample after rehydration, g.

2.3.4. Color

A CM-700d spectrophotometer was used to determine the color of small white apricots during the drying process, and the values of L^*, a^*, and b^* were recorded. To ensure accuracy, the determination of each sample was repeated six times, and the average value was taken. Among them, the value L^* indicated the brightness of small white apricots, the value a^* indicated the red-green value of small white apricots, the value b^* indicated the yellow-blue value of small white apricots, and the value ΔE indicated the color difference between dried small white apricots and fresh small white apricots. The color parameters of fresh small white apricots: L_0 = 60.02, a_0 = 6.81, b_0 = 46.77. The formula for ΔE is shown in Equation (6) below.

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \tag{6}$$

2.3.5. Vitamin C

For the preparation of the standard solution, 100.00 mg of L(+)-ascorbic acid standard was accurately weighed and dissolved in 2% oxalic acid solution. The resulting solution was then transferred to a 100 mL brown volumetric flask and diluted to the mark with the same solvent. The flask was thoroughly shaken to ensure homogeneity, resulting in a standard solution with a concentration of 1.0 mg/mL of L(+)-ascorbic acid. This standard solution was then kept in standby condition for further use. Extraction of vitamin C from small white apricots: The dried small white apricots were first processed by removing the cores and grinding them into a fine powder using a pulverizer. A precise 1.00 g sample of the apricot powder was then weighed and combined with 2% oxalic acid solution at a material-to-liquid ratio of 1:20 (g/mL). Extraction was performed under an ice bath with the aid of 200 W ultrasonic waves for 30 min. Following extraction, the mixture was centrifuged at 8000 r/min for 10 min to separate the supernatant, which was collected for further analysis.

In order to avoid the influence of the color of the sample solution, the vitamin C content in small white apricots was determined by 2,6-dichloroindophenol reverse titration [23], and the content was calculated according to Equation (7) (the vitamin C content in small white apricots was expressed on a dry basis).

$$A = \frac{c \times V_1 \times V_2}{V_3 \times W} \tag{7}$$

where A is vitamin C content, mg/100 g; c is the concentration of L(+)-ascorbic acid standard solution, mg/mL; V_1 is the volume of ascorbic acid standard solution consumed for titration of 5 mL of 2,6-dichloroindophenol sodium salt, mL; V_2 is the total volume of the sample solution; and V_3 is the volume of the sample solution consumed for the titration of 5 mL of 2,6-dichloroindophenol sodium salt, mL; W is the dry weight of the sample taken, g.

2.3.6. Titratable Acids

Measurement of titratable acid content in small white apricots was performed by acid–base titration [24]. Using an electronic balance, 0.3 g of small white apricot powder was accurately weighed and placed in a mortar and pestle, 6 mL of distilled water was added, and the powder was fully ground and mixed. An appropriate amount of milled sample solution was added to a 50 mL centrifuge tube and centrifuged in a centrifuge for 10 min, with the centrifugation condition set at 4000 r/min. Add 1 mL of centrifugal supernatant with 20 mL of distilled water in a conical flask, followed by two drops of phenolphthalein indicator, and shake until evenly mixed. Titrate using 0.1 mol/L NaOH solution until slight red color does not fade for 30 s. Record the volume consumed by consuming 0.1 mol/L NaOH solution. The titratable acid content was calculated as shown in Equation (8) below.

$$Titratable\ acids(\%) = \frac{V \times C \times (V_1 - V_0) \times F}{V_s \times W} \times 100\% \tag{8}$$

where V is the total volume of sample extract, mL; V_s is the volume of filtrate taken during titration, mL; C is the titratable molar concentration of sodium hydroxide, mol/mL; V_1 is the number of milliliters of sodium hydroxide solution consumed to titrate the filtrate, mL; V_0 is the number of milliliters of sodium hydroxide solution consumed in the titration of distilled water, mL; W is the sample mass, g; F is the conversion factor, g/mmol.

