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Evaluation of Persimmon (*Diospyros kaki* L.) with Alternative Drying Technologies: Comparison of Laser-Heated, Convective and Lyophilization Methods

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ABSTRACT: This study evaluates the physicochemical quality characteristics of *Diospyros kaki* L. (cultivars 'Hana Fuyu' and 'Jiro') processed using three distinct drying technologies: Convective (oven), freeze-drying (lyophilization), and laser-heated drying. Key quality parameters; including color, pH, water activity (a_w), dry matter content, texture and the presence of aflatoxin were comprehensively analyzed to assess the industrial viability of each method. The results indicated that; while freeze-drying offered the highest retention of color and brightness, its industrial application is constrained by the operating costs and slow drying kinetics. Conversely, oven drying achieved the highest dry matter content but resulted in significant degradation of color and aroma. Notably, laser-heated drying emerged as a promising alternative, achieving target moisture levels within a significantly reduced processing time compared to convective methods, while numerically maintaining higher pH levels and softer textural properties (0.87–0.89 N) without inducing adverse quality degradation. While direct energy consumption was not measured, the substantial reduction in drying duration suggests a potential for increased operational efficiency. Furthermore, all drying methods successfully reduced water activity below the microbial safety limit (<0.6), and no aflatoxin contamination was detected. Consequently, the Laser-Heated Drying system is identified as a competitive technology for maintaining the physicochemical integrity of persimmons while offering significant time-saving advantages in processing.

Keywords – Persimmon, laser-heated drying, freeze drying, oven drying, aflatoxin

1. Introduction

Persimmon (*Diospyros kaki* L.) is a significant fruit species belonging to the *Diospyros* genus of the *Ebenaceae* family, with production increasing globally. Originating in China, this species spread to Japan and other Asian countries over the centuries; it entered Türkiye via Trabzon, subsequently spreading across the country and gaining acceptance as the "Trabzon persimmon" (Öz & Özelkök, 2003; Altunkanat et al. 2025). Persimmon is a fruit of high nutritional value; cultivated particularly in the Aegean, Black Sea, and Mediterranean regions of Türkiye (Bozkır & Ergün, 2020). Known locally by names such as "Paradise fruit," "Japanese persimmon," or "Amme," this fruit draws attention for its high antioxidant capacity, rich phenolic components and vitamin-mineral content (Wright & Kader, 1997; Chen et al. 2008; Rashwan et al. 2017; Ann et al. 2025). It has been reported that; regular consumption of persimmons can lower blood pressure and cholesterol, support the immune

system and improve digestive health (Wright & Kader, 1997; Butt et al.2015; López-Bermudo et al. 2024; Ann et al. 2025).

Persimmon is rich in carbohydrates, pectin, tannins and vitamins A, C, and E. Furthermore, the consumption of its leaves as green tea in some countries demonstrates that the plant allows for holistic utilization beyond just its fruit (Mannino & Cosio, 1997; Hossain & Shahidi, 2023). However, the most significant factor limiting fresh consumption is the astringent taste caused by its high tannin content. Various methods, such as ethanol vapor, carbon dioxide, immersion in warm water, freezing, and drying, are applied to remove this astringency (Taira et al. 1997; Matsuo, 1998; Frost et al. 2017; Medel-Marabolí et al. 2017). Drying is one of the most effective methods used for the long-term preservation of fruits and vegetables. Drying this fruit is an essential food processing method that both extends shelf life and preserves nutritional value (Ertekin & İpek, 2020). Drying extends the shelf life of fruits by reducing water activity (a_w) to levels that effectively inhibit microbial growth and enzymatic degradation (Geankoplis, 1993; Ünlütürk & Turantaş, 1999; Giannakourou et al., 2025). However; traditional methods such as sun or shade drying lag behind modern systems due to long drying times, high labor requirements and the risk of contamination (Soysal, 2004; Kingsly & Singh, 2007). Consequently; hot air (convective), microwave, vacuum, freeze-drying and newly developed laser-heated drying systems have become widely used in the industry (Güngör & Özbalt, 1997; Ramachandran et al. 2024). In the freeze-drying method, moisture is removed via sublimation, which is the direct transition of water from the solid phase to the vapor phase under low pressure (Yağcıoğlu, 1999).

Recent research reveals that; the drying method has a direct effect on the product's color, texture, water activity, dry matter content and sensory properties (Akyıldız et al. 2004; Polatçı, 2013; Yıldız Akbulut, 2021). Different drying methods may have significant effects on the nutritional content and bioactive components of persimmons (Arkain & Alibas, 2025). In this context; high-temperature drying generally leads to the degradation of heat-sensitive components such as phenolic compounds and vitamins, whereas low-temperature and controlled drying methods are more effective in preserving these components (Dikme, 2025). For instance; Akyıldız et al. (2004) reported that color and phenolic content were maximally preserved in persimmons dried without additives at 60°C, while Polatçı (2013) stated that; heat pump systems stand out among different dryers in terms of energy efficiency and color quality. In a study by Yıldız Akbulut (2021), significant changes in water activity and color values were detected as a result of drying persimmons using microwave and oven drying methods.

