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Innovative drying methods of kiwi fruit: Effects on phenolic content, antioxidant activity, and microstructural properties

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RESEARCH ARTICLE

Abstract

This study investigates the effects of different drying methods and temperatures on the total phenolic content (TPC), antioxidant activity, and microstructural properties of kiwi fruit. Fresh samples were subjected to hot air drying (HAD), vacuum drying (VD), ultrasound-assisted vacuum drying (UAVD), and freeze drying (FD) at 50°C, 60°C, and 70°C. Drying time significantly decreased with increasing temperature across all methods, with the shortest duration recorded for VD at 70°C (210 min), while UAVD at 60°C presented an optimal balance of drying efficiency and quality retention (300 min). TPC was strongly influenced by drying conditions; FD samples showed the highest TPC (5216.7-mg gallic acid equivalent [GAE]/100-g dry matter [DM]), followed by UAVD at 60°C (4760.9-mg GAE/100-g DM). Antioxidant activity measured by 2,2-diphenyl-1-picrylhydrazyl (DPPH) also peaked in UAVD70 (38.6 mg *Trolox equivalent* [TE]/100-g DM) and FD (35.1 mg TE/100-g DM), showing a strong positive correlation with TPC (R^2 > 0.85). 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid (ABTS) values remained more stable but declined slightly, compared to fresh samples, with UAVD70 (8.30 mg TE/100-g DM) performing comparably to FD (8.76 mg TE/100-g DM). Among phenolic acids, chlorogenic acid was best preserved in UAVD50 (14.92 µg/mL), while FD maintained the highest caffeic acid content (0.72 µg/mL). Color analysis showed significant differences: FD resulted in the brightest product (L^* = 71.2), while HAD70 yielded darker tones and the highest a^* shift because of chlorophyll degradation. The environmental scanning electron microscopy imaging confirmed that FD retained the best cellular integrity, while HAD70 caused pronounced structural collapse. UAVD-treated samples maintained porosity and structure, confirming the beneficial effect of ultrasound on preservation of microstructure. Overall, FD proved superior in preserving nutritional and structural quality, while UAVD, especially at 60°C, emerged as a promising and efficient alternative for producing high-quality dried kiwi fruit.

Keywords: ESEM; kiwi fruit; phenolic retention; ultrasound-assisted drying; vacuum drying

Introduction

Kiwi, known as *Actinidia deliciosa*, is a widely consumed tropical fruit because of its high nutritional value and distinctive flavor. Kiwi is rich in bioactive components, such as vitamins C and E, folate, and potassium, which give this fruit strong free radical scavenging capabilities. Kiwi reduces oxidative stress and disease

risk and prevents cardiovascular diseases, thanks to its anti-inflammatory, antibacterial, anticarcinogenic, and antioxidant properties (Moysidou *et al.*, 2024; Zehra *et al.*, 2020). However, because of seasonal availability, kiwi fruit's shelf life and consumption are limited. Additionally, even in low-temperature storage environments, fresh kiwi fruit is extremely susceptible to microbial contamination. These challenges of kiwi fruit need to be overcome by using processing for its off-season availability (Akcicek *et al.,* 2023; Satpal *et al.,* 2021).

Drying is a food processing technique that extends shelf life because it reduces water activity and mass of the product. This method ensures quality and stability and reduces spoilage and contamination. It also facilitates packaging and transportation, changes sensory properties both positively and negatively depending on the nature of the drying process applied, and significantly affects quality of the final product (Petikirige *et al.,* 2022).

Drying methods are basically divided into two types: natural drying and artificial drying. Artificial drying methods are better in terms of efficiency and quality. Artificial drying methods are hot air drying (HAD), microwave drying, vacuum drying (VD), freeze drying (FD), osmotic drying, infrared drying, heat pump drying, and hybrid drying.

Sun drying, which is a natural drying method, is one of the most common methods and a good method in terms of energy efficiency. However, concerning disadvantages, foods with low sugar and acid content are at a high risk of spoilage, insect infestation, dust, and length of drying time.

The HAD method is a cheap method, but it causes serious component changes, oxidation, and changes in odor in the final product, so it is not a good method in terms of quality. This technique is frequently applied to fruits such as grapes, apples, and bananas. On the other hand, HAD might change fruit's texture and flavor and result in the loss of heat-sensitive nutrients.

Microwave drying is a good method in terms of power consumption and final product quality, but the efficiency of this method can be increased by using hybrid techniques, taking into account thermal and oxidative stress. It is observed that properties such as color, damage, and darkness of products, such as carrots and grapes, dried by microwave drying show better results (Changrue *et al.,* 2006; Hassoun *et al.*, 2025; Petikirige *et al.*, 2022).