2.3.7. Microstructure

Representative samples were selected from the dried finished products and processed using liquid nitrogen flash-freezing technology to rapidly freeze the specimens. Subsequently, these frozen samples were quickly fractured to create a brittle cross-section, which was then utilized for microscopic observation. Following this, the selected samples were affixed to carbon-conductive adhesive-coated sample trays. The surfaces of the samples were then sputter-coated with gold to enhance conductivity. The prepared samples were subsequently scanned using an electron microscope, allowing for the examination of the tissue structure of different sections within each sample from multiple orientations. The resulting images with distinctive features were retained for further analysis in the subsequent step.

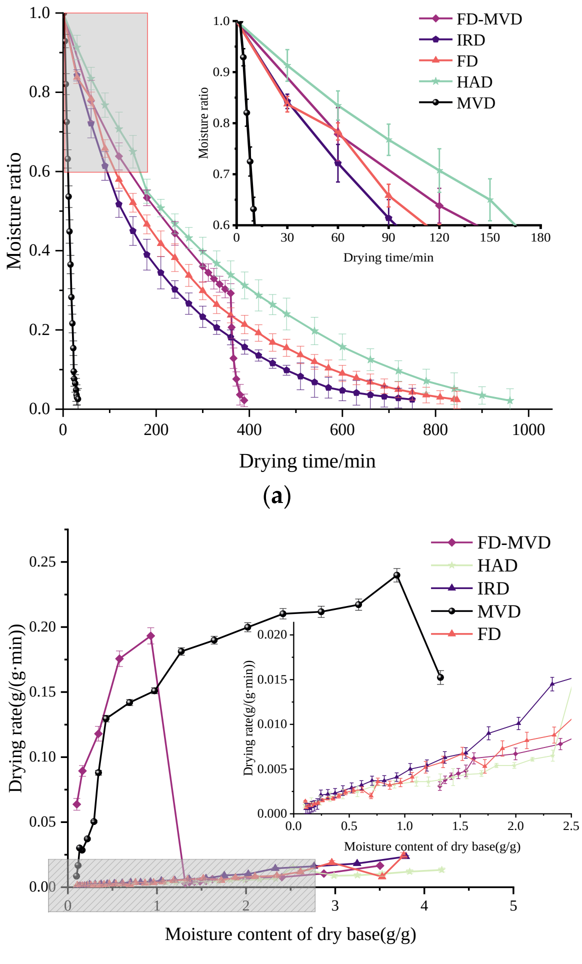
2.4. Data Analysis

The collected data were subjected to statistical analysis using SPSS 27.0 software. All mean values were calculated, and the significance of the observed differences was assessed using a one-way analysis of variance (ANOVA) at a significance level of 0.05. Additionally, Origin 2021 software was applied for data visualization and plotting [25]. The test was repeated three times and the average of the results was taken for analysis.

3. Results and Discussion

3.1. Drying Characteristics of Small White Apricot

The drying rate reflects the speed of drying of the material in the drying process. Figure 1a,b represent the effects of different drying methods of small white apricots on drying kinetics. The drying kinetics of small white apricots varied significantly among different drying methods. The drying times of IRD, FD, HAD, MVD, and FD-MVD were 12.5, 14.1, 16, 0.53, and 6.15 h, respectively. The shortest drying time was observed in MVD, which was also found by Li et al. [26] in their study of the effect of drying mode on the drying kinetics and volatile components of longan pulp. This may be due to the fact that MVD drying heat is generated directly from the inside of the material, with small energy loss and high conversion efficiency. HAD takes the longest time, and the drying rate decreases with the extension of time. This is probably due to the low drying temperature and the fast diffusion of moisture on the surface; the internal moisture cannot diffuse to the surface in time, making the surface of the material produce wrinkling, which is not conducive to the diffusion of moisture. This phenomenon was also found in the study of the effects of different drying methods on the drying characteristics and quality of *Dictyophora rubrovolvata* by Dai et al. [27]. The drying time of IRD was 11.3% and 21.9% shorter than that of FD and HAD, respectively, which could be attributed to the fact that infrared radiation can directly pass through the surface of the material to the interior, which contributes to the acceleration of the drying rate [28].



