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Far-Infrared Radiation Heating-Assisted Pulsed Vacuum Drying (FIR-PVD) Enhanced the Drying Efficiency and Quality Attributes of Raspberries

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Abstract: An emerging drying method, far-infrared radiation heating-assisted pulsed vacuum drying (FIR-PVD), was employed to dry raspberries. In this study, the impacts of FIR-PVD, freeze drying (FD), and hot air drying (HAD) on drying characteristics and quality attributes, including color, rehydration ratio, content of total phenolics (TP), content of total monomeric anthocyanins (TMA), antioxidant activity, and microstructural attributes of dried raspberries, were examined. Results indicated that FIR-PVD notably shortened the drying time by 47.78% compared to HAD and by 73.89% compared to FD. The FIR-PVD samples exhibited the highest TP content, DPPH radical scavenging activity, and FRAP value, which were 17.73%, 6.09%, and 38.16% higher than those of the FD samples, respectively, and 2.78%, 2.77%, and 18.74% higher than those of the HAD samples. Significant correlations ($p < 0.05$) were observed between antioxidant capacity, as measured by DPPH and FRAP assays, and TP content. However, FD at a low temperature led to a higher TMA content than FIR-PVD and HAD. FIR-PVD resulted in the highest ΔE values of dried products due to the lightness enhancement. In addition, the dried products obtained by FIR-PVD had better rehydration capacity. These findings indicate that FIR-PVD presents a promising alternative method for drying raspberries, as it enhances drying efficiency and improves the quality attributes of the dried products.

Keywords: raspberries; FIR-PVD; drying curves; color; total phenolics; microstructure; antioxidant capacity; total monomeric anthocyanins

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1. Introduction

Raspberry (*Rubus idaeus* L.), a member of the *Rosaceae* family, is a widely cultivated berry fruit in the temperate regions of Europe, Asia, and North America owing to its endearing flavor and color. It is abundant in anthocyanins, phenolic compounds, ellagic acids, and flavonoids, which play a key role in preventing aging, improving immunity, and protecting the cardiovascular system [1–3]. Due to its dual features of being a medicine and food, raspberry is widely consumed daily. However, fresh raspberries are extremely perishable even in refrigerator conditions due to their soft texture and highly sensitive skin, which restricts their commercialization [4]. With the exception of being available in fresh and frozen forms, the majority of raspberries are processed into wines, snacks, juices, and jellies [5].

Practices have proved that drying processing is an efficient approach to prolonging the shelf life and improving the value of fresh raspberry. Hot air drying (HAD) is a commonly adopted drying technique for industrial raspberry processing. Nevertheless, fresh raspberries are coated with a distinctive waxy hydrophobic layer on their surface, which hinders the transfer of moisture from the inner to the outer regions during the dehydration procedure, thereby prolonging the drying time [6]. Moreover, the elevated air temperature may promote the substantial degradation of bioactive compounds. To optimize both the efficiency and quality of dehydrated raspberries, several alternative techniques, namely freeze drying, microwave drying, and vacuum drying, have been explored for their processing. The microwave drying method is popular for processing agro-materials because of its high drying efficiency and energy-saving characteristics, although uneven heating remains an inherent drawback of microwave drying [7,8]. Freeze and vacuum drying could significantly retain the bioactive compounds by reducing thermal degradation and oxidation reactions [9–11].

The novel technology of far-infrared radiation heating-assisted pulsed vacuum drying (FIR-PVD) has the potential to facilitate an improvement in both the efficiency and product quality of raspberry drying. During the FIR-PVD process, the boiling point of moisture in the material decreases as the surrounding pressure is reduced. Consequently, under the same heat transfer conditions, the material in the vacuum environment requires less time for the moisture to reach its boiling point and vaporize. This reduction in boiling point under vacuum conditions enhances moisture diffusion, thereby improving the overall drying efficiency. Furthermore, the alternating cycles of pressure within the drying chamber create disturbances in the vapor pressure of water at the material surface. This frequent disruption of the equilibrium between the vapor pressure of the material and the surrounding medium promotes the expansion of the material's micropores, thereby facilitating moisture migration [12]. The long-term vacuum environment could reduce the decomposition of organic compounds with bioactive properties. Also, the heat source of FIR could improve the drying uniformity and save energy [13,14]. Currently, the application of FIR-PVD has been demonstrated to be a viable primary processing technique for a variety of agricultural products, including fruits and vegetables. Deng et al. [15] employed FIR-PVD processing on red pepper and found that the dried products produced by FIR-PVD demonstrated superior retention of red pigment and ascorbic acid compared to those produced by HAD and infrared-assisted hot air drying (IR-HAD). Liu et al. [16] reported that FIR-PVD decreased the drying period for blueberries by 32.14% and improved the retention of total phenolics and total monomeric anthocyanins compared to HAD under identical drying conditions. Moreover, Wang et al. [17] applied FIR-PVD in drying hawthorn slices and observed that FIR-PVD could notably reduce the degradation of both ascorbic acid and citric acid compared to HAD. Nevertheless, no prior published work has explored the influence of FIR-PVD on the physicochemical characteristics of raspberries.

