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RESEARCH PAPER

A comparative evaluation of physical characteristics, bioactive compounds, and antioxidant capacity of *Rhodomyrtus tomentosa* berry by different drying methods

[1,2]Dingjin, L., [2]Qiuxia, D., [1,2]Yipeng, G., [1, *]Nor Afizah, M., [2]Zhenhua, D., [2]Yingjian L. and [1]Jiao, D.

[1]*Department of Food Technology, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*

[2]*College of Food and Biological Engineering, Guangxi Key Laboratory of Health Care Food Science and Technology, Hezhou University, Hezhou, Guangxi, 542800, China*

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Abstract

The *Rhodomyrtus tomentosa* berry (RTB) has attracted the attention of researchers for its medicinal and nutritional characteristics. However, there is limited research on the influence of different drying methods on RTB quality. The objective of this work was to evaluate the effect of vacuum microwave drying (VMD), heat pump drying (HPD), and sun drying (SD) on the quality characteristics, microstructure, and antioxidant capacity of RTB. Results indicated that compared with HPD and SD, VMD enhanced the quality of RTB and could complete the drying process in a shorter time (3.6 hrs). In addition, VMD was able to retain a higher level of bioactive compounds and antioxidant capacity with an improved rehydration ratio. The microscopic images showed that the VMD had an obvious porous structure, facilitating the water evaporation. This suggested that VMD is an efficient drying technology for producing high-quality dried products.

1. Introduction

Rhodomyrtus tomentosa (Ait.) Hassk (Myrtaceae family) is distributed in China, Malaysia, Indonesia, and Vietnam (Wang, Yao, Lin *et al*., 2022). *Rhodomyrtus tomentosa* flowers from April to May, and fruits ripen from July to August forming purplish pulp (Zhao *et al*., 2020). In traditional Chinese and Vietnamese medicine, unripe fruit has been used to treat diarrhoea or dysentery, while ripe fruit was used to stimulate the immune system (Lai *et al.,* 2013). Nevertheless, the fruit is underutilized and has no commercial application. Recent studies have shown that *R. tomentosa* berry (RTB) is rich in dietary fibre (66.56±2.31%, db), protein (4.00±0.12%, db), digestible carbohydrate (19.96%, db) and lipids (4.19±0.07%, db) (Vo and Ngo, 2019). Phenolic compounds from *R. tomentosa* can improve gut microbiota dysbiosis and mitigate the dysfunction of the intestinal barrier and inflammation (Wang, Yao, Meng *et al*., 2022). The moisture content of fresh RTB was reported to be as high as 84.5% (wet basis), making it prone to spoilage. The fresh RTB has a storage life of only 3 to 5 days, causing significant economic losses for the sellers. Drying is one of the preservation techniques known to effectively improve the storage life of the fruit. This is achieved by lowering the moisture content and water activity, thus inhibiting the propagation of microorganisms and enzyme activity in the fruit (An *et al*., 2022). Nevertheless, nutrient losses and structural changes are unavoidable during the drying. Therefore, there is an urgent need to investigate the effect of dehydration on RTB quality.

Traditional hot air drying typically causes degradation to the heat-sensitive bioactive compounds, substantial colour loss, and changes in food structure (Punthi *et al.*, 2022). Freeze drying is often considered the most efficient technique for obtaining high-quality products. However, it is a time-consuming and expensive technique (Waghmare *et al*., 2022). Therefore, novel drying techniques have emerged to solve the disadvantages of traditional techniques while producing high-quality products. Vacuum microwave drying (VMD) is a highly efficient technique known for its rapid drying speed, minimal shrinkage, and energy-efficient while producing dried products with excellent rehydration properties. Heat pump drying (HPD) offers energy-efficient, precise, and gentle drying while preserving product quality and reducing environmental impact (Loemba *et al*., 2023). A previous study reported that the HPD significantly enhances the quality of jujube

*Corresponding author.
Email: *nor_afizah@upm.edu.my*

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slices by successfully minimizing the discolouration and shrinkage of the dried fruit (Hou *et al*., 2020).

