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Effects of Different Drying Techniques on Bioactive Compounds and Functional Properties of SCOBY-Fermented Pomelo Substrate Powders

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Abstract

Drying is a critical post-fermentation process because it influences product stability and the retention of bioactive compounds. The present study evaluated the effects of different drying techniques on the physicochemical characteristics, functional properties, bioactive compounds, and antioxidant activities of SCOBY-fermented pomelo peel substrate powders. Pomelo peel substrates fermented with 6% (*w/w*) SCOBY inoculum for 25 days were subjected to freeze drying (FD), hot-air drying (HAD; 50, 70, and 90 °C), and radio-frequency drying (RFD; electrode distances of 14, 15, and 16 cm). Drying kinetics, effective moisture diffusivity (D_{eff}), water activity, color, particle size distribution, functional properties, total phenolic content (TPC), total flavonoid content (TFC), and antioxidant activities were determined. RFD showed comparable or slightly higher moisture diffusivity ($1.19\text{--}2.06 \times 10^{-9} \text{ m}^2/\text{s}$) compared with HAD ($1.03\text{--}1.95 \times 10^{-9} \text{ m}^2/\text{s}$) under suitable drying conditions, suggesting that radio-frequency heating effectively promoted internal moisture migration through volumetric dielectric heating. FD retained the highest antioxidant activity, with DPPH radical scavenging activity of 74.25% and TEAC of 24.85 $\mu\text{mol TE/g}$. However, moderate thermal treatments enhanced phenolic extractability, and HAD at 50 °C showed the highest TPC (161.65 mg gallic acid equivalents (GAE)/g DW). Among the RFD treatments, RFD at 15 cm exhibited the highest TFC (27.18 mg rutin equivalents (RE)/g DW) and maintained relatively high antioxidant capacity. FD powders showed superior water solubility and swelling capacity, whereas RFD produced finer particle distributions and improved drying efficiency. These findings demonstrate that drying techniques significantly influence the quality attributes of SCOBY-fermented pomelo substrate powders, and RFD represents a promising alternative drying technology for balancing drying efficiency and bioactive compound retention.



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1. Introduction

Pomelo (*Citrus grandis* (L.) Osbeck) is one of the major citrus fruits cultivated in Asian countries and is widely consumed because of its characteristic flavor, nutritional value, and abundance of bioactive compounds, including phenolics, flavonoids, vitamin C, and dietary fiber [1]. However, pomelo processing generates a substantial amount of peel

by-products, accounting for approximately 30–50% of the total fruit weight [2]. These by-products are frequently discarded as agricultural waste despite containing considerable amounts of functional compounds with antioxidant potential. Therefore, the valorization of pomelo peel has attracted increasing attention as a sustainable strategy for reducing food waste and developing value-added functional ingredients [2,3].

Fermentation is widely recognized as an effective bioprocessing approach for enhancing the nutritional quality, physicochemical characteristics, and bioactivity of plant-derived materials [4]. Among the various fermentation systems, symbiotic culture of bacteria and yeast (SCOBY), commonly used in kombucha fermentation, has gained increasing scientific interest because of its ability to produce diverse metabolites such as organic acids, enzymes, vitamins, and bioactive compounds during fermentation [5]. The metabolic activities of microorganisms in SCOBY fermentation can alter substrate composition and improve the release and bioavailability of phenolic compounds through enzymatic hydrolysis and biotransformation processes [6].

Previous studies have demonstrated that kombucha fermentation can enhance antioxidant activities and functional properties in various plant substrates, including tea, fruits, herbs, and agricultural by-products [7,8]. Citrus by-products are particularly suitable substrates for fermentation because they are rich in pectin, flavonoids, essential oils, and phenolic acids [9]. Microbial fermentation of pomelo peel has been reported to improve total phenolic content, antioxidant capacity, and functional characteristics while reducing undesirable bitterness [10].

In our previous study, SCOBY fermentation of pomelo peel substrates exhibited dynamic microbial succession during the fermentation process and significantly promoted the generation of bioactive compounds. The optimized fermentation conditions resulted in enhanced antioxidant activity and functional characteristics, demonstrating the potential of SCOBY fermentation as an effective approach for valorizing pomelo peel by-products [11]. These findings suggested that SCOBY-fermented pomelo substrates could serve as promising functional food materials for further processing and industrial applications.

Drying is an essential post-fermentation process used to improve product stability, shelf life, storage efficiency, and transportation convenience [12]. However, drying conditions greatly influence the retention of bioactive compounds and the physicochemical and functional properties of food materials [13]. Different drying methods involve distinct heat and mass transfer mechanisms, which can significantly affect moisture removal, structural integrity, color, particle size, water activity, and antioxidant preservation [14].

FD is considered one of the most effective drying methods for preserving heat-sensitive compounds because water is removed under low-temperature and vacuum conditions. This method generally maintains product structure, color, and bioactive compounds more effectively than thermal drying techniques. Nevertheless, FD is associated with high operational costs and long processing times, limiting its industrial scalability [15]. HAD is one of the most commonly applied drying methods in the food industry because of its operational simplicity and low processing cost. However, prolonged exposure to elevated temperatures may accelerate degradation of phenolic compounds, pigments, and volatile constituents, thereby reducing product quality [16].

RFD has recently emerged as an alternative dielectric heating technology capable of providing rapid volumetric heating and reduced drying times [17]. Compared with conventional HAD, RFD has been reported to improve drying efficiency and better preserve product quality in agricultural materials [17,18]. In addition, drying-induced structural modifications may affect functional properties such as water-holding capacity, oil-holding capacity, swelling capacity, and water solubility, which are important characteristics for food powder applications in beverages, bakery products, and nutraceutical formulations [19].

Although numerous studies have investigated the drying characteristics of fruits and vegetable by-products, limited information is available regarding the effects of different drying techniques on SCOBY-fermented pomelo substrates. Understanding the influence of drying methods on physicochemical characteristics, functional properties, bioactive compounds, and antioxidant activities is important for optimizing the industrial utilization of fermented citrus by-products.

Therefore, the objective of this study was to evaluate the effects of FD, HAD, and RFD on the physicochemical properties, functional properties, bioactive compounds, and antioxidant activities of SCOBY-fermented pomelo substrate powders. The findings of this study may provide useful information for the development of value-added functional food ingredients derived from fermented citrus by-products.

2. Materials and Methods

2.1. Raw Materials and SCOBY Preparation

Fresh pomelo (*Citrus grandis* (L.) Osbeck) fruits were obtained from Bali District, New Taipei City, Taiwan. The fruits were thoroughly washed with tap water and then peeled. After the removal of seeds and inner membranes, the remaining peels, including the exocarp (flavedo) and mesocarp (albedo), were cut into small cubes ($1 \times 1 \times 1$ cm) and stored at -20 °C until use. The symbiotic culture of bacteria and yeast (SCOBY) used in this study was obtained from Biozyme Biotechnology Co., Ltd. (New Taipei City, Taiwan). The SCOBY was originally isolated from a mixed fruit and vegetable fermentation broth prepared from various plant materials and subsequently subcultured to obtain a stable cellulose pellicle culture for fermentation applications.

2.2. Fermentation of SCOBY-Fermented Pomelo Peel Substrate

The SCOBY-fermented pomelo peel substrate was prepared and fermented according to the method described in [11], with slight modifications. Different SCOBY inoculum levels and pomelo peel concentrations were previously evaluated to determine the optimal fermentation condition. Among the tested treatments, the substrate prepared with 6% (*w/w*) SCOBY inoculum and 25 g pomelo peel (S6-P25) exhibited the highest TFC and antioxidant activity after 25 days of fermentation. Therefore, this optimized fermentation condition was selected for the subsequent drying experiments.

