

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**EFFECT OF AIR FRYER ROASTING ON THE YIELD AND
QUALITY OF HAZELNUT OIL OBTAINED BY COLD
PRESSING METHOD**

ZEYNEP KESKİN MALKOÇ

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF CHEMICAL ENGINEERING**

ADVISOR: PROF. DR. MURAT ÖZDEMİR

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GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**HAVA FRİTÖZÜ İLE KAVURMA İŞLEMİNİN SOĞUK
SIKIM YÖNTEMİYLE ELDE EDİLEN FINDIK YAĞI
VERİMİNE VE KALİTESİNE ETKİSİ**

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YÜKSEK LİSANS TEZİ
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To my Family...

ABSTRACT

The objectives of this study are to investigate the effects of air fryer roasting conditions on the color and texture of hazelnuts, examine the influence of roasting temperature and time on the oil yield of cold-pressed and air-fried hazelnuts, and determine the chemical characteristics and antioxidant activity of oils obtained from air fryer roasted hazelnuts. Roasting conditions were set at 120, 150, and 180 °C for 5, 10, and 15 min, respectively. The L, a, and b* values, color difference (ΔE), and textural properties of unroasted (raw) and roasted hazelnuts were evaluated. The ΔE of hazelnuts increased with both roasting temperature and time, reaching its highest value (26) at 180 °C for 15 min. A substantial reduction in hardness was observed as roasting temperature and time increased, with the lowest hardness (19.75 N) determined in hazelnuts roasted at 180 °C for 15 min. The extracted hazelnut oils were evaluated for oil yield, free fatty acid content (FFAC), acid value (AV), peroxide value (PV), p-anisidine value (pAV), totox value (TV), conjugated dienes (CD), conjugated trienes (CT), ΔE , fatty acid composition, and antioxidant activity. The highest oil yield (67.40%) was obtained from hazelnuts roasted at 180 °C for 15 min, whereas unroasted hazelnuts produced the lowest oil yield (52.56%). FFAC, AV and PV slightly increased with rising roasting temperature and time, reaching to 0.43%, 0.85 mg KOH/g oil, and 2.70 mEq O₂/kg oil, respectively, at 180 °C for 15 min of roasting. Both pAV and TV increased with higher roasting temperature and time, reaching 3.01 and 8.39, respectively, at 180 °C for 15 min. CD and CT followed a similar trend, peaking at 12.03% and 11.56%, respectively, under the same conditions. ΔE gradually increased with higher roasting temperatures and longer roasting times, reaching a maximum value of 4.80 at 180 °C for 15 min. Analysis of fatty acid composition revealed that roasting led to gradual decreases in oleic and linoleic acids, while other fatty acids were only slightly affected. The antioxidant activity of hazelnut oils, measured using the ferric reducing antioxidant power (FRAP) assay, increased from 8.01 mg trolox equivalents (TE)/100 mL in oil from unroasted hazelnuts to 16.82 mg TE/100 mL in oil from hazelnuts roasted at 180 °C for 15 min. Overall, roasting at 180 °C for 15 min notably influenced oil yield, antioxidant activity, and quality parameters. While this condition maximizes oil yield and antioxidant activity, lower roasting temperatures may be preferable to limit oxidation. Air-fryer roasting of hazelnuts, particularly when combined with cold press method, offers a practical approach to enhance both oil yield and antioxidant activity of hazelnut oil.

Keywords: Hazelnut Oil, Air Fryer Roasting, Cold Press, Oil Yield, Oil Quality

ÖZET

Bu çalışmanın amacı, hava fritözü ile kavurma koşullarının fındıkların renk ve tekstürü üzerindeki etkilerini araştırmak, kavurma sıcaklığı ve süresinin soğuk preslenmiş ve hava fritözü ile kavrulmuş fındıkların yağ verimi üzerindeki etkisini incelemek ve hava fritözü ile kavrulmuş fındıklardan elde edilen yağların kimyasal özelliklerini ve antioksidan aktivitesini belirlemektir. Kavurma koşulları sırasıyla 120, 150 ve 180 °C sıcaklıkta 5, 10 ve 15 dakika olarak belirlenmiştir. L*, a* ve b* değerleri, renk farkı (ΔE) ve kavrulmamış (çiğ) ile kavrulmuş fındıkların tekstürel özellikleri değerlendirilmiştir. Fındıkların ΔE değeri, kavurma sıcaklığı ve süresi arttıkça artmış ve en yüksek değeri (26) 180 °C sıcaklıkta 15 dakika kavurma koşulunda elde edilmiştir. Kavurma sıcaklığı ve süresinin artmasıyla sertlikte belirgin bir azalma gözlenmiş ve en düşük sertlik değeri (19,75 N) 180 °C sıcaklıkta 15 dakika kavrulmuş fındıklarda gözlenmiştir. Elde edilen fındık yağları, yağ verimi, serbest yağ asidi içeriği (FFAC), asit değeri (AV), peroksit değeri (PV), p-anizidin değeri (pAV), totox değeri (TV), konjuge dienler (CD), konjuge trienler (CT), ΔE , yağ asidi bileşimi ve antioksidan aktivite açısından değerlendirilmiştir. En yüksek yağ verimi (%67,40) 180 °C sıcaklıkta 15 dakika kavrulmuş fındıklardan elde edilirken, kavrulmamış fındıklar en düşük yağ verimini (%52,56) vermiştir. FFAC, AV ve PV, kavurma sıcaklığı ve süresi arttıkça hafifçe artmış ve 180 °C sıcaklıkta 15 dakika kavurma koşulunda sırasıyla %0,43, 0,85 mg KOH/g yağ ve 2,70 mEq O₂/kg yağ değerlerine ulaşmıştır. Hem pAV hem de TV, kavurma sıcaklığı ve süresi arttıkça yükselmiş ve 180 °C sıcaklıkta 15 dakika kavurma koşulunda sırasıyla 3,01 ve 8,39 değerlerine ulaşmıştır. CD ve CT benzer bir eğilim göstermiş ve aynı koşullar altında sırasıyla %12,03 ve %11,56 ile en yüksek değerlere ulaşmıştır. ΔE , kavurma sıcaklığı ve süresi arttıkça kademeli olarak artmış ve 180 °C sıcaklıkta 15 dakika kavurma koşulunda maksimum 4,80 değerine ulaşmıştır. Yağ asidi bileşimi analizleri, kavurmanın oleik ve linoleik asitlerde kademeli azalmaya yol açtığını, diğer yağ asitlerinde ise sadece hafif değişiklikler gözlemlendiğini ortaya koymuştur. Ferrik redükleyici antioksidan gücü (FRAP) yöntemi ile ölçülen fındık yağlarının antioksidan aktivitesi, kavrulmamış fındıklardan elde edilen yağda 8,01 mg trolox eşdeğeri (TE)/100 mL iken, 180 °C sıcaklıkta 15 dakika kavrulmuş fındıklardan elde edilen yağda 16,82 mg TE/100 mL değerine yükselmiştir. Genel olarak, 180 °C sıcaklıkta 15 dakika kavurma, yağ verimi, antioksidan aktivite ve kalite parametrelerini belirgin şekilde etkilemiştir. Bu koşul, yağ verimi ve antioksidan aktiviteyi maksimize etse de, oksidasyonu sınırlamak için daha düşük kavurma sıcaklıkları tercih edilebilir. Fındıkların hava fritözünde kavrulması, özellikle soğuk pres yöntemi ile birleştirildiğinde, fındık yağının hem yağ verimini hem de antioksidan aktivitesini artırmak için pratik bir yöntem sunmaktadır.

