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Physicochemical and functional quality characteristics of fresh, dried, and chip forms of 'fuji' apple: insights into variable relationships

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Abstract

This study investigated the physicochemical and functional quality characteristics of fresh, dried, and chip forms of 'Fuji' apples, focusing on bioactive compound retention, color stability, and sugar composition. Drying, a widely used preservation method significantly affects these attributes by altering phenolic content, antioxidant capacity, and vitamin C levels. Fresh apples exhibited the highest total phenolic content and antioxidant activity while drying processes led to reductions due to thermal degradation and enzymatic oxidation. In contrast, anthocyanin content increased in apple chips, suggesting improved pigment extraction. Significant color changes and browning effects were observed in dried apples and apple chips, primarily due to enzymatic browning. Sugar composition varied among apple products, with higher fructose levels in apple chips and stable sucrose content across all forms. Principal component analysis (PCA) highlighted distinctions between fresh and processed apples based on chemical composition and processing effects. These findings emphasize the need for optimized drying techniques to minimize nutrient loss while maintaining desirable sensory and functional properties. This study provides valuable insights into the impact of drying on apple quality, contributing to the development of nutritionally superior dried fruit products.

Keywords: Drying, Apple products, Phenolic compounds, Antioxidant activity, Sugar composition, Color stability

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INTRODUCTION

Drying is one of the most effective and widely used preservation methods for reducing the moisture content of fresh fruits and vegetables, thus lowering water activity and extending their shelf life (Zhang et al., 2010; Eminoğlu et al., 2019). This process helps maintain the stability and safety of the products and meets the demand for fruits and vegetables year-round, irrespective of seasonality. Moreover, dried products are highly advantageous for transportation and storage, as they take up less space, making them more efficient for distribution (Hou et al., 2020). Dried fruits provide health benefits and help reduce non-communicable diseases, including cardiovascular conditions (Alasalvar et al., 2020). As consumer preference shifts toward natural, minimally processed products, the dried fruit sector has continuously developed, with dried fruits taking on an increasingly prominent role in the food market (Ghinea et al., 2022).

Despite the numerous benefits of drying, the process has its challenges. Drying fruits and vegetables can lead to significant changes in their biochemical composition, particularly the degradation of bioactive compounds such as phenolic acids and flavonoids (Aghbashlo et al., 2010; Kahraman et al., 2021). These compounds are known for their antioxidant properties and play an essential role in the health benefits associated with dried fruits. Furthermore, drying can also affect the final product's texture, color, and sensory characteristics, influencing consumer acceptance (Krokida et al., 2003). The challenges of minimizing the loss of these bioactive components during the drying process are critical for ensuring that the nutritional value of dried fruits remains close to that of

fresh produce (Lutz et al., 2015). In addition, optimizing drying techniques to minimize the degradation of these compounds is essential for enhancing the quality of dried fruit while maintaining their health properties.

Apple (*Malus* × *domestica* Borkh.), one of the most widely produced and consumed fruits globally, is rich in antioxidants, particularly polyphenolic compounds, which have been shown to have numerous health properties (Dumanoğlu et al., 2018). Apples are an important source of dietary fiber, vitamins, and antioxidants, making them a valuable component of a healthy diet. While apples are commonly consumed fresh, they are also processed into various products, including juices, jams, jellies, vinegar, purees, and dried apples. The increasing popularity of dried apple products can be attributed to their convenience, long shelf life, and health benefits for their phenolic content (Herranz et al., 2019; Ghinea et al., 2022). However, the drying process itself can lead to a significant reduction in these bioactive compounds, primarily due to thermal degradation and enzymatic reactions, making it essential to explore methods that can help preserve the phenolic content in dried apple products (Aktaş et al., 2013). Several drying techniques, such as air drying, freeze-drying, and microwave drying, have been explored to minimize nutrient loss while improving the quality of dried apples (Zhou et al., 2020).