Based on the optimized fermentation condition (S6-P25), the fermentation substrate was prepared by mixing 250 g of pomelo peel with a 5% (*w/w*) sucrose solution, and distilled water was added to obtain a final volume of 1000 mL. The SCOBY was then inoculated at 6% (*w/w*) of the total fermentation medium, thoroughly homogenized, and subjected to static aerobic fermentation at 30 °C for 25 days. After fermentation, the fermented substrates were homogenized using a high-speed blender (Osterizer, Sunbeam-Oster Company, Boca Raton, FL, USA) for 10 min to obtain uniform samples for subsequent drying and physicochemical analyses.

2.3. Drying Treatments

2.3.1. Freeze-Drying (FD)

The SCOBY-fermented substrates were packed in polyethylene zipper bags, and excess air was manually removed before sealing to minimize contamination and moisture absorption. The samples were pre-frozen at -20 °C for 24 h to ensure complete freezing prior to lyophilization. After pre-freezing, the frozen samples were transferred to freeze-drying containers and dried using a freeze dryer (FD24, Jin Ming Industrial Co., Ltd., Taipei, Taiwan) under vacuum conditions. Freeze drying was performed for 72 h until

a constant weight was achieved. The dried samples were stored in a desiccator before subsequent analyses.

2.3.2. Hot-Air Drying (HAD)

The SCOBY-fermented substrates were uniformly spread as a single layer on metal trays to ensure uniform heat and mass transfer during drying. HAD was performed using a forced-air drying oven (RHDM-452, Hong Sheng Instrument Co., Ltd., Taipei, Taiwan) at 50, 70, and 90 °C until the moisture content decreased to below 10% (wet basis), which was defined as the operational endpoint for sample collection [12]. After drying, the samples were cooled to room temperature and stored for subsequent analyses.

2.3.3. Radio Frequency Drying (RFD)

The SCOBY-fermented substrates were uniformly spread as a single layer on plastic trays to ensure uniform heating and efficient moisture transfer. RFD was performed using an RFD system (EDB-5D, Yi Da Biotechnology Co., Ltd., Yilan, Taiwan) operated at a frequency of 40.68 MHz and output power of 1000 W with electrode distance of 14, 15, and 16 cm [20]. Drying was continued until the moisture content decreased to below 10% (wet basis), which was defined as the operational endpoint for subsequent analyses. Changes in sample temperature during the drying process were monitored at predetermined time intervals. After drying, the samples were cooled to room temperature and stored for subsequent analyses.

2.4. Analysis of Drying Characteristics

2.4.1. Moisture Content (MC)

The moisture content of SCOBY-fermented pomelo peel substrates during drying was determined [21]. Approximately 3 g of sample was placed in a pre-dried aluminum dish (for HAD) or glass Petri dish (for RFD). The empty containers were previously dried at 103 °C for 1 h, cooled in a desiccator for 30 min, and weighed to a constant mass.

During drying, the samples were periodically removed and weighed to determine the sample mass at each drying time. The weighing interval was 10 min for hot-air drying and 3 min for RFD. After each measurement, the samples were returned to the drying equipment to continue the drying process. To determine the dry matter content, the samples were subsequently dried in a hot-air oven at 103 °C until constant weight was achieved.

The moisture content on a wet basis was calculated according to Equation (1):

$$MC(\%) = \frac{M_t - M_d}{M_t} \times 100 \quad (1)$$

where M_t is the sample weight at drying time (g), and M_d is the dry weight of the sample after oven drying at 103 °C to constant weight (g).

2.4.2. Moisture Ratio (MR)

The drying behavior of SCOBY-fermented pomelo peel substrates was evaluated using the moisture ratio [21–23]. The MR at each drying time was calculated according to Equation (2):

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \quad (2)$$

where M_t is the moisture content at drying time t (g water g^{−1} dry matter), M_0 is the initial moisture content (g water g^{−1} dry matter), and M_e is the equilibrium moisture content

(g water g⁻¹ dry matter). Because the equilibrium moisture content was relatively small compared with M_t and M_0 , the moisture ratio was simplified as follows (3):

$$MR = \frac{M_t}{M_0} \quad (3)$$

The moisture contents used for the calculation were obtained from the moisture content measurements during drying. The variation in MR with drying time was used to compare the drying characteristics of hot-air drying and RFD treatments.

2.4.3. Effective Moisture Diffusivity (D_{eff})

The effective moisture diffusivity of SCOBY-fermented pomelo substrates during drying was estimated using Fick's second law of diffusion for slab-shaped materials [21,23]. Assuming uniform initial moisture distribution, negligible shrinkage, constant diffusivity, and one-dimensional moisture movement, the moisture ratio can be expressed as follows (4):

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-\frac{\pi^2 D_{\text{eff}} t}{4L^2}\right) \quad (4)$$

where MR is the moisture ratio, D_{eff} is the effective moisture diffusivity (m²/s), t is the drying time (s), and L is half of the sample thickness (m). The SCOBY-fermented substrate was spread as a uniform layer with a thickness of 2 mm; therefore, L was taken as 0.001 m for all calculations.

Taking the natural logarithm of Equation (4) yields:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{\text{eff}}}{4L^2}\right) t \quad (5)$$

Linear regression analysis was performed by plotting $\ln(MR)$ against drying time. The coefficient of determination (R^2) was used to evaluate the goodness of fit of the regression model. The effective moisture diffusivity (D_{eff}) was calculated from the slope (k) of the linear regression according to Equation (6):

$$D_{\text{eff}} = \frac{4L^2 k}{\pi^2} \quad (6)$$

where k is the absolute value of the slope obtained from the linear regression of $\ln(MR)$ versus drying time.

2.5. Physicochemical Properties

2.5.1. pH Measurement

The pH of the SCOBY-fermented pomelo substrate was measured at room temperature (25 ± 2 °C) using a calibrated pH meter (Orion Star A111, Thermo Fisher Scientific Inc., Waltham, MA, USA). Prior to measurement, 1 g of the dried powder sample was dispersed in 10 mL of distilled water and mixed thoroughly to form a homogeneous suspension.

2.5.2. Total Soluble Solids (°Brix)

Total soluble solids (TSS) were determined using a digital refractometer (BX-90, TECPEL Co., Ltd., Taipei, Taiwan; range 0–32 °Brix). Prior to analysis, 1 g of the dried powder sample was dispersed in 10 mL of distilled water and stirred thoroughly to obtain a homogeneous suspension. The mixture was then allowed to equilibrate, and the supernatant was obtained for analysis. Approximately 2–3 drops of the supernatant were placed onto the prism surface of the refractometer, and the stabilized reading was recorded. Results were expressed as °Brix.

2.5.3. Titratable Acidity (TA)

Titrate acidity (TA) was determined according to a previously reported method with slight modifications [24]. Prior to analysis, 10 mL of the sample solution was transferred into a beaker. Two to three drops of phenolphthalein indicator were added, and the sample was titrated with 0.1 N NaOH under continuous stirring until a faint pink color persisted for at least 30 s. The volume of NaOH consumed was recorded. TA was calculated and expressed as citric acid equivalents (%). The TA value was calculated using Equation (7):

$$\text{TA}(\%) = \frac{(V \times N \times 0.064 \times 100)}{S} \quad (7)$$

where V is the volume of NaOH consumed (mL), N is the concentration of NaOH (N), 0.064 is the conversion factor for citric acid, and S is the sample volume (mL).

2.5.4. Water Activity (A_w)

Water activity was determined using a water activity meter (Testo 635, Testo Inc., Lenzkirch, Germany). Approximately 2 g of dried SCOBY-fermented pomelo substrate powder was uniformly placed into a circular plastic sample container (4.5 cm diameter $\times$ 1.5 cm height), filling approximately two-thirds of the container volume to facilitate moisture equilibration. The sample was measured for 30 min, during which the instrument continuously monitored the equilibrium relative humidity (RH) within the headspace. After stabilization, the average RH value was recorded, and the water activity was calculated by dividing the equilibrium relative humidity (%) by 100.

2.5.5. Color Measurement

Color characteristics of the dried SCOBY-fermented pomelo substrate powder were determined using a colorimeter (X-Rite 60, X-Rite Color Technology Co., Ltd., Grand Rapids, MI, USA). The samples were placed in circular sample containers (3.5 cm diameter) to ensure a uniform sample surface and consistent measurement conditions [25].