Therefore, the principal aims of the present work are as follows: (i) to evaluate the impact of FIR-PVD and HAD on the drying characteristics of raspberries; (ii) to analyze in detail the quality properties of raspberries dried by FIR-PVD, FD, and HAD, which include contents of total phenolics (TP), color parameters, contents of total monomeric anthocyanins (TMA), antioxidant capacity, rehydration ratio, and microstructure. This experimental study aims to provide valuable insights into practical methods for processing raspberries.

2. Materials and Methods

2.1. Preparation of Materials

In May 2024, fresh raspberries were sourced from a local supermarket in Beijing and refrigerated at 4 °C with 95% relative humidity for no more than 3 days. To maintain uniformity, the fruits were carefully selected based on consistent size and the prevention of external damage, with a mean diameter of 16 ± 1 mm for experimental purposes. The initial moisture content of the fresh raspberries was measured using methods outlined by the AOAC [18], with a measurement of 86.98% ± 0.56% (wet basis).

2.2. Drying Methods

2.2.1. Freeze Drying

Roughly 200 g of raspberry was subjected to a pre-freezing process for 3 h in an LGJ-25C vacuum freeze-dryer (Sihuan Scientific Instrument Co., Ltd., Beijing, China) at −50 °C, followed by lyophilization for 24 h under the same apparatus with a constant pressure of 20 Pa. The temperature settings for the material trays and condenser were fixed at 30 °C and −50 °C, respectively.

2.2.2. Far-Infrared Radiation Heating-Assisted Pulsed Vacuum Drying (FIR-PVD)

The dryer utilized for the FIR-PVD experiments at the College of Engineering, China Agricultural University, is illustrated in Figure 1. A comprehensive description of its specifications was sourced from the study of Wang et al. [17]. The apparatus for the dehydration process incorporates a vacuum module, a heating module, a cooling module, a weighing module, and an electronic control module. Among them, the electronic control module is equipped with the capability of automatically regulating the drying conditions based on user-defined parameters. According to preliminary experiments, the drying temperature, vacuum holding time, and ambient holding time were set to 65 °C, 15 min, and 4 min, respectively. Each drying experiment involves distributing approximately 200 g of the sample evenly across each stainless steel tray.

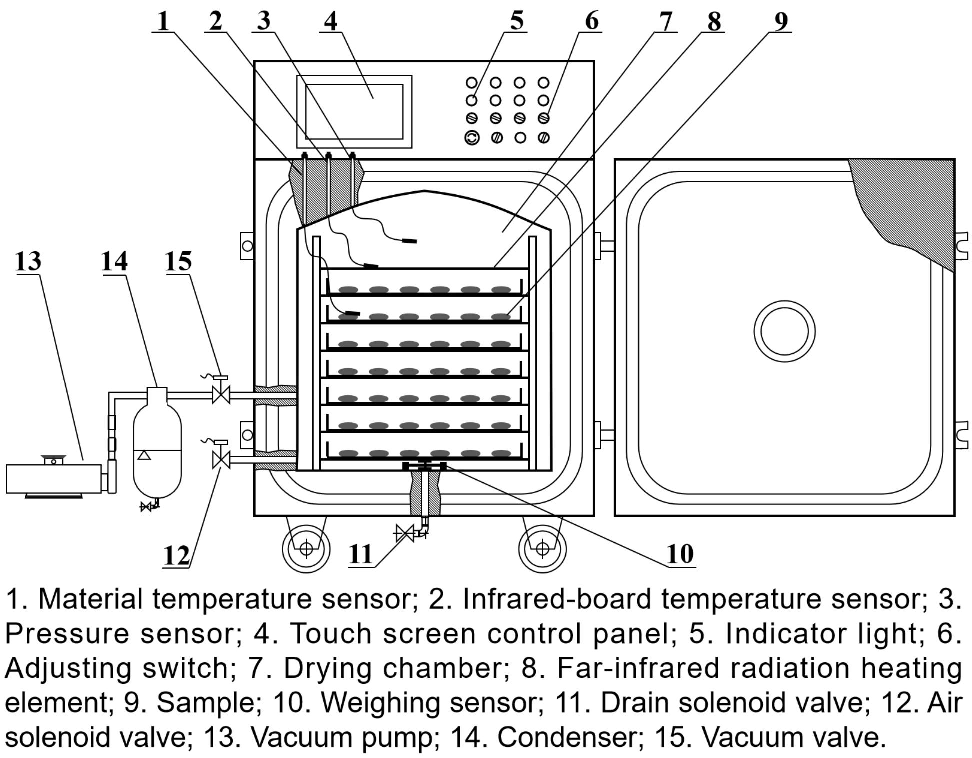
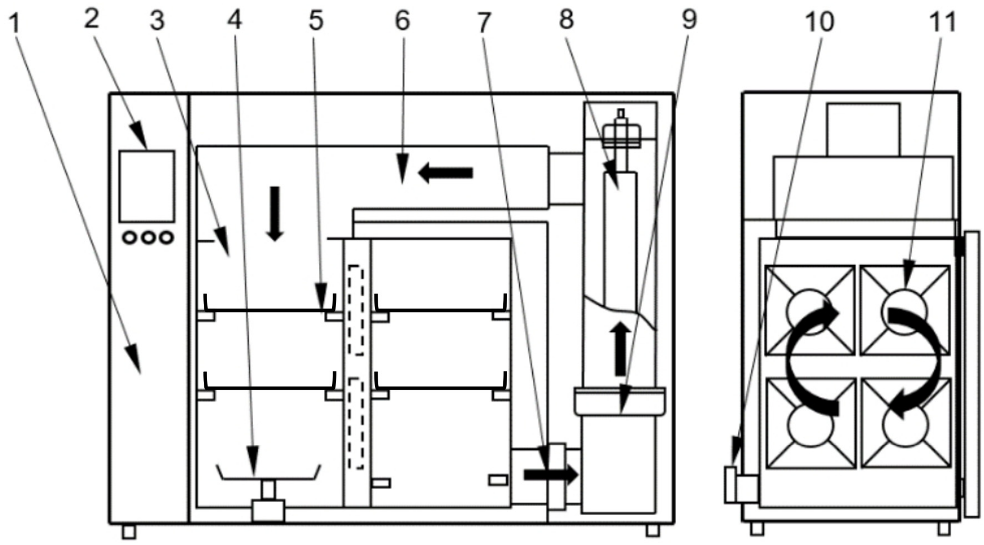