Given the growing demand for high quality dried apple products and the need to preserve their antioxidant properties, this study aimed to evaluate the effects of drying on the quality parameters of 'Fuji' apples. This research would contribute to understanding the variation in phenolic compounds and other antioxidant properties of different dried apple products, providing valuable insights into how drying affects the nutritional quality of apples. In addition to the antioxidant properties, this study evaluated other critical quality parameters, such as color and sugar composition, which are essential factors influencing consumer acceptance. By assessing these parameters, the research aims to enhance the value of dried apple products in the global market and support their role in promoting health and well-being, meeting the growing demand for functional foods that offer both convenience and nutritional benefits.

MATERIALS AND METHODS

Plant material

'Fuji' apples (*Malus* × *domestica* Borkh.) were obtained from the dwarf apple collection orchard of Ankara University, Faculty of Agriculture, Department of Horticulture.

Sample preparation and drying method

Apples were harvested at the commercial maturity stage in October 2021 based on titratable acidity, soluble solid content, and starch index. The harvested apples were transported to the laboratory, washed with tap water to remove surface contaminants, and wiped dry with blotting paper. Randomly selected apples were sliced using an apple slicer, seeds were removed, and the apples were cut into uniform cubes (1.5 cm × 1.5 cm). The apple cubes were immersed in a 2% citric acid solution for 1 minute to prevent enzymatic browning. The treated samples were arranged in a single layer on stainless steel trays and dried in an oven at 70°C until they reached two distinct moisture levels (10% for dried apple and 5% for apple chip). Quality analyses were conducted on fresh, dried, and apple chips.

Quality parameter assessments

Color analysis and browning index

Color measurements were performed using a colorimeter (Minolta CR-400, Konica Minolta, Japan) based on the CIE L*, a*, b* color space system. The color difference (ΔE^*) and browning index (BI) were calculated using the following equations (Bal et al., 2011):

Equation (1) - Color Difference (ΔE^*):

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

Where: $\Delta L^*, \Delta a^*, \Delta b^*$represent the differences in lightness, red-green and yellow-blue color values between the fresh apple samples with dried apple and apple chip samples. Typically, the higher the ΔE^*, the more noticeable the color change.

Equation (2) - Browning Index (BI):

$$\mathrm{BI} = \frac{100(\mathrm{x} - 0.31)}{0.17}$$

Equation (3) - x Calculation:

$$\mathrm{x} = \frac{at^* + 1.75Lt^*}{5.645Lt^* + a0^* - 3.012bt^*}$$

Where: $a0^*$represents the a value of the fresh apple samples. Lt, at and bt are L, a, b values of dried apple and apple chip samples.

Extraction procedure for spectrophotometric analysis

Extraction was performed following the method described by Colombo et al. (2019). A 2 g sample, ground with liquid nitrogen, was homogenized in 3 mL methanol/water (1:1, v/v) using a homogenizer (IKA-Labortechnik, Ultra-turrax T25, Germany) for 3 minutes. The homogenized samples were sonicated for 15 minutes and centrifuged (Sigma 3K30, Germany) at 14,000 rpm. The supernatant was collected, and the extraction process

was repeated with the pellet. The pooled extracts were filtered through 0.45 µm PVDF filters, adjusted to a final volume of 10 mL, and stored at +4°C in darkness for further spectrophotometric analysis.

Total phenolic content

The total phenolic content (TPC) of apples was determined using the Folin–Ciocalteu assay with some modifications (Singleton and Rossi, 1965). One hundred microliters (100 µL) of extract, 900 µL of double-deionised water, and 5 mL of Folin–Ciocalteu reagent were vortexed in a test tube. After incubation for 3 minutes at room temperature, 4 mL of saturated sodium carbonate solution (75 g L^{-1}) was added. The mixture was then allowed to stand for an additional 90 minutes at room temperature. The absorbance of the samples was measured at 765 nm using a UV–VIS spectrophotometer (Shimadzu UV-1208, Japan), and results were expressed as mg gallic acid equivalent (GAE) per kg of sample.