Anahtar Kelimeler: Fındık Yağı, Hava Fritözü ile Kavurma, Soğuk Pres, Yağ Verimi, Yağ Kalitesi

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	vi
ÖZET	vii
ACKNOWLEDGEMENTS	viii
TABLE OF CONTENTS	ix
LIST OF SYMBOLS AND ABBREVIATIONS	xi
LIST OF FIGURES	xii
LIST OF TABLES	xiii
1. INTRODUCTION	1
1.1. Hazelnuts and Their Composition	1
1.2. Roasting of Hazelnuts	2
1.3. Air Fryer Roasting	3
1.4. Oil Extraction from Nuts	4
1.5. Lipid Oxidation of Nut Oil	7
2. PURPOSE OF THE STUDY	9
3. MATERIALS AND METHODS	10
3.1. Chemicals and Raw Materials	10
3.2. Proximate Analysis of Hazelnuts	10
3.2.1. Determination of Moisture Content	10
3.2.2. Determination of Ash Content	11
3.2.3. Determination of Protein Content	11
3.2.4. Determination of Oil Content	12
3.3. Preliminary Trials for Roasting and Cold Pressing	12
3.4. Air Fryer Roasting of Hazelnuts	13
3.4.1. Color Analysis	14
3.4.2. Texture Analysis	15
3.5. Cold Press Extraction of Hazelnut Oil	15
3.6. Oil Yield	16
3.7. Oil Analysis	16
3.7.1. Free Fatty Acid Content	16
3.7.2. Peroxide Value	17
3.7.3. p-Anisidine Value and Totox Value	18
3.7.4. Conjugated Dienes and Trienes	18
3.7.5. Color Analysis	19
3.7.6. Determination of the Fatty Acid Composition by GC-FID	19
3.7.7. Determination of Antioxidant Activity	20
3.8. Statistical Analysis	21
4. RESULTS AND DISCUSSION	22
4.1. Proximate Analysis	22
4.2. Effect of Roasting on Color of Hazelnuts	22
4.3. Effect of Roasting on Texture of Hazelnuts	23
4.4. Effect of Roasting on Hazelnut Oil Yield	24
4.5. Hazelnut Oil Analysis	26
4.6. Pearson Correlation Analysis	34
5. CONCLUSIONS	38

REFERENCES	39
BIOGRAPHY	45
PUBLICATIONS AND PRESENTATIONS FROM THE THESIS	46



LIST OF SYMBOLS AND ABBREVIATIONS

AV	: Acid value
CD	: Conjugated diene
CT	: Conjugated triene
FAMES	: Fatty acid methyl esters
FFAC	: Free fatty acid content
FRAP	: Ferric reducing antioxidant power
GC-FID	: Gas Chromatography-Flame Ionization Detector
HMF	: Hydroxymethylfurfural
pAV	: p-anisidine value
PV	: Peroxide value
TE	: Trolox equivalents
TPTZ	: Tripyridyltriazine
TV	: Totox value
ΔE	: Color difference

LIST OF FIGURES

	<u>Page</u>
Figure 3.1: Air fryer	13
Figure 3.2: (a) Raw hazelnuts, (b) roasted hazelnuts at 120 °C for 5 min, (c) roasted hazelnuts at 120 °C for 10 min, and (d) roasted hazelnuts at 120 °C for 15 min	13
Figure 3.3: (a) Raw hazelnuts, (b) roasted hazelnuts at 150 °C for 5 min, (c) roasted hazelnuts at 150 °C for 10 min, and (d) roasted hazelnuts at 150 °C for 15 min	14
Figure 3.4: (a) Raw hazelnuts, (b) roasted hazelnuts at 180 °C for 5 min, (c) roasted hazelnuts at 180 °C for 10 min, and (d) roasted hazelnuts at 180 °C for 15 min	14
Figure 3.5: Screw press	16

LIST OF TABLES

	<u>Page</u>
Table 3.1: GC analysis conditions for FFA analysis	20
Table 4.1: Proximate analysis of unroasted hazelnut kernels	22
Table 4.2: L*, a*, b* and ΔE values of roasted and unroasted hazelnuts	23
Table 4.3: Effect of roasting conditions on the textural properties of hazelnuts	24
Table 4.4: Effect of roasting conditions on oil yield and total oil content of hazelnuts	25
Table 4.5: Effect of roasting conditions on FFAC, AV, PV, pAV, and TV of hazelnut oils	26
Table 4.6: CD and CT values of hazelnut oils	28
Table 4.7: L*, a*, b* and ΔE values of hazelnut oils	29
Table 4.8: Fatty acid composition of oil extracted from unroasted and roasted hazelnuts at different roasting conditions	31
Table 4.9: Effect of roasting on antioxidant activities of hazelnut oils	33
Table 4.10: Pearson correlation coefficients	34

1. INTRODUCTION

1.1. Hazelnuts and Their Composition

Hazelnut is one of the most widely consumed nuts worldwide. It is primarily cultivated along the Black Sea coast of Türkiye, in Southern Europe (including Italy, Spain, Portugal, and France), and in specific regions of the United States, particularly Oregon and Washington. Additionally, hazelnut is produced in countries such as New Zealand, China, Azerbaijan, Chile, Iran, Georgia, Kyrgyzstan, Poland, and Croatia [Ciemniewska-Żytkiewicz et al., 2015; Pelvan et al., 2012; Marzocchi et al., 2016]. Türkiye is the world's leading producer of hazelnuts, with an annual production of 325,000 metric tons (in-shell basis) for the 2023-2024 season, representing approximately 62% of global production [INC, 2024]. Türkiye cultivates seventeen hazelnut varieties, including Acı, Cavcava, Çakıldak, Fosa, İncekara, Kalinkara, Kan, Karafındık, Kargalak, Kuş, Mincane, Palaz, Sivri, Tombul, Uzunmusa, Yassı Badem, and Yuvarlak Badem [Köksal et al., 2006]. Among these eighteen cultivars, only Tombul variety, which is primarily grown in the Giresun region of Türkiye, is classified as premium quality due to its high oil content, distinctive flavor and aroma, and the ease with which its brown skin can be removed after roasting. The remaining cultivars grown throughout Türkiye are generally considered second-grade in quality [Alasalvar et al., 2010].