Figure 1. Structure diagram of far-infrared radiation heating-assisted pulsed vacuum dryer.

2.2.3. Hot Air Drying

The dryer of HAD utilized in the dehydration procedure was developed by the Laboratory of Agricultural Product Processing Technology and Equipment at the College of Engineering, China Agricultural University, as illustrated in Figure 2. The dehydration tests were conducted at 65 °C and an airflow speed of 3 m/s, with each tray uniformly loaded with 200 g of fresh raspberries. All drying trials were performed in triplicate.



1. Distribution box; 2. Control system; 3. Drying chamber; 4. Weighing module; 5. Tray; 6. Air bellow assembly; 7. Return air flue; 8. Electric heater; 9. Axial flow fan; 10. Moisture removing centrifugal fan; 11. Turbulent flow fan.

Figure 2. Diagrammatic illustration of the hot air dryer.

2.3. Drying Characteristics

Weight data for the FIR-PVD process were recorded every 45 min, while for the HAD process, they were recorded every 30 min. The moisture content of raspberries at time t (M_t, g/g, dry basis) was calculated using the primary moisture content (M_0, g/g, dry basis), the primary weight, and the raspberries' weight at time t. Additionally, the moisture ratio (MR) of the samples was evaluated based on the following equation.

$$MR = \frac{M_t}{M_0} \tag{1}$$

2.4. Total Phenolic (TP) Content

TP content was determined using the method mentioned by Liu et al. [16]. A 2.0 g sample of raspberry was transferred into a mortar and finely ground using 5 mL of a 1% hydrochloric acid–70% methanol solution. Quartz sand was introduced to aid in grinding the sample into a paste; afterward, 20 mL of a 1% hydrochloric acid–70% methanol solution was mixed in, and the resulting mixture was subsequently homogenized. The mixture was subsequently treated via ultrasonic extraction (160 W for 30 min, KQ5200DE, Kunshan Ultrasonic Instrument Co., Ltd., Kunshan, China) and subsequent centrifugation (8000 rpm and 4 °C for 15 min, GL-20G-II, Shanghai Anting Scientific Instrument Factory, Shanghai, China). The resulting solution was designated as the extract.

To quantify the content of total phenolics, 0.2 mL of the sample extract was produced by combining this quantity with 0.5 mL of Folin–Ciocalteu reagent (BR, Macklin Biochemical Technology Co., Ltd., Shanghai, China) plus 5.8 mL of distilled water. After thorough mixing, the solution was allowed to stand for 10 min. Subsequently, 1.5 mL of a 20% Na_2CO_3 solution was introduced to the mixture, which was then subjected to homogenization. The solution was placed in a light-tight environment at 20 °C for 60 min. The measurement of the absorbance was conducted at a wavelength of 750 nm, utilizing a spectrophotometer (Beijing Purkinje General Instrument Co., Ltd., Beijing, China). In expressing the contents of total phenolics, the values were presented in terms of gallic acid equivalence, specifically expressed as mg GAE/g DW.

2.5. Total Monomeric Anthocyanin (TMA) Content

The content of TMA was performed with slight modifications to the procedure outlined by Liu et al. [16]. Specifically, 1 mL of the extract obtained in Section 2.4 was combined with 9 mL of buffer solutions, each adjusted to a pH of 1.0 and 4.5, respectively. Following thorough mixing, the mixtures were permitted to react in the absence of light at 20 °C for 15 min. The measurement of the absorbance of the solutions was determined at wavelengths of 520 nm and 700 nm. TMA content was calculated and provided as mg Cy-3-G/100 g DW.

2.6. Antioxidant Capacity

The extract from Section 2.4 was employed as a measure of antioxidant activity [15]. The current work evaluated the antioxidant capacity using a 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity assay and ferric reducing antioxidant power (FRAP) assay. The data were presented in mmol Trolox/g DW.

In the DPPH assay, a 0.5 mL aliquot of the sample extract was combined with 1.5 mL of 70% methanol and 2.0 mL of a DPPH solution (Macklin Biochemical Technology Co., Ltd., Shanghai, China) with a concentration of 0.2 mg/mL. The aforementioned blend was thoroughly mixed and permitted to react in the light-tight conditions of a laboratory at room temperature for half an hour. Subsequently, the absorbance measurements of the mixture were taken at 517 nm.