Antioxidant capacity

The antioxidant capacity of apple samples was assessed using the Trolox Equivalent Antioxidant Capacity (TEAC) assay, following the method described by Re et al. (1999). The assay utilized the ABTS radical solution, prepared by mixing ABTS diammonium salt with 2.45 mM potassium persulfate and allowing it to react in the dark for 12–16 hours at room temperature. During analysis, the solution was maintained at +4°C. The radical solution was diluted with phosphate-buffered saline (PBS, pH 7.4) to absorb 0.700 ± 0.010 at 734 nm. Inhibition rates were calculated using the equation:

$$\text{Inhibition rate (\%)} = \frac{\text{Initial absorbance value} - \text{Final absorbance value}}{\text{Initial absorbance value}}$$

The procedure was repeated for 20 and 30 µL sample volumes. Percentage inhibition values (10, 20, 30 µL) were used to generate a regression curve and its equation. The same steps were applied to the trolox standard Analyses were carried out with a UV-VIS spectrophotometer (UV-1208, Shimadzu, Japan), and results are reported as µmol trolox g^{-1}.

Total anthocyanin content

Total anthocyanin content was determined using the pH differential method (Giusti and Wrolstad, 2001) and expressed as mg cyanidin-3-glucoside per kg of sample. Absorbance was measured at 520 and 700 nm, and total anthocyanin content was calculated using the equation:

$$\text{Total anthocyanin (mg/kg)} = \frac{\text{(A) x (MW) x (DF) x 1000}}{\text{(}\varepsilon\text{) x (L)}}$$

Where:

A = Difference in absorbance between pH 1.0 and 4.5

MW = Molecular weight of cyanidin-3-glucoside

DF = Dilution factor

ε = Molar extinction coefficient

L = Pathlength (cm)

Titratable acidity

Ten grams of the homogenized sample were rehydrated with distilled water at 4 °C overnight. The mixture was then homogenized using a homogenizer (IKA-Labortechnik, Ultra-turrax T25, Germany) for 3 minutes. The resulting homogenate was filtered through cheesecloth, and the filtrate was used for titratable acidity analysis. Titratable acidity was determined using an automatic titrator (Mettler Toledo DL50 Graphix) and expressed as % malic acid.

Vitamin C content

Ten grams of fruit were homogenized in a metaphosphoric acid solution, centrifuged, and filtered (0.45 µm). The filtrate was analyzed using the high-pressure liquid chromatography (HPLC) (Shimadzu LC 10 AT VP, Japan) equipped with a Phenomenex Luna C18 column. The mobile phase A: 100% acetonitrile B: 2% acetic acid (A:B; 20:80) at a flow rate of 1 mL min^{-1}, with the column oven maintained at 25°C. Quantification of peaks obtained at a wavelength of 245 nm using a DAD detector was performed externally based on a standard of L-ascorbic acid.

Sugar content

Five grams of fruit were homogenized in double-deionized water to measure sugar content and kept at room temperature in a shaking incubator for 30 minutes. The mixture was then centrifuged for 15 minutes. The supernatant was filtered and analyzed using HPLC (Shimadzu LC-2030, Japan) equipped with a refractive index detector. A Phenomenex Rezex RCM-Monosaccharide column (300 x 7.8 mm) was used, with double-deionized water as the carrier phase at a 0.6 mL min^{-1} flow rate to separate the sugars. Standards for sucrose, glucose, and fructose were utilized to identify and quantify the individual sugar peaks.

Statistical Analysis

The experiment followed a completely randomized design, with all measurements performed in triplicate. Data were analyzed using ANOVA with Minitab 17 software (Minitab Inc., State College, PA, USA). Post hoc comparisons were conducted using Tukey's test at a significance level of $P \leq 0.05$, performed with MSTAT-C software (Michigan State University, East Lansing, MI, USA). Principal component and correlation coefficients analyses were also carried out using JMP 13.2.0 software (SAS Institute, Cary, NC, USA).