Therefore, detailed investigation of the effects of different methods applied in persimmon drying on sugars, organic acids, phenolic compounds, and antioxidant capacity is of great importance (Gao et al. 2012; Wang et al. 2025).

Although the effects of various drying methods on fruits; such as pomegranate, mulberry, and terebinth have been investigated (Dikme, 2025; Abbaspour-Gilandeh et al. 2020), the impact of processing persimmons with different drying methods on bioactive potential and nutritional value has not yet been fully elucidated (Arkain & Alibas, 2025). In this regard, laser-heated drying technology, which attracts attention for its energy-saving and product-quality benefits, has the potential to preserve the product's color, flavor and nutritional value by providing rapid drying without requiring pre-treatment. This rapid moisture removal significantly shortens the overall processing time compared to conventional multi-stage methods, thereby improving industrial energy efficiency and contributing to the preservation of heat-sensitive volatile compounds (Wolf et al., 2023; Santos et al., 2025). Literature indicates that this system is a modern technology that provides rapid drying with energy savings, without causing caramelization or color darkening on the product surface (Ceylan et al. 2006). Additionally; since it takes place in a closed and controlled environment, it tends to reduce the risk of mycotoxin contamination. Such a controlled environment not only minimizes contamination risks but also ensures more homogeneous drying and consistent product quality (Urbano et al., 2023). In particular, phenolic compounds and carotenoids have been reported to undergo less degradation under laser systems compared to conventional oven drying, supporting superior pigment stability (Cemeroğlu et al., 2003; Njumbe Ediage et al., 2015; Lim & Eom, 2022).

The primary aim of this study; is to determine how processing persimmons with different drying methods affects the fruit's nutritional value and bioactive properties, thereby increasing the industrial potential of this valuable fruit. This research aims to expand the utilization areas of dried fruit in the food industry by comprehensively evaluating the thermal, sensory, and nutritional properties of persimmon drying (Arkain & Alibas, 2025). The specific objective of this study is the comparative evaluation of the physical (color, texture) and chemical (pH, dry matter, water activity, presence of aflatoxin) properties of products obtained by drying 'Hana Fuyu' and 'Jiro' persimmon varieties grown in Hatay province using different drying methods (oven, freeze, and laser-heated drying). Ultimately; the goal is to develop an energy-efficient, safe, and high-quality drying system in a short time.

2. Materials and Methods

2.1. Raw Material Supply and Pre-treatments

The 'Hana Fuyu' and 'Jiro' persimmon varieties (*Diospyros kaki* L.)(**Fig 1**) utilized in this research were harvested at the commercial maturity stage from the Research and Application Orchard of Hatay Mustafa Kemal University, located in the Dörtöyl district of Hatay province, Türkiye. Intact, non-damaged, and homogeneously mature fruits were strictly selected and classified in accordance with the physical, varietal, and quality criteria defined by the Turkish Standard (TS 5919) for Persimmons (TSE, 1987). To ensure compliance with global marketing and commercial quality control frameworks, raw material sorting, defect tolerances, and structural uniformity parameters were verified against international dried produce layout requirements (UNECE, 2026). The selected raw materials were immediately transferred to the laboratory and subjected to initial sanitation procedures under running tap water to eliminate post-harvest surface contaminants and phytopathogenic residues according to international food hygiene guidelines (FAO, 2026). After washing, the fruits were manually peeled using a standardized stainless-steel knife. To eliminate variations in surface area and ensure uniform heat and mass transfer during the subsequent dehydration processes, the peeled fruits were mechanically sliced into uniform disc profiles using a calibrated industrial food slicer. A precise slice thickness of 2 mm was chosen based on comprehensive preliminary optimization trials evaluating structural shrinkage, water diffusivity, and color preservation. Mechanistically, slice thickness directly dictates the internal mass transfer resistance and moisture removal rate during dehydration (Bozkır & Ergün, 2020). Preliminary tests revealed that 1 mm slices suffered from severe thermal browning and excessive brittleness, leading to structural damage and operational collapse. Conversely, 4 mm slices exhibited excessive internal resistance to moisture movement, which drastically prolonged the required drying duration and consequently triggered undesirable non-enzymatic browning and quality degradation on the fruit matrix. Therefore, the 2 mm thickness was established as the optimum geometric configuration to end-product quality. Following this stage, all processes were continued with slicing into 2 mm thick discs and drying. No chemical pre-treatments or anti-browning additives were applied to any sample groups to preserve a clean-label product profile.



Fig 1. Hana Fuyu a) and Jiro b) cultivars of Trabzon persimmons (*Diospyros kaki* L.)