For analysis with the FRAP method, 25 μL of the sample extract was combined with 775 μL of 70% methanol and 3.2 mL of FRAP reagent. The solution from this combination was then incubated at 37 °C in a water bath for half an hour. The absorbance of the resulting solution was then evaluated at a wavelength of 593 nm.

2.7. Color

A LabScan XE spectrophotometer (Hunter Associates Laboratory, Inc., Reston, VA, USA) was utilized in reflectance mode to quantify the L^*, a^*, and b^* values of the samples. The L^* value, which represents lightness, ranges from 0, which corresponds to black, to 100, which corresponds to white. The a^* value, which corresponds to the green–red axis, ranges from −60 to +60, as does the b^* value, indicating the blue–yellow axis. The total color difference (ΔE) between the fresh and dried raspberries was computed using the formula provided below:

$$\Delta E = \left[(L^* - L_0^*)^2 + (a^* - a_0{}^*)^2 + (b^* - b_0{}^*)^2 \right]^{1/2} \tag{2}$$

where $L_0{}^*$, $a_0{}^*$, and $b_0{}^*$ represent the control group, which is composed of the color parameters for the fresh raspberry.

2.8. Rehydration Ratio (RR)

The RR experiment on raspberry was conducted utilizing the procedure outlined by Liu et al. [16], with minor modifications. Dried samples (10 g) were combined with 200 mL of distilled water at 90 °C, and the mixture was then permitted to stand for 1 h. Subsequently, the samples underwent a moisture removal process utilizing absorbent paper. Afterward, the samples were weighed using an electronic balance. The following formula was utilized to calculate the RR:

$$RR = \frac{W_w}{W_d} \tag{3}$$

where W_w (g) and W_d (g) denote the mass of the raspberry following and preceding a rehydration process, respectively.

2.9. Microstructure

Samples of dried raspberries, cut into 5 mm × 5 mm sections, were affixed to an observation stage with conductive tape. Each sample was then sputtered with a thin layer of gold for 30 s. Subsequently, observation was carried out using a SU3500 scanning electron microscope (Hitachi, Tokyo, Japan) operated at an accelerating voltage of 15 kV. This was carried out for the purpose of observing the surface and epidermal corneum. Images were obtained at magnifications of 20× and 200×, respectively.

2.10. Statistical Analysis

The experimental results are shown as the mean ± standard deviation. A one-way analysis of variance (ANOVA) was conducted, followed by Duncan's multiple range test for statistical analysis. A *p*-value of less than 0.05 was deemed statistically significant. The data were analyzed using IBM SPSS Statistics, version 27.0 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Drying Curves

Figure 3 illustrates the impact of HAD and FIR-PVD on the drying kinetics of raspberries at a constant drying temperature of 65 °C. As anticipated, the moisture ratio of the raspberries tended to decrease with the prolongation of the drying time. The total drying duration required to attain the target moisture content was 376, 720, and 1440 min for FIR-PVD, HAD, and freeze drying (FD), respectively. Notably, FIR-PVD markedly decreased the drying time by 47.78% and 73.89% in comparison to HAD and FD, respectively. This effect may be explained by the crust formation observed on the surface of the material during the HAD process, which impedes water migration from the interior to the exterior. FIR-PVD might facilitate the creation of micro-porous channels via the application of successive pressure variations within the drying apparatus [19].

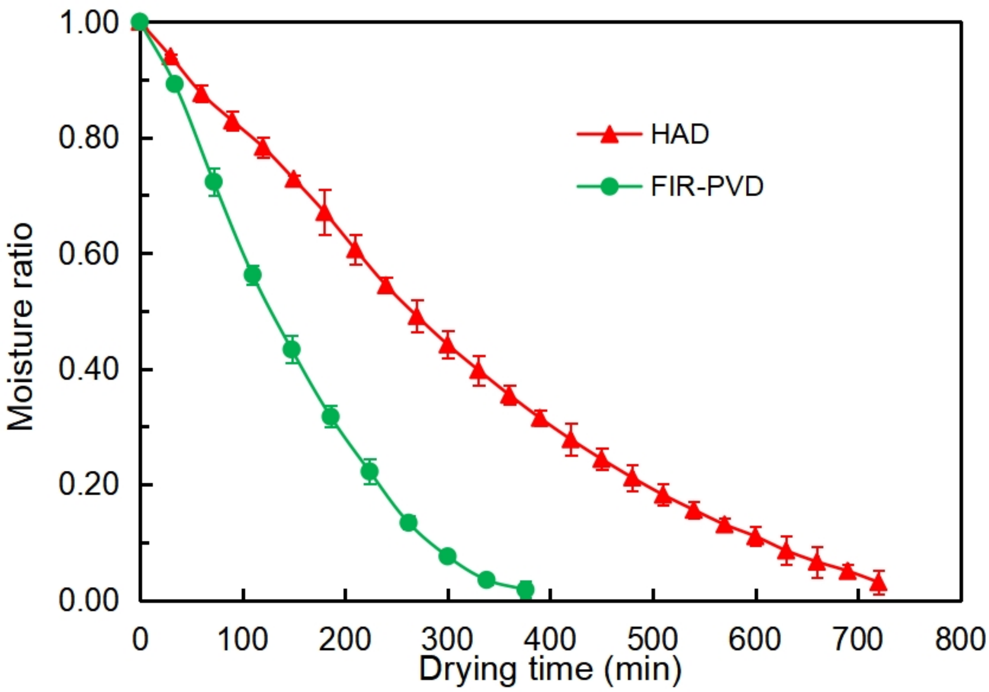


Figure 3. Moisture ratio curves of raspberries subjected to HAD and FIR-PVD.