Color values were recorded in the CIELAB color space, where L^* represents lightness (0 = black, 100 = white), a^* represents the red–green axis ($+a^*$ = red, $-a^*$ = green), and b^* represents the yellow–blue axis ($+b^*$ = yellow, $-b^*$ = blue). Measurements were performed at three different positions for each sample, and the average value was used for analysis.

The total color difference (ΔE) between the freeze-dried (FD) sample and the other dried samples was calculated according to Equation (8):

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (8)$$

where L_0^* , a_0^* , and b_0^* represent the color parameters of the freeze-dried sample, while L^* , a^* , and b^* represent the color parameters of the corresponding hot-air-dried or radio-frequency-dried samples.

2.5.6. Determination of Particle Size Distribution

The particle size distribution of the dried SCOBY-fermented pomelo substrate powders was determined according to previously reported methods with slight modifications [26]. Approximately 10 g of each dried powder sample was placed in a stack of standard sieves and separated using a vibratory sieve shaker (CK-600SA, Chin Kang Industry Co., Ltd., New Taipei City, Taiwan) for 5 min.

After sieving, the powder retained on each sieve and in the collection pan was collected and weighed separately. The particle size distribution was classified into seven size fractions: 106–125, 125–150, 150–212, 212–300, 300–425, 425–600, and 600–850 μm . The

proportion of each particle size fraction was expressed as a percentage of the total sample weight and calculated according to Equation (9):

$$\text{Particle size fraction(\%)} = \frac{W_i}{W_t} \times 100 \quad (9)$$

where W_i is the weight of powder retained within a specific particle size fraction (g), and W_t is the total sample weight (g).

2.6. Functional Properties

2.6.1. Oil-Holding Capacity (OHC)

The oil-holding capacity of the dried SCOBY-fermented pomelo substrate powders was determined according to a previously reported method with slight modifications [27]. Briefly, 1 g of powder sample (M_0) was mixed with 20 g of soybean oil in a centrifuge tube (M_1) and allowed to stand at room temperature for 30 min to ensure sufficient oil absorption. The mixture was then centrifuged at 5000 rpm and 4 °C for 30 min using a refrigerated centrifuge (Megafuge 8R, Thermo Fisher Scientific, Waltham, MA, USA). After centrifugation, the supernatant oil was carefully decanted, and the weight of the centrifuge tube containing the oil-absorbed residue was recorded (M_2). The OHC was calculated using Equation (10):

$$\text{OHC(g/g)} = \frac{(M_2 - M_1)}{M_0} \quad (10)$$

where M_0 is the initial weight of the dry powder sample (g), M_1 is the weight of the centrifuge tube with the dry sample (g), and M_2 is the weight of the centrifuge tube containing the oil-absorbed residue after decanting the supernatant (g).

2.6.2. Water-Holding Capacity (WHC)

The water-holding capacity was determined according to a previously reported method with slight modifications [27]. Briefly, 1 g of powder sample (M_0) was dispersed in 20 mL of distilled water in a 50 mL centrifuge tube (M_1) and shaken at 120 rpm for 30 min at room temperature. The suspension was then centrifuged at 9000 rpm and 4 °C for 30 min. After removing the supernatant, the weight of the centrifuge tube containing the hydrated residue was recorded (M_2). The WHC was calculated using Equation (11):

$$\text{WHC(g/g)} = \frac{(M_2 - M_1)}{M_0} \quad (11)$$

where M_0 is the initial weight of the dry powder sample (g), M_1 is the weight of the centrifuge tube with the dry sample (g), and M_2 is the weight of the centrifuge tube containing the hydrated residue after removing the supernatant (g).

2.6.3. Water Solubility (WS)

Water solubility was determined according to a previously reported method with slight modifications [28]. Following the WHC analysis, the supernatant obtained after centrifugation was transferred to a pre-weighed beaker and dried in a hot-air oven at 105 °C to constant weight. The weight of the dried soluble solids was recorded as M_1 . The WS was calculated using Equation (12):

$$\text{WS(\%)} = \frac{M_1}{M_0} \times 100 \quad (12)$$

where M_0 is the initial dry sample weight (g) and M_1 is the weight of the dried solids recovered from the supernatant (g).

2.6.4. Swelling Capacity (SC)

The swelling capacity was determined according to a previously reported method with slight modifications [28]. Briefly, 0.1 g of dried powder sample (M_0) was placed in a graduated cylinder, and 10 mL of distilled water was added. The mixture was allowed to stand at room temperature for 18 h to reach hydration equilibrium. The final volume occupied by the hydrated sample was recorded, and SC was expressed as the volume increase per gram of dry sample. The SC was calculated using Equation (13):

$$SC \left(\frac{\text{mL}}{\text{g}} \right) = \frac{V_2 - V_1}{M_0} \quad (13)$$

where V_1 is the initial volume (mL), V_2 is the volume after swelling (mL), and M_0 is the dry sample weight (g).

2.7. Bioactive Compounds and Antioxidant Activities

2.7.1. Total Phenolic Content (TPC)

The total phenolic content of the extracts was determined using the Folin–Ciocalteu method according to a previously reported method with slight modifications [29]. Briefly, 10 μL of sample extract was mixed with 100 μL of Folin–Ciocalteu reagent and 80 μL of 1 M sodium carbonate (Na_2CO_3) solution in a 96-well microplate. After incubation at room temperature for 15 min, the absorbance was measured at 765 nm using a microplate reader (SP8001, Hong Sheng Instrument Co., Ltd., Taipei, Taiwan). Gallic acid was used as the calibration standard, and the results were expressed as milligrams of gallic acid equivalents per gram of dry sample (mg GAE/g sample).

2.7.2. Total Flavonoid Content (TFC)

Total flavonoid content was determined using the aluminum chloride colorimetric method with slight modifications [30]. Briefly, 100 μL of sample extract was mixed with 30 μL of 5% sodium nitrite (NaNO_2) solution and allowed to react for 1 min at room temperature. Subsequently, 60 μL of 10% aluminum chloride (AlCl_3) solution was added and incubated for 5 min. Then, 200 μL of 1 M sodium hydroxide (NaOH) solution was added, and the mixture was thoroughly mixed. An aliquot (180 μL) of the reaction mixture was transferred to a 96-well microplate, and the absorbance was measured at 510 nm using a microplate reader. Rutin was used as the calibration standard, and the results were expressed as milligrams of rutin equivalents per gram of dry sample (mg RE/g sample).

2.7.3. DPPH Radical Scavenging Activity

The DPPH radical scavenging activity was determined using a previously reported method with slight modifications [31]. Briefly, 0.1 mL of sample extract was mixed with 3.9 mL of 0.1 mM DPPH solution prepared in methanol. The reaction mixture was incubated in the dark at room temperature for 30 min, and the absorbance was measured at 517 nm using a microplate reader. The DPPH radical scavenging activity was calculated according to Equation (14):

$$\text{DPPH scavenging activity}(\%) = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad (14)$$

where A_{control} is the absorbance of the control solution and A_{sample} is the absorbance of the sample solution.

2.7.4. Trolox Equivalent Antioxidant Capacity (TEAC)

The Trolox equivalent antioxidant capacity was determined using the ABTS radical cation decolorization assay with slight modifications [32]. The ABTS $\bullet^+$ working solution was prepared by mixing 7 mM ABTS with 2.45 mM potassium persulfate and allowing the mixture to react in the dark at room temperature for 12–16 h. Prior to analysis, the solution was diluted with ethanol to obtain an absorbance of 0.70 ± 0.02 at 734 nm.

For the assay, 0.1 mL of sample extract was mixed with 3.9 mL of ABTS $\bullet^+$ solution and allowed to react for 6 min at room temperature. The absorbance was then measured at 734 nm using a microplate reader. Trolox was used as the calibration standard, and the antioxidant capacity was expressed as micromoles of Trolox equivalents per gram of dry sample ($\mu\text{mol TE/g sample}$).