Freeze drying provides exceptional preservation of the final product quality, but its disadvantages include length of drying time and cost. Berries, apples, and citrus fruits are the examples of high-value fruits that work well with this method because they are particularly heat-sensitive. One of the finest methods for preserving fruit quality is FD, which keeps to a large extent fruit's shape, color, flavor, and nutritional content (Ciurzyńska and Lenart, 2011).

Vacuum drying is a good method in terms of low operating temperature, working capacity in a low-oxygen atmosphere, and drying speed, and the efficiency of this method is increased by using hybrid techniques. This method is effective for fruits that are sensitive to heat, such as strawberries and blueberries. VD helps in preserving the color, flavor, and nutritional contents of fruits in a better manner than HAD (Bezyma and Kutovoy, 2005; Sun *et al.,* 2019).

The ultrasound (US)-assisted vacuum drying (UAVD) technology is widely used because it shortens drying time without the need for heating under vacuum conditions and increases drying efficiency by increasing dehydration rate. It is particularly ideal for fruits, such as mangoes and pineapples, as it minimizes drying time and increases the quality of dried product by maintaining more of fruit's natural features (Zhang and Abatzoglou, 2020).

Blueberry fruit was dried using a variety of techniques in recent studies, including FD, HAD, and UAVD. Drying kinetics, total phenolic content (TPC), antioxidant activity, microstructural characteristics, and anthocyanin content of each drying method were identified. We looked at its content and how it affected the qualities of color (Akcicek *et al.,* 2023). Dried fruits include papaya, mango, and banana. The cellular structure of plant tissues is damaged during the drying process, changing dried tropical fruit's overall quality. Studies conducted on fruits, including bananas, however, revealed that color deterioration and shape deformation are not greatly impacted by drying methods such as FD. On the other hand, very little is known about how drying methods affect tropical fruit's sensory qualities. Therefore, in order to ascertain how drying methods affect tropical fruits, such as pineapple, scientific research is required (Petikirige *et al.,* 2022).

In the current research, kiwi fruit was subjected to different drying methods, such as HAD, UAVD, and FD, at three different temperatures (50°C, 60°C, and 70°C). The study aimed to examine the effect of these drying techniques on drying kinetics, TPC, antioxidant activity, microstructural properties, anthocyanin content, and color properties.

Materials and Methods

Fresh kiwi fruit (Hayward) used in this study was purchased from a local grocery store (Migros Tic. A.Ş., Gölbasi, Turkey). The initial moisture content of the fruit was determined as 85.58±0.93% using a vacuum oven at

70°C for 6 h (Agroindustrias, 2013). Approximately five fresh kiwi fruits (30 g) were used for each process. All the chemicals and standards utilized in this study were sourced from Merck (Darmstadt, Germany).

Sample preparation

Kiwi samples underwent drying process using four distinct methods: HAD, VD, UAVD, and FD. The drying process was conducted at three different temperatures: 50°C, 60°C, and 70°C. During HAD, air was circulated at a constant speed of 1.3 m/s, which was measured using a vane probe anemometer (Testo 440, Taiwan). The air was directed horizontally over the surface of the kiwi slices to ensure uniform drying. The UAVD process followed the protocol detailed in prior studies, ensuring optimal conditions for ultrasound assistance (Akcicek *et al.*, 2023). A vacuum pump (EVP 2XZ-2C, Zhejiang, China) was utilized for VD and UAVD methods, maintaining a steady vacuum pressure of 60 mbar with a pump speed of 2 L/s. The FD process was executed using a freeze-drying system (Martin Christ, Beta 1-8 LSC plus, Osterode am Harz, Germany) (Martin ,Christ, Beta 1–8 LSC Plus,), with kiwi samples pre-frozen at -80°C overnight before drying. The weight of kiwi samples was monitored at regular intervals (every 60 min) during HAD, VD, and UAVD to track loss of moisture over time. The drying process for each method continued until the moisture content of the samples was reduced to 0.2 kg water/ kg dry matter (DM).

Extraction procedure

The extraction of bioactive compounds was performed using a 1:1 mixture of methanol and water. For this purpose, 1 g of the sample was transferred into a test tube, and 10 mL of methanol–water mixture was added to achieve homogenization. The mixture was then shaken at 5,000 rpm for 1 h at room temperature. Following this, it was centrifuged at 5,000 rpm for 10 min to separate the phases. The resulting supernatant was filtered and stored at –20°C.

Determination of total phenolic content

The TPC of samples was assessed using a modified version of the Folin–Ciocalteu method (Singleton *et al.*, 1965). For this analysis, 0.5 mL of extract was mixed with 2.5 mL of a 10-fold diluted Folin–Ciocalteu phenol reagent and 2 mL of 7.5% Na_2CO_3 solution. The mixture was incubated at room temperature in the dark for 30 min, after which spectrophotometric measurements were taken at 760 nm using a Shimadzu UV-1800 device. Results were reported as milligrams of gallic acid equivalent (mg GAE)/g of DM.