3.2. Total Phenolic (TP) Content

Figure 4 presents the total phenolic (TP) content of dried raspberries produced using various drying techniques. As depicted in Figure 4, the choice of drying method significantly influenced the total phenolic (TP) content of the dried products. The highest

TP content occurred in FIR-PVD, i.e., 22.43 mg GAE/g DW. However, the FD method resulted in much lower TP retention than other drying methods, i.e., 19.05 mg GAE/g DW. Si et al. [20] also found that FD led to the lowest TP content of raspberry powders compared to HAD, infrared radiation drying (IRD), hot air and explosion puffing drying (HA-EPD), as well as infrared radiation-assisted microwave vacuum drying (IR-MVD). Li et al. [21] further reported that freeze-dried walnut kernel exhibited a diminished TP content compared to samples dried by gradient hot air drying and constant hot air drying methods. Maybe the long drying time of 1440 min caused by the low-temperature dehydration treatment made the phenolics unstable, which led to a more serious degradation. Additionally, heat treatment increases the breakdown of material tissues, thereby enhancing the extraction of phenolic compounds. The alternating pressure shifts between vacuum and atmospheric conditions notably altered the structures of cellular organelles [15]. Comparable results were observed by Liu et al. [12] for blueberries processed with FIR-PVD in contrast to HAD.

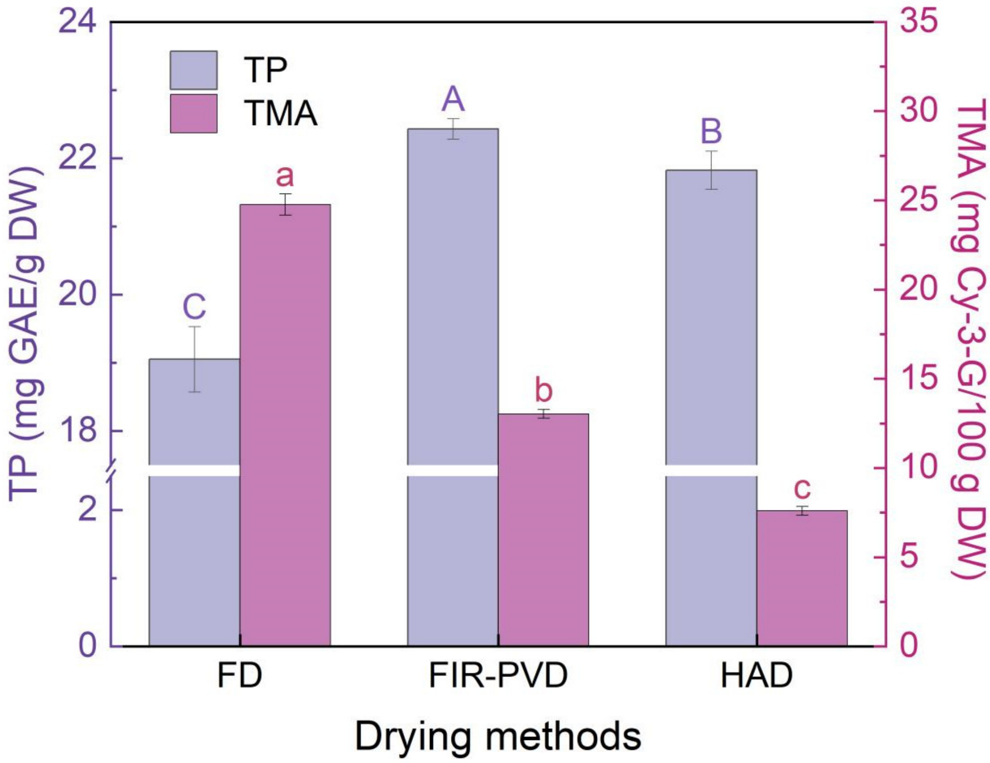


Figure 4. The content of total phenolics (TP) and total monomeric anthocyanins (TMA) of raspberries with various drying methods. Note: the uppercase letters (A–C) indicate significant differences ($p < 0.05$) in TP between different groups, while the lowercase letters (a–c) indicate significant differences ($p < 0.05$) in TMA between different groups.

3.3. Total Monomeric Anthocyanin (TMA) Content

Anthocyanins, one of the primary bioactive compounds in many fruits and vegetables, are notably more sensitive to heat compared to other phenolic compounds [22,23]. The total monomeric anthocyanin (TMA) content of dried raspberries obtained through various drying technologies is demonstrated in Figure 4. TMA contents of FD, FIR-PVD, and HAD products were 24.76, 13.03, and 7.59 mg Cy-3-G/100 g DW. FD at a low temperature led to a higher TMA content than FIR-PVD and HAD. The analysis revealed that the dried samples belonging to the HAD group exhibited the lowest TMA content. The alternating fluctuations between vacuum and atmospheric pressure during the FIR-PVD process may significantly disrupt cellular integrity. Conversely, the vacuum condition and shortened dehydration period reduced the oxidation reaction and heat degradation of anthocyanins. However, the longer heat process during the HAD process promoted the thermal degradation of TMA.