Hazelnuts are a valuable component of a healthy diet due to their rich nutritional profile. A 100-gram serving provides approximately 634 kilocalories. The raw hazelnut kernels usually contain 50-73% fat, 10-22% carbohydrates, 10-24% protein, 1-3% fiber, 1-3.4% ash and 2-6.5% moisture [Köksal et al., 2006]. They are also rich in essential minerals such as magnesium, calcium, phosphorus, and potassium, as well as vitamins B₁, B₃, B₆, and E, and various amino acids [Marzocchi et al., 2016].

Hazelnuts play a vital role in human nutrition due to their rich composition of lipids, proteins, carbohydrates, vitamins, minerals, dietary fiber, and phenolic compounds [Cosmulescu et al., 2013; Marzocchi et al., 2016; Öz et al., 2021]. However, the morphological and nutritional characteristics of hazelnuts vary among genotypes,

largely influenced by geographical and ecological factors [Ferreira et al., 2010; Rovira et al., 2005; Öz et al., 2021].

1.2. Roasting of Hazelnuts

Roasting is a heat-processing method generally employed to remove pellicles from kernel surfaces, inactivate enzymes, eliminate bacteria, and reduce water activity [Özdemir et al., 2001]. Additionally, roasting also enhances organoleptic properties of foods by improving product color, texture, and flavor [Burdack-Freitag et al., 2010]. The roasting process induces several physical changes, such as moisture loss [Amaral et al., 2006], color changes [Alamprese et al., 2009], and biochemical transformations, including lipid degradation and Maillard reactions. These reactions are responsible for the formation of pyrazine compounds, which contribute to the characteristic roasted aroma [Saklar et al., 2001].

Cienniewska-Żytikiewicz et al. [2014] conducted a study assessing the roasting of a specific hazelnut cultivar at temperatures of 100, 130, and 160 °C, concluding that 130 °C and 160 °C were optimal for achieving the desired product characteristics.

Cienniewska-Żytikiewicz et al. [2014] observed a substantial reduction in moisture content and notable changes in color values (L^* and a^*) with increased roasting temperature and time. Pelvan et al. [2012] reported an estimated 66.3% loss in total phenolic content following roasting, primarily due to the removal of the phenol-rich skins. Regarding tocopherol content, Schlörmann et al. [2015] reported reductions of approximately 34% in α -tocopherol and 40% in β -tocopherol as a result of roasting. However, Amaral et al. [2006] documented only a 9% decrease in α -tocopherol after roasting hazelnuts at 185 °C for 15 min. Alasalvar et al. [2003], who analyzed the volatile profiles of unroasted and roasted hazelnuts (165 °C for 25 min), reported a more complex and intensified aroma profile in roasted samples, attributed to the formation of additional volatile compounds not present in the unroasted nuts.

The roasting process leads to the release of various volatile substances, including aldehydes, ketones, pyrazines, alcohols, aromatic hydrocarbons, furans, pyrroles, terpenes, and organic acids. Filbertone has been identified as the key odor-active compound responsible for the distinctive nutty and roasted hazelnut aroma

[Alasalvar et al., 2003; Marzocchi et al., 2016]. Alasalvar et al. [2010] investigated the oil content and fatty acid composition of various roasted hazelnut species and reported increased oil yield along with slight modifications in fatty acid profiles compared to unroasted nuts. Roasting is a widely adopted pre-treatment method in oilseed processing, aimed at enhancing oil extraction efficiency and altering oil quality parameters. Research has shown that both the roasting method and conditions (such as temperature and time) significantly influence the physicochemical and sensory characteristics of oils derived from roasted seeds [Shi et al., 2017; Zou et al., 2018; Suri et al., 2019]. Roasted hazelnuts are widely incorporated into various food products, including spreads, confectionery, cereal bars, and bakery items [Cucu et al., 2011].

1.3. Air Fryer Roasting

An air fryer is a mechanical cooking device designed to circulate hot air rapidly, allowing food to be fried with minimal oil. During operation, a motorized fan generates hot air that swiftly circulates around the food, creating a crispy outer layer through rapid heat transfer [Tewari et al., 2015]. A typical hot air fryer consists of five primary components: a heating element, electric fan, frying chamber, air duct, and temperature sensors. The electric fan, positioned above the heater, draws air upward from the cooking chamber and propels it at high velocity. As the air passes through the heating element, it is heated and directed back into the cooking chamber with minimal energy and velocity loss. The air guide located at the base of the chamber redirects the airflow vertically, ensuring uniform heat distribution throughout the food [Arslan et al., 2018].

Air frying technology significantly reduces oil and fat usage compared to traditional deep-frying methods. As a result, it generates minimal waste oil (resulting in zero effluent discharge) and produces relatively low levels of gas emissions. By reducing reliance on oils from both plant and animal sources; including palm, sesame, sunflower, soybean, olive, and animal fats; air frying helps lower the carbon footprint. Therefore, air frying method is increasingly favored by environmentally conscious and health-oriented consumers as an alternative to conventional oil immersion frying [Téllez-Morales et al., 2024].

Nuts are among the most commonly consumed foods globally due to their numerous health benefits. Thermal processing offers several advantages in food preparation, including enhanced antioxidant levels, improved flavor development, inhibition of microbial growth, and extended shelf life [Sruthi et al., 2021]. Various appliances such as air fryers, convection ovens, microwave ovens, drum roasters, and hot air roasters are commonly used for roasting nuts [Kutlu et al., 2022; Ha et al., 2024]. While roasted nuts were traditionally purchased from local markets, the shift toward home cooking, particularly during the COVID-19 pandemic, has led to increased use of air fryers for this purpose. These methods are favored for their safety and energy efficiency [Kalla, 2017; Ha et al., 2024]. Nevertheless previous studies have shown that nuts roasted using convection ovens exhibit varying physicochemical characteristics. In contrast, there is limited research on the chemical properties of nuts roasted using air fryers especially in relation to fatty acid composition, color parameters, non-enzymatic browning index, antioxidant activity, and overall phenolic content [Ha et al., 2024].

1.4. Oil Extraction from Nuts

Basic principles of oil extraction include avoiding damage to the oil during processing, obtaining oil with the fewest possible impurities, minimizing residual fat in the cake, and maximizing oil yield from the raw material [Ionesu et al., 2017]. Despite differences in technology, all extraction methods adhere to these core principles [Cakaloglu et al., 2018].