2.2. Application of Drying Methods

In this study, three drying methods were used to compare the quality parameters and preservation characteristics of persimmon slices: convective (oven) drying, freeze-drying (lyophilization) and laser-heated drying (**Fig 2**).

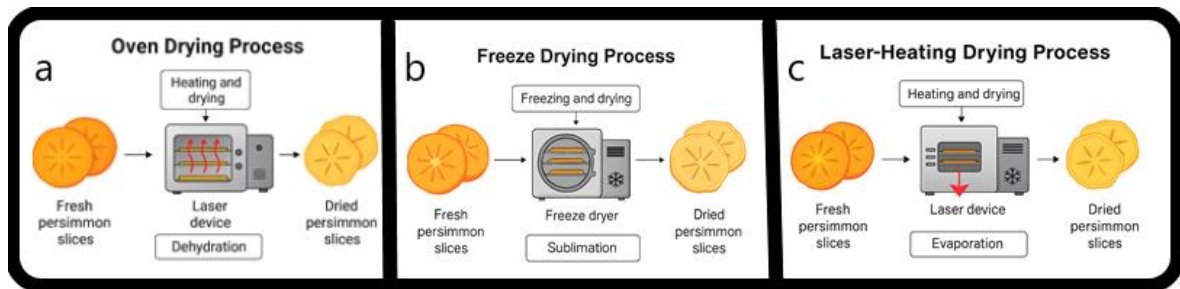


Fig 2. Oven-drying (left), freeze-drying (middle), laser-heated-drying (right)

In all methods, the prepared 2 mm thick samples were used and the products obtained after the completion of the drying process were subjected to quality analyses (**Fig 3**).



Fig 3. Oven-dried persimmon slices (left), freeze-dried persimmon slices (middle), laser-heated-dried persimmon slices (right)

2.2.1. Convective (Oven) Drying

Optimal temperature and drying time norms were determined by conducting preliminary trials at every 5-degree interval between 50-85 °C. The drying time varied between 1.5 and 5 hours at each temperature range. However, due to the increased energy and time costs at lower temperatures and the need to prevent rapid darkening at higher temperatures, it was decided to process the product at 75 °C for 2-3 hours. Consequently, the prepared 2 mm thick persimmon slices were distributed in a single uniform layer with a controlled sample loading density of 500g/tray on stainless steel trays measuring 40 x 50 cm. The drying process was executed in a laboratory tray dryer (Memmert, Germany) operating at 75 °C with a constant cross-flow air velocity maintained at 0.8m/s under light-deprived conditions until a stable final moisture content was reached (Ertekin & İpek, 2020). At the end of the drying process, the samples were cooled to room temperature under laboratory conditions for analysis.

2.2.2. Freeze-Drying (Lyophilization)

For the lyophilization process, the uniform 2 mm thick persimmon slices were initially subjected to an explicit pre-freezing step at -40 °C for 4 hours to ensure complete and rapid ice crystal formation within the fruit tissue. Following the pre-freezing stage, the sublimation process was completed using a lab-scale freeze dryer (FreeZone Benchtop Freeze Dryer, Model: 71020 2.5 L and -84 °C series, Labconco Corp., Kansas City, MO, USA) over a total duration of 20 hours. The system operated continuously under a minimum vacuum pressure fixed at 0.045 mbar (4.5 Pa) with a minimum condenser temperature maintained at -84 °C. At the end of the drying process, the samples were transferred to a desiccator until they equilibrated to room temperature, ensuring they were fully sealed against ambient moisture prior to subsequent quality analyses (Keskin et al., 2021).

2.2.3. Laser-Heated Drying

Laser-heated drying treatments were executed using a Fareffect FMK-1000 sun-effect energy drying system (Fareffect, Istanbul, Türkiye). The technical architecture of this novel dehydration equipment comprises a total heating capability with a maximum rated power of 27 kW and operates at an industrial electrical voltage of 380 V (50 Hz) under an IP44 protection classification. The drying chamber dimensions are 220 × 140 × 140 cm, housing 40 individual process trays with specific dimensions of 75 × 60 cm, establishing a maximum operational processing capacity of 1000 kg/day. The system features an automated smart programming control unit integrated with a built-in over-heating safety mechanism to ensure

precise thermal regulation. For the dehydration processes, the uniform 2 mm thick persimmon slices were distributed in a single layer on the trays and dried at an internal chamber temperature equivalent of 75 °C. The processing window was dynamically adjusted between 1.5-2 h based on the real-time weight loss curves of the samples until the target moisture content was successfully achieved. This continuous photon-based energy transmission facilitates rapid moisture removal by significantly reducing internal mass transfer resistance, which successfully shortens the total processing time while effectively suppressing surface browning and maintaining the natural physicochemical integrity of the fruit matrix without requiring chemical pre-treatments (Pinto et al., 2024; Wolf et al., 2023).