2.8. Statistical Analysis

All experiments were independently performed in triplicate using three separate fermentation batches as biological replicates. The results are expressed as the mean $\pm$ standard deviation (SD). Statistical analyses were conducted using SAS software (Version 9.4, SAS Institute Inc., Cary, NC, USA) and JMP software (Version 16, SAS Institute Inc., Cary, NC, USA). Differences among treatments were evaluated by one-way analysis of variance (ANOVA), followed by Tukey's HSD test for post hoc comparisons. Statistical significance was established at $p < 0.05$.

3. Results and Discussion

3.1. Drying Kinetics of Hot-Air Drying and Radio-Frequency Drying

Figure 1 shows the changes in moisture ratio of SCOBY-fermented pomelo peel substrates during HAD and RFD. In both drying methods, MR decreased continuously with drying time, exhibiting a typical falling-rate drying pattern. The rapid decline observed during the initial drying stage was attributed to the removal of free water, whereas the subsequent slower reduction was associated with the diffusion of bound water from the interior of the substrate matrix [13].

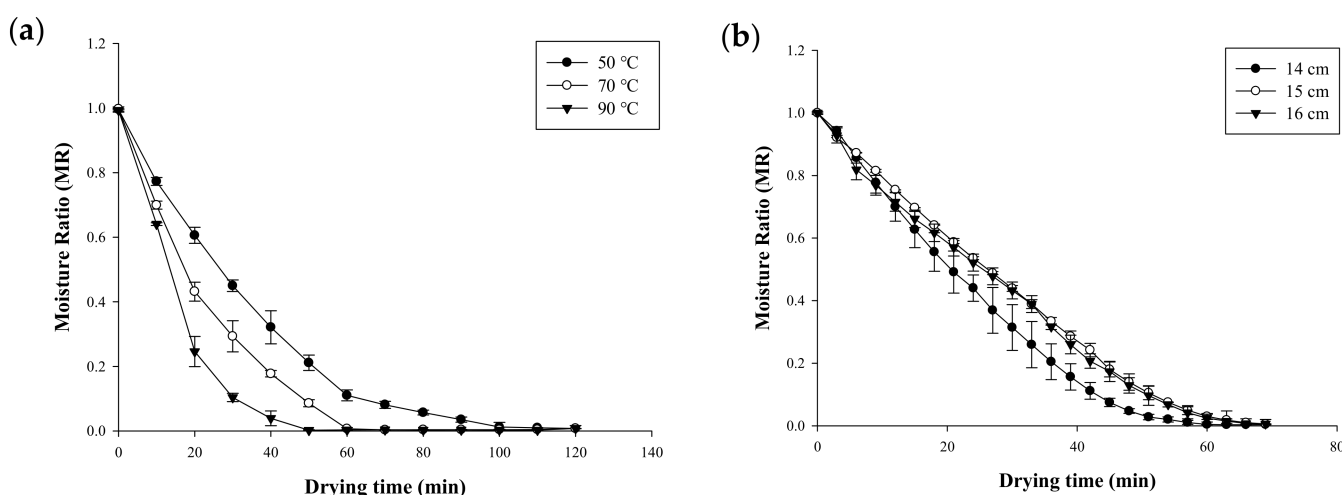


Figure 1. Changes in moisture ratio (MR) of SCOBY-fermented pomelo peel substrates during (a) hot-air drying at different temperatures (50, 70, and 90 °C) and (b) radio-frequency drying at different electrode distances (14, 15, and 16 cm).

In HAD (Figure 1a), increasing the drying temperature significantly accelerated moisture removal. The samples dried at 90 °C reached an MR below 0.01 within approximately 50 min, whereas those dried at 70 and 50 °C required approximately 60 and 110 min,

respectively. The enhanced drying rate at higher temperatures can be attributed to increased heat transfer and moisture diffusivity, which promote water evaporation from the substrate surface [14]. Similarly, RFD (Figure 1b) effectively reduced the moisture content of the fermented substrates. The drying time required to reach an MR below 0.01 was approximately 63, 66, and 69 min at electrode distances of 14, 15, and 16 cm, respectively. Among the tested conditions, the 14 cm electrode distance showed the fastest drying rate, which may be related to the higher electric field intensity generated by the shorter electrode distance. Stronger dielectric heating enhances volumetric energy absorption and facilitates moisture migration from the interior of the material [18]. These findings suggest that RFD can provide rapid moisture removal while potentially reducing the thermal exposure time of the substrate.

3.2. Effective Moisture Diffusivity Under Different Drying Conditions

The linear regression equations, coefficients of determination (R^2), and effective moisture diffusivities (D_{eff}) of SCOBY-fermented pomelo peel substrates under different drying conditions are presented in Table 1. The coefficients of determination (R^2) ranged from 0.6897 to 0.9612, indicating that the linear relationship between $\ln(\text{MR})$ and drying time varied among drying conditions. The HAD treatments showed relatively high R^2 values (0.9145–0.9612), suggesting a satisfactory fit of the simplified Fick's diffusion model, whereas the RFD treatments exhibited more variable fitting performance, particularly at an electrode distance of 15 cm ($R^2 = 0.6897$).

Table 1. Linear regression equations, coefficients of determination (R^2), and effective moisture diffusivity (D_{eff}) of SCOBY-fermented pomelo peel substrates under different drying conditions.

Drying Conditions	Linear Regression Equation	R^2	D_{eff} ($10^{-9} \text{ m}^2/\text{s}$)
HAD 50 °C	$\ln \text{MR} = -0.0007x + 0.6231$	0.9457	1.03 ± 0.08^b
HAD 70 °C	$\ln \text{MR} = -0.0007x + 0.2698$	0.9612	1.14 ± 0.00^b
HAD 90 °C	$\ln \text{MR} = -0.0012x + 0.5150$	0.9145	1.95 ± 0.13^a
RFD 14 cm	$\ln \text{MR} = -0.0011x + 0.5164$	0.9576	2.06 ± 0.20^a
RFD 15 cm	$\ln \text{MR} = -0.0008x + 0.4143$	0.6897	1.19 ± 0.08^b
RFD 16 cm	$\ln \text{MR} = -0.0009x + 0.5650$	0.8825	1.73 ± 0.28^a

Values are expressed as the mean $\pm$ standard deviation (SD). Different superscript letters within the same column indicate significant differences ($p < 0.05$).

For HAD, the mean D_{eff} values ranged from 1.03×10^{-9} to $1.95 \times 10^{-9} \text{ m}^2/\text{s}$. The lowest diffusivity was observed at 50 °C ($1.03 \times 10^{-9} \text{ m}^2/\text{s}$), followed by 70 °C ($1.14 \times 10^{-9} \text{ m}^2/\text{s}$), while the highest value was obtained at 90 °C ($1.95 \times 10^{-9} \text{ m}^2/\text{s}$). The increase in D_{eff} with drying temperature indicates that elevated temperatures enhanced internal moisture diffusion by reducing mass transfer resistance, which is consistent with previous studies on convective drying of agricultural materials [21,25].

For RFD, the calculated D_{eff} values ranged from 1.19×10^{-9} to $2.06 \times 10^{-9} \text{ m}^2/\text{s}$. The highest diffusivity was observed at an electrode distance of 14 cm ($2.06 \times 10^{-9} \text{ m}^2/\text{s}$), followed by 16 cm ($1.73 \times 10^{-9} \text{ m}^2/\text{s}$) and 15 cm ($1.19 \times 10^{-9} \text{ m}^2/\text{s}$). However, the RFD 15 cm treatment showed a relatively lower linear fitting performance ($R^2 = 0.6897$), indicating that the simplified Fick's second law model may not fully describe the moisture migration behavior under this condition. Therefore, the D_{eff} value obtained for RFD 15 cm should be interpreted with caution. Unlike HAD, the relationship between electrode distance and D_{eff} in RFD did not show a monotonic trend. This behavior may be related to the complex interaction among electrode configuration, electric field distribution, dielectric

properties of the samples, and energy transfer efficiency during radio-frequency heating. Therefore, changes in electrode distance may not always result in proportional changes in moisture diffusivity. Despite this limitation, the higher D_{eff} values observed for RFD 14 cm and 16 cm suggest that appropriate electrode spacing can enhance internal moisture migration through volumetric heating [17]. Compared with HAD, the RFD 14 cm treatment exhibited a D_{eff} comparable to HAD at 90 °C, indicating the potential of radio-frequency heating to improve drying efficiency through enhanced internal moisture transport.