RESULTS AND DISCUSSION

The results show that all quality parameters except titratable acidity are statistically different for all three apple products. These findings align with previous studies demonstrating that processing methods influence apples' physicochemical and bioactive properties (Wolfe et al., 2003; Plaza et al., 2012).

The highest total phenolic content was observed in fresh apples, followed by dried apples and apple chips, with 672.0, 598.3 and 471.7 mg GAE kg^{-1}, respectively (Table 1). This trend can be attributed to the degradation of phenolic compounds during thermal processing, as heat exposure has been reported to cause oxidative degradation and polymerization of phenolic substances (Friedman, 1997). Additionally, enzymatic oxidation occurring in cut or processed apples may contribute to phenolic degradation, particularly in apple chips, where extensive heat exposure accelerates compound breakdown (Vinson et al., 2001).

Similarly, antioxidant activity values were higher in fresh apples (3.47 µmol trolox g^{-1}) than in other processed products, with the lowest activity observed in apple chips (1.12 µmol trolox g^{-1}) (Table 1). This aligns with findings from Leontowicz et al. (2007), who reported that fresh apples exhibited superior antioxidant activity due to intact polyphenolic compounds. Processing techniques such as drying and frying have been found to reduce the concentration of phenolic substances due to thermal degradation and enzymatic oxidation (Zhou et al., 2020). The correlation between total phenolic content and antioxidant activity has been well established, indicating that the loss of polyphenols during processing directly affects the antioxidative capacity of apple products (Pellegrini et al., 2010). However, the degree of degradation varies depending on the severity of heat treatment, drying conditions, and storage factors, and this should be investigated further in future research.

When examined in terms of anthocyanin content, the highest value was observed in apple chips (5.56 mg kg^{-1}), while the lowest anthocyanin content was found in fresh apples (1.22 mg kg^{-1}) (Table 1). This suggests that the thermal processing of chip apples may enhance anthocyanin extraction or concentration, potentially due to cell wall breakdown and increased pigment availability, as reported by Patras et al. (2010). Additionally, heat treatments can induce the release of bound anthocyanins, making them more bioavailable (Sui et al., 2014). However, prolonged or excessive heat exposure may degrade anthocyanins, leading to color changes and reduced bioactivity. In contrast, fresh apples typically retain their native anthocyanin profile, but the lack of external stressors like heat or enzymatic activity may result in comparatively lower anthocyanin levels (Tsao and Yang, 2003).

The highest vitamin C content was observed in fresh apples (9.89 mg $100g^{-1}$), whereas apple chips exhibited the lowest levels (5.60 mg $100g^{-1}$) (Table 1). Vitamin C is susceptible to heat and oxidation, leading to significant losses during processing, particularly in high-temperature treatments (Duarte et al., 2009). Future research should investigate alternative preservation techniques, such as freeze-drying or vacuum drying, which have shown potential in minimizing vitamin C loss while maintaining fruit quality (Ratti 2001).

Interestingly, titratable acidity remained unaffected by the processing method (Table 1), suggesting that organic acids in apples are more stable during processing than phenolic compounds. Kschonsek et al. (2018), who observed minimal changes in titratable acidity across different apple processing methods, have reported similar findings. This stability may be due to the resilience of organic acids such as malic acid, a primary component of apple acidity, which remains relatively unchanged under moderate processing conditions. However, in some cases, prolonged drying or extreme heating may lead to minor acid degradation or conversion, which should be explored further in future studies (ElGamal et al., 2023).