2.3. Analyses

The dried persimmon samples were evaluated in terms of quality parameters, including color, texture, moisture content, pH values and the presence of aflatoxin. All analyses were performed in triplicate.

2.3.1. Color Analysis

Pre- and post-drying color measurements were conducted using a Konica Minolta CR-400 colorimeter. Measurements were expressed in the CIELAB system as L^* (lightness), a^* (redness), and b^* (yellowness) values (Nowacka et al. 2018; Bayram, 2024). Using these values, chromaticity (C^* , chroma), hue angle (h° , hue) and total color difference (ΔE) values were derived and calculated (Djekić et al. 2018; Zhang et al. 2024; Kaplan et al. 2025). These parameters are critical for quantitatively evaluating the effect of the drying process on the visual acceptability and color stability of persimmons (Hssaini et al. 2021; Schouten et al. 2024). Furthermore, as a freshness indicator, the ΔE_{ab}^* value was also used to differentiate the drying methods' effects on the color of final products. For this purpose, ΔE_{ab}^* was used as a numerical value to calculate the color differences between samples according to the CIELAB color space (Djekić et al. 2018; Zhang et al. 2024; Kaplan et al. 2025). Mathematically, the Euclidean distance between the L^* , a^* , and b^* values of the fresh product and the L^* , a^* , and b^* values of the dried product is used for the calculation of ΔE_{ab}^* (Eq.1):

$$\Delta E_{ab}^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad \text{Eq.1}$$

- $\Delta E_{ab}^* < 2$: Hardly noticeable,
- $\Delta E_{ab}^* = 2-10$: Significant but acceptable difference,
- $\Delta E_{ab}^* = 10-20$: Large difference, color perception changes significantly,
- $\Delta E_{ab}^* > 20$: Very large difference, significant difference compared to fresh (Djekić et al. 2018; Zhang et al. 2024; Kaplan et al. 2025).

2.3.2. Texture Analysis

The textural properties of the dried samples were determined using a TA-XT Plus Texture Analyzer. For this purpose, a Texture Profile Analysis (TPA) test was applied and the hardness value was determined (Kilcast, 2010; AACC, 2002; Lotfy et al. 2022). The hardness value was determined according to the AACC (2002) method 74-09. These analyses revealed the effects of drying methods on the structural integrity and mouthfeel of the fruit.

2.3.3. Chemical Properties (Water Activity, Dry Matter and pH)

Water Activity (a_w) Determination: To determine the shelf life of the product, the a_w value was measured at 25°C using an Atago RX-50000 device. The a_w value was recorded when the samples placed in the device chamber reached equilibrium (Yıldız Akbulut, 2021; Vakula et al. 2021; Jovanovic, 2023).

Dry Matter Determination (Moisture Content): The dry matter ratio was calculated gravimetrically based on the AOAC (1990) method 934.01. Moisture content was determined by drying the samples in an oven at 75°C until they reached a constant weight (Sertkaya & İnanlı, 2023).

pH Determination: The dried samples were weighed, and 1 gram was taken from each. Then, deionized water (without CO₂) was added at a ratio of 1/10 (w/w) and mixed at room temperature. After the samples were homogenized, the pH value was determined using a digital pH meter (Thermo Scientific A211) (Yıldız Akbulut, 2021; Kaba et al. 2025).

2.3.4. Aflatoxin Analysis

These analyses were conducted to evaluate potential mycotoxin contamination in persimmons due to drying processes and to determine compliance with food safety standards. The High-Performance Liquid Chromatography (HPLC-Shimadzu) method was applied. Quantitative determination of AFB1, AFB2, AFG1, and AFG2 was performed using a

fluorescence detector following immunoaffinity column (IAC) purification (Açu & Özdestan Ocak, 2010). Standard curves and corresponding peak areas for each aflatoxin were prepared, and derivatization was carried out prior to analysis. The mobile phase consisted of water, methanol, and acetonitrile (60:20:20). Separation was achieved on a reversed-phase C18 column (250 × 4.6 mm, 5 µm particle size) maintained at 28°C. Fluorescence detection was performed at an excitation wavelength of 360 nm and emission wavelength of 440 nm. Operating conditions included a flow rate of 1 mL/min, maximum pressure of 400 bar, and a run time of 20 minutes. Aflatoxin concentrations in samples were calculated from the standard curves and expressed as ng/mL.

2.4. Statistical Analysis

Data obtained from all analyses were evaluated using SPSS 20.0 software. Differences between groups were determined by Two-way Analysis of Variance (ANOVA) and significant differences were examined using the Duncan multiple comparison test ($p \leq 0.05$) (Yıldız Akbulut, 2021).

3. Results and Discussion

3.1. Color Values

The color parameters of 'Hana Fuyu' and 'Jiro' persimmons were significantly influenced by the respective drying techniques, as comprehensively presented in **Table 1**.