Determination of antioxidant capacity (DPPH and ABTS)

For determining antioxidant activity using 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay, 0.1 mL of each sample extract was mixed with 3.9 mL of freshly prepared DPPH solution (0.1 mM in methanol). The mixture was incubated in the dark at room temperature for 60 min. Following incubation, the absorbance was measured at 517 nm using a ultraviolet-visible (UV-Vis) spectrophotometer. Antioxidant activity was calculated based on a Trolox calibration curve, and results were expressed as milligrams of Trolox equivalent/100 grams of DM (mg TE/100 g DM). 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid (ABTS) radical scavenging activity was determined according to the method described by Akcicek *et al.* (2023). Results were expressed as Trolox equivalent.

Phenolic component analysis

The quantification of caffeic acid and chlorogenic acid was performed using a C18 column (250 × 4.6 mm; 5 µm) with a gradient elution system consisting of acetonitrile (containing 2.5% formic acid) and 2.5% formic acid aqueous solution (10:90 v/v). The analysis was carried out at 25°C with a flow rate of 0.5 mL/min. A diode-array detector in the HPLC system (Shimadzu LC-20A; Kyoto, Japan) was used to monitor compounds at 320 nm. Stock solution of each compound was prepared at a concentration of 1 mg/mL using standard materials. Calibration solution of each compound was prepared by diluting appropriate amount of stock solution with mobile phase (50:50 v/v). These calibration solutions were injected into the HPLC system under specified conditions, and calibration curves were constructed based on the peak areas corresponding to different concentrations. For each standard compound, calibration curves were established using five concentrations, each analyzed in quintuplicate, yielding calibration equations with $R^2 > 0.99$. For sample analysis, 500 µL of each extract was mixed with mobile phase (50:50 v/v) to a final volume of 1 mL. After vortexing for 30 s, 20 µL of solution was injected into the HPLC system under defined conditions. Quantification of the compounds was carried out using the calibration equations obtained for each compound.

Color measurement

The color analysis of samples was performed using a colorimeter (Konica Minolta CR-400, Japan). L*, a*, and b*

parameters, representing lightness/darkness, redness/greenness, and yellowness/blueness, respectively, were measured after calibration under a standard illuminant. The overall color change of the samples was expressed as ΔE.

Environmental scanning electron microscopy (ESEM)

The internal cross-sectional microstructure of both fresh and dried kiwis was visualized using ESEM. To prepare the samples, the kiwis were halved with a knife. The imaging was performed using an ESEM (Thermo Scientific™ Quattro ESEM) set to an operating voltage of 3 kV.

Statistical analysis

Data were analyzed using the JMP 9 software (JMP Pro, Version 9; SAS, NC). Arithmetic mean values and standard deviations of relevant variables were calculated. One-way analysis of variance and Tukey's test were employed to determine significant differences between variables.

Result and Discussion

Drying curves

Drying durations for kiwi fruit exhibited notable differences based on the applied drying techniques and temperatures. HAD recorded the longest period, requiring 600 min, 450 min, and 330 min at 50°C, 60°C, and 70°C, respectively. Decrease in drying period with increasing temperature was attributed to enhanced thermal energy transfer, promoting faster moisture evaporation. VD demonstrated improved efficiency with drying period of 420 min, 360 min, and 210 min at the same temperature levels, benefiting from reduced pressure conditions that facilitated moisture removal. UAVD presented a distinct trend, with drying period of 390 min, 300 min, and 330 min at 50°C, 60°C, and 70°C, respectively. The prolonged drying period at 70°C may be linked to uneven ultrasound energy distribution or structural changes in material at elevated temperatures. While HAD proveds effective for rapid drying at high temperatures, VD and UAVD offered more controlled drying environments. Among these, UAVD at 60°C stands out as an ideal condition, balancing efficiency and potential preservation of the fruit's nutritional and structural qualities. The effect of temperature on moisture content and drying period is illustrated in Figure 1, highlighting distinct drying patterns observed for each method at different temperature levels.

Studies indicate that the application of ultrasound is an effective method for accelerating the drying process (Llavata *et al.,* 2024a). According to a study conducted by García-Pérez *et al.* (2023), ultrasound creates microcracks within the samples and generates micro-agitation on the surface, significantly facilitating mass transfer. This mechanism enhances moisture loss, thereby shortening drying period. Similarly, a study conducted by Llavata *et al.* (2024a) reported that drying processes at 70°C never exceeded 6 h, and the use of ultrasound reduced the drying period by 19%. These findings further confirmed that higher temperatures provided greater energy content, enhancing the mobility of water molecules and accelerating phase transition from liquid to vapor.