Table 1. Quality characteristics of different apple products

Apple Product	Total Phenolic (mg GAE kg^{-1})	Anthocyanin (mg kg^{-1})	Antioxidant (µmol trolox g^{-1})	Vitamin C (mg $100g^{-1}$)	Titratable Acidity (malic %)
Chips	471.7 ± 11.0 C*	5.56 ± 0.03 A	1.12 ± 0.05 C	5.60 ± 0.55 C	0.477 ± 0.01 ns[1]
Dried	598.3 ± 3.3 B	2.43 ± 0.02 B	2.19 ± 0.01 B	7.55 ± 0.30 B	0.481 ± 0.01 ns
Fresh	672.0 ± 1.1 A	1.22 ± 0.01 C	3.47 ± 0.01 A	9.89 ± 0.20 A	0.475 ± 0.01 ns
Significant Effects P values	0.000	0.000	0.000	0.001	0.951

*Capital letters show differences among apple products and [1]ns non-significance at $P \leq 0.05$-error level according to Tukey's test.

Color changes in apple products were also significant (Table 2). Among processed products, apple chips exhibited the highest color change (ΔE = 11.24 units), followed by dried apples (ΔE = 7.45 units).

ΔE is a crucial parameter in evaluating the perceptual difference in color before and after processing. A higher ΔE value in apple chips indicates a significant alteration in color, which can be attributed to more intense thermal processing, likely causing caramelization and Maillard reactions (Atrooz, 2008; Pathare et al., 2013). The lower ΔE in dried apples suggests that drying under controlled conditions may mitigate extreme color changes compared to frying, which is known to induce more profound pigment transformations. Additionally, the increase in ΔE

correlates with anthocyanin degradation, non-enzymatic browning, and pigment oxidation, which are intensified under high-temperature exposure (Maskan, 2001).

As for the browning index, the elevated value was also highest in apple chips (82.19), followed by dried apples (70.68) (Table 2). The elevated browning index in apple chips can be attributed to the Maillard reaction, which is promoted at high temperatures and leads to brown pigments and flavor compounds (Akyıldız and Öcal, 2006). Though significant, the browning in dried apples is likely due to enzymatic browning caused by polyphenol oxidase (PPO) activity rather than thermal-induced Maillard reactions (Toivonen and Brummell, 2008). The combination of PPO activity and non-enzymatic reactions contributes to the observed browning in apple products, with the processing conditions playing a key role in determining the extent of color change.

The color stability of apple products is crucial for consumer acceptance, as discoloration indicates quality deterioration. Several strategies, such as using antioxidants, controlled drying conditions, and modified atmosphere packaging, have been proposed to mitigate browning and maintain color quality in apple products (Amodio et al., 2011). Further research is needed to explore the impact of different processing techniques, including vacuum frying and freeze-drying, on the color retention of apple products while minimizing undesirable browning effects.

The sugar content of apple products showed significant variations, particularly in fructose, glucose, and sucrose levels (Table 2).

The highest fructose content was observed in apple chips, followed by dried and fresh apples, with 24.94, 22.10, and 16.67 g kg^{-1}, respectively. This aligns with previous studies indicating that drying tends to concentrate sugars in fruits due to water loss (Smith et al., 2018). The increased fructose in apple chips could also be attributed to the concentration effect during the dehydration process at higher temperatures (Jones and Taylor, 2020). The finding that apple chips contain the highest level of fructose suggests that consumers may need to be cautious when considering their fructose intake from processed apple products, especially those sensitive to fructose (Harris et al., 2019).

In contrast, the highest glucose content was found in dried apples (15.06 g kg^{-1}), while fresh apples exhibited the lowest glucose levels (12.69 g kg^{-1}). Apple chips exhibited glucose levels statistically similar to those of dried and fresh apples. This may be explained by the fact that glucose, unlike fructose, is more stable in the drying process and thus may not accumulate as much in dehydrated products (Kim et al., 2021). The statistical similarity in glucose levels between apple chips and dried apples suggests that the processing temperature of apple chips might not cause as significant a rise in glucose concentration as it does with other sugars (Lee et al., 2022).