(**a**)

(**b**)

Figure 1. Drying characteristic curve of small white apricot berries: (**a**) moisture ratio—drying time curve; (**b**) dry base moisture content—drying rate curve.

3.2. Drying Quality of Small White Apricot

3.2.1. Comparison of the Color and Luster of Small White Apricots with Different Drying Methods

The assessment of color and luster constitutes a pivotal quality indicator for dried apricot products, significantly influencing their overall commodity value. In the case of dried small white apricot products, particular emphasis is placed on their brightness and yellow hue. Therefore, the analysis of color differences primarily focuses on the L^* (lightness) and b^* (yellow-blue) values. The variations in color under diverse drying methodologies are presented in Table 2. It is evident that the L^* values of the small white apricots decreased following the drying treatment, indicating a darker brightness in the dried products compared to the fresh samples. Among the different drying methods, the L^* values of FD-MVD and FD samples were comparable and significantly higher than the rest of the drying methods. Conversely, the IRD and HAD methods resulted in the lowest L^* values, suggesting that combined drying approaches are more effective in preserving the lightness of small white apricots. Due to the elevated drying temperatures and prolonged drying durations associated with IRD and HAD, the material underwent browning processes induced by Maillard reactions and oxidative reactions, resulting in a notable decrease in the L^* value, as reported by Sheng et al. [29]. Notably, the longer duration of the HAD process compared to IRD led to a more pronounced decrease in the L^* value. Microwave vacuum drying exhibits heating inhomogeneity, potentially leading to localized overheating of the material, thereby inducing coking and resulting in a slight black discoloration on the surface of the dried product [30]. Comparing the red-green value a^* and blue-yellow value b^*, microwave vacuum drying has the largest a^* value of 11.62 ± 0.68. This may be due to the excessive microwave power, which produces local overheating, and then leads to the uneven heating that makes the a^* value increase. The b^* value of vacuum freeze drying was closest to that of fresh samples, followed by FD-MVD. Zhang et al. [31] also found that the vacuum condition could better maintain the color and luster when studying the effect of drying conditions on the drying characteristics and physicochemical properties of broccoli. This was due to the fact that the vacuum environment inhibited enzymatic browning, which made the b^* and L^* values closer to those of fresh samples.

Table 2. The color parameters of small white apricots under different drying methods.

Drying Methods		L^*	a^*	b^*	ΔE
Fresh		63.19 ± 1.10^{a}	7.23 ± 0.35^{e}	48.79 ± 0.23^{a}	-
HAD		37.51 ± 1.68^{e}	8.26 ± 0.96^{c}	19.67 ± 0.69^{f}	38.84 ± 0.49^{a}
MVD		46.58 ± 0.95^{c}	11.62 ± 0.68^{a}	33.45 ± 0.56^{d}	23.03 ± 0.14^{c}
IRD		40.06 ± 1.78^{d}	6.60 ± 0.49^{f}	25.33 ± 1.25^{e}	32.95 ± 2.15^{b}
FD		60.37 ± 1.18^{b}	10.81 ± 0.16^{b}	42.53 ± 0.78^{b}	7.74 ± 0.06^{e}
FD-MVD		60.42 ± 2.31^{b}	7.70 ± 0.62^{d}	37.76 ± 1.75^{c}	11.38 ± 1.68^{d}

Note: Different lowercase letters in the same column indicate significant differences ($p < 0.05$).

The ΔE FD and FD-MVD samples, among the five drying methodologies applied, exhibited a high degree of similarity and remained minimal in comparison to fresh samples. This similarity was attributed to the low-temperature, low-pressure, and low-oxygen content environment utilized during the drying processes of FD and FD-MVD, which effectively suppressed the browning reaction and consequently minimized the ΔE of the dried samples. In contrast, the IRD and HAD drying processes led to more significant color variations in the samples. This was attributed to the prolonged exposure of the materials to hot air, moisture, and enzymes, resulting in enzymatic browning caused by oxidation and higher temperatures. Additionally, non-enzymatic reactions and heat-induced decomposition of pigments further contributed to the observed color changes [32]. Taken together, these results show that the drying method using low temperature and a vacuum can better maintain the color of small white apricots.