Extraction process significantly affects the quality, flavor, aroma, antioxidant activity, and oxidative stability of nut oils. In recent years, various oil extraction techniques such as solvent extraction, aqueous enzymatic extraction, supercritical fluid extraction, hydraulic pressing, and screw pressing have been extensively studied [Zhou et al., 2016; Wu et al., 2024]. Although solvent extraction produces a high yield, it can compromise the nutritional quality of the oil by introducing undesirable flavors and aromas. Moreover, the organic solvents used in this method may pose health and environmental risks. The practical application of aqueous enzymatic extraction is limited by high costs and challenges in enzyme recovery. Supercritical fluid extraction has emerged as a promising alternative to solvent

extraction. However, its industrial use remains limited due to the high costs associated with equipment and processing [Wu et al., 2024].

Hydraulic pressing and screw pressing are mechanical methods used for oil extraction. These processes rely on mechanical energy to extract oil from raw materials [Jokić et al., 2015]. The advantages of mechanical extraction include ease of use, rapid processing, suitability for small quantities of raw material, applicability to various oilseeds, and low cost. Additionally, the process yields a protein-rich press cake as a valuable by-product [Singh et al., 2000; Cakaloglu et al., 2018].

In hydraulic pressing, oil is extracted by pressing seeds enclosed in filter cloth within pressing chambers. The resulting oil passes through the filter, while the press cake remains in the cloth and is manually removed. The key parameters affecting the efficiency of this process are pressure and temperature [Lanoiselle et al., 1994; Cakaloglu et al., 2018]. A hydraulic press generates no heat, allowing the product to remain at ambient temperature, which positively influences oil quality by yielding lower levels of conjugated trienes and peroxide values compared to screw pressing [Sena-Moreno et al., 2015; Panzanini et al., 2024]. When unroasted raw materials are used, the temperature reached during screw pressing may enhance the sensory profile of the oil [Celenk et al., 2009]. Conversely, roasting the nuts before extraction using hydraulic press has been shown to improve both the organoleptic and chemical properties of the oil. Due to its higher yield and capability for continuous operation, the screw press is increasingly replacing the hydraulic press in both industrial and laboratory applications [Panzanini et al., 2024].

A screw press typically includes an inlet for feeding the nuts and an outlet for the extracted oil and defatted cake. The efficiency of screw pressing is influenced by several factors, including the initial characteristics of the raw material (e.g., shell presence, moisture and oil content, and seed type), feeding rate, temperature (hot or cold pressing), rotational speed, die diameter, and any pretreatment applied prior to screw pressing [Cakaloglu et al., 2018]. Screw pressing does not require expensive machinery or extreme temperature and pressure conditions, making it a cost-effective and energy-efficient method. It also avoids the use of harmful solvents, reducing the risk of producing toxic or undesirable compounds. Moreover, screw pressing enables continuous or semi-continuous operation [Martínez et al., 2017]. Currently, screw

pressing is the most favorable technique for the extraction of nut oils [Ouzir et al., 2021].

The temperature applied during screw pressing significantly influences both the yield and overall quality of the extracted oils [Rabadán et al., 2018]. Elevated temperatures can alter the lipid structure and cause protein denaturation in oilseeds, thereby enhancing oil extraction efficiency. Flavor, a critical factor for consumer acceptance of edible oils, is highly affected by pressing temperature. However, excessive heat can lead to a loss of nutritional value in the final product [Ghiasi et al., 2022]. Screw pressing generates heat primarily through friction and pressure, with temperatures rising considerably during operation to optimize yield [Álvarez-Ortí et al., 2012]. The performance of the screw press is highly dependent on the nature of the raw material and the conditioning techniques applied. Since different nuts or oilseeds may not behave similarly under the same conditions, specific processing parameters must be tailored for each raw material [Martínez and Maestri, 2015; Fantino et al., 2020]. Research has shown that all technological parameters such as temperature, roasting, screw speed, and die diameter exert distinct effects on the volatile compound profile of the resulting oils [Ojeda-Amador et al., 2020].

Edible oils have been used in culinary practices since ancient times. In recent years, consumer interest in unrefined edible oils particularly "cold-pressed oils" has grown due to their nutritional and health-related benefits. Cold pressing is an oil extraction method that excludes heat treatment, refining, solvent use, and chemical additives [Akin et al., 2018]. The main concern during cold pressing is to maintain low processing temperatures. The distinctive nutty flavor and fresh taste of cold-pressed oils are attributed to the non-chemical process and controlled temperature conditions [Jokić et al., 2015; Król et al., 2021].

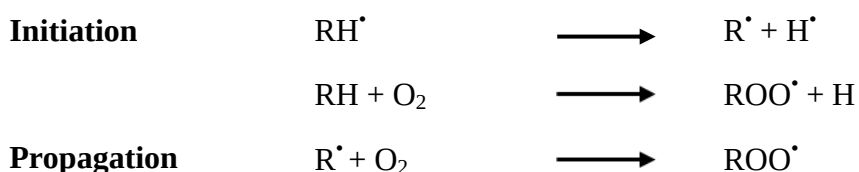
Suri et al. [2019] investigated the effects of air fryer roasting of peanuts at 140, 160, and 180 °C for 5 and 10 min, and extraction methods (solvent and mechanical) on the quality characteristics of cold-pressed peanut oil below 50 °C, including oil yield, oxidative stability, and Maillard reaction products. Li et al. [2023] examined the effects of conventional roasting at different temperatures (120, 150, and 180 °C) and times (10, 20, and 30 min) on oil yield, fatty acid composition, oxidative stability, antioxidant activity, and flavor of walnut oil, which was extracted using the cold

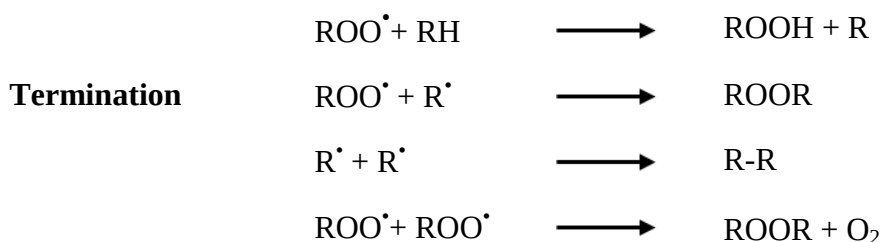
pressing method at 30 °C. **Król et al. [2021]** analyzed changes in the fatty acid profiles and quality parameters of hazelnut oils obtained from six different cultivars during a nine-month storage period, where cold pressing was carried out using a continuous expeller screw press at 40 °C. **Keskin Uslu et al. [2024]** investigated the physicochemical, aromatic, and sensory characteristics of cold-pressed tiger nut oil, extracted using a cold press at 40 °C. **Akin et al. [2018]** evaluated the fatty acid composition, phytosterol and phenolic content, organic acids, carotenoids, and antioxidant activity of raw pumpkin seeds grown in four different regions of Central Anatolia, Türkiye, by extracting the oils using the cold pressing method at 40 °C. **Martínez et al. [2017]** carried out almond and walnut oil extraction using cold pressing at 35-40 °C. **Ojeda-Amador et al. [2018]** characterized walnut oils obtained from three different walnut varieties using cold press extraction at a temperature of 50 °C.