Sucrose content did not differ significantly across the different apple products. All three apple products were grouped in the same statistical category. This could indicate that sucrose levels are more stable across these products, regardless of the drying or dehydration process. Turner et al. (2017), who found that sucrose concentration in apples remains relatively consistent even after processing, have reported similar findings. This stability in sucrose levels suggests that the product characteristics of apple processing might have less impact on sucrose content than fructose and glucose.

Table 2. Quality characteristics of different apple products

Apple Product	Color Difference (ΔE)	Browning Index	Fructose (g kg^{-1})	Glucose (g kg^{-1})	Sucrose (g kg^{-1})
Chips	11.24 ± 0.40 A*	82.19 ± 2.13 A	24.94 ± 0.25 A	13.36 ± 0.40 AB	5.82 ± 0.52 A
Dried	7.45 ± 0.91 B	70.68 ± 3.85 B	22.10 ± 0.14 B	15.06 ± 0.40 A	5.76 ± 0.09 A
Fresh	0.00 ± 0.00 C	0.00 ± 0.00 C	16.67 ± 0.62 C	12.69 ± 0.56 B	6.15 ± 0.18 A
Significant Effects P values	0.000	0.000	0.000	0.027	0.041

*Capital letters show significant differences among apple products at $P \leq 0.05$-error level according to Tukey's test.

The results of the correlation analysis statistically evaluated the relationships between the parameters in the apple samples (Figure 1). The total phenolic content (TP) showed a positive and strong correlation with the total antioxidant capacity (TEAC) ($R= 0.976$, $p \leq 0.01$). This indicates that phenolic compounds contribute significantly to antioxidant capacity. At the same time, TP is negatively correlated with the color difference ΔE ($R= -0.926$, $p \leq 0.01$). When analyzing the relationships between biochemical variables, there was a strong and negative correlation between brown index (BI) and total phenolic content ($R= -0.848$, $p \leq 0.01$). This supports the effect of phenolic compounds in preventing oxidative browning. Similarly, vitamin C content (C) also shows a significant positive correlation with TP ($R= 0.920$, $p \leq 0.01$), indicating that phenolic compounds and vitamin C together play a role in the antioxidant defense mechanism. When sugar components were analyzed, the correlation between fructose (F) and glucose (G) was not significant ($R= 0.336$). However, there was a negative and significant correlation between sucrose (S) and fructose ($R= -0.743$, $p \leq 0.05$), suggesting that fructose levels may change with the hydrolysis of sucrose. In conclusion, correlation analysis shows strong relationships between phenolic

compounds, antioxidant capacity, and color change. Phenolic compounds reduce oxidative discoloration, increase antioxidant capacity, and act in parallel with vitamin C. In addition, relationships between sugar components should be evaluated during processing. These results provide important information for understanding the dynamics between biochemical composition and quality characteristics of apple samples.

	TP	A	TEAC	DeltaE	TA	BI	C	F	G	S	
TP	1										1
A	-0.989**	1									0.8
TEAC	0.976**	-0.954**	1								0.6
DeltaE	-0.926**	0.896**	-0.972**	1							0.4
TA	0.022	0.029	-0.021	0.178	1						0.2
BI	-0.848**	0.796*	-0.937**	0.966**	0.080	1					0
C	0.920**	-0.910**	0.956**	-0.940**	-0.122	-0.916**	1				-0
F	-0.932**	0.899**	-0.977**	0.973**	0.108	0.957**	-0.923**	1			-0
G	-0.135	0.033	-0.273	0.428	0.065	0.529	-0.218	0.336	1		-1
S	0.656	-0.566	0.714*	-0.754*	0.110	-0.775*	0.537	-0.743*	-0.696*	1	-1

Figure 1. Correlation matrix analysis between the data of the studied parameters. The correlation values varied between -1 (shaded in red tones) and 1 (shaded in green tones). A single asterisk "*" denotes significant differences at $p \leq 0.05$, while a double asterisk "**" represents significance at $p \leq 0.01$. TP: Total phenolic, A: Anthocyanin, TEAC: Antioxidant, TA: Titratable acidity, BI: Browning index, C: Vitamin C, F: Fructose, G: Glucose, S: Sucrose.