3.2.2. Rehydration

Rehydration provides an assessment of the quality of dried products and reveals the strengths and weaknesses of various drying methods. It reflects the extent of structural alterations and cellular damage inflicted by the drying process. A higher rehydration ratio signifies minimal structural changes and less cellular disruption due to drying, indicating a greater ability to revert to the original fresh fruit state. Consequently, a higher rehydration ratio corresponds to a more effective drying process [33]. The rehydration behavior of small white apricots under various drying conditions is illustrated in Figure 2. After soaking for 2 h, notable differences emerged in the rehydration capacity of the dried apricots. Specifically, the rehydration ratios for the products processed using the HAD, IRD, FD, MVD, and FD-MVD methods were 2.91, 3.15, 4.32, 3.63, and 3.87, respectively. It is worth noting that the rehydration ratios for the FD and FD-MVD groups were significantly higher compared to the other three drying methods. The higher rehydration ratios observed in the FD and FD-MVD groups are attributable to the freeze drying process, which involves the direct sublimation of water. During this process, the formation of ice crystals disrupts the cell walls, resulting in the creation of a porous, spongy tissue structure that facilitates rapid rehydration. In contrast, the HAD method demonstrates the lowest rehydration ratio. This is primarily due to the slow migration of moisture from the interior to the exterior of the material during the drying process, which is accompanied by solute migration. This migration results in a decrease in internal osmotic pressure. Additionally, heat transfer from the exterior to the interior of the material causes surface overheating and hardening, thereby impeding the rate and efficiency of rehydration. The lower rehydration rate after HAD drying compared to MVD and FD was also found by Gaware et al. in their study of the effect of different drying methods on the rehydration rate of tomatoes [34]. Furthermore, the severe deformation and contraction of the tissue structure of HAD samples is also a major reason for limiting the rehydration rate, leading to a reduction in rehydration performance. IRD is similar to HAD and has better rehydration than HAD because of the relatively short drying time. Due to the swelling effect of MVD, the internal pores of small white apricot cells increased and enlarged, and the tissue was loosened, which facilitated the secondary entry of water and increased the rehydration property. This phenomenon was also found by Kemerli-Kalbaran while studying the effect of microwave and freeze drying methods on the drying kinetics, physicochemical properties, and antioxidant activity of pine nuts [35]. In summary, the rehydration quality of dried small white apricot products in the FD and FD-MVD groups was the best.

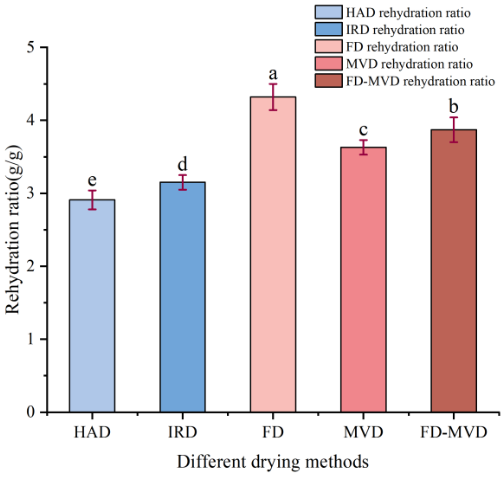


Figure 2. Rehydration ratio of small white apricots under different drying methods. Different letters in the figure reveal significant differences ($p < 0.05$).