Cold pressing is regarded as an exceptionally suitable technique for producing edible oils enriched with health-beneficial compounds. This method minimizes the thermal degradation of bioactive constituents such as phytosterols, tocopherols, unsaturated fatty acids, vitamins, and carotenoids. Oils extracted by cold pressing are also more appealing to consumers due to their enhanced nutritional and functional qualities. Growing interest in health and wellness has contributed to the increasing popularity of cold pressing for the production of a wide range of nut and seed oils [**Jafari et al., 2012; Akin et al., 2018**].

1.5. Lipid Oxidation of Nut Oil

The oxidation of oils is defined as a series of successive chain reactions that negatively affect oil quality. It is a crucial reaction responsible for the loss of desirable flavor and the formation of undesirable compounds in oils. The oxidation of oils occurs in three stages: initiation, propagation, and termination as given below:





In the initiation phase of the oxidation mechanism, a hydrogen atom is removed from the chain of an unsaturated fatty acid, resulting in the formation of a free radical. When oxygen binds to this free radical, a peroxy radical ($\text{ROO}^\bullet$) is formed. In the propagation phase, peroxy radicals remove a hydrogen atom from another unsaturated fatty acid molecule to stabilize themselves, leading to the formation of the primary oxidation product, hydroperoxide (ROOH). These compounds are unstable and subsequently decompose into secondary oxidation products, such as carbonyl compounds including aldehydes, ketones, epoxy acids, and hydrocarbons. The reaction continues as long as oxygen and unsaturated fatty acid molecules are available in the medium. In the termination phase, free radicals react with each other to form dimeric (ROOR) and polymeric compounds, which alter the sensory characteristics of the oil [Sahin et al., 2009].

The primary factors affecting the oxidation of nut oils include fatty acid composition, free fatty acids, mono- and diglycerides, processing conditions, heat and light, the amount and type of oxygen, heavy metals, peroxides, thermally oxidized compounds, pigments, and antioxidants. Among these, the most important factor accelerating oxidation is the degree of unsaturation, or the number of double bonds in the fatty acids. In general, oxidation occurs more rapidly in nut oils than in other fats in solid form. This is primarily because nut oils contain a higher proportion of unsaturated fatty acids. The main changes resulting from the oxidation of nut oils include development of rancid flavors and odors, discoloration due to pigment degradation, formation of toxic compounds, loss and deterioration of taste and aroma, and degradation of vitamins A, D, and E, as well as essential fatty acids. These factors cause nutritional losses in nut oils, reducing consumer acceptance and shelf life [Choe et al., 2006].

2. PURPOSE OF THE STUDY

The extraction process constitutes a critical determinant of the quality of oils obtained from oilseeds and nuts. In recent years, both consumers and the oil production industry have increasingly emphasized the assessment of quality differences among oils produced by various extraction and processing methods. In the present study, cold-press extraction was employed to investigate the oxidative susceptibility of hazelnut oil. Although a limited number of studies have examined the physicochemical properties of air-fried hazelnuts, the chemical characteristics of hazelnut oil obtained from air fryer roasted hazelnuts via cold pressing has not been investigated. Therefore, the objectives of this study are to:

- Investigate the effects of air fryer roasting conditions on the texture and color of hazelnuts.
- Examine the impact of roasting temperature and time on the oil yield of cold-pressed and air-fried hazelnuts.
- Determine the chemical characteristics (free fatty acid content, peroxide value, p-anisidine and totox values, conjugated dienes and trienes, color, fatty acid composition and antioxidant activity) of hazelnut oils obtained from air fryer roasted hazelnuts.

3. MATERIALS AND METHODS

3.1. Chemicals and Raw Materials

A total of 24 kg of vacuum-packed hazelnuts (2024 harvest), belonging to the Tombul cultivar (*Corylus avellana* L.) with a diameter of 13-15 mm, were supplied by Altun Gıda (Giresun, Türkiye). Chloroform, acetic acid, ethyl alcohol, fatty acid methyl esters (FAMES), hydrochloric acid, isooctane, phenolphthalein, potassium hydroxide, sodium hydroxide, sodium sulfate, sodium thiosulfate and starch were purchased from Merck (Darmstadt, Germany). Ferric chloride, p-anisidine, and 2,4,6-tripyridyl-s-triazine (TPTZ) were obtained from Sigma-Aldrich (St. Louis, MO, USA). Hexane and potassium iodide were purchased from Tekkim (Bursa, Türkiye). Deionized water was used in all analyses. All reagents were of analytical grade.

3.2. Proximate Analysis of Hazelnuts

3.2.1. Determination of Moisture Content

Approximately 2-5 g of sample was weighed into a pre-weighed glass dish. The sample was dried in a hot air oven (Ecocell D-82166, MMM Medcenter Einrichtungen GmbH, München, Germany) at 105 ± 2 °C until constant weight was achieved (typically 4-6 hours). After drying, the dishes were transferred to a desiccator, allowed to cool to room temperature, and then weighed using a precision balance to determine the dry matter content. The moisture content of hazelnut samples was calculated using Equation (3.1) as given by [Nielsen, 2010].

$$\text{Moisture (\%)} = \frac{\text{weight of wet sample} - \text{weight of dry sample}}{\text{weight of wet sample}} \times 100 \quad (3.1)$$

3.2.2. Determination of Ash Content

Approximately 5-10 g of sample was weighed into a pre-weighed crucible. The crucibles were placed into a muffle furnace. The samples were incinerated at approximately 550 °C for overnight. After ashing, the furnace was turned off and allowed to cool until the internal temperature dropped below 250 °C. The crucibles were then promptly transferred to a desiccator and covered with an aluminum foil. Once the samples cooled to room temperature, they were weighed to determine the ash content using Equation (3.2) as given by [Nielsen, 2010].

$$\text{Ash (dry basis)(\%)} = \frac{\text{weight after ashing} - \text{tare weight of crucible}}{\text{original sample weight} \times \text{dry matter coefficient}} \times 100 \quad (3.2)$$

3.2.3. Determination of Protein Content

The Kjeldahl method was used to determine the total protein content in hazelnuts. The organic nitrogen present in the sample was digested with sulfuric acid and converted into ammonium sulfate. The released ammonia was then distilled under alkaline conditions, trapped in a standard acid solution, and quantified by back titration. The total nitrogen obtained was multiplied by a conversion factor of 6.25 to calculate the total protein content [James, 1995; Nielsen, 2010]. The total protein content was calculated using Equation (3.3).