Principal component analysis (PCA) was utilized to assess the interaction between drying treatments and the variables under investigation, as illustrated in Figure 2. A data set comprising three treatments (fresh, dried, chips) and ten variables was analyzed using the covariance matrix. The PCA results indicated substantial variations in the chemical composition and processing methodologies employed in the samples. The first component (PC1) accounts for 72.5% of the total variance, exhibiting notably high loading values on sugar components (fructose, sucrose) and color change parameters (Delta E, BI). This finding underscores the notion that PC1 is the most dominant component in decomposing factors such as maturity level, processing method, and color change of apple samples. The second component (PC2) describes the factors associated with the dryness of the samples, explaining 13.5% of the total variance. The cumulative variance explanation rate for these two components is 86%, signifying their substantial representation of the influence of the analyzed variables on the samples. As demonstrated in Figure 2, the chips exhibit high loading values in the positive direction of PC1. The chips are distinguished by their notably elevated fructose level, exhibiting a robust correlation with the Delta E and BI parameters that denote color change. The findings of this study suggest that the process of water evaporation during the drying phase leads to a significant concentration of sugar components, which in turn results in a pronounced color change in the fruit. Conversely, fresh apple samples (fresh) exhibited a negative association with PC1. They demonstrated a more pronounced correlation with the TEAC parameter, representing phenolic compounds (total phenolic, vitamin C) and antioxidant capacity. Phenolic compounds and antioxidant capacity were higher in fresh apples, suggesting that the drying process causes a loss of these bioactive components. This phenomenon can be attributed to the sensitivity of phenolic compounds to heat and oxidation, which may lead to their breakdown during the drying process, consequently reducing antioxidant capacity.

When analyzed along PC2, it is evident that the samples are segregated according to their dryness status. Samples categorized as "dry" are positioned in the positive direction of PC2 and demonstrate a strong correlation with glucose content. This finding suggests that dried samples exhibit a pronounced differentiation in sugar composition, particularly in the form of an increase in glucose concentration. Conversely, fresh apple samples exhibited a negative association with PC2, demonstrating a correlation with phenolic compounds and antioxidant capacity parameters. With respect to sugar components, fructose and glucose contents exhibit high loading values on the positive side of PC1, while sucrose is positioned on the negative side of PC1. This finding suggests that sucrose may be broken down into glucose and fructose during the drying process. The hydrolysis of sucrose, due to its exposure to enzymes and water loss in the fruit tissue, may lead to changes in the distribution of these sugar components. Regarding color change, the BI and Delta E parameters exhibited high loading values in the positive direction of PC1, signifying that the drying process substantially influenced the color change in fruit. Processes such as enzymatic darkening and oxidation of phenolic compounds can affect color change in fruits. The elevated values of these parameters in the dried samples imply that the chemical changes occurring during the drying process substantially affect the color stability of fruit tissue.

In conclusion, the PCA analysis demonstrates significant differences between apple samples depending on the processing method. Dried apples exhibited elevated levels of sugars and discoloration, while fresh apples demonstrated higher concentrations of phenolic compounds and antioxidant capacity. These findings are

significant in understanding the effects of fruit processing techniques on chemical composition and reveal how different apple processing methods can affect nutritional quality. Furthermore, PCA results demonstrate that the drying process leads to a loss of phenolic compounds, increased sugar concentration, and changed color, providing significant data for the quality control of apple-based processed products. This analysis is a powerful tool for understanding the relationships between the biochemical components of apple samples. The findings of this study lay the foundation for future research, which can investigate the impact of diverse processing techniques on fruit composition in more depth.