When comparing the two drying methods, RFD treatments exhibited comparable or slightly higher D_{eff} values than HAD treatments under suitable drying conditions. In particular, RFD 14 cm showed the highest D_{eff} value among all treatments ($2.06 \times 10^{-9} \text{ m}^2/\text{s}$), which was comparable to that of HAD 90 °C ($1.95 \times 10^{-9} \text{ m}^2/\text{s}$). This result indicates that RF energy transfer effectively enhanced internal moisture migration through volumetric heating. However, the higher D_{eff} value did not necessarily result in a shorter drying time. Although RFD 14 cm enhanced moisture diffusivity, its drying time was approximately 3 min longer than that of HAD 70 °C, possibly due to reduced RF energy absorption efficiency during the later drying stage as moisture content decreased [18,20].

3.3. Water Activity and Moisture Content

The water activity (A_w) and moisture content (MC) of SCOBY-fermented pomelo peel substrates dried under different drying methods and conditions are presented in Table 2. Both parameters were significantly affected by the drying method and processing conditions. In general, higher drying intensity resulted in lower A_w and MC values, indicating more effective moisture removal and improved storage stability. FD samples exhibited the highest A_w (0.34 ± 0.01) and MC ($2.52 \pm 0.02\%$) among all treatments. Although freeze drying effectively removes water via sublimation under vacuum conditions, the highly porous structure formed during drying may facilitate moisture adsorption from the surrounding environment during handling and storage, resulting in slightly higher residual moisture content [33].

Table 2. Water activity and moisture content of dried SCOBY-fermented pomelo peel substrates obtained under different drying methods and conditions.

Drying Conditions		Water Activity	Moisture Content (%)
FD	—	0.340 ± 0.016^a	2.52 ± 0.02^a
HAD	50 °C	0.300 ± 0.008^b	2.35 ± 0.03^b
	70 °C	0.230 ± 0.016^c	2.10 ± 0.07^c
	90 °C	0.220 ± 0.008^c	2.09 ± 0.03^c
RFD	14 cm electrode distance	0.220 ± 0.016^c	2.10 ± 0.02^c
	15 cm electrode distance	0.300 ± 0.008^b	2.35 ± 0.04^b
	16 cm electrode distance	0.320 ± 0.008^{ab}	2.43 ± 0.02^{ab}

Values are expressed as the mean $\pm$ standard deviation (SD). Different superscript letters within the same column indicate significant differences ($p < 0.05$).

For HAD, both A_w and MC decreased as drying temperature increased. The A_w value declined from 0.30 at 50 °C to 0.23 and 0.22 at 70 and 90 °C, respectively, while MC decreased from 2.35% to approximately 2.10%. The reduction in residual moisture at elevated temperatures can be attributed to enhanced heat transfer and accelerated water evaporation, which improve drying efficiency and reduce the amount of water remaining within the substrate matrix [34]. Similar trends have been reported for dried fruit and vegetable products, where increasing drying temperature resulted in lower moisture content and water activity due to intensified moisture removal [19].

A similar tendency was observed for RFD. Among the tested electrode distances, the 14 cm electrode distances produced the lowest Aw (0.22 ± 0.01) and MC ($2.10 \pm 0.02\%$), whereas the 16 cm electrode distances showed the highest Aw (0.32 ± 0.00) and MC ($2.43 \pm 0.02\%$). The lower residual moisture observed at the 14 cm electrode distance is consistent with the higher drying rate and effective moisture diffusivity reported in Sections 3.1 and 3.2. A shorter electrode distance generates a stronger electric field, enhancing volumetric heating and facilitating moisture migration from the interior of the material [18].

3.4. pH, Soluble Solid Content, and Titratable Acidity

The pH, soluble solid content, and titratable acidity of dried SCOBY-fermented pomelo peel substrates obtained under different drying methods and conditions are presented in Table 3. The results indicate that the drying method significantly affected the retention of organic acids and soluble solids in the dried products.

Table 3. pH, soluble solid content ($^{\circ}$ Brix), and titratable acidity (TA) of dried SCOBY-fermented pomelo peel substrates obtained under different drying methods and conditions.

Drying Conditions		pH	$^{\circ}$ Brix	TA (%)
FD	—	3.26 ± 0.07^e	6.6 ± 0.17^a	0.42 ± 0.02^a
HAD	50 $^{\circ}$ C	3.85 ± 0.02^a	5.8 ± 0.19^b	0.24 ± 0.01^f
	70 $^{\circ}$ C	3.81 ± 0.01^{ab}	5.8 ± 0.08^b	0.28 ± 0.01^e
	90 $^{\circ}$ C	3.68 ± 0.01^{bc}	5.3 ± 0.14^c	0.34 ± 0.02^{bc}
RFD	14 cm electrode distance	3.51 ± 0.04^d	6.5 ± 0.05^a	0.36 ± 0.02^b
	15 cm electrode distance	3.57 ± 0.03^{cd}	6.3 ± 0.12^a	0.31 ± 0.01^{cd}
	16 cm electrode distance	3.56 ± 0.04^{cd}	6.4 ± 0.05^a	0.29 ± 0.02^{de}

Values are expressed as the mean $\pm$ standard deviation (SD). Different superscript letters within the same column indicate significant differences ($p < 0.05$).

Among all treatments, FD produced the lowest pH (3.26 ± 0.07) and the highest TA ($0.42 \pm 0.02\%$). This result suggests that FD was most effective in preserving fermentation-derived organic acids. Because freeze drying is conducted under low-temperature and vacuum conditions, thermal degradation and volatilization of organic acids are minimized, thereby maintaining the acidic characteristics of the fermented substrate [35]. In addition, FD samples exhibited the highest soluble solid content ($6.6 \pm 0.17^{\circ}$ Brix), indicating superior retention of soluble compounds during the drying process.

For HAD, pH values ranged from 3.68 to 3.85, whereas TA increased from 0.24% at 50 $^{\circ}$ C to 0.34% at 90 $^{\circ}$ C. The decrease in pH and increase in TA with increasing drying temperature may be attributed to moisture removal and the consequent concentration of non-volatile organic acids. Meanwhile, $^{\circ}$ Brix values decreased slightly from 5.8 to 5.3 as drying temperature increased, suggesting that prolonged exposure to elevated temperatures may have promoted degradation or transformation of certain soluble constituents. Similar trends have been reported in dried fruit products, where high-temperature drying altered the balance between sugar retention and acid concentration [36].

RFD resulted in pH values between 3.51 and 3.57, $^{\circ}$ Brix values between 6.3 and 6.5, and TA values ranging from 0.29% to 0.36%. Compared with HAD, RFD samples generally exhibited lower pH, higher $^{\circ}$ Brix, and higher TA values, indicating better preservation of fermentation-derived compounds. Among the RFD treatments, the 14 cm electrode distances yielded the lowest pH (3.51 ± 0.04) and highest TA ($0.36 \pm 0.02\%$), which corresponded to the highest drying efficiency and effective moisture diffusivity observed in Sections 3.1 and 3.2. The volumetric heating generated by radio frequency energy

likely shortened thermal exposure time and reduced degradation of acid and soluble components [37].

3.5. Color Parameters

The color parameters (L^* , a^* , b^* , and ΔE) of SCOBY-fermented pomelo peel powders obtained using different drying methods and conditions are presented in Table 4. Color is an important quality attribute affecting consumer acceptance and is often used as an indicator of chemical changes occurring during food processing, including pigment degradation, oxidation, and non-enzymatic browning reactions [38]. The FD sample exhibited L^* , a^* , and b^* values of 50.83, 3.20, and 23.88, respectively, and was used as the reference for calculating the total color difference (ΔE). Freeze drying is generally recognized as a mild dehydration technique capable of preserving the original color of plant materials because of its low processing temperature and reduced oxidative deterioration [39]. Therefore, the FD sample was considered an appropriate benchmark for evaluating color changes induced by other drying methods.