Therefore, fresh raspberries after FIR-PVD contained a higher TMA content than after HAD. Similar observations were described by Si et al. [20], who conducted a comparison of various drying methods and their effects on the total anthocyanin content in raspberries. Also, Liu et al. [16] discovered that the content of TMA of FIR-PVD blueberries was more than twice that of HAD at the same drying time.

3.4. Antioxidant Capacity

The antioxidant capacity of dried raspberry was evaluated using DPPH and FRAP assays, with the resulting values presented in Figure 5. The DPPH and FRAP values of the dried products ranged from 23.43 to 24.86 mmol Trolox/g DW and 171.91 to 237.52 mmol Trolox/g DW, in the respective order. The highest values for both DPPH and FRAP were measured for the FIR-PVD method at 65 °C, with values of 24.86 and 237.52 mmol Trolox/g DW, respectively. The lowest DPPH and FRAP values were observed for samples prepared using the FD method, with values of 23.43 and 171.91 mmol Trolox/g DW. Kumazawa et al. [24] assessed the antioxidant capacity of seven types of berries, including *R. hirsutus* Thunb., *R. microphyllus* L. fil., *R. palmatus* Thunb., *R. trifidus* Thunb., *R x medius* Kuntze, blackberry, and raspberry. The DPPH radical scavenging activity (expressed as percentage scavenging of DPPH radicals at 50 µg/mL) and FRAP values were found to be 38.4, 50.3, 42.1, 28.3, 44.2, 35.1, and 42.4, and 56.7, 58.2, 53.4, 37.0, 42.2, 83.8, and 45.4 µmol Trolox/g DW, respectively. FIR-PVD noticeably improved the antioxidant capacity of dried raspberries. However, FD had no leverage on the retention of antioxidant components in the samples. Similar trends were observed in the change in DPPH and FRAP values under various drying methods, which correlated with the TP content. The data demonstrate a notable correlation ($p < 0.05$) between the DPPH, FRAP, and TP content, as illustrated in Figure 6. These findings are consistent with the results published by Li et al. [21], Zhang et al. [25], and Yang et al. [26], who observed that the antioxidant activity of walnut kernel, yellow maize, and quinoa seed grains was significantly correlated with TP content. During the drying process, the degradation of phenolic compounds might potentially diminish the antioxidants in the finished product.

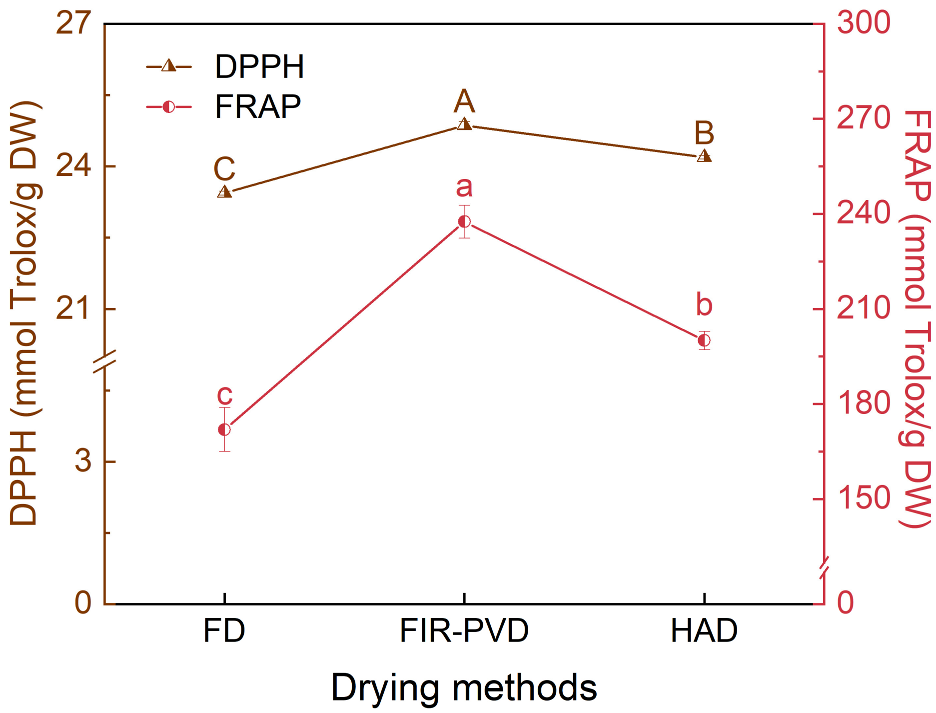


Figure 5. The DPPH and FRAP values of raspberries with different drying methods. Note: the uppercase letters (A–C) indicate significant differences ($p < 0.05$) in DPPH between different groups, while the lowercase letters (a–c) indicate significant differences ($p < 0.05$) in FRAP between different groups.