In the 'Hana Fuyu' cultivar, the highest L^* value (74.22) was determined in the freeze-drying method, while the lowest L^* value (51.62) was found in convective (oven) drying. A similar trend was observed in the 'Jiro' cultivar, with the highest lightness in freeze-drying (64.22) and the lowest in laser drying (53.98).

Table 1. Color values of fresh and dried persimmons

Value	Jiro (Fresh)	Jiro (dried)			Hana Fuyu (Fresh)	Hana Fuyu (dried)		
		Oven-	Freeze-	Laser-heated-		Oven-	Freeze-	Laser-heated-
L^*	73.75±2.43 ^{aA}	57.84±6.04 ^{cA}	64.22±1.87 ^{bB}	53.98±16.89 ^{cB}	66.22±1.94 ^{bB}	51.62±8.51 ^{cB}	74.22±3.27 ^{aA}	67.18±10.02 ^{bA}
a^*	14.58±0.73 ^{aB}	14.57±2.94 ^{aA}	04.23±2.68 ^{cB}	07.98±1.76 ^{bA}	20.55±1.11 ^{aA}	06.23±2.44 ^{cB}	03.31±1.59 ^{dA}	09.34±3.53 ^{bA}
b^*	47.56±1.34 ^{bA}	43.14±4.26 ^{cA}	37.59±6.78 ^{dB}	59.79±7.25 ^{aA}	44.85±1.74 ^{bB}	32.28±2.23 ^{dB}	40.60±7.68 ^{cA}	59.79±7.76 ^{aA}
C^*	49.72±1.42 ^{aA}	45.66±3.10 ^{bA}	39.68±6.54 ^{cA}	49.85±7.09 ^{aB}	49.35±1.88 ^{bA}	32.94±1.83 ^{dB}	40.74±7.79 ^{cA}	60.59±7.61 ^{aA}
h°	72.94±0.70 ^{bA}	71.10±5.32 ^{bB}	78.42±1.09 ^{aB}	79.44±3.94 ^{aB}	65.99±1.35 ^{cB}	78.90±4.73 ^{bA}	85.48±1.30 ^{aA}	80.96±3.58 ^{abA}

Lowercase letters: Indicate the difference between fresh fruit and drying methods within the same cultivar (column). Uppercase letters

(A, B): Indicate the difference between Jiro and Hana Fuyu cultivars when the same process is applied (row).

This finding is associated with the low-temperature conditions and limited oxidative reactions during freeze-drying, which contribute to the preservation of lightness. This highlights the potential of freeze-drying to maintain the color integrity of biomaterials compared to other drying methods (Jovanovic, 2023). This method plays a critical role in increasing the sensory acceptability of the product by minimizing color loss, especially in the processing of fruits and vegetables (Djekić et al. 2018).

Redness (a^*) and Yellowness (b^*) values showed a significant increase with the laser-heated drying method. This increase can be explained by the maximum preservation of color pigments and the minimization of Maillard reactions due to short-term exposure to high temperatures. These findings parallel the results previously reported by Akyıldız et al. (2004) and Polatçı (2013). Optimizing color parameters, which have a direct impact on the visual appeal of dried products and consumer preferences, is of central importance in process development studies. Indeed, drying processes have generally been observed to lead to decreases in L^* values (except freeze-drying) and decreases increase in a^* and b^* values, indicating a darkening of the products and the acquisition of more red-yellow tones (Kaveh et al. 2025).

The high chroma (C^*) values in laser-heated-dried samples indicate that a bright and natural color appearance was successfully preserved. This feature is considered a critical quality criterion for consumer acceptance. Similarly, in delicate fruits like persimmon, freeze-drying provides superiority over other methods in maintaining the product's original color by minimizing the degradation of color pigments, as it occurs under low temperature and low pressure (Bas-Bellver et al. 2022; Jha et al. 2024). ΔE_{ab}^* value can also be used as an indicator of freshness when calculating the color difference between a fresh sample and a processed sample (Table 2).

Table 2. Calculated ΔE_{ab}^* values during drying processes

Cultivar	Drying method	ΔE_{ab}^*
Jiro	Oven-	16.52 ^{bB}
	Freeze-	17.24 ^{bA}
	Laser-heated	24.17 ^{aA}
Hana Fuyu	Oven-	24.01 ^{aA}
	Freeze-	19.47 ^{bA}
	Laser-heated	18.71 ^{bB}

Lowercase letters indicate significant differences between different drying methods within the same column/cultivar ($p \leq 0.05$). Capital letters indicate significant differences between the cultivars (Jiro and Hana Fuyu) when the same drying method is applied ($p \leq 0.05$).

Two-way ANOVA results revealed a significant interaction between drying methods and cultivars regarding ΔE_{ab}^* values ($p \leq 0.05$). This interaction highlights that the color stability of persimmons during dehydration is not only determined by the drying technique but is also highly dependent on the cultivar's specific biochemical effect.