Effect of drying methods on total phenolic content and antioxidant capacity of kiwi fruits

The TPC and antioxidant capacity of fresh and dried kiwi fruits are presented in Table 1. The TPC of fresh kiwi was determined as 2801.2 mg GAE/100 g DM. Drying methods and temperatures had significant effects on the

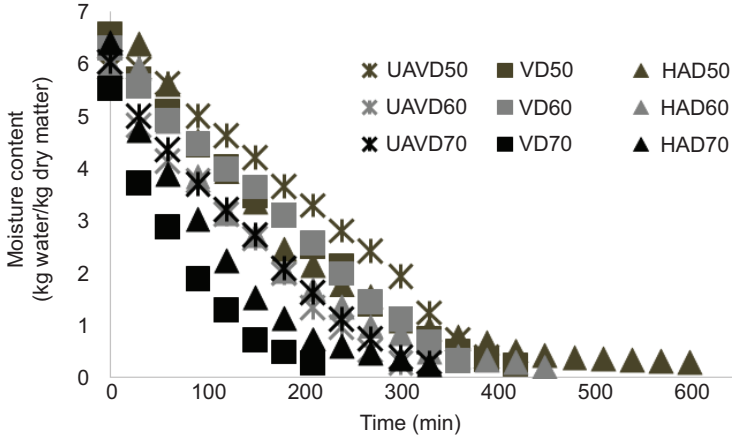

Figure 1. Drying curves of kiwi fruit dried with HAD, UAVD, and VD.

preservation of phenolic compounds. The highest TPC of 5216.7 mg GAE/100 g DM was achieved with the FD method, and was significantly higher statistically than other methods ($p < 0.05$). HAD yielded the lowest TPC of 3179.10 mg GAE/100 g DM at 50°C, and a noticeable decline in TPC as 3319.4 mg GAE/100 g DM was observed with increasing temperature at 70°C. The VD method demonstrated relatively better performance in preserving TPC, with 3798.6 mg GAE/100 g DM at 60°C. UAVD outperformed both VD and HAD at all temperatures, achieving the highest TPC value of 4760.9 mg GAE/100 g DM at 60°C.

Statistical analysis indicated significant differences between different temperatures and methods ($p < 0.05$). Notably, significant phenolic loss was observed at 70°C for both HAD and VD, while UAVD showed more stable results. These findings suggested that FD was the most effective method for preserving bioactive compounds, while UAVD emerged as a promising alternative because of its phenolic retention capacity and process efficiency.

In a similar study, the combination of ultrasound application and high temperatures led to significant improvement in TPC. This increase could be attributed to the ability of ultrasound to rupture cell membranes, facilitating the extraction of phenolic compounds, and the binding of hydroxyl radicals to aromatic rings (Llavata *et al.,* 2024b).

The DPPH radical scavenging activity (mg TE/100 g DM) of fresh and dried kiwi fruits is presented alongside TPC results (Table 1). Fresh kiwi showed the lowest antioxidant capacity at 9.9 mg TE/100 g DM. FD yielded a DPPH value of 35.1 mg TE/100 g DM, demonstrating superior antioxidant preservation, compared to other methods. HAD at 50°C exhibited a relatively low antioxidant capacity (29.0 mg TE/100 g DM), which decreased further at 60°C (33.2 mg TE/100 g DM) before increasing unexpectedly to 42.1 mg TE/100 g DM at 70°C, possibly because of the formation of Maillard reaction products known for antioxidant activity (Llavata *et al.*, 2022). In general, VD and UAVD showed better antioxidant capacities compared to HAD. UAVD at 70°C provided the highest antioxidant value (38.6 mg TE/100 g DM), followed by 60°C (35.7 mg TE/100 g DM). Statistical analysis revealed a strong positive correlation between TPC and DPPH antioxidant capacity, indicating that higher TPC contributes significantly to antioxidant activity. The results highlight FD and UAVD as superior methods for maintaining both phenolic compounds and antioxidant activity, with UAVD being particularly effective at moderate to high temperatures.