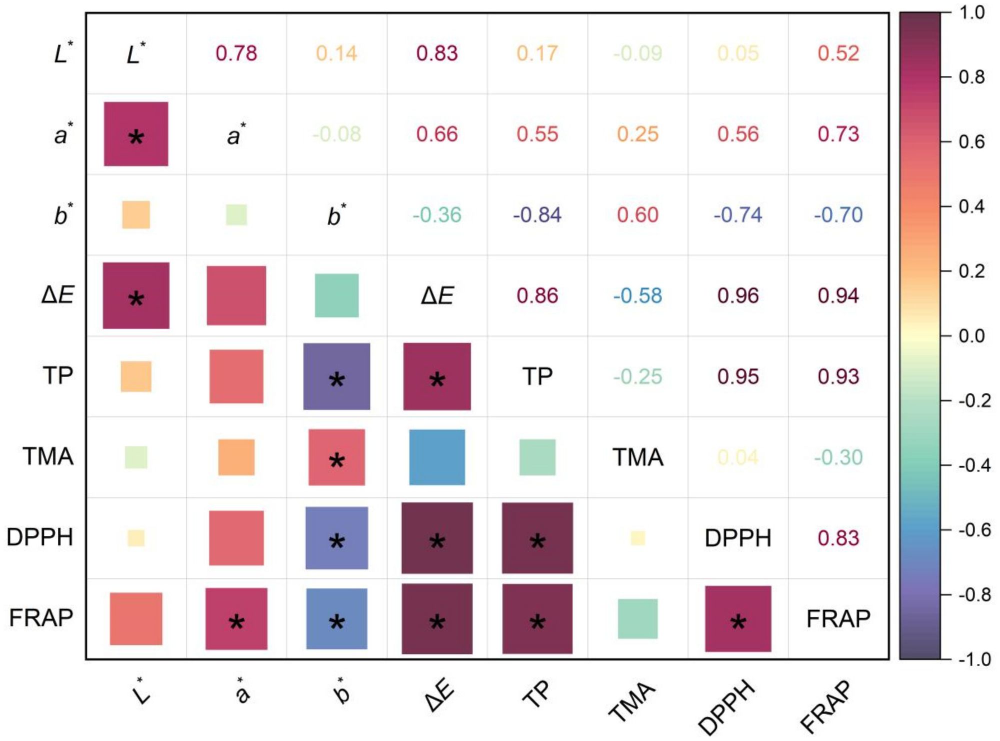


Figure 6. Pearson's correlation analysis of various physicochemical parameters in raspberries. Note: the asterisk (*) indicates a significant correlation between the two variables under $p < 0.05$.

3.5. Color

Color characteristics of dehydrated fruits represent the retention of pigments such as carotenoids, anthocyanins, chlorophyll, and phenols. These color parameters may serve as quality indicators, guiding the optimization of drying conditions and the minimization of bioactive compound degradation [27]. The color parameters of dried raspberries obtained by different drying methods are illustrated in Table 1. The L^*, a^*, and b^* values of fresh samples were 32.24, 23.79, and 7.02, respectively. Different drying methods significantly influenced the color values of dried products. Compared with the fresh samples, the L^* and a^* values of the FIR-PVD samples increased significantly by 12.59% and 32.79%, indicating the brightest and reddest appearance. However, HAD led to the lowest L^*, a^*, and b^* values, i.e., 29.38, 23.97, and 1.05, respectively. Freeze-dried samples resulted in the lowest ΔE values of dried materials and the overall appearance of the products was close to the fresh sample. The highest ΔE values of dried products occurred with FIR-PVD. These phenomena can be attributed to the considerable modifications in the internal structure of materials caused by FIR-PVD, which subsequently led to a more pronounced surface color [28]. During the HAD process, the extended drying time led to the materials having more exposure to the hot air and thus promoted browning reactions [29,30]. In contrast, FD significantly reduced color deterioration. These results indicated that the extended exposure to heat and air increased the degradations of pigments.

3.6. Rehydration Ratio

The RR of dried materials was applied to determine their water absorption ability, which generally reflected the changes in tissue structure. A higher RR in dried samples indicates a lesser extent of structural alteration, which is associated with superior product quality [31]. The effects of various drying methods on the rehydration ratio of dried products are shown in Figure 7. As can be seen from Figure 7, the highest rehydration ratio was noted for the samples prepared by FIR-PVD, i.e., 3.62. Nevertheless, no notable difference was found in the rehydration ratio between FD and HAD. The difference in rehydration ratio between different drying methods might be caused by various changes in the materials' structure. Several studies indicated that FIR-PVD induced a more porous structure in materials due to the cyclic pressure fluctuations between vacuum and ambient pressure, thereby enhancing their rehydration capacity [15,19,32].

Table 1. Images and color parameters of raspberries under various conditions.

	Fresh	FD	FIR-PVD	HAD
Images				
L^*	32.24 ± 0.80 ^{b}	30.27 ± 0.75 ^{c}	36.30 ± 0.23 ^{a}	29.38 ± 0.47 ^{c}
a^*	23.79 ± 0.66 ^{c}	27.35 ± 0.82 ^{b}	31.97 ± 0.87 ^{a}	23.97 ± 0.20 ^{c}
b^*	7.02 ± 0.22 ^{a}	5.57 ± 0.32 ^{b}	3.54 ± 0.11 ^{c}	1.05 ± 0.19 ^{d}
ΔE		4.39 ± 0.56 ^{c}	9.79 ± 0.66 ^{a}	6.64 ± 0.20 ^{b}

Note: means followed by different lowercase letters $^{(a–d)}$ in succession indicate statistically significant differences ($p < 0.05$).