- For the Jiro cultivar: The lowest color difference was observed in oven-dried samples (16.52^{bb}), while the highest difference was recorded in the laser-heated drying method (24.17^{aa}). The pronounced color shift in Jiro under laser treatment can be attributed to its specific sugar profile and phenolic composition. The intense light energy of the laser may have accelerated non-enzymatic browning and Maillard reactions more aggressively in this cultivar, leading to a significant decrease in L^* and b^* values (Santos et al. 2025).
- For the Hana Fuyu cultivar: Conversely, the laser-heated drying method resulted in the lowest ΔE_{ab}^* value (18.71^{bb}) for this cultivar. The superior color stability of Hana Fuyu in the laser system indicates that its tissue density and antioxidant capacity might provide better protection against oxidative pigment loss. This suggests that Hana Fuyu is more resilient to rapid thermal radiation, allowing for better preservation of carotenoids compared to the Jiro cultivar (Lim & Eom, 2022).

From a visual and commercial perspective, laser-heated drying showed strong performance in both cultivars due to the high chroma (C^*) values, indicating a vibrant yellow-orange appearance. While freeze-drying maintains lightness (L^*) to a large extent with some loss in saturation (C^*) and a moderate shift in hue (h°) toward yellow, laser-heated drying provides a slightly darker but more vibrant color with a significant shift toward a golden orange hue. These findings demonstrate that while freeze-drying ensures superior visual quality from a scientific standpoint, laser-heated drying emerges as a promising alternative for achieving commercial appeal through enhanced color saturation.

The results of the general analysis of the dried samples are given in **Table 3**.

Table 3. General characterization of dried persimmons

Cultivar Analyses	Hana Fuyu			Jiro		
	Oven-dried	Freeze-dried	Laser-Heated dried	Oven-dried	Freeze-dried	Laser-Heated dried
pH	4.82 ± 0.02 ^{bB}	6.18 ± 0.18 ^{aA}	6.16 ± 0.01 ^{aA}	4.99 ± 0.01 ^{bA}	6.22 ± 0.06 ^{aA}	6.11 ± 0.01 ^{aA}
Water Activity (a_w)	0.35 ± 0.006 ^{cB}	0.42 ± 0.005 ^{bB}	0.48 ± 0.001 ^{aB}	0.37 ± 0.007 ^{cA}	0.45 ± 0.002 ^{bA}	0.49 ± 0.004 ^{aA}
Dry Matter (%)	89.57 ± 0.76 ^{aA}	89.95 ± 0.38 ^{aA}	87.70 ± 8.36 ^{aA}	87.94 ± 2.83 ^{aA}	88.97 ± 0.38 ^{aA}	83.92 ± 3.73 ^{aA}
Hardness (N)	0.93 ± 0.03 ^{aA}	0.96 ± 0.02 ^{aA}	0.89 ± 0.02 ^{aA}	0.91 ± 0.04 ^{aA}	0.94 ± 0.03 ^{aA}	0.87 ± 0.05 ^{aA}
Aflatoxin	ND	ND	ND	ND	ND	ND

ND.: non detected. Lowercase letters (a, b, c): Indicate the difference between drying methods within the same cultivar (column). Uppercase letters (A, B): Indicate the difference between Hana-Fuyu and Jiro cultivars when the same drying method (row) is applied.

3.2. pH Values

Two-way ANOVA results indicated that both drying methods and cultivars, as well as their interaction, significantly affected the pH values of persimmons ($p < 0.05$). This significant interaction suggests that the biochemical response of the fruit to thermal treatment varies depending on the specific cultivar. pH values ranged from 4.82 to 6.18 in 'Hana Fuyu' samples and from 4.99 to 6.22 in 'Jiro' samples. While freeze and laser-heated drying preserved higher pH levels across both cultivars, Jiro exhibited slightly higher pH retention than Hana-Fuyu in oven-drying conditions (4.99^A vs 4.82^B), suggesting a cultivar-specific resistance to acidification during thermal processing.

The higher pH values were detected in the laser-heated and the freeze-dried samples (and statistically similar), while the lowest values were found in the oven drying group (statistically different). The high pH retention in freeze-drying and laser-heated systems can be attributed to the prevention of acidic component formation reactions. In laser-heated drying systems, drying occurs in a significantly shorter period, limiting acidic component formation reactions (enzymatic oxidation, Maillard and similar reactions), and consequently, the pH can remain higher. Similarly, freeze-drying also prevents acidic component formation reactions, thereby preventing a decrease in pH. A study by Yıldız Akbulut (2021) also showed that in microwave drying, acid loss is lower, thus ensuring a shorter drying time and maintaining higher pH values; this is similar to our study. Laser heated drying technology significantly shortens the drying time without altering the natural structure and sensory integrity of the fruit; thus, it more successfully preserves the characteristic flavor profile, texture, and color quality of the fruit compared to traditional methods (Pinto et al. 2024).

