



Effect of air fryer pretreatment on quality parameters of dried zucchini slices: A pilot study

Hava fritözü ön işleminin kurutulmuş kabak dilimlerinin kalite parametrelerine etkisi: Bir pilot çalışma

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Abstract

This study investigated the effects of air fryer pretreatments, namely AF1 (150 °C–5 min), AF2 (160 °C–15 min), and AF3 (170 °C–25 min), on the physicochemical properties, color parameters, total phenolic content (TPC), antioxidant activity, and textural characteristics of zucchini prior to hot-air drying. Air frying caused substantial increases in total phenolic content and antioxidant activity, with the highest values observed in AF3 (170 °C–25 min), while also inducing pronounced changes in color (L^* , a^* , b^* , ΔE). In contrast, texture parameters did not differ significantly among treatments. Multivariate analyses clearly distinguished raw and control samples from all air-fried groups, with AF3 forming a distinct subcluster due to its intensified chemical responses. Overall, air frying, especially under high temperature–time conditions, proved to be an effective pretreatment for enhancing the functional and chemical quality of dried zucchini without compromising its structural integrity.

Keywords: Zucchini, Air fryer pretreatment, Drying, Total phenolic content, Antioxidant activity

1 Introduction

Vegetables are globally recognized for their nutritional value and functional compounds, such as phenolics and antioxidants, which contribute to human health by mitigating oxidative stress and chronic diseases. Thermal processing significantly influences these bioactive components, with both beneficial and detrimental effects reported depending on the method and conditions applied. For example, various cooking techniques, including boiling, microwave, and air frying, have been shown to alter phenolic contents and antioxidant activity in vegetables, sometimes enhancing and other times reducing these compounds depending on the specific matrix and conditions used [1].

Low in calories, primarily composed of water, and containing carbohydrates, protein, and a small amount of fat, as well as minerals such as folate, vitamin C, potassium, magnesium, phosphorus, and iron, squash (*Cucurbita pepo* L.) is widely consumed in society [2]. Drying is a common preservation method that effectively reduces water activity and prolongs storage, but it can also result in significant

Öz

Bu çalışmada, sıcak hava ile kurutma öncesinde kabaklara uygulanan hava fritözü ön işlemlerinin; AF1 (150 °C–5 dk), AF2 (160 °C–15 dk) ve AF3 (170 °C–25 dk), fizikokimyasal özellikler, renk parametreleri, toplam fenolik madde içeriği, antioksidan aktivite ve tekstürel özellikler üzerindeki etkileri araştırılmıştır. Hava fritözü uygulaması, özellikle AF3 koşulunda (170 °C–25 dk) toplam fenolik içerik ve antioksidan aktivitede belirgin artışlara yol açmış ve renk parametrelerinde (L^* , a^* , b^* , ΔE) belirgin değişiklikler oluşturmuştur. Buna karşın, tekstür değerleri uygulamalar arasında anlamlı bir farklılık göstermemiştir. Çok değişkenli analizler, çiğ ve kontrol örneklerini tüm hava fritözü uygulanmış gruplarından net şekilde ayırmış, AF3 ise kimyasal tepkisindeki yüksekliğe bağlı olarak ayrı bir alt küme olarak konumlanmıştır. Sonuçlar, hava fritözü işleminin özellikle yüksek sıcaklık–zaman koşullarında, kabak kurutma prosesinde fonksiyonel ve kimyasal kaliteyi artıran etkili bir ön uygulama olduğunu göstermektedir.

Anahtar Kelimeler: Kabak, Hava fritözü ön işlemi, Kurutma, Toplam fenolik madde, Antioksidan aktivite

quality changes. Previous studies on zucchini drying primarily focused on drying kinetics and mathematical modeling under convective hot-air or microwave-assisted drying conditions, demonstrating that increased drying temperature and reduced sample thickness improve drying rate and moisture diffusivity, but they did not address impacts on functional quality attributes such as phenolic content or antioxidant capacity [3].

To mitigate quality losses during drying, pretreatments like citric acid dipping, hot water blanching, ultrasound, or osmotic dehydration have been applied successfully in various fruits and vegetables, improving mass transfer and color retention during subsequent drying [4]. However, there is a notable gap in the literature regarding the application of air fryer pretreatment prior to drying, especially for zucchini. Air-frying, a convection-based technique that employs high-velocity hot air, has been shown to enhance phenolic content and antioxidant activity in other vegetables such as eggplant and brassicas, likely due to enhanced extractability and potential formation of heat-induced bioactive compounds

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[5]. Despite these promising findings, systematic studies on air fryer pretreatment effects on zucchini quality and its integration with drying processes remain scarce.