It was observed in the literature that freeze VD and ultrasound-assisted pre-treatment had no significant effect on the DPPH free radical scavenging capacity of kiwi fruit, compared to fresh samples (Yue *et al.,* 2025; Zhang *et al.,* 2019). The ABTS radical scavenging activity (mg TE/100 g DM) results for fresh and dried kiwi fruits revealed significant variations depending on the drying method and temperature. Fresh kiwi showed the highest antioxidant capacity (10.6 mg TE/100 g DM), while FD samples had a slightly lower but still higher value of 8.76 mg TE/100 g DM, indicating minimal degradation during the drying process. At 50°C, HAD samples exhibited the lowest antioxidant activity (6.77 mg TE/100 g DM, suggesting significant thermal degradation of antioxidants. As temperature increased to 70°C, a slight recovery in ABTS activity was observed (8.42 mg TE/100 g DM), likely because of the formation of new antioxidant compounds. VD and UAVD maintained relatively stable ABTS values across temperatures, with UAVD at 70°C achieving a comparable level (8.30 mg TE/100 g DM) to FD. Statistical analysis showed a moderate positive correlation between TPC and ABTS values, indicating that phenolic compounds were partially responsible for antioxidant activity, although other non-phenolic antioxidants might also contribute. FD and UAVD emerged as effective methods for retaining antioxidant capacity, with UAVD providing competitive results even at higher temperatures.

Effect of drying methods on phenolic compounds of kiwi fruits

Chlorogenic acid content (μg/mL) in fresh and dried kiwi fruits varied significantly with drying method and temperature (Table 2). Fresh kiwi contained 1.93 μg/mL, while FD preserved 12.00 μg/mL. At 50°C, VD yielded the highest chlorogenic acid content (14.92 μg/mL), followed by HAD yielding 13.39 μg/mL and UAVD yielding 12.06 μg/mL. At higher temperatures (60°C and 70°C), a significant decline in chlorogenic acid was observed across all methods, with UAVD at 70°C yielding the lowest content (4.86 μg/mL). These results indicated that FD and UAVD at 50°C were most effective in preserving chlorogenic acid, while higher temperatures lead to significant degradation.

Caffeic acid content (μg/mL) in fresh and dried kiwi fruits showed notable differences based on drying method and temperature (Table 2). Fresh kiwi had the lowest content of caffeic acid as 0.11 μg/mL, while FD preserved the highest content at 0.72 μg/mL. At 50°C, HAD retained 0.52 μg/mL, followed by VD yielding 0.41 μg/mL and UAVD yielding 0.34 μg/mL. At higher temperatures (60°C and 70°C), the caffeic acid content decreased significantly across all methods, with UAVD at 70°C showing the lowest value of 0.20 μg/mL. These results suggested that FD was most effective in preserving caffeic acid, and higher drying temperatures led to a reduction in its content.

Table 1. Total phenolic content and antioxidant activity values of fresh and dried kiwi fruits.

Fresh	FD		HAD	VD	UAVD
TPC (mg GAE/100 g DM)					
2801.2±99.18^{G}	5216.7±132.23^{A}	50°C	3179.10±60.61^{F}	4686.8±11.02^{B}	3592.1±27.55^{D,E}
		60°C	3595.98±11.02^{D,E}	3798.6±66.12^{D}	4760.9±27.55^{B}
		70°C	4620.6±16.53^{B}	3319.4±126.72^{E,F}	4125.8±121.21^{C}
DPPH (mg TE/100 g DM)					
9.9±0.24^{H}	35.1±0.24^{C}	50°C	29.0±0.03^{E}	23.4±0.20^{G}	25.0±0.07^{F}
		60°C	33.2±0.19^{D}	28.9±0.36^{E}	35.7±0.24^{C}
		70°C	42.1±0.16^{A}	33.5±0.35^{D}	38.6±0.28^{B}
ABTS (mg TE/100 g DM)					
10.6±0.01^{A}	8.76±0.0^{B}	50°C	6.77±0.30^{C}	7.17±1.06^{B,C}	8.24±0.45^{B,C}
		60°C	8.53±0.04^{B,C}	8.13±0.50^{B,C}	7.78±0.63^{B,C}
		70°C	8.42±0.37^{B,C}	8.15±0.03^{B,C}	8.30±0.01^{B,C}

Different superscripted capital letters in the same row indicate differences between samples subjected to different drying methods ($p < 0.05$).
FD: freeze drying; HAD: hot air drying; VD: vacuum drying; TPC: total phenolic content; UAVD: ultrasound-assisted vacuum drying.
TPC, DPPH, and ABTS radical scavenging assays were used to assess antioxidant capacity.

Table 2. Chlorogenic acid and caffeic acid values of fresh and dried kiwi fruit.