These obtained results support that laser-heated systems better preserve fruit components; this is a particularly advantageous parameter in terms of sensory quality and taste. The rapid moisture removal observed in the laser-heated system contributes to a reduction in total processing time, which is often a key factor in industrial energy considerations. However, a detailed life-cycle energy analysis is necessary for a definitive economic comparison (Wolf et al. 2023).

3.3. Water Activity (a_w)

Water activity (a_w) values, which directly affect the shelf life of products, showed significant differences depending on the drying method ($p \leq 0.05$). The results of the Two-way ANOVA revealed that the effect of the drying technique on moisture removal was significantly influenced by the persimmon variety used. Across all drying conditions, the Jiro cultivar consistently exhibited slightly higher a_w values compared to Hana-Fuyu ($p \leq 0.05$), with values ranging from 0.37 to 0.49 in Jiro and 0.35 to 0.48 in Hana-Fuyu.

The lowest a_w value was measured in oven drying (0.35^c - 0.37^c) and the highest value in laser-heated drying (0.48^a - 0.49^a). In freeze-dried samples, a_w values were found in the range of 0.42^b - 0.45^b . Despite these variations, the a_w values were below 0.6 in all three methods, the products were considered safe in terms of microbial growth (Ünlütürk & Turantaş, 1999; Giannakourou et al. 2025). These low levels of water activity values are an important factor for preserving product safety and quality from a microbial perspective during storage (Kaba et al. 2025). This indicates that different drying techniques have distinct effects on moisture removal mechanisms and consequently, on the stability potential of the final product (Vakula et al. 2021). The results obtained are consistent with the findings of a similar study by Yıldız Akbulut (2021). The researcher reported that a_w values of products in the microwave drying method were higher than traditional methods, but still remained below the microbial limit.

The final moisture content of the dried persimmon samples ranged between 10.43% and 16.08%, which safely falls within the commercial stability thresholds for dehydrated fruits. In food preservation engineering, absolute moisture percentage is secondary to a_w when defining safety indices against microbial proliferation. All three dehydration configurations successfully reduced the product a_w values below 0.49. According to global food standards—specifically the modern quality frameworks for dried persimmons (UNECE, 2026) and regional food contaminant standards (FAO, 2026)—dried fruit matrices are categorized as highly stable and fully secure against the growth of xerophilic molds, halophilic yeasts, and subsequent mycotoxin pathways when the operational a_w is strictly suppressed below the

critical thermodynamic benchmark of 0.60. The exact processing durations exhibited significant disparities, requiring 2-3 h for convective oven drying, 24 h for freeze-drying, and 2 h for the novel laser-heated drying. These variations in drying are directly governed by the specific energy transmission mechanisms involved in each system (Pinto et al., 2024; Wolf et al., 2023). In oven-drying, moisture removal is limited by external boundary-layer resistance and slow capillary migration, which often causes thermal stress on outer tissues. In freeze-drying, while structural integrity is maximally preserved under low temperatures, the processing efficiency is inherently constrained by the slow sublimation kinetics of ice crystals within the porous cell matrix, resulting in prolonged industrial cycles. In contrast, the primary operational advantage of the laser-heated drying system lies in its ability to circumvent these mass transfer limitations. The high-density photon energy delivered by the Fareffect FMK-1000 system couples directly with the volumetric water molecules of the 2 mm slices, inducing rapid moisture evaporation along the cellular capillary channels without establishing a severe thermal gradient across the sample boundaries (Ashtiani & Martynenko, 2025; Pinto et al., 2024). Consequently, the laser-heated system provides a major industrial alternative by accelerating internal moisture movement and optimizing drying curves within a remarkably compressed time window, while effectively mitigating the structural hardening or surface case-hardening risks commonly encountered in extended convective procedures (Pinto et al., 2024; Wolf et al., 2023).

3.4. Dry Matter Content

According to the Two-way ANOVA results, no significant interaction or main effects were detected between drying methods and cultivars regarding dry matter ratios ($p>0.05$). Although numerical variations were observed, the dry matter content remained statistically uniform across all samples, ranging from 83.92% to 89.95%. The highest dry matter ratio was numerically found in oven-dried Hana Fuyu samples (89.57%), followed by freeze-drying (88.97%) and laser-heated drying (87.70%) methods.