Therefore, a comprehensive evaluation of air fryer pretreatment on zucchini drying quality is warranted. Specifically, the effects of different air fryer temperature–time combinations on physicochemical properties, color parameters, textural characteristics, total phenolic content (TPC), and antioxidant activity have not been reported in the literature. Moreover, multivariate approaches such as principal component analysis (PCA) and hierarchical clustering analysis (HCA), which can reveal relationships and treatment patterns across multiple quality indices, have yet to be employed in this context.

The aim of this study was to investigate the effects of air fryer pretreatments with different temperature–time combinations (150 °C–5 min, 160 °C–15 min, and 170 °C–25 min) on the physicochemical properties, color parameters, TPC, antioxidant activity, and textural characteristics of zucchini prior to hot-air drying. Additionally, multivariate analyses (PCA and HCA) were employed to comprehensively evaluate the relationships among treatments and identify clustering patterns based on chemical and physical quality attributes.

2 Materials and methods

The zucchini samples used in the study were purchased from a local market in Niğde, Türkiye. Before starting the procedures, the zucchini samples were thoroughly washed under tap water. Then, the zucchini samples were cut into 5 mm thick slices and 3 cm in diameter with a knife without peeling the skin. The samples were then placed in an air fryer (Airfryer Combi 7000 Series XXL, Philips). The samples were subjected to heat treatments in the air fryer at 150°C for 5 min (AF1), 160°C for 15 min (AF2), and 170°C for 25 min (AF3). Afterwards, they were dried in an oven at 40°C for 72 hours, ground, and stored in airtight bags at room temperature in a dark environment until the analyses were performed. On the other hand, the control sample was only dried in hot air at 40°C for 72 hours and then ground. The air frying conditions were selected based on preliminary trials to investigate the combined effects of temperature and processing time under increasing thermal severity, while ensuring effective dehydration without excessive quality deterioration. Treatment duration was intentionally increased with temperature to intensify the overall thermal load and to achieve progressively severe processing conditions rather than relying on a single extreme temperature–time combination. Raw and air fryer pretreatment of samples were shown in Figure 1.

The ash content of the samples has been determined according to the official method [6]. The moisture content of the samples was determined using the standard gravimetric method by drying in an oven at 105 °C for 2 h. Drying was conducted under fixed temperature–time conditions, and sample moisture content was determined after drying. Continuous monitoring of weight or moisture during the process was not performed. The water activity of the samples was measured with a water activity meter (AXIS, Türkiye)

after calibration. The color values (L^* , a^* , b^*) of the samples were determined by measuring them with a colorimeter, and the ΔE values (color difference) were subsequently calculated using Equation 1.

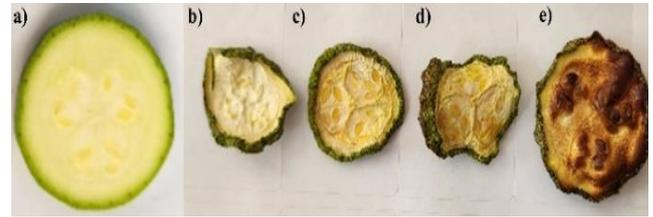


Figure 1. Raw zucchini sample a), control b) air-fried at 150°C for 5 min c), 160°C for 15 min d), 170°C for 25 min e)

2.1 Proximate analysis

$$\Delta E = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (1)$$

2.2 Extraction process

Before analysis, samples were extracted according to a previous method [5]. Two grams of sample were added to 20 ml of ethanol solution (50% ethanol, distilled water v/v) and extracted in an ultrasonic bath at 35 kHz frequency for 60 min, at 25°C temperature and at 100% power. The extracts were then centrifuged at 3000×g for 10 minutes, filtered through Whatman filter paper, and stored at +4°C until analysis.

2.3 Determination of total phenolic content and antioxidant activity

TPC of zucchini samples was determined using the modified Folin–Ciocalteu method [7]. Antioxidant activity in zucchini samples was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) method with modifications outlined by Payet [8].

2.4 Texture analysis of zucchini samples

The three-point bend rig probe (HDP/3PB) was used for the texture analysis (TA.XT plus, Stable Micro System, Great Britain) of the samples. The texture device was calibrated before starting the analysis. Test mode before texture analysis: compression, pre-test: speed 3 mm/sec, test speed: 3 mm/sec, post-test speed 10 mm/sec, target mode: distance was selected, and then measurements were started. Measurements were taken for the hardness (g), brittleness/flexibility (mm), and toughness (g/mm) parameters of the control and AF1, AF2, and AF3 samples.