There have been several reports on the effect of drying on the physicochemical properties of RTB. A study exhibited that combined microwave-hot air drying was effective in retaining RTB nutrients compared to hot air and microwave drying. Combined drying techniques also improve the antioxidant activity of berries compared to single drying techniques (Zhao *et al*., 2017). Another researcher utilized the spray drying technique to prepare *R. tomentosa* flavonoids. The research revealed that after spray drying, the flavonoid extract's scavenging activity on DPPH free radicals remained unaffected (Wu *et al*., 2014). However, these scholars have mainly focused on traditional drying techniques. The effect of novel drying techniques on RTB quality has yet to be studied.

The purpose of this work was to investigate the effects of vacuum microwave drying (VMD), heat pump drying (HPD), and sun drying (SD) on the physical characteristics, bioactive compounds, and antioxidant capacity of RTB.

2. Materials and methods

2.1 Chemical and fruit materials

Fresh RTB was bought from local markets (Hezhou, China). All chemical reagents were purchased from Sinopharm Chemical Reagent Co., Ltd (Beijing, China).

2.2 Drying of fresh Rhodomyrtus tomentosa berry

Fresh RTB was dried using three different techniques, namely, vacuum microwave drying (VMD), heat pump drying (HPD), and sun drying (SD). Whole RTB fruits at approximately 1000 g were used for each drying method. Table 1 shows the conditions for the different drying methods.

Table 1. Drying conditions of different drying methods.

Drying methods	VMD	HPD	SD
Atmospheric pressure	-9.00×10^5 Pa	1.01×10^5 Pa	1.01×10^5 Pa
Heating source	Microwave	Hot air	Solar energy
Microwave power	1.5 kW	-	-
Temperature	-	60°C	30°C

VMD: vacuum microwave drying, HPD: heat pump drying, SD: Sun drying.

2.2.1 Vacuum microwave drying

The fresh RTB was spread as a single layer of fruit on trays (thickness = 1 cm) and then dried in a vacuum microwave dryer (Guiyang Novel Industrial Microwave Co. LTD) until the sample's moisture content was ≤ 3%.

2.2.2 Heat pump drying

The fresh RTB was spread as a single layer of fruit on trays (thickness = 1 cm) and then dried in a heat pump dryer (ZWH-KFY-B, Guangdong Wei er xin Industrial Co., LTD, Guangdong, China) until the sample's moisture content was ≤ 3%.

2.2.3 Sun drying

The fresh RTB was spread as a single layer of fruit on trays (thickness = 1 cm) and then exposed in an open space to dry until the sample's moisture content was ≤ 3%.

2.3 Physical properties of dried Rhodomyrtus tomentosa berry

2.3.1 Moisture content

Moisture content was measured using the oven method (Lachowicz *et al*., 2019). The dried RTBs were sliced before the analysis (thickness = 5 mm). The slices (5 g) were dried at 105°C to a constant weight.

2.3.2 Colour measurement

The colour of dried RTBs was analyzed using a colourimeter (CR400, Konica Minolta Inc, Tokyo, Japan) (Nemzer *et al*., 2018). The dried RTBs were pulverized prior to the analysis. The powder was then placed in a 35 mm petri dish. Equation (1) was used to calculate the total colour difference (ΔE).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

2.3.3 Shrinkage ratio

The shrinkage ratio was measured according to the method by Feng *et al*. (2021). The shrinkage ratio was calculated using Equation (2).

$$Shrinkage\ ratio\ (\%) = \frac{V_a - V_b}{V_a} \times 100 \quad (2)$$

where V_a and V_b represent the volumes (cm^3) before and after drying, respectively.

2.3.4 Rehydration ratio

The rehydration ratio was determined following the method by Xu *et al*. (2020). Dried RTBs (5 g) were immersed in distilled water (500 mL) at 25°C. The dried fruits were removed at every 5-min interval, surface dried with absorbent paper and weighed. The samples were re-soaked in distilled water and the process was repeated until the samples reached a constant mass. Equation (3) was used to calculate rehydration ratio.

$$Rehydration\ ratio = \frac{Mt}{M0} \quad (3)$$

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Where M_0 denotes the weight (g) before rehydration, M_t denotes the weight (g) at any rehydration time.

2.3.5 Scanning electron microscope

Dried RTBs were pulverized before analysis. Samples were gold-plated by ion sputtering. Using the Scanning Electron Microscope (SEM) to observe the microstructure of samples. Images were taken at 2000× magnification (Bao *et al*., 2023).