Fresh	FD		HAD	VD	UAVD
Chlorogenic acid (µg/mL)					
1.93^{K}	12.00^{D}	50°C	13.39^{B}	14.92^{A}	12.06^{C}
		60°C	5.93^{I}	10.36^{E}	9.64^{F}
		70°C	8.19^{H}	8.64^{G}	4.86^{J}
Caffeic acid (µg/mL)					
0.11^{J}	0.72^{A}	50°C	0.52^{B}	0.41^{D}	0.34^{E}
		60°C	0.30^{G}	0.30^{G}	0.47^{C}
		70°C	0.26^{H}	0.33^{F}	0.20^{I}

Different superscripted capital letters in the same row indicate differences between samples subjected to different drying methods ($p < 0.05$).
FD: freeze drying; HAD: hot air drying; VD: vacuum drying; TPC: total phenolic content; UAVD: ultrasound-assisted vacuum drying.

Caffeic acid and its derivatives are common phenolic compounds found in various kiwi cultivars (Zhu *et al.,* 2021). A study conducted by Liu *et al.* (2019) reported that chlorogenic acid content in kiwi samples was significantly higher, ranging from 3.98 mg/kg to 77.39 mg/kg. On the other hand, levels of caffeic acid varied between 0.89 mg/kg and 18.30 mg/kg, with most values being notably higher than those reported previously by Bursal and Gulcin (2011) and Ma *et al.* (2017). The increase in caffeic acid and chlorogenic acid in dried kiwi fruit, compared to fresh ones, could be attributed to the concentration of these compounds because of moisture removal and the intensification of fruit components during heating. Similar findings were reported in related studies, where thermal processes facilitated the release or formation of bound phenolics, thereby enhancing their overall concentration in dried fruit products (Nunes *et al.,* 2016; Özcan *et al.,* 2020).

Color

The color parameters (L*, a*, b*, and ΔE) of fresh and dried kiwi fruits were significantly influenced by the drying methods and temperature (Table 3). For the lightness parameter (L*), fresh kiwi had the lowest value (46.3±0.61), which increased significantly in FD samples (71.2±1.15), indicating a notable preservation of brightness during the drying process. At 50°C, both VD and UAVD showed similar L* values (44.5±2.22 and 45.0±4.18, respectively), with HAD showing a slightly higher value (48.9±1.85). As the temperature increased to 60°C and 70°C, all drying methods resulted in reduced L* values, compared to fresh kiwi, indicating an overall darkening of samples. The lowest L* value was observed in UAVD at 70°C (41.5 ± 0.12), suggesting more pronounced thermal degradation.

Regarding a* parameter (red–green chromaticity), fresh kiwi exhibited a negative value (–5.1 ± 1.33), consistent with its natural green color. At 50°C, UAVD produced the most intense red hue (a* = 5.6 ± 1.28), followed by HAD (4.3 ± 0.17) and VD (2.37 ± 1.50), potentially because of pigment transformation or concentration effects during drying. At higher temperatures (60°C and 70°C), in general, a* values decreased, and the shift toward red was

less pronounced particularly in VD (1.5 ± 0.57 at 60°C) and UAVD (1.27 ± 0.04 at 60°C).

For b* parameter (yellow–blue chromaticity), fresh kiwi showed the highest value (14.3 ± 2.69), indicating a more pronounced yellow hue. At 50°C, FD exhibited the highest b* value among dried samples (16.2 ± 2.17), which could reflect a concentration effect of chromophores during freeze-drying. However, since this value surpassed that of fresh kiwi, it may also indicate a shift in color, rather than improved preservation. It's important to note that a higher b* value does not necessarily signify better retention of yellow hue if it exceeds the natural reference point. As drying temperature increased to 60°C and 70°C, b* values declined across all methods, probably because of the thermal degradation of yellow pigments, such as carotenoids. UAVD at 70°C presented the lowest b* value (8.75 ± 0.56), indicating a notable loss of yellow tone and a shift toward a more neutral or bluish appearance. Notably, VD at 70°C (13.69 ± 0.59) had a higher b* value than at 50°C (12.1 ± 0.15), suggesting better retention of yellow color at a higher temperature in this method, possibly because of shorter drying period or different heat transfer dynamics.

In Llavata *et al.* (2024b), drying temperature and UAVD were examined, revealing that high temperatures led to compound degradation and Maillard browning (da Silva Júnior *et al.*, 2018). Regardless of drying conditions, color parameters changed significantly, with increased drying temperature intensifying these effects. While some studies reported reduced brightness (Bhat *et al.,* 2022; Martins *et al.,* 2019), Simal *et al.* (2005) found that brightness increased with temperature in dried kiwi samples. The transition from green to red hues was linked to chlorophyll degradation, a heat-sensitive pigment (Kroehnke *et al.,* 2021).