2.5 Statistical analysis

All data are reported as mean values accompanied by standard deviations. One-way ANOVA analysis was performed to evaluate important differences ($p \leq 0.05$) among experimental conditions, followed by Tukey's test for post hoc comparisons. Statistical analyses were conducted using Minitab® 21 software (Minitab Inc., USA). Chemometric methods, including PCA and HCA, were employed for assessing differences between methods. HCA

utilized the Euclidean distance and complete linkage algorithm in the same program.

3 Result and discussion

The initial moisture content of raw zucchini was extremely high (95.13%), which is typical for fresh cucurbit vegetables. Similar moisture levels (93–96%) for zucchini have been reported previously [9–11]. All drying treatments significantly reduced moisture and water activity (Table 1). Among the processed samples, AF3 exhibited the lowest moisture (11.84%) and shared the lowest water activity value with the control group (0.17). The decrease in moisture and a_w with increasing air fryer severity reflects the combined effect of thermal exposure and intensified surface dehydration at higher temperatures and longer durations. Achieving $a_w < 0.22$ in all dried samples indicates that microbial stability can be ensured under these conditions, consistent with the microbial growth threshold reported by Beuchat [12].

Color parameters showed clear differentiation among treatments. Raw zucchini displayed the highest L^* value, and the brightness decreased progressively with thermal intensity. Similar reductions in L^* with increasing thermal severity have been reported for zucchini and other green vegetables due to chlorophyll degradation and surface browning [13–14]. AF3 exhibited a markedly lower L^* (51.81), consistent with surface browning and pigment degradation under harsher conditions. The a^* coordinate shifted from strongly negative in the raw sample (−8.04), characteristic of green tissues, to positive values in AF3 (6.72), indicating substantial loss of chlorophylls and formation of brownish or reddish pigments, an effect documented in thermally treated cucurbits [11].

Similarly, b^* values increased in AF1–AF3, suggesting the enhancement of yellow hues, likely due to caramelization and Maillard-derived pigments. These color modifications were captured in the ΔE results, where AF3 showed the highest color deviation (36.23), consistent with the general trend that higher thermal intensity yields more pronounced color shifts in dried vegetables [15].

Ash content also varied among treatments. The control group had the highest ash level (9.46%), whereas AF2 exhibited the lowest (7.61%). Differences may be attributed

to uneven mineral concentration associated with variable moisture removal. Variability in ash after thermal treatments has also been observed in other zucchini samples [11,16,17].

Texture analysis revealed no statistically significant differences among samples ($p \leq 0.05$) (Table 2). Hardness values were highly variable, particularly in AF1, where the large standard deviation suggests heterogeneity in structural collapse during drying. Similarly, in previous studies conducted on thinly sliced zucchini, it has been reported that heat treatments applied to frozen zucchini samples did not create a significant difference in terms of hardness [9]. AF3 tended to show lower hardness, which may indicate disruption of cell wall integrity at high temperatures, in line with observations from other thermally pretreated vegetables [18].

Table 1. Texture properties of zucchini samples

Samples	Hardness (g)	Brittleness/Flexibility (mm)	Toughness (g/mm)
Control	1405±495 ^a	2.08±0.65 ^a	671±114 ^a
AF1	1042±841 ^a	1.21±0.61 ^a	1044±847 ^a
AF2	1021±225 ^a	2.21±0.79 ^a	494±160 ^a
AF3	738±69 ^a	1.56±0.66 ^a	594±400 ^a

There is a statistically significant difference between the examples in the same column of the table that are indicated by different letters ($p \leq 0.05$).

Toughness and brittleness/flexibility values also did not differ significantly. The absence of statistical separation may be associated with the thin slice thickness (5 mm), which likely minimized structural differences between treatments despite differences in air frying conditions. The similarities across samples imply that air frying, within the tested range, does not profoundly alter the fundamental mechanical behavior of dried zucchini.

Figure 2 shows that TPC and antioxidant activity varied noticeably among treatments. TPC and radical scavenging activity increased markedly with air fryer pretreatment intensity. A series of studies have investigated the effect of thermal processing on the TPC of zucchini [19–21]. Similar increases in phenolic extractability following heat pretreatments have been documented in zucchini [13].