2.4 Analysis of bioactive compounds

2.4.1 Polysaccharide content

The phenol-sulfuric acid method was used to determine polysaccharide content (Hu *et al*., 2017).

2.4.2 Proanthocyanidins content

A 0.1 g sample (powder) with methanol (30 mL) was placed in an ultrasonic extractor to prepare extract of proanthocyanidins. The samples were extracted by ultrasonic extraction at 250 W and 50 kHz for 20 mins. After centrifugation (5500 rpm/min) for 10 mins, the supernatant was used for analysis (Mokrani, 2023).

The supernatant (0.5 mL), butanol-HCl solution (3 ml; 95:5, v/v) (3 mL), and 2% $NH_4Fe(SO_4)_2$ (0.1 mL) were added into the colourimetric tube, shaken well, and reacted in 100°C water for 60 mins. After cooling, the absorbance was measured at 530 nm.

$$Proanthocyanidins\ content\ (g/100g\ dw) = \frac{c \times V \times V_2 \times 1000}{m \times V_1 \times 1000 \times 1000} \times 100 \quad (4)$$

where c denotes the amount of proanthocyanidins in the reaction mixture (μg/mL), V denotes the total volume of the sample (mL), V_1 denotes the sample reaction volume (mL), V_2 denotes the total volume after the reaction of the sample (mL), m denotes the sample mass (mg).

2.4.3 Total flavonoid content

The colourimetric method was used to determine the total flavonoid content (TFC) (Liu, Liu, Shan *et al*., 2022). RTB extract (1 mL), distilled water (4 mL), and 5% sodium nitrite (0.3 mL, w/v) were added into the colourimetric tube. After 5 min, 10% $AlCl_3$ (0.6 mL, w/v) was added and reacted for 6 mins. Then, 1M NaOH (2 mL) and distilled water (2.1 mL) were added. The absorbance was measured at 510 nm and the blank control group was distilled water. Calculation of TFC according to rutin concentration.

2.4.4 Analysis of gallic acid and ferulic acid

Analysis of gallic acid and ferulic acid was performed by using HPLC (Shimadzu Instrument Manufacturing Company CO., LTD, China), with some modifications (Mohammad *et al*., 2022). Ultrapure water (A) and acetonitrile (B) were used as the mobile phases. The test conditions were as follows: 0-5 mins, 30% B; 5-25 mins, 60% B; 25-30 mins, 100% B; 30-35 mins, 15% B; and 35-40 mins, 30% B. The injection volume was 10 μL, and the detector wavelength was 280 nm.

2.5 Antioxidant capacity

2.5.1 ABTS assay

The mixture of RTB extract (0.15 mL) with 7.4 mM $ABTS^{\bullet+}$ (1.35 mL) solution was reacted for 2 hrs at 25°C in the dark. The absorbance was measured at 734 nm (Xiong *et al*., 2019). Trolox was used as the standard solution, and methanol was used as blank.

2.5.2 Free radical scavenging activity using DPPH assay

DPPH was measured according to Ahmed *et al*. (2019) with some modifications. The mixture of RTB extract (0.15 mL) was mixed with 1.35 mL of 1.22 mM DPPH radical solution. The reaction was carried out at 25°C in dark conditions for 30 mins. The absorbance was measured at 515 nm. Trolox and methanol were used as the standard solution and blank group, respectively.

2.5.3 Ferric reducing antioxidant power assay

The determination of ferric reducing antioxidant power (FRAP) was based on the method by Rao *et al.* (2018). The mixture of RTB extract (60 μL), FRAP solution (1.80 mL), and ultrapure water 1 (180 μL) was reacted at 37°C for 40 mins. The absorbance was measured at 593 nm.

2.6 Statistical analysis

Prism 10 and SPSS were used to analyze the experimental data. Duncan's test was used to analyze the significant between-group differences ($p < 0.05$).

3. Results and discussion

3.1 The effect on drying time, moisture content, and colour of Rhodomyrtus tomentosa berry

The drying time for VMD, HPD, and SD were found to be 3.6±0.02 hrs, 36.5±0.01 hrs, and 74.6±0.05 hrs, respectively (Table 2) ($P < 0.05$). VMD shortened drying time by a factor of 10 and 20 compared to HPD and SD, respectively. This indicates that VMD is a very efficient drying technique. This is attributed to the mechanism in which the microwave is able to heat both inside and outside of the material almost simultaneously, eventually reducing the heat conduction time. At the same time, water vapour is rapidly formed under vacuum conditions, building a pressure difference between the product and its surroundings. These changes promote rapid water

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evaporation from the matrix of the food product, thus improving the drying rate (Pankyamma *et al*., 2019).