$$\text{Protein (\%)} = \frac{(V_{\text{sample}} - V_{\text{blank}}) \times N \times 14.007}{\text{Sample weight (mg)}} \times F \times 100 \quad (3.3)$$

V_{sample} : Volume of HCl used for the sample (mL)

V_{blank} : Volume of HCl used for the blank (mL)

N: Normality of HCl

14.007: Atomic weight of nitrogen (mg/mmol)

F: Nitrogen to protein conversion factor (6.25)

3.2.4. Determination of Oil Content

The oil content of the hazelnut samples was determined using Soxhlet extraction, following the AOAC Official Method 948.22 [AOAC, 1990]. Approximately 3-5 g of ground and dried sample was placed into a cellulose extraction cartridge. The cartridge was inserted into the Soxhlet apparatus, and hexane was used as the extraction solvent. The system was heated and operated for 6-8 hours, allowing the solvent to continuously extract oil from the sample. After extraction, the solvent was evaporated using a rotary evaporator (Laborota 4000, Heidolph, Schwabach, Germany). The flask was then dried, weighed, and the oil content was calculated gravimetrically using Equation (3.4).

$$\text{Crude Oil (\%)} = (W_1 - W_0) / M \times 100 \quad (3.4)$$

W_0 : Weight of the empty extraction flask (g)

W_1 : Weight of the flask after oil extraction and drying (g)

M : Weight of the dried ground sample placed into the extraction cartridge (g)

3.3. Preliminary Trials for Roasting and Cold Pressing

Preliminary trials were conducted to determine the optimal roasting and pressing conditions for cold-pressed oil extraction from hazelnuts. For this purpose, hazelnut kernels were roasted in an air fryer at temperatures ranging from 120 to 200 °C for 5 to 20 min, followed by oil extraction using a screw press. Roasting at 200 °C for 5 to 20 min resulted in over-roasted hazelnuts. Screw press temperatures of 25, 40, and 65 °C were used to determine the optimal pressing temperature for both roasted and raw hazelnuts. A screw pressing temperature of 40 °C resulted in the most efficient oil extraction and press cake separation. Screw pressing was also performed for both whole and ground hazelnuts, and pressing whole hazelnuts yielded higher oil recovery than pressing ground hazelnuts. Therefore, whole hazelnuts were used for screw pressing in subsequent experiments.

3.4. Air Fryer Roasting of Hazelnuts

The hazelnuts were randomly divided into ten groups of 500 g each, with nine groups subjected to roasting and one group serving as the control. Nine distinct roasting treatments were conducted, each performed in triplicate. The hazelnuts were roasted in an air fryer (M30 Maxifry, Yui, Shenzhen, China), as shown in **Figure 3.1**. Roasting was carried out at temperatures of 120, 150, and 180 °C for 5, 10, and 15 min. The hazelnuts in their raw form and after roasting under different conditions were presented in **Figures 3.2-3.4**. Following roasting, the samples were promptly removed from the air fryer and allowed to cool to room temperature. All samples were pressed on the same day without storage.



Figure 3.1: Air fryer.



Figure 3.2: (a) Raw hazelnuts, (b) roasted hazelnuts at 120 °C for 5 min, (c) roasted hazelnuts at 120 °C for 10 min, and (d) roasted hazelnuts at 120 °C for 15 min.



Figure 3.3: (a) Raw hazelnuts, (b) roasted hazelnuts at 150 °C for 5 min, (c) roasted hazelnuts at 150 °C for 10 min, and (d) roasted hazelnuts at 150 °C for 15 min.



Figure 3.4: (a) Raw hazelnuts, (b) roasted hazelnuts at 180 °C for 5 min, (c) roasted hazelnuts at 180 °C for 10 min, and (d) roasted hazelnuts at 180 °C for 15 min.

3.4.1. Color Analysis

The color of unroasted and roasted hazelnut samples was measured using a chromameter (CR-400, Konica Minolta Inc., Osaka, Japan). The samples were chopped for 5 min using a household mixer (HR2653/90 ProMix, Philips, Shenzhen, China) in which twenty hazelnuts were used for each roasting treatment. The chopped pieces were then placed in the transparent cup of the chromameter for measurement. The results were expressed in accordance with the CIELab* color space. In this system, L^* represents lightness (0 = black, 100 = white), a^* indicates the green ($-a^*$) to red ($+a^*$) axis, and b^* represents the blue ($-b^*$) to yellow ($+b^*$) axis. The color difference (ΔE) was calculated to quantify the perceptible difference

between the colors of two samples. ΔE values were determined from the measured L^* , a^* , and b^* values using Equation (3.5).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3.5)$$

3.4.2. Texture Analysis

The texture of unroasted and roasted hazelnuts was measured using a texture analyzer (Lloyd TA1, Lloyd Instruments Ltd., West Sussex, UK) with a load cell of 50 N, and the data were processed using Nexygen™ (Nexy-Gen Plus, Lloyd Instruments, Hampshire, UK) software. For each analysis, 20 hazelnuts were selected from each of the nine roasted groups and the raw hazelnut group. The hazelnuts were placed individually on the test plate, and a cylindrical probe (diameter = 50 mm) was used with a test speed of 1.0 mm/s and initial force of 1.0 Newton [Kita et al., 2006]. Hardness (N), the maximum force required to break the sample and fracturability (mm), the distance at the point of break, were calculated from the force-time curves.

3.5. Cold Press Extraction of Hazelnut Oil

Hazelnut oil from unroasted and roasted hazelnuts (465 g each) was extracted using a screw press (Köprülü Machine, İzmir, Türkiye) as shown in **Figure 3.5**. Cold pressing was performed at a screw rotation speed of 150 rpm and a temperature of 40 ± 5 °C. The temperature of the extracted oil was monitored throughout the cold pressing using a digital thermometer. After pressing, both the oil and press cake were collected, and the oil was filtered through a cotton cloth followed by a polyester filter cartridge to remove suspended particulates. The filtered oil was allowed to settle for 24 hours in sealed, dark glass bottles stored below 15 °C. The clear oil was then decanted from the sediment and centrifuged at 6000 rpm for 30 min using a centrifuge (FC5714, Ohaus, Munich, Germany). Final cold-pressed oils were stored in dark green glass bottles and analyzed within 24 hours.