Table 2. Physicochemical properties of zucchini samples

Samples	Moisture (%)	Water activity	L^*	a^*	b^*	ΔE	Ash (%)
Raw	95.13±0.28 ^a	0.93±0.03 ^a	82.72±1.69 ^a	-8.04±0.77 ^c	23.89±1.69 ^b	-	0.41±0.13 ^d
Control	14.56±0.66 ^c	0.17±0.01 ^d	76.88±6.37 ^{ab}	-3.14±0.54 ^d	24.18±1.61 ^b	9.96±3.59 ^c	9.46±1.05 ^a
AF1	15.99±1.37 ^b	0.20±0.01 ^c	69.85±3.83 ^{bc}	0.19±0.78 ^b	30.13±2.17 ^a	18.05±2.80 ^b	8.78±0.12 ^{ab}
AF2	12.70±0.1 ^d	0.22±0.01 ^b	68.35±7.15 ^c	-1.33±0.62 ^c	29.06±3.2 ^a	18.67±6.11 ^b	7.61±0.12 ^c
AF3	11.84±0.12 ^d	0.17±0.01 ^d	51.81±9.36 ^d	6.72±1.55 ^a	28.75±4.37 ^a	36.23±8.53 ^a	8.07±1.21 ^{bc}

Raw: Unprocessed. Control: Oven-dried. AF1: Air fryer at 150°C for 5 minutes. AF2: Air fryer at 160°C for 15 minutes. AF3: Air fryer at 170°C for 25 minutes. There is a statistically significant difference between the examples in the same column of the table that are indicated by different letters (a-e) ($p \leq 0.05$).

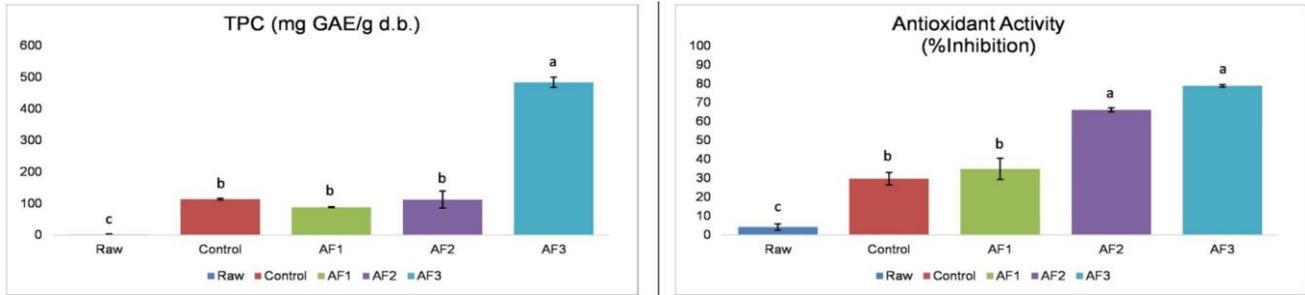


Figure 2. Total phenolic content and antioxidant activity of zucchini samples

Measured TPC values (dry basis) were: Raw 1.8, Control 113.4, AF1 88.1, AF2 112.2, and AF3 483.8 mg GAE g⁻¹ d.b. Corresponding DPPH inhibition values were Raw 4.2%, Control 29.7%, AF1 34.9%, AF2 66.1%, and AF3 78.8%. Thus, AF3 exhibited by far the highest TPC and antioxidant activity. The sharp increase in AF3 may be linked to enhanced release of bound phenolics and the formation of thermally derived reducing compounds such as Maillard reaction intermediates, both of which are known to react with Folin–Ciocalteu reagent and DPPH [7]. Recent studies have demonstrated that air-frying can enhance total phenolic content and antioxidant activity in vegetables, often exceeding the effects of conventional thermal treatments [22, 23]. However, the extent of these changes strongly depends on the applied temperature–time combination. Short-duration air-frying has been reported to maximize phenolic and antioxidant responses, whereas prolonged exposure may induce degradation of bioactive compounds [24]. In addition, antioxidant activity has been shown to increase with higher temperatures and longer processing times during air fryer-roasting, emphasizing the importance of overall thermal severity [25]. These findings are consistent with the trends observed in the present study.

3.1 Chemometric results of zucchini samples

The chemometric results for the samples are presented in Figure 3 and Figure 4 as principal component analysis and cluster analysis results, respectively. According to the

principal component analysis results, PC1 explains 69% of the samples, while PC2 explains 17.1% of the samples. PCA results (Figure 3) demonstrated clear separation of samples based on their physicochemical and functional properties. The raw and control samples clustered distinctly from AF treatments, indicating that air frying introduces unique chemical and color-related changes that are not solely attributable to drying. Similar PCA-based separations have been reported in studies evaluating thermal effects on phenolic compounds and color attributes in zucchini samples [13, 26].