Colour is widely recognized as a key indicator of the quality of a dried product. Changes in colour properties may be due to pigment (anthocyanidin) degradation or non-enzymatic browning during drying (Piskov *et al*., 2020). Table 2 shows that the L^* value of fresh RTB was 31.78±0.94. As for SD and HPD, the L^* values decreased. However, the L^* value remained unchanged in VMD. Compared to fresh samples, the a^* values of the dried RTBs were higher, with the VMD showing the highest value. This was attributed to the higher moisture content in the fresh sample, causing the distribution of red pigment (anthocyanin) to be dispersed throughout the fruit matrix, leading to a relatively low value. In contrast, the drying process caused the pigment to be concentrated, hence increasing the a^* values. In general, a yellow colour is desirable for dried samples, thus a higher b^* value is preferred (Lyu *et al*., 2020). The b^* values increased after the drying process in comparison to the fresh RTB. The highest b^* value was recorded in the VMD sample (5.44±0.30). The samples obtained from the HPD process showed the highest ΔE value (4.71±0.28). The ΔE was positively correlated with drying time (R = 0.779). This observation could be associated with the prolonged drying and high temperatures resulting in a higher degree of Maillard reaction, which leads to colour degradation and a darker appearance (Calín-Sánchez *et al*., 2020). The ΔE value of the VMD samples showed the lowest value VMD has the advantage of low temperature and high-efficiency drying, which reduces the Maillard reaction and provides a better colour for the final product (Cavieres *et al*., 2021). This study suggests that drying at low temperatures, for a shorter time, and under low oxygen conditions will better preserve the colour of the dried product.

3.2 Scanning electron microscopy

Figure 1 illustrates the microstructure of the powdered dried samples. The VMD has a distinct porous and loose structure. In contrast, compact structures without porosity were observed in HPD and SD, with SD showing higher compactness. The application of microwave radiation along with the presence of a vacuum during drying using the VMD created a high vapour pressure in the samples, therefore allowing rapid moisture evaporation into the surroundings. Thus, the structural collapse was prevented (Zielinska *et al*., 2013). Hence reducing shrinkage and obtaining a higher-quality product.

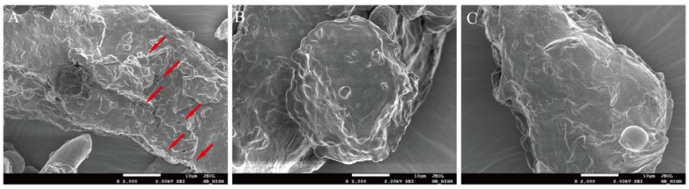

Figure 1. SEM images of RTB obtained from different drying methods: (A) VMD, (B) HPD, (C) SD). Porosity is indicated by red arrows.

3.3 Shrinkage ratio

The drying method had a significant effect ($P<0.05$) on the shrinkage ratio (Figure 2A). It is worth emphasizing that VMD has an extremely low shrinkage ratio of 1.33±0.11%. The shrinkage ratio (SR) was 51±1.01% and 68.04±0.55% for HPD and SD, respectively. Figure 3 shows that the VMD morphology is essentially the same as that of the fresh RTB, with no structural collapse or deformation. The SR positively correlated (r = 0.965) (Figure 4) with the drying time. This could be attributed to the nature of the drying mechanism of VMD that increases the water evaporation rate while reducing drying time, promotes the formation of a strong cytoskeleton, and eventually helps to maintain the cell structure (Huang *et al*., 2023). In contrast, the poor drying conditions of both HPD and SD such as prolonged time, uneven drying, and slower water evaporation rate, caused the fruit matrix to undergo a process of water redistribution during the water evaporation process. This phenomenon resulted in the severe deformation and structural collapse of the hard cytoskeleton. Therefore, the samples showed an extreme shrinkage. This study suggested that VMD contributed to maintaining the structure and prevention of shrinkage in dried RTB.