Table 4. Color parameters (L^* , a^* , b^* , and ΔE) of dried SCOBY-fermented pomelo peel substrates obtained under different drying methods and conditions.

Drying Conditions			L^*	a^*	b^*	ΔE
FD	—		50.83 ± 0.16^d	3.20 ± 0.06^c	23.88 ± 0.09^b	—
HAD	50 °C		57.74 ± 0.47^b	2.85 ± 0.02^c	24.12 ± 0.15^b	6.92 ± 0.43^c
	70 °C		52.06 ± 0.25^c	1.66 ± 0.01^e	19.33 ± 0.05^d	4.97 ± 0.08^d
	90 °C		52.54 ± 0.45^c	2.29 ± 0.27^d	20.83 ± 0.49^c	3.64 ± 0.40^e
RFD	14 cm electrode distance		56.63 ± 0.37^b	7.74 ± 0.16^b	23.97 ± 0.62^b	7.39 ± 0.47^{bc}
	15 cm electrode distance		58.95 ± 0.24^a	7.81 ± 0.01^b	25.37 ± 0.03^a	9.61 ± 0.33^a
	16 cm electrode distance		56.70 ± 0.25^b	8.33 ± 0.03^a	21.65 ± 0.08^c	8.11 ± 0.26^b

Values are expressed as the mean $\pm$ standard deviation (SD). Different superscript letters within the same column indicate significant differences ($p < 0.05$).

Among the HAD treatments, the L^* value increased at 50 °C (57.74) and subsequently decreased at higher temperatures (52.06–52.54). The a^* values of HAD samples ranged from 1.66 to 2.85, which were lower than that of the FD sample, suggesting a reduction in redness during hot-air drying. The b^* values varied between 19.33 and 24.12, indicating relatively minor changes in yellowness. Furthermore, the ΔE values of HAD samples decreased from 6.92 at 50 °C to 3.64 at 90 °C, suggesting that increasing the drying temperature reduced the overall color deviation from the FD sample. A possible explanation is that higher drying temperatures substantially shortened the drying time, thereby limiting prolonged exposure to oxygen and reducing pigment oxidation and other color-degrading reactions [13]. Similar observations have been reported for dried fruit and vegetable products, where shorter processing times at elevated temperatures contributed to improved color retention [40].

In contrast, the RFD samples exhibited higher L^* values (56.63–58.95) than the FD and HAD samples, indicating greater lightness based on instrumental measurements. Although the RFD powders appeared relatively darker and redder in the photographs, this difference may reflect the discrepancy between visual perception and instrumental color measurement. The higher L^* values obtained for RFD powders may also be associated with their finer particle size distribution, as smaller particles can enhance diffuse light scattering and increase the apparent lightness measured by a colorimeter, even when the intrinsic color appears darker visually. Therefore, the color results in this study were interpreted mainly from the objective color measurements. Moreover, the a^* values of the RFD powders (7.74–8.33) were higher than those of the FD and HAD treatments, leading to larger ΔE values (7.39–9.61). Although RFD is considered a rapid volumetric heating technique that reduces overall thermal exposure compared with conventional HAD, localized temperature variations may occur due to non-uniform electromagnetic field distribution during dielectric heating. These localized hot spots could promote thermal pigment degradation and non-enzymatic browning reactions, contributing to the increased redness (a^*) observed in RFD powders [20,41]. Therefore, the higher a^* values in RFD samples may be attributed to localized thermal effects rather than prolonged thermal exposure.

3.6. Particle Size Distribution

The particle size distributions of SCOBY-fermented pomelo substrate powders produced by different drying methods are shown in Figure 2. As shown in Figure 2a, FD powder exhibited the highest proportion of coarse particles, with 42.0% of particles distributed within the 425–600 μm fraction and 28.0% exceeding 600 μm . In contrast, only 0.4% of particles were smaller than 150 μm .

The predominance of larger particles in FD samples may be attributed to the porous structure generated during sublimation, which reduced particle fragmentation during grinding. Similar findings have been reported for freeze-dried fruit and vegetable powders, where the preservation of cellular structure resulted in larger particle sizes and lower proportions of fine particles [42].

Compared with FD, HAD treatments produced finer powders, particularly at elevated drying temperatures. The combined proportion of coarse particles (>425 μm) was 38.0%, 47.0%, and 51.0% for HAD at 50, 70, and 90 °C, respectively, while the proportion of intermediate-sized particles (212–425 μm) remained relatively high, accounting for 45.0–56.7% of the total particle distribution. The increased brittleness caused by moisture removal and structural shrinkage during hot-air drying may have facilitated particle breakage during milling, resulting in a more homogeneous particle size distribution [43].

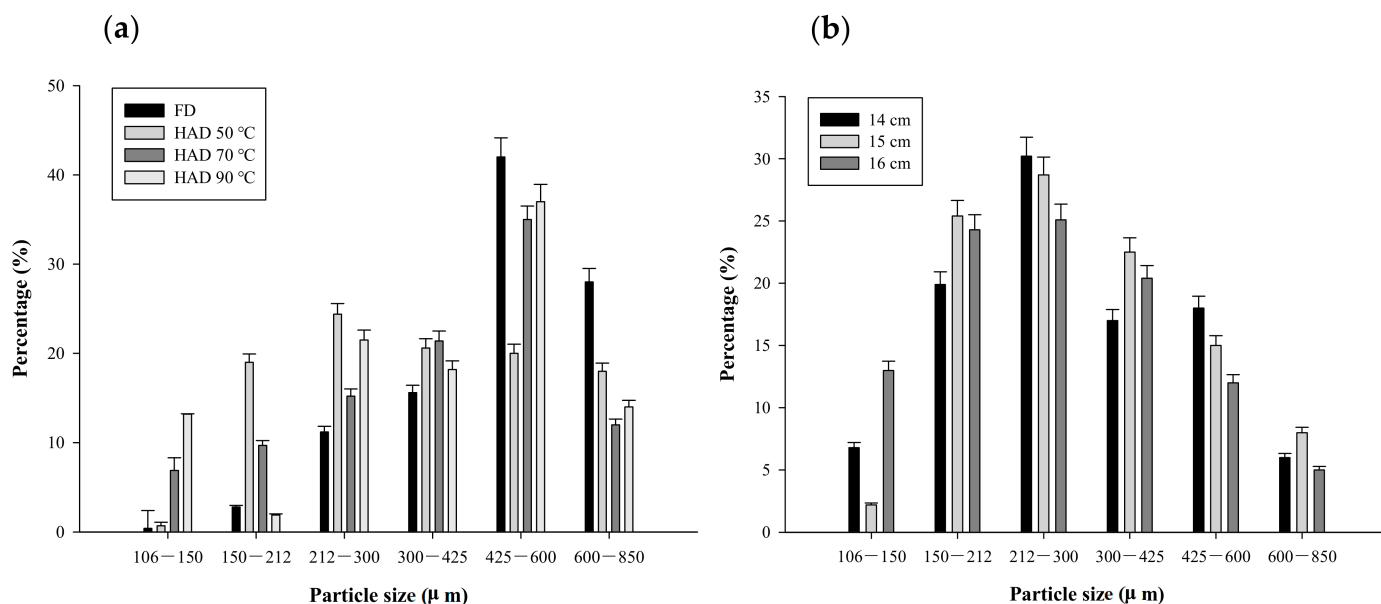


Figure 2. Particle size distribution of dried SCOBY-fermented pomelo peel substrates using different drying methods: (a) FD and HAD at 50, 70, and 90 °C; (b) RFD at electrode distances of 14, 15, and 16 cm. FD, freeze drying; HAD, hot-air drying; RFD, radio-frequency drying. Values are expressed as the mean $\pm$ standard deviation (SD).