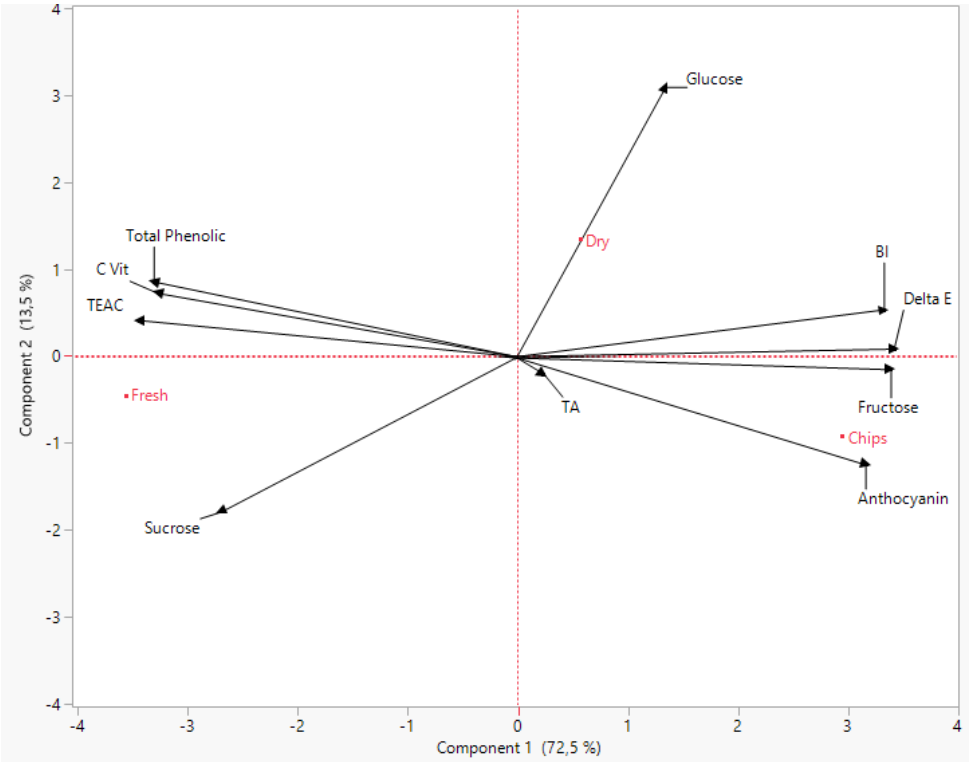

Figure 2. The biplot of scores and loadings for the Principal Component Analysis (PCA) of all data shows the distribution of reaches according to the first two components.

CONCLUSION

The present study demonstrates that drying processing significantly influences the physicochemical and functional properties of 'Fuji' apples, particularly regarding bioactive compound retention, color stability, and sugar composition. Fresh apples exhibited the highest levels of total phenolic content and antioxidant activity, reinforcing the adverse effects of thermal processing on bioactive compounds. While anthocyanin extraction improved in apple chips, vitamin C degradation and increased browning were observed in dried and chip products. The correlation analysis and PCA results highlighted strong relationships between phenolic content, antioxidant capacity, and color stability, further emphasizing the impact of processing methods on apple quality. Given the rising consumer demand for nutritionally rich dried apple products, optimizing drying conditions is essential to minimizing nutrient loss while preserving desirable sensory characteristics. Future research should explore advanced drying techniques to enhance the retention of phenolic compounds and other antioxidants. These insights contribute to developing high-quality dried apple products that meet nutritional and market expectations.

Compliance with Ethical Standards

Peer-review

Externally peer-reviewed.

Declaration of Interests

Ö. Horzum, H. Tahmaz Karaman, H. Dumanoğlu declare that they have no competing interests.

Author contribution

All authors contributed to the study conception and design. Material preparation by Ö.H, H.T.K., H.D. The first draft of the manuscript was written by Ö.H and H.T.K. and all authors read and approved of the final manuscript.

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