3.4 Rehydration ratio

The rehydration ratio is one of the critical attributes

Table 2. Drying time, moisture content, colour, and proanthocyanins content of RTB samples by different drying methods.

Drying methods	Drying time (hrs)	Moisture content (%)	Colour				POC (g/100 g dw)
			L*	a*	b*	ΔE	
Fresh	NP	84.50±0.17^a	31.78±0.94^a	7.19±0.57^c	1.46±0.06^c	1.22±0.50^d	3.30±0.10^a
VMD	3.60±0.02^c	3.00±0.03^b	31.08±0.19^a	9.15±0.6^a	5.44±0.30^a	2.66±0.32^c	3.13±0.14^a
HPD	36.50±0.01^b	3.00±0.05^b	27.05±0.21^b	9.09±0.33^a	2.44±0.08^b	4.71±0.28^a	0.03±0^b
SD	74.60±0.05^a	2.90±0.05^b	27.59±0.08^b	8.88±0.17^b	2.40±0.11^b	4.21±0.06^b	0.01±0^b

Values are presented as mean±SD. Values with different superscripts within the same column are statistically significantly different ($p \leq 0.05$). NP: not performed, POC: proanthocyanins content.

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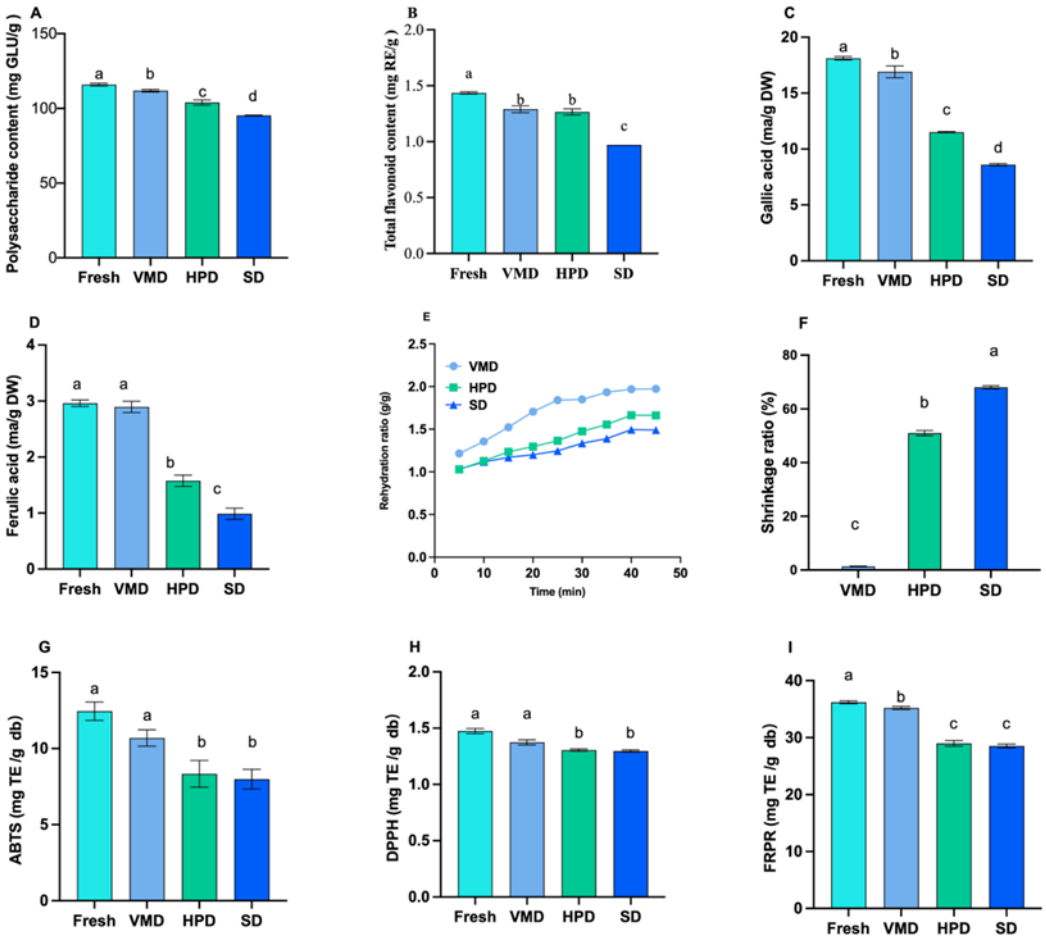

Figure 2. Effects of different drying methods on polysaccharide content (A), total flavonoid content (B), gallic acid (C), ferulic acid (D), rehydration ratio (E), shrinkage ratio (F), and antioxidant activities of RTB (G-I). Bars with different notations within the same chart are statistically significantly different ($p<0.05$).