3.2.3. Vitamin C

Vitamin C, a water-soluble essential nutrient, exhibits a pronounced instability due to its sensitivity to various environmental factors, particularly light, temperature, and oxygen, thereby rendering it susceptible to rapid decomposition [36]. Based on Figure 3, it is evident that the vitamin C content in dried small white apricot products obtained from the FD and FD-MVD groups is notably higher compared to the other three groups. This significant difference can primarily be attributed to the fact that the MVD, HAD, and IRD methods involve heat-drying throughout the entire process. The prolonged exposure to heat during the drying process leads to enzymatic oxidation and thermal degradation of vitamin C, resulting in lower vitamin C content in these groups [37]. The vitamin C content of small white apricots was higher under MVD compared to HAD and IRD. It may be due to the short drying time and short contact time of vitamin C with hot air, which resulted in less loss and higher content. It can be seen that the FD and FD-MVD techniques can better retain the ascorbic acid content, which is due to the low-temperature and low-oxygen environment that is more favorable for vitamin C retention. This is consistent with the conclusions of Yuan et al. [17], who studied the relationship between the change in vacuum level and vitamin C retention in the microwave freeze drying of blueberries.

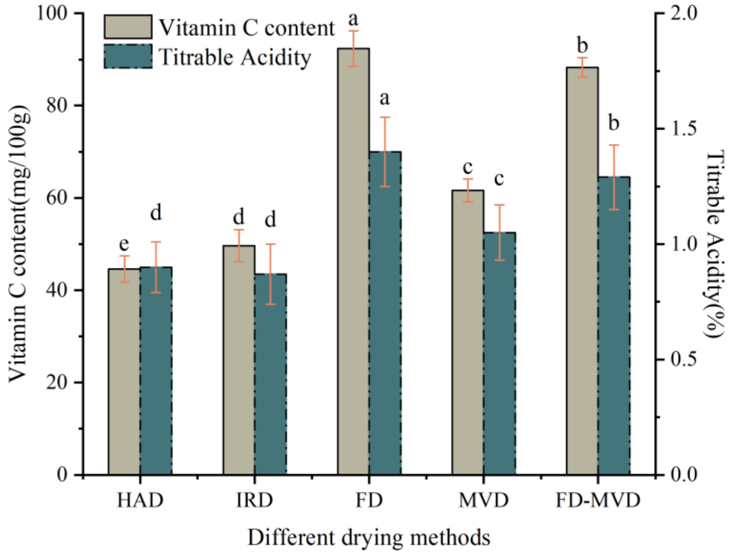


Figure 3. Vitamin C and titratable acid contents of small white apricots under different drying methods. Different letters in the figure reveal significant differences ($p < 0.05$).

3.2.4. Titratable Acid

Titratable acid is one of the important constitutive traits of fruit quality and has an important influence on the taste, flavor, and processing properties of fruits and vegetables [38]. As observed in Figure 3, the titratable acid contents of dried apricots produced using various drying methods exhibit the following trend: FD > FD-MVD > MVD > HAD > IRD. The loss of titratable acid was particularly significant during HAD and IRD. This significant loss can be attributed to the prolonged exposure to atmospheric pressure and high air flow velocity environments during the drying process, which facilitates the dissociation and loss of volatile acids, ultimately resulting in a decrease in titratable acid content. Following the freeze drying process, the residual titratable acid content of small white apricots was determined to be 1.36%. For the freeze drying followed by the microwave vacuum drying process, the content was 1.25%, significantly lower than freeze drying. Nonetheless, the combined drying approach significantly reduced the overall drying time compared to freeze drying alone, while achieving a superior drying effect compared to microwave vacuum drying, hot air drying, and infrared radiation drying.