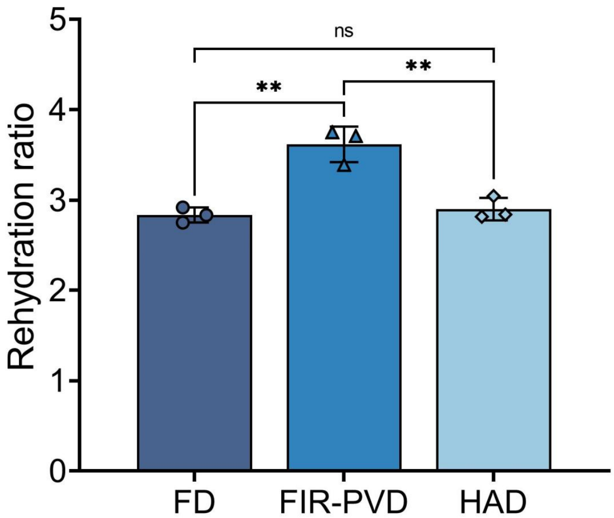


Figure 7. The rehydration ratios of dried raspberries under various drying methods. The ns indicates no significance, ** $p < 0.01$.

3.7. Microstructure by SEM

The modification of microstructure has a significant impact on the macroscopic properties and overall quality of dried materials. This process is fundamental for elucidating the underlying cellular mechanisms and assessing the effectiveness of various drying techniques [33,34]. From the microstructure of materials, as shown in Figure 8, the micropores in FD samples had a minor diameter of up to 4 mm, whereas those in HAD samples were approximately less than 1 mm, with the micropores in FIR-PVD samples falling in between these methods. It can be seen that FD led to a relatively regular waxy and thinner epidermis. The skin of FD samples looked fragile. The application of FIR-PVD treatment resulted in the contraction of the tissue material, which led to an increase in the thickness of the cuticular layer due to its exposure to alternating vacuum and atmospheric pressures. Also, the microstructure obtained by FIR-PVD was more porous in the cross-section of the epidermis. However, HAD resulted in serious cell tissue collapse and epidermal crusting. This confirmed that the dried products obtained by FIR-PVD had better rehydration performance. Similar findings were reported by Liu et al. [16], who found that the blueberries dried by FIR-PVD showed greater rehydration capability than those treated by HAD.

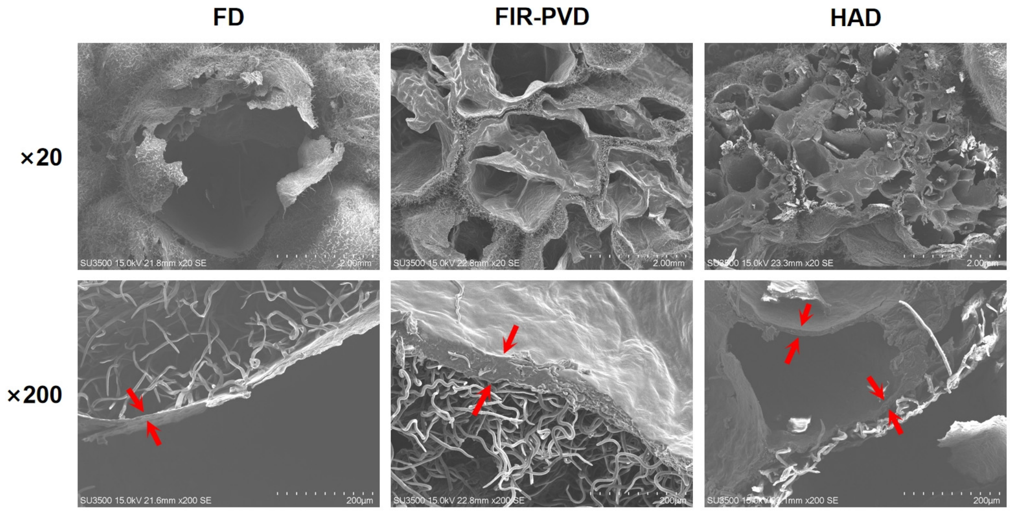


Figure 8. Microstructural images of dried raspberries at 20 and 200 magnification under various drying methods. Note: The red arrows indicate the vertical cross-section of the raspberry cell wall.

4. Conclusions

FIR-PVD was employed to process fresh raspberries. The overall drying period necessary to achieve the desired FIR-PVD moisture content was 376 min. Compared to HAD and FD, FIR-PVD demonstrated a notable reduction in drying time, with a decrease of 47.78% and 73.89%, respectively. The highest TP content occurred in FIR-PVD, i.e., 22.43 mg GAE/g DW. FD at a low temperature led to a higher TMA content than FIR-PVD and HAD. In addition, the highest DPPH and FRAP values were observed for FIR-PVD at 65 °C, i.e., 24.86 and 237.52 mmol Trolox/g DW, respectively. Significant positive relationships were observed between DPPH, FRAP, and TP content ($p < 0.05$). However, the highest values of the ΔE for the dried products were observed for the samples treated with the FIR-PVD method, due to the observed lightness enhancement. The dried products obtained by FIR-PVD had better rehydration performance. The alternating pressure between ambient and vacuum pressure during FIR-PVD made the material tissue shrink and thus resulted in a thicker cuticular layer. Overall, the FIR-PVD method produced higher quality dried raspberries. Current studies highlight the potential of FIR-PVD as an effective drying method for berry materials with similar structures, contributing to improving their quality attributes. However, potential challenges such as the need for specialized equipment, higher energy requirements, and initial investment may require further consideration to enhance its scalability and cost-effectiveness for broader industrial applications.

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