Finally, for color difference (ΔE), fresh kiwi fruit had no comparison baseline. FD resulted in maximum color change (25.16), while other drying methods at 50°C, such as VD and UAVD, showed respective ΔE values of 11.25 and 9.78, indicating a moderate color change. At higher temperatures, ΔE values did not follow a uniform decreasing trend across all drying methods. While HAD and UAVD exhibited lower ΔE values at 60°C, compared to 50°C, VD showed an increase. Among all methods and temperatures, UAVD at 60°C showed the lowest color difference (ΔE = 6.40), indicating the best color retention relative to fresh sample. This suggested that higher drying temperatures led to a greater color degradation in all methods. In summary, FD maintained the brightest and most distinct color, with a slight reduction in hue shift, while higher drying temperatures resulted in darker and

Table 3. Color characteristics of dried and fresh kiwi fruits with different temperatures and drying methods.

Fresh	FD		HAD	VD	UAVD
L*					
46.3±0.61^{B}	71.2±1.15^{A}	50ºC	48.9±1.85^{B}	44.5±2.22^{B}	45.0±4.18^{B}
		60ºC	48.4±1.58^{B}	43.4±2.85^{B}	46.2±1.44^{B}
		70ºC	46.7±0.88^{B}	45.2±0.68^{B}	41.5±0.12^{B}
a*					
-5.1±1.33^{D}	–2.7±0.40^{D}	50ºC	4.3±0.17^{A,B}	2.37±1.50^{B,C}	5.6±1.28^{A}
		60ºC	1.7±0.02^{B,C}	1.5±0.57^{B,C}	1.27±0.04^{C}
		70ºC	2.8±0.39$^{A–C}$	2.8±0.29$^{A–C}$	4.5±0.16^{A,B}
b*					
14.3±2.69^{A,B}	16.2±2.17^{A}	50ºC	15.0±0.76^{A}	12.1±0.15^{A,B}	11.1±2.08^{AB}
		60ºC	13.5±0.60^{A,B}	13.5±1.68^{A,B}	13.6±1.11^{A,B}
		70ºC	12.6±0.27^{A,B}	13.69±0.59^{A,B}	8.75±0.56^{B}
ΔE					
-	25.16^{A}	50ºC	9.78^{E}	7.81^{H}	11.25^{D}
		60ºC	7.13^{I}	14.36^{B}	6.40^{J}
		70ºC	8.10^{F}	7.94^{G}	12.06^{C}

Different superscripted capital letters in the same row indicate differences between samples subjected to different drying methods ($p < 0.05$).
FD: freeze drying; HAD: hot air drying; VD: vacuum drying; TPC: total phenolic content; UAVD: ultrasound-assisted vacuum drying.
Color measurements were expressed using the CIE Lab* system, where L* represents lightness/darkness, a* indicates redness/greenness chromaticity, b* indicates yellowness/blueness chromaticity, and ΔE is the color difference.

less vibrant kiwi fruit colors. UAVD at 50°C effectively preserved both lightness and color hues, while higher temperatures led to significant color degradation across all methods.

Environmental scanning electron microscopy

The ESEM images revealed distinct microstructural changes in kiwi samples subjected to different drying methods and temperatures (Figure 2). Fresh kiwi sample showed smooth and intact cellular structures indicative of natural moisture retention. FD kiwi samples maintained a highly porous, well-preserved structure because of sublimation under vacuum, thereby minimizing cellular damage. In contrast, HAD at increasing temperatures (50°C to 70°C) caused pronounced shrinkage, cell collapse, and fragmentation, with HAD70 exhibiting the most severe structural damage because of thermal stress. VD showed moderate disruption, with less compact and more defined structures than HAD, while UAVD samples demonstrated better cell integrity and a more porous texture, suggesting that ultrasound helps to mitigate structural damage during drying.

As observed in Wang *et al.* (2019), ultrasound pretreatment, particularly with 20- and 30-min applications, led to the formation of larger pores and tunnels, facilitating improved mass transfer during drying. Similarly, in our study, UAVD demonstrated enhanced moisture