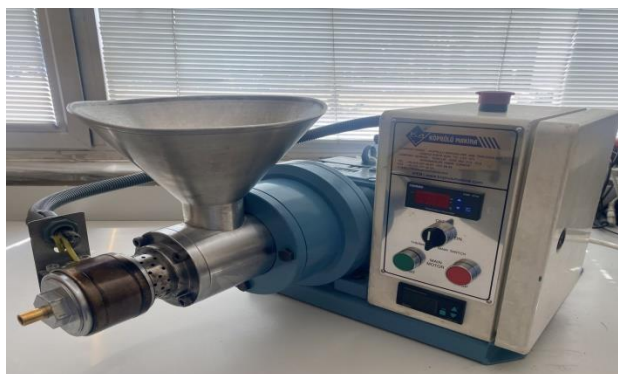


Figure 3.5: Screw press.

3.6. Oil Yield

The oil yield was calculated based on the initial oil content of the hazelnuts and the amount of oil extracted [Suri et al., 2019]. The oil content of both raw and roasted hazelnuts was determined by Soxhlet extraction using n-hexane for 6-8 hours. After extraction, the solvent was removed using a rotary vacuum evaporator at 80 °C and 30 rpm. The oil content was determined gravimetrically and expressed as a weight percentage on a dry matter basis. The oil extraction yield was calculated using Equation (3.6).

$$\text{Oil Yield (\%)} = \frac{\text{quantity of the extracted oil (g)}}{\text{quantity of total oil present in the hazelnuts (g)}} \times 100 \quad (3.6)$$

3.7. Oil Analysis

3.7.1. Free Fatty Acid Content

Free fatty acid content (FFAC) of hazelnuts was determined according to the AOCS Official Method Cd 5a-40 [AOCS, 1990]. Approximately 5-10 g of the oil sample was weighed into a conical flask, and it was neutralized with 50 mL isopropanol. Subsequently, 50 mL of hot 95% (v/v) ethanol was added, and the mixture was stirred to ensure complete dissolution. Then, 2 mL of phenolphthalein was added as the indicator. The sample was titrated with 0.1 N NaOH until a faint but permanent

pink color persisted, indicating the endpoint. The FFAC (%) expressed as oleic acid was calculated using Equation (3.7).

$$FFAC (\%) = V \times N \times 28.2/W \quad (3.7)$$

V = volume of NaOH titrant (mL)

N = normality of NaOH titrant (mol/1000 mL)

28.2 = equivalent weight of oleic acid

W = Weight of the oil sample (g)

The acid value (AV) was interconverted with FFAC using Equation (3.8).

$$AV (\text{mg KOH/g oil}) = FFAC (\%) \times \frac{28.2}{56.1} = FFAC (\%) \times 1.99 \quad (3.8)$$

56.1 = molecular weight of KOH

3.7.2. Peroxide Value

Peroxide value (PV) was determined using the AOCS Official Method Cd 8-53 [AOCS, 1990]. Approximately 5 g of hazelnut oil was weighed into an Erlenmeyer flask, followed by the addition of 30 mL of an acetic acid-chloroform mixture (3:2, v/v). The flask was gently shaken until the oil was completely dissolved. Then, 0.5 mL of saturated potassium iodide solution was added, and the mixture was allowed to stand for 1 min in the dark to permit the reaction between peroxides and iodide ions. Next, 30 mL of deionized water was added, and after thorough mixing, 2 mL of 1% (w/v) starch solution was introduced as an indicator. The liberated iodine was titrated with 0.01 N standardized sodium thiosulfate ($\text{Na}_2\text{S}_2\text{O}_3$) solution until the dark blue coloration disappeared, indicating the endpoint. A blank was prepared using the same procedure but without the oil sample. The PV was determined using Equation (3.9).

$$PV (\text{mEq } \text{O}_2/\text{kg oil}) = (S - B) \times N \times 1000/W \quad (3.9)$$

S = volume of Na₂S₂O₃ titrant (mL) used for sample

B = volume of Na₂S₂O₃ titrant (mL) used for blank

N = normality of Na₂S₂O₃ solution (mEq/mL)

W = Weight of the oil sample (g)

3.7.3. p-Anisidine and Totox Values

The p-anisidine value (pAV) was determined according to the AOCS Official Method Cd 18-90 [AOCS, 1990]. An oil sample weighing between 0.5 and 4.0 g was accurately measured and dissolved in 25 mL of isooctane. The absorbance of this solution was measured at 350 nm using a UV-VIS spectrophotometer (Lambda 35, Perkin Elmer, MA, USA), with isooctane serving as the blank. A 5 mL aliquot of the oil solution was then mixed with 1 mL of a p-anisidine solution (0.25 g p-anisidine/100 mL in glacial acetic acid). For the blank, 5 mL of isooctane was combined with 1 mL of the p-anisidine solution. After allowing the sample to react for approximately 10 min in the dark at room temperature, the absorbance of the reacted solution was measured again at 350 nm against the blank. The pAV of the oil samples was calculated using Equation (3.10).

$$pAV = 25 \times [1.2 \times (A_s - A_b)/W] \quad (3.10)$$

A_s: Absorbance value of the oil solution after reaction with p-anisidine solution

A_b: Absorbance value of the oil solution before reaction

The totox value (TV) was calculated according to Equation (3.11).

$$TV = (2 \times PV) + pAV \quad (3.11)$$

3.7.4. Conjugated Dienes and Trienes

The conjugated diene (CD) and conjugated triene (CT) values were determined according to the AOAC Official Method 957.13 [AOAC, 1990]. An oil sample of 0.25 g was accurately weighed into a volumetric flask and diluted to 25 mL with

isooctane to prepare a 1% (w/v) solution. Isooctane was used as the blank. The absorbance range was adjusted to fall within 0.1-0.8. The absorbances of the solutions for CD and CT were measured at 232 and 270 nm, respectively, using a UV-VIS spectrophotometer (Lambda 35, Perkin Elmer, MA, USA). CD (%) and CT (%) values were calculated using Equations (3.12) and (3.13), respectively.

$$CD (\%) = 0.84 \times ((A_s / (b \times c)) - K_0) \quad (3.12)$$

$$CT (\%) = 0.84 \times (A_s / (b \times c)) - K_0 \quad (3.13)$$

K_0 : Absorptivity of acid and ester groups

A_s : Absorbances measured at 232 and 270 nm for CD and CT, respectively

b : Length of spectrophotometric cuvette used in measurement

c : Sample concentration (g/mL)

3.7.5. Color Analysis

The color values of extracted oils were measured with a chromameter (CR-400, Konica Minolta Inc., Osaka, Japan). The results were presented in accordance with the CIE $L^*a^*b^*$ color space. The color was quantified using the three-dimensional color diagram (L^* , a^* , and b^*). L^* is a measure of lightness, ranging from 0 (black) to 100 (white), a^* denotes greenness ($-a^*$) or redness ($+a^*$) while b^* denotes blueness ($-b^*$) or yellowness ($+b^*$). ΔE values were computed using Equation (3.14).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3.14)$$