The lack of a significant difference between the drying processes and cultivars stems from the fact that all drying processes were conducted to reach a similar final moisture target. However, the slight numerical differences observed can be attributed to the direct effect of drying time and ambient temperature on moisture removal capacity. It is thought that the application of relatively shorter heat treatment in the laser-heated drying method limited the moisture removal to a specific level compared to longer-term methods. In contrast, the application of oven drying for a longer time and at a higher temperature ensured more

effective removal of water from the cell matrix, resulting in a higher dry matter content. The slight numerical variations observed can be attributed to the distinct moisture removal mechanisms. While oven drying applies continuous thermal energy to drive off moisture, freeze-drying utilizes ice sublimation under deep vacuum conditions, which, over an extended 24 h cycle, effectively extracts unbound water molecules from the porous cellular architecture, numerically resulting in a highly concentrated dry matter accumulation (Wojdyło et al., 2020). However, it was taken into account that color, flavor, and sensory integrity were better preserved in products dried with this method. This situation further supports the information stated by literature (Cemeroglu, 2003; Aguilar et al. 2025; Prayitno et al. 2025) that long-term heat treatment at high temperatures leads to color and aroma losses. The shorter exposure to thermal treatment in laser-heated drying is expected to better preserve heat-sensitive volatile compounds compared to long-term oven drying, although further aromatic profiling is required to confirm this effect (Santos et al. 2025).

3.5. Textural Properties

The Two-way ANOVA results revealed that neither the drying methods, the cultivars, nor their interaction had a statistically significant effect on the hardness values of the samples ($p>0.05$). This statistical uniformity indicates that the structural response of the fruit tissue during moisture removal is relatively consistent across both the 'Hana Fuyu' and 'Jiro' varieties. It was determined that hardness values were numerically lower (0.87–0.89 N) in samples dried with the laser-heated drying method, whereas relatively higher values were reached in the freeze-drying method (0.94–0.96 N) (**Table 3**). Although these differences were not statistically significant ($p>0.05$), the freeze-drying may make the structure more porous and increase brittleness, while the laser-heated drying method provides a softer texture. These findings reveal the critical role of different drying techniques in determining the physical properties of products and directly affect the sensory acceptability of the final product (Vakula et al. 2021). This result indicates that the laser-heated system protects the fruit tissue from sudden thermal shock, allowing for a softer and more preferable structure to be obtained. On the other hand, the increased hardness observed in freeze-dried products can be associated with the preservation of integrity in the cell structure, while lower hardness values are generally reported in other methods such as microwave drying (Ma et al. 2023). These findings are consistent with the "lower hardness = higher consumer appreciation" approach reported by Kilcast (2010) and AACC (2002).

3.6. Aflatoxin Content

In the analyses performed, AFB1, AFB2, AFG1, and AFG2 toxins were not encountered in any of the drying methods. This finding indicates that the raw materials used in the study were free from initial aflatoxin contamination and that the drying process was carried out under hygienic conditions. Since aflatoxins are heat-stable compounds and are not eliminated by drying processes, the absence of these toxins in the final products confirms that the processing environment and the execution of the laser-heated drying system in a closed environment successfully prevented cross-contamination. Furthermore, this result is consistent with the findings of Njumbe Ediage et al. (2015), supporting the principle that maintaining low water activity ($a_w < 0.60$) and short drying times are essential to inhibit fungal growth and prevent subsequent mycotoxin development during storage. Therefore, the analyzed samples were found to be in compliance with food safety standards, ensuring consumer health and product quality for potential commercial production (Arkain and Alibas, 2025).

4. Conclusion

This study comparatively evaluated the quality parameters of products obtained by processing persimmon (*Diospyros kaki* L.) varieties ‘Hana Fuyu’ and ‘Jiro’ using different drying methods (convective/oven-, freeze-, and laser-heated-). The findings demonstrated that the drying method is a determining factor on the product's color, pH, water activity, dry matter and textural properties.

Freeze-drying was the most effective method for preserving the color and gloss of persimmons; however, its industrial application is constrained by high energy demands and long processing times. Oven drying yielded the highest dry matter content but caused pronounced losses in both color and aroma. In contrast, laser-heated drying demonstrated notable advantages, achieving high color retention within a short processing time, alongside significantly lower hardness values (0.87–0.89 N) and elevated pH levels. In texture analyses, which are of critical importance for consumer appreciation, the laser-heated drying method provided the lowest hardness values, creating the softest texture among the tested methods. These results indicate that shortening the drying time minimizes acid production/formation reactions which explains the observed higher pH levels and supports the preservation of the fruit's natural physicochemical profile.

Additionally, all drying methods evaluated in this study successfully reduced the water activity of the samples below the microbial safety limit ($a_w < 0.6$), and no aflatoxin

contamination was detected, ensuring the microbiological safety and storage stability of the final products.

Overall, the Laser Heated Drying system has been identified as a promising and competitive technology for industrial-scale persimmon processing, as it combines high- quality physicochemical and textural parameters with the advantages of significantly reduced processing times. While the shorter duration suggests a potential for energy efficiency, this study primarily highlights the method's capacity to maintain product integrity. However, while this method offers advantages such as significantly shorter processing times and better preservation of physicochemical properties (e.g., higher pH and softer texture), it still needs optimization for heat-sensitive bioactive compounds. Therefore, future studies focusing on the applicability of this method should be directed towards temperature-time optimization across diverse fruit matrices. This could help prioritize the development of systems that minimize losses of both phenolic and aroma components. In this way, the industrial potential of laser-heated drying could also be revealed.

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