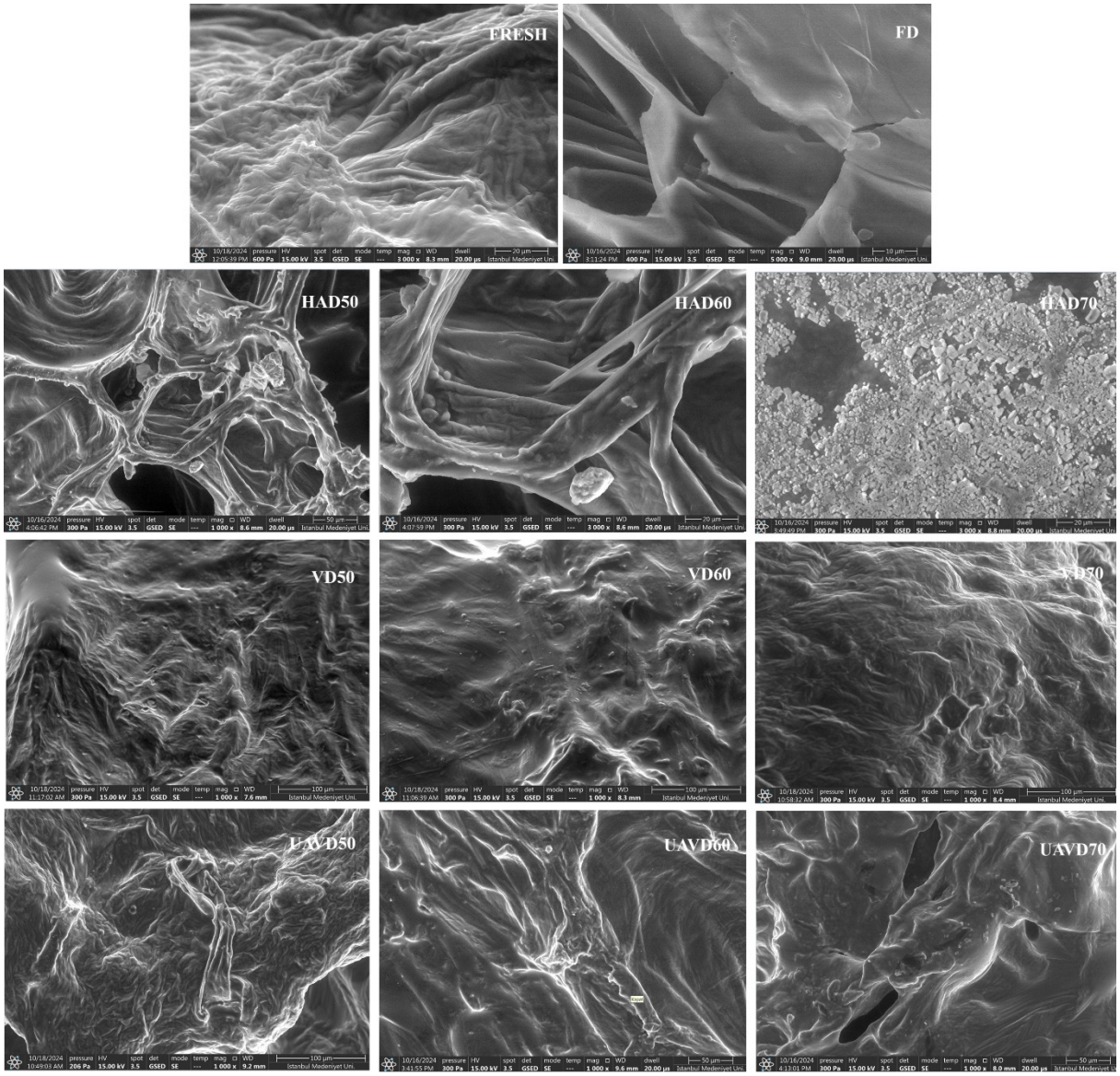

Figure 2. Microstructural images of dried and fresh kiwi fruits with different temperatures and drying methods. FD: freeze drying; HAD: hot air drying; VD: vacuum drying; TPC: total phenolic content; UAVD: ultrasound-assisted vacuum drying.

removal efficiency, probably because of the structural modifications induced by ultrasound. Similar microstructural images were reported for raspberries and blueberries, both dried using different drying methods (Akcicek *et al.*, 2023; Tekin Cakmak *et al.*, 2021).

Conclusions

This study comprehensively assessed the influence of different drying techniques, HAD, VD, UAVD, and FD, at varying temperatures (50°C, 60°C, and 70°C) on the phenolic composition, antioxidant capacity, color, and microstructure of kiwi fruit. Among these methods, FD resulted in the highest TPC (5216.7 mg GAE/100 g DM) and superior antioxidant preservation, but with longer drying periods. In contrast, UAVD at 60°C proved to be a highly effective method, with strong phenolic retention (4760.9 mg GAE/100 g DM), higher antioxidant activity (35.7 mg TE/100 g DM), and minimal structural degradation. It also offered better preservation of chlorogenic and caffeic acids and achieved the lowest overall color change (ΔE = 6.40), indicating its potential for maintaining the sensory and nutritional qualities of dried kiwi fruit. Microstructural analysis supported these findings, with UAVD-treated samples displaying well-preserved porosity and cellular structure. Therefore, UAVD at moderate temperatures presented a promising and efficient drying alternative, particularly for the functional food industry. Future research should explore the scalability of UAVD and its effects on other tropical fruits, as well as its integration into hybrid drying systems to optimize both energy efficiency and product quality.

Competing Interests

The author had no relevant financial or nonfinancial interests to disclose.

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Conflicts of Interest

None.

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