Figure 3. Dried RTB was obtained from different drying methods: (A) Fresh, (B) vacuum microwave drying (VMD), (C) heat pump drying (HPD), and (D) sun drying (SD).

in evaluating the quality of dried product. A greater rehydration capacity reflects a faster recovery of freshness (Ren *et al*., 2022). The rehydration ratio increases with time (Figure 2B). All samples reached maximum rehydration ratio at 40 mins of soaking time, with values of 1.96±0.01, 1.66±0.01, 1.49±0.00 for VMD, HPD, and SD, respectively. The rehydration ratio of all samples remained nearly constant after 40 min of soaking.

Porosity facilitates the reconstitution and rehydration of dried food. A lower shrinkage and higher porosity have been associated with a greater rehydration ability (Boateng *et al*., 2021). The product will collapse and lose elasticity during drying, which can lead to irreversible damage. Furthermore, the shrinkage will inhibit the rehydration capacity (Joardder *et al*., 2017). In this work, the VMD-treated samples have a porous structure (Figure 2A), contributing to accelerated water penetration into the samples, hence improving the rehydration capacity. However, non-porous and compact structures were observed in HPD and SD, with SD being more compact, causing the low rehydration capacity. The study demonstrated that the microstructural damage caused by the drying method can detrimentally affect the rehydration capacity.

3.5 Bioactive compounds

3.5.1 Polysaccharide content

Figure 2C shows the polysaccharide content (PC) of RTB. Significant differences existed between the fresh, VMD, HPD, and SD samples ($P<0.05$). The drying

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process reduced the PC of the RTB. The fresh sample had the highest PC of 115.94±0.89 (mg GLU/g), followed by VMD (111.94±0.81 mg GLU/g), HPD (106.59±1.05 mg GLU/g), and SD (95.35±0.29 mg GLU/g). In HPD and SD drying, high temperatures and prolonged drying perhaps caused polysaccharide degradation. Figure 4 shows that drying time negatively (r = -0.988) correlated with PC. Previous studies have shown that high temperatures and prolonged drying resulted in polysaccharides degradation (Zhang *et al*., 2019; Gu *et al*., 2020). Therefore, low temperatures and shorter drying were more conducive to preserving polysaccharides.

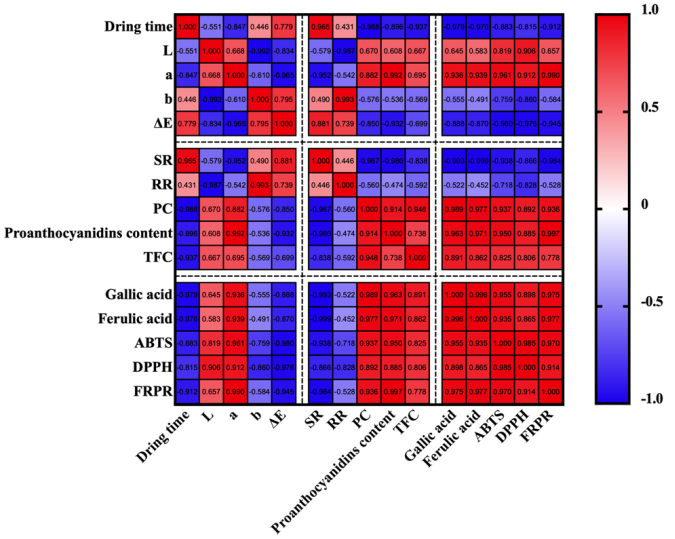

Figure 4. Pearson correlation analysis on various parameters of RTB.