The particle size distributions of RFD powders are presented in Figure 2b. Unlike FD and HAD samples, RFD treatments produced substantially finer powders. The proportion of particles smaller than 300 μm increased from 56.1% at an electrode distances of 14 cm to 69.6% and 62.4% at electrode distance of 15 and 16 cm, respectively. In particular, the fraction below 150 μm reached 13.0% in the RFD-16 cm treatment, which was approximately 32-fold higher than that observed for FD powder. Conversely, the proportion of coarse particles (>425 μm) decreased from 24.0% at 14 cm to 17.0% at both 15 and 16 cm. The generation of finer particles in RFD-treated samples may be attributed to volumetric heating, which promotes rapid moisture removal throughout the material matrix. This heating mechanism can induce internal vapor pressure gradients and microstructural disruption, resulting in a more fragile structure that is readily fragmented during grinding. Similar effects of dielectric heating on structural weakening and particle size reduction have been reported in radio-frequency- and microwave-assisted drying studies [44]. Furthermore, the reduced proportion of large particles in RFD powders suggests improved milling efficiency compared with conventional hot-air drying.

In terms of mean particle size, a clear drying-method-dependent trend was observed. The average particle diameter decreased substantially from FD (471.15 ± 1.22 μm) to HAD treatments (351.03 ± 0.37 – 388.63 ± 2.78 μm), and further to RFD samples (262.78 ± 0.69 – 294.14 ± 0.60 μm). Among all treatments, RFD-16 cm exhibited the lowest average particle diameter (262.78 ± 0.69 μm), representing a reduction of approximately 44.3% compared with FD powder. This marked decrease in mean particle size may be associated with structural modifications induced by dielectric volumetric heating, resulting in improved particle fragmentation during grinding.

3.7. Effects of Drying Methods on the Functional Properties of SCOBY-Fermented Pomelo Peel Powders

The oil holding capacity, water holding capacity, water solubility, and swelling capacity of SCOBY-fermented pomelo peel powders produced using different drying methods and conditions are summarized in Figure 3. The FD sample exhibited relatively high OHC

(2.24 g/g), WS (59.60%), and SC (11.91 mL/g), suggesting that freeze drying effectively preserved the structural integrity of the fermented pomelo peel matrix. During freeze drying, the sublimation of ice crystals creates a porous network within the material, facilitating water penetration and enhancing the release of soluble components [45].

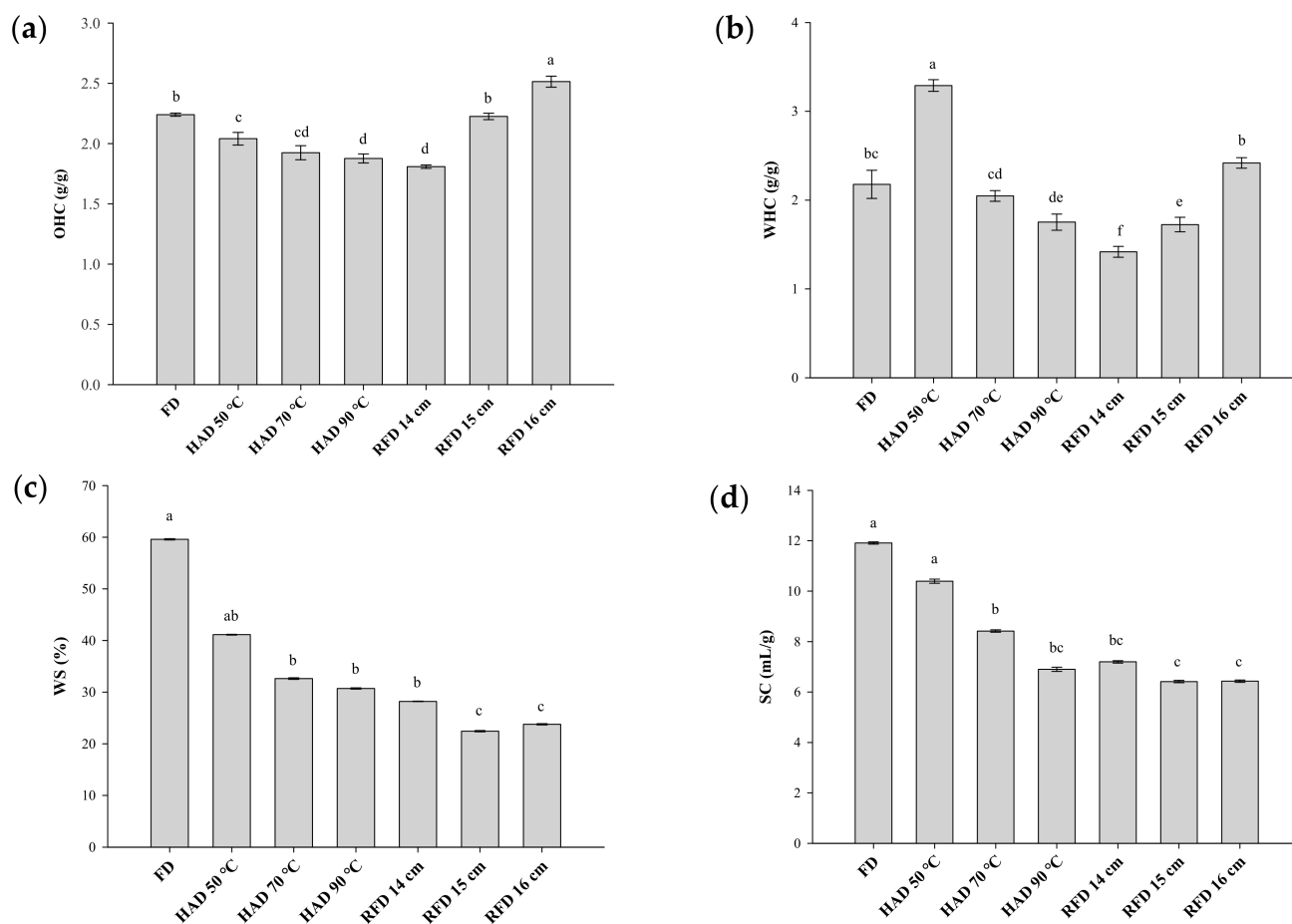


Figure 3. Effects of different drying methods and conditions on the functional properties of dried SCOBY-fermented pomelo peel substrates: (a) oil holding capacity (OHC), (b) water holding capacity (WHC), (c) water solubility (WS), and (d) swelling capacity (SC). FD, freeze drying; HAD, hot-air drying; RFD, radio-frequency drying. Values are expressed as the mean $\pm$ standard deviation (SD). Different lowercase letters above the bars indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

For HAD, OHC gradually decreased from 2.04 g/g at 50 °C to 1.88 g/g at 90 °C. Likewise, WHC declined from 3.29 to 1.75 g/g as the drying temperature increased. The reductions in WHC and SC may be associated with structural shrinkage and collapse induced by thermal treatment, which decrease the number of available hydrophilic sites capable of binding water [46]. In addition, WS decreased markedly from 41.14% at 50 °C to 30.72% at 90 °C, indicating that exposure to higher temperatures may alter the physical structure of the matrix and reduce the dissolution of soluble constituents [47].

The RFD samples exhibited distinct functional characteristics compared with FD and HAD powders. The OHC values ranged from 1.81 to 2.51 g/g, with the highest value observed in the RFD 16 cm treatment. In contrast, the WHC (1.42–2.42 g/g), WS (22.45–28.23%), and SC (6.41–7.20 mL/g) values of RFD powders were generally lower than those of the FD sample. The relatively low WS and SC values suggest that RFD altered the physical characteristics of the dried matrix, thereby limiting water diffusion and swelling behavior. Interestingly, the elevated OHC observed in the RFD 16 cm treatment may

indicate increased exposure of hydrophobic regions within the dried material, enhancing its ability to retain oil. Similar observations have been reported in plant-based powders subjected to dielectric heating processes, where drying conditions influenced the balance between hydrophilic and hydrophobic interactions within the matrix [37]. The lower WHC and SC values observed in RFD powders may also be related to their finer particle size distribution, which can alter pore structure and reduce water entrapment capacity.