3.2.5. Microstructure

Figure 4 shows the electron microscope scans of the microstructures of small white apricots dried by different drying methods. As illustrated in the figures, notable disparities exist in the microstructures of small white apricots dried via various methods. The small white apricots after FD, MVD, and FD-MVD all exhibited a sponge-porous structure that was more homogeneous. However, MVD and FD-MVD samples were more loose and had a porous structure. This may be due to the good swelling effect of MVD, which resulted in more internal pores. Tang et al. [39] also found that the microwave-dried samples were loose in structure and showed a more porous structure with a good puffing effect when they investigated the effects of different drying methods on the drying characteristics and nutrient composition of Sanhua plum slices. Among them, FD-MVD has more obvious and relatively uniform pores than FD, which can better maintain the original appearance of small white apricots [40]. The surface of the MVD sample has many microcracks. They may be due to the rupture of the surface cells caused by the high microwave vacuum drying temperature, the moisture dissipation, which is too fast, and the surface forming a tight shrinkage [41]. The HAD and IRD samples exhibited significant alterations in cell morphology, featuring a laminated fiber structure, a collapsed cell wall structure, and the absence of a pore structure. These changes were caused by the extended drying duration associated with these two methods, ultimately leading to the formation of a hardened surface layer [42]. This observation also reveals that the cellular structures in the HAD and IRD samples suffered severe damage, with wrinkled surfaces and greater shrinkage, yielding harder products.

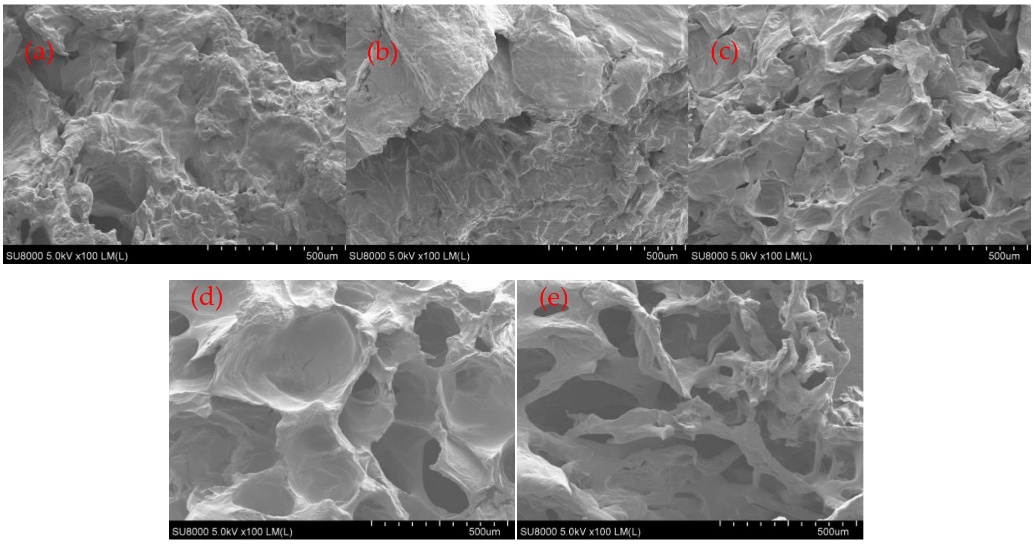


Figure 4. Effect of different drying methods on the microstructure of small white apricots: (**a**) Hot air drying; (**b**) Infrared radiation drying; (**c**) Freeze drying; (**d**) Microwave vacuum drying; (**e**) Freeze drying combined with microwave vacuum drying.

4. Conclusions

In this study, small white apricots were dried and the effects of different drying methods (HAD, IRD, MVD, FD, FD-MVD) on the drying kinetics and quality (color, rehydration, content of vitamin C and titratable acids, and microstructure) of small white apricots were compared. The findings indicate that MVD exhibited the fastest drying rate, closely followed by FD-MVD, while HAD demonstrated the slowest rate. In terms of color retention, vitamin C content, titratable acid content, and rehydration capacity, the combined drying method of FD-MVD performed marginally less favorably compared to FD. However, it significantly surpassed MVD, HAD, and IRD in these quality metrics. By comparing the electron microscope images of dried small white apricots under the five drying techniques, it can be seen that the surface of the FD-MVD samples formed the most homogeneous cell texture, whereas the surface of the infrared radiation drying and hot air drying was most severely wrinkled. In conclusion, FD-MVD proves to be superior to the other four drying methods, offering significant advantages in terms of enhancing the drying rate, reducing drying time, and improving the quality of dried small white apricots. This novel drying technique holds great potential for further development and application.

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