3.5.2 Proanthocyanidins content

Table 2 shows the proanthocyanins content of RTB. There is no substantial difference in proanthocyanidins content between samples subjected to VMD and that of fresh samples. The proanthocyanidins content of the VMD sample was 3.13±0.14 (g/100 g dw). Following the HPD and SD, proanthocyanidins content was significantly reduced to a negligible value, 0.03±0.00 and 0.01±0.00 (g/100 g dw), respectively. Proanthocyanidins are known to be very sensitive to oxygen, light, and temperature during drying and storage (Chen *et al*., 2021). It can be concluded that the minimal loss of proanthocyanidins in the VMD samples benefited from the low temperature and low oxygen conditions during drying.

3.5.3 Total flavonoid content

The fresh RTBs showed the highest total flavonoid content (TFC) with a value of 1.43±0.01 mg RE/g, followed by VMD (1.29±0.04 mg RE/g), HPD (1.27±0.03 mg RE/g) and SD (0.97±0.00 mg RE/g) (Figure 2D). The temperature and air (oxygen) during the drying process are the main factors affecting TFC, attributed to its susceptibility to oxidation and degradation when being exposed to high temperatures and the presence of oxygen (Liu *et al*., 2019). Therefore, to preserve the TFC of RTB to the greatest extent, low-temperature drying conditions should be selected during drying.

3.5.4 Phenolic compounds

Gallic acid content is shown in Figure 2E. The gallic acid content for fresh, VMD, HPD, and SD were 18.12±0.15 mg/g DW, 16.89±0.50 mg/g DW, 11.51±0.06 mg/g DW, 8.60±0.10 mg/g DW, respectively ($P<0.05$). There was barely any difference in ferulic acid content between fresh (2.96±0.06 mg/g DW) and VMD (2.90±0.10 mg/g DW) RTBs (Figure 2F). The ferulic acid content of VMD samples was 1.8 times higher than that of HPD (1.58±0.10 mg/g DW) and 2.9 times greater than that of SD (0.99±0.10 mg/g DW). Previous studies have shown that increased temperature and oxygen can negatively impact the stability of phenolic compounds (Liu, Zhang, Lu *et al*., 2022). Higher temperatures and prolonged exposure during drying using HPD led to the degradation of phenolic compounds in the dried RTB, whereas the lower value recorded in the SD sample was attributed to the long drying time. In addition, the enzymatic reactions and migratory bond breaking may promote the degradation of these compounds (Malakar *et al*., 2022).

3.6 Antioxidant capacity

The antioxidant activities (ABTS, DPPH, and FRAP) of RTB dried using all drying techniques were significantly lower than the fresh sample (Figure 2G, 2H, 2I). Among all the dried samples, the VMD recorded a higher ABTS radical scavenging capacity (10.70±0.53 mg TE/g db), followed by HPD (8.34±0.88 mg TE/g db) and SD (7.98±0.65 mg TE/g db). The DPPH radical scavenging ability and FRAP of VMD were superior to HPD and SD. Proanthocyanidins, polysaccharides, flavonoids, gallic acids, and ferulic acids are important antioxidants in fruits (Pešić *et al*., 2019; Cao *et al*., 2019). The antioxidant capacities (ABTS, DPPH, and FRPR) strongly correlated with PC, R = 0.937, R = 0.892, and R = 0.936, respectively. The structure of polysaccharides consists of uronic acid and monosaccharides. It has been shown that the excellent FRPR and ABTS radicals scavenging activity of polysaccharides was associated with their uronic acid content (Yarley *et al*., 2021). Polysaccharides with low molecular weight have been reported to have higher DPPH radical scavenging activity (Xu *et al*., 2019). During HPD and SD, the high temperature and prolonged exposure to oxygen perhaps greatly reduced the proanthocyanidins, total phenolic, gallic acids, and

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ferulic acid contents of the RTB. This leads to a decrease in their antioxidant capacity. In VMD, low oxygen and temperature conditions better maintain these antioxidants and exhibit higher antioxidant activity.

4. Conclusion

In conclusion, the study showed that VMD significantly reduced drying time while retaining the colour and structure of the dried fruit, resulting in an end product with a low degree of shrinkage and a high rehydration ratio attributed to its high porosity. VMD has better retention of bioactive compounds, hence a higher antioxidant capacity than HPD and SD. VMD stands out as a promising dehydration technology, offering a rapid drying and high-quality dry product. This technique offers great potential for large-scale commercial production of dried fruits.

Conflict of interest

The authors declare no conflict of interest.

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