AF3 was positioned furthest from the raw sample in the PCA score plot, driven primarily by high ΔE , elevated b^* , and reduced L^* values, reflecting the strong influence of thermal severity on color parameters. The biplot indicated that antioxidant activity and phenolic content contributed substantially to the discrimination among AF levels, with AF1 and AF2 positioned closer to vectors representing TPC and DPPH. This supports the earlier observation that moderate air frying enhances bioactive compound concentration.

The dendrogram (Figure 4) separated the samples into two main groups: raw and control, and all air fryer-treated samples. AF1 and AF2 clustered closely, while AF3 appeared as a distinct sub-cluster due to its markedly higher phenolic content, antioxidant activity, and stronger color changes. This pattern confirms that air fryer pretreatment intensity is the primary driver of sample differentiation.

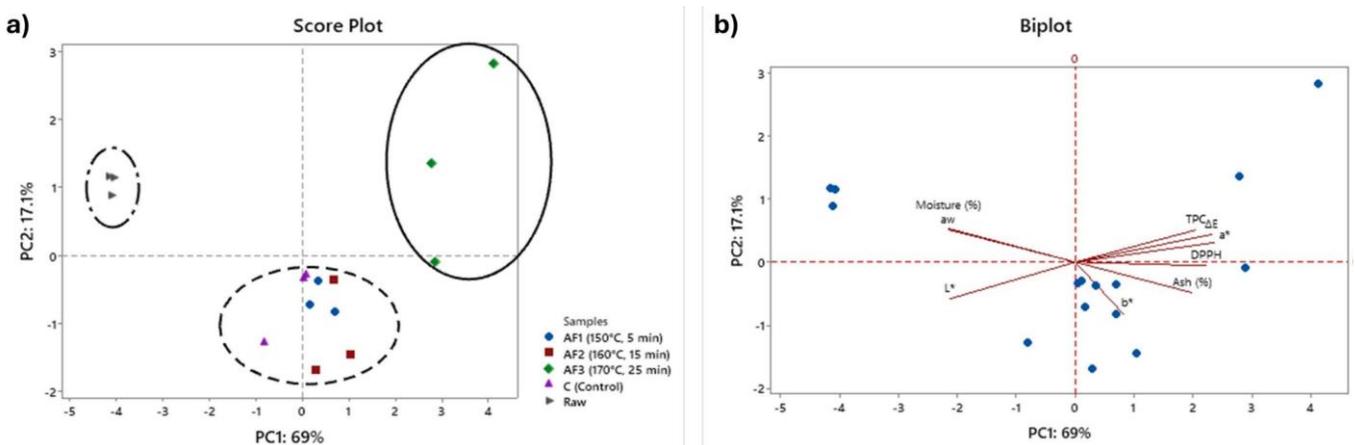


Figure 3. Score plot and Biplot results of zucchini samples

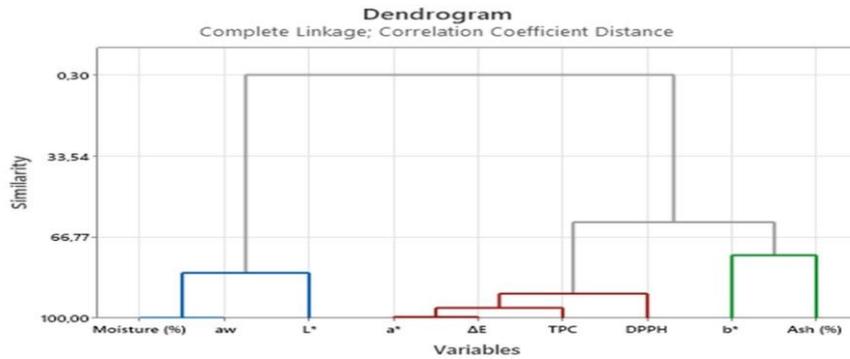


Figure 4. Dendrogram result of zucchini samples according to the analyses

4 Conclusion

Air fryer pretreatment significantly influenced the chemical composition and color characteristics of zucchini prior to drying, while textural attributes remained statistically unchanged among treatments. The highest phenolic content, antioxidant activity, and color deviation were observed in AF3, suggesting that more severe thermal conditions intensified the release of extractable bioactive compounds and pigment transformations. PCA and HCA consistently differentiated untreated samples (Raw and Control) from all air-fried samples, with AF3 forming a distinct subcluster due to its pronounced chemical responses. Overall, the results indicate that air frying, particularly at high temperature–time combinations may serve as a promising pretreatment for enhancing the functional and chemical quality of dried zucchini without inducing detectable adverse effects on texture under the conditions investigated.

Conflict of interest

The author declares that there is no conflict of interest.

Similarity (iThenticate): 12%

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