3.8. Effects of Drying Methods on Antioxidant Activity and Bioactive Compounds of SCOBY-Fermented Pomelo Peel Powders

The antioxidant activities and bioactive compound contents of SCOBY-fermented pomelo peel powders obtained under different drying methods and conditions are presented in Figure 4. The FD treatment exhibited the highest DPPH radical scavenging activity (74.25%) and TEAC value (24.85 $\mu\text{mol TE/g}$), suggesting that freeze drying effectively preserved antioxidant compounds by minimizing thermal degradation and oxidative deterioration. The low-temperature conditions employed during freeze drying have been reported to better maintain heat-sensitive phytochemicals and antioxidant capacity in plant-based materials [39].

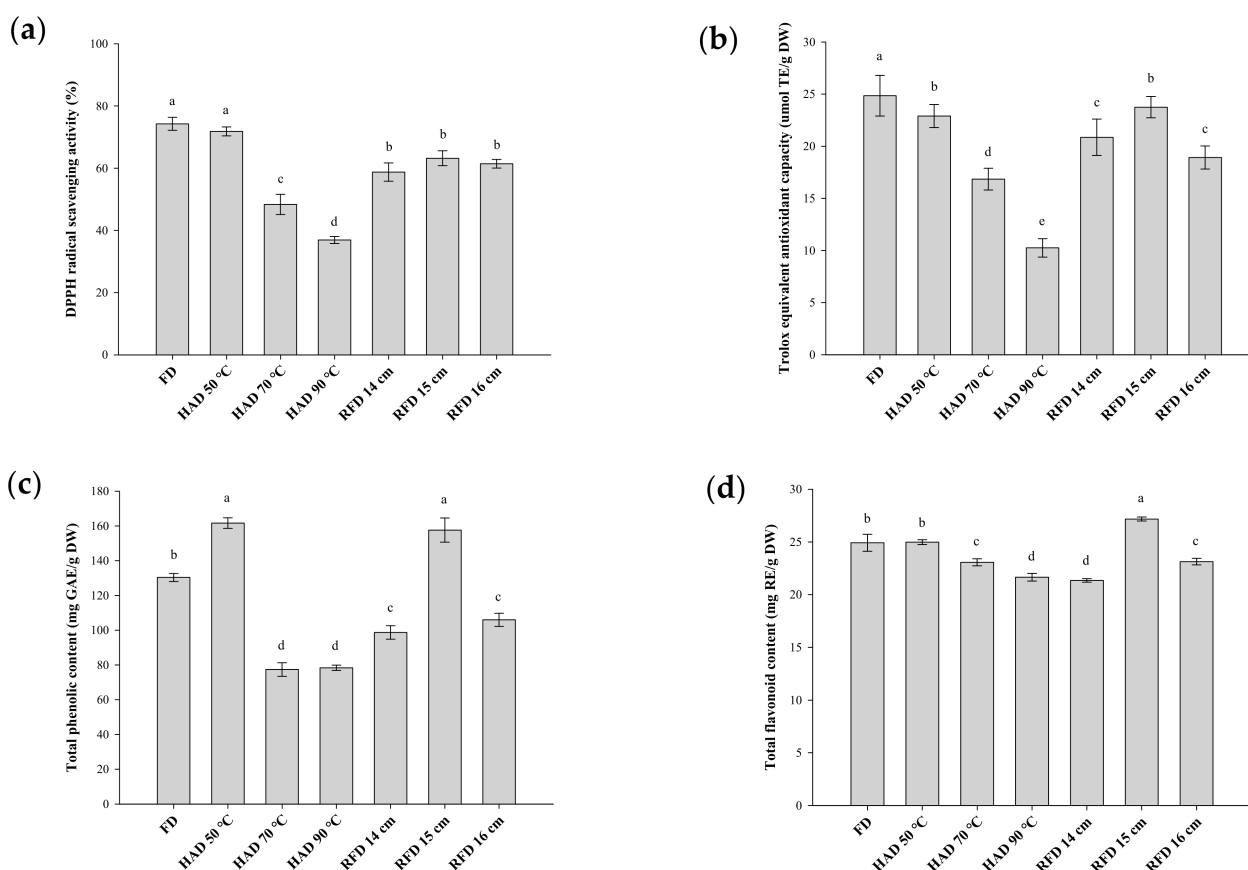


Figure 4. Effects of different drying methods and conditions on the antioxidant activities and phytochemical contents of dried SCOBY-fermented pomelo peel substrates: (a) DPPH radical scavenging activity, (b) Trolox equivalent antioxidant capacity (TEAC), (c) total phenolic content (TPC), and (d) total flavonoid content (TFC). FD, freeze drying; HAD, hot-air drying; RFD, radio-frequency drying. Values are expressed as mean $\pm$ standard deviation (SD). Different lowercase letters above the bars indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

Among the HAD treatments, both antioxidant activity and flavonoid content generally decreased with increasing drying temperature. DPPH radical scavenging activity declined markedly from 71.82% at 50 °C to 36.92% at 90 °C, while TEAC values decreased from

22.90 to 10.25 $\mu\text{mol TE/g}$. Similarly, TFC decreased from 24.99 to 21.66 mg RE/g as the drying temperature increased. These results suggest that exposure to elevated temperatures promoted the degradation of antioxidant constituents, particularly flavonoids, thereby reducing the free radical scavenging capacity of the powders [48]. Interestingly, the TPC value of HAD 50 °C (161.65 mg GAE/g) was significantly higher than that of the FD treatment (130.37 mg GAE/g). This increase may be attributed to the release of bound phenolic compounds resulting from moderate thermal treatment, which enhanced their extractability [49].

The RFD treatments demonstrated intermediate antioxidant properties between FD and HAD. Among the RFD samples, the 15 cm electrode distance exhibited relatively high DPPH activity (63.18%), TEAC value (23.75 $\mu\text{mol TE/g}$), TPC (157.61 mg GAE/g), and the highest TFC (27.18 mg RE/g). These results indicate that the 15 cm electrode distance provided a more favorable balance between heating intensity and temperature uniformity, thereby enhancing the retention of phenolic and flavonoid compounds. In contrast, the RFD 14 cm and 16 cm treatments exhibited lower TPC and antioxidant activities, indicating less favorable heating conditions. Previous studies have also reported that optimized radio frequency drying conditions effectively preserve antioxidant compounds while improving processing efficiency [18,20]. However, the optimal electrode distance depends on factors such as sample composition, dielectric properties, moisture content, sample thickness, electrode configuration, and equipment specifications. Therefore, the 15 cm electrode distance identified in this study should be considered optimal only under the present experimental conditions rather than as a universal optimum for radio frequency drying.

4. Conclusions

Drying methods significantly affected the quality and functionality of SCOBY-fermented pomelo peel substrate powders. RFD exhibited higher effective moisture diffusivity than HAD, indicating enhanced moisture transport during drying. FD best preserved antioxidant activity and rehydration-related functional properties, whereas HAD at 50 °C resulted in the highest total phenolic content. Among the RFD treatments, an electrode distance of 15 cm provided a favorable balance between overall drying performance and bioactive compound retention, although the increased color deviation should be considered. Although FD preserved antioxidant activity and rehydration-related properties more effectively than the other drying methods, RFD, particularly at a 15 cm electrode distance, may represent a promising alternative for producing value-added functional ingredients from SCOBY-fermented pomelo peel substrates. Future studies should further investigate phenolic profiles, microstructural characteristics, and storage stability to support industrial applications. However, the variability in moisture-diffusivity model fitting for RFD treatments represents a limitation of this study, and further validation using additional replicates and alternative kinetic models is recommended.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr14152481/s1>, Table S1: Numerical data underlying Figure 2 (particle size distribution); Table S2: Numerical data underlying Figure 3 (functional properties); Table S3: Numerical data underlying Figure 4 (antioxidant activities and phytochemical contents).

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