3.7.6. Determination of Fatty Acid Composition by GC-FID

The fatty acid profile of hazelnut oils obtained using cold pressing was determined according to TS EN ISO 12966-4:2015 standard [TSE, 2015]. This method is designed to analyze the fatty acid composition in the C_8 - C_{24} range by converting triglycerides into their corresponding methyl esters, which are then analyzed using a

gas chromatography (GC) (7890A, Agilent Technologies, Inc., CA, USA). The fatty acid methyl esters (FAME) were prepared according to TS EN ISO 12966-2:2017 standard [TSE, 2017] where approximately 0.1-0.2 g of the oil sample was dissolved and reacted with methanolic potassium hydroxide to form fatty acid methyl esters (FAMES). These esters were subsequently extracted using hexane. The FAME extract was dried over anhydrous sodium sulfate and spiked with an internal standard. One μL aliquot of the FAME solution was injected into the GC system and analyzed under the operating conditions presented in **Table 3.1**. Quantitative analysis was performed using internal standard correction, and peak areas were used to calculate the relative percentage of each FAME based on the total peak area.

Table 3.1: GC analysis conditions for FFA analysis.

GC Parameter	Value
Injection Volume	1 μL
Carrier Gas	Helium (1.0 mL/min)
Detector Temperature	260 $^{\circ}\text{C}$
Injector Temperature	250 $^{\circ}\text{C}$
Column Temperature	140 $^{\circ}\text{C}$ (hold 5 min) $\rightarrow$ increase by 4 $^{\circ}\text{C}/\text{min}$ to 240 $^{\circ}\text{C}$
Program	hold 15 min

3.7.7. Determination of Antioxidant Activity

The ferric reducing antioxidant power (FRAP) assay was used to determine the antioxidant activity of the samples, following the method of **Benzie and Strain [1996]**. The assay is based on the reduction of ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}) in the presence of antioxidants. Ferric ions form a complex with 2,4,6-tripyridyl-s-triazine (TPTZ), generating a ferric-TPTZ complex (Fe(III)-TPTZ), which is subsequently reduced by antioxidants to the ferrous form (Fe(II)-TPTZ). The resulting Fe(II)-TPTZ complex produces an intense blue coloration with a maximum absorbance at 593 nm. Antioxidant activity was expressed as Trolox equivalents.

For preparation of the FRAP reagent, a 10 mM TPTZ solution in 40 mM HCl was diluted to 100 mL with deionized water. Separately, 20 mM FeCl_3 and 0.3 M acetate

buffer (pH 3.6) were prepared. Equal volumes of the TPTZ solution, FeCl₃ solution, and acetate buffer were then combined to form the FRAP reagent. In the assay, 285 µL of the freshly prepared FRAP reagent was added to each well of a microplate, followed by 15 µL of the sample. After incubation for 30 min at room temperature, absorbance was measured at 593 nm. Trolox served as the standard antioxidant.

3.8. Statistical Analysis

Results were expressed as means $\pm$ standard deviation ($n = 3$) for each determination. Data were subjected to nested one-way analysis of variance (ANOVA) using Minitab statistical software (version 21.4.1, Minitab LLC, State College, PA, USA) followed by Tukey's multiple comparison test as the post-hoc test with a significance level of $p < 0.05$.

4. RESULTS AND DISCUSSION

4.1. Proximate Analysis

Unroasted (raw) Giresun Tombul hazelnut kernels were found to have a moisture content of 3.04%, protein content of 14.69%, ash content of 2.05%, and oil content of 66.23% (**Table 4.1**).

Table 4.1: Proximate analysis of unroasted hazelnut kernels.

	%
Moisture	3.04 ± 0.41
Protein	14.69 ± 0.45
Ash	2.05 ± 0.33
Total oil	66.23 ± 0.64

4.2. Effect of Roasting on Color of Hazelnuts

The color (L^* , a^* , and b^*) and ΔE values for hazelnuts are presented in **Table 4.2**. The highest L^* value obtained was 71.43 for raw hazelnuts. However, L^* values decreased significantly ($p < 0.05$) with increasing roasting temperature and time while a^* , b^* , and ΔE values increased significantly ($p < 0.05$) with rising roasting temperature and time. The decrease in L^* value and increase in ΔE are attributed to the formation of some pigments such as melanoidins as a result of Maillard reactions, which darken the nut color [Zhang et al., 2022]. Our results are consistent with the findings reported by [Ha et al. 2024], who also observed a decrease in L^* value and increase in a^* and b^* values of peanuts, almonds, cashew nuts, hazelnuts, and sacha inchi roasted in an air fryer at different temperatures (150 and 180 °C) and times (5, 10, 15, and 20 min). Marzocchi et al. [2016] also observed similar results for the roasting of hazelnuts using the conventional method at 130 °C for 40, 50, and 60 min and 160 °C for 20, 25, and 30 min. In terms of consumer acceptability, medium roasting degree is generally preferred for hazelnuts. Dark or over-roasted samples are usually less favored by consumers because of their burnt flavor and harder texture. Saklar et al. [2001] reported that consumers typically prefer roasted hazelnuts with

L* values ranging from 57.51 to 75.26 and ΔE values between 0.93 and 19.60 under different roasting conditions.

Table 4.2: L*, a*, b* and ΔE values of roasted and unroasted hazelnuts.

		L*	a*	b*	ΔE
	Unroasted	71.43±0.63 ^a	6.47±0.50 ^a	19.35±0.65 ^{ab}	-
	5 min	69.08±0.41 ^b	6.84±0.39 ^{ab}	20.94±0.82 ^{abc}	3.08±0.43 ^b
120 °C	10 min	67.60±0.89 ^{bc}	6.27±0.09 ^a	19.03±0.95 ^a	3.93±0.65 ^b
	15 min	67.11±0.28 ^{cd}	7.31±0.28 ^{abc}	18.99±0.15 ^a	4.46±0.74 ^b
	5 min	65.49±0.79 ^{de}	7.77±0.30 ^{bc}	21.21±0.96 ^{bc}	6.41±0.22 ^c
150 °C	10 min	64.57±0.34 ^e	8.12±0.12 ^c	22.77±0.34 ^{cd}	7.87±0.59 ^c
	15 min	62.32±0.60 ^f	10.30±0.21 ^d	24.67±0.90 ^{de}	11.26±0.33 ^d
	5 min	59.82±0.74 ^g	11.01±0.81 ^d	24.91±0.33 ^e	13.74±0.57 ^e
180 °C	10 min	55.00±0.37 ^h	13.37±0.14 ^e	28.38±0.33 ^f	20.01±0.34 ^f
	15 min	48.58±0.80 ⁱ	14.41±0.44 ^e	28.82±0.71 ^f	26.00±0.75 ^g

Values (mean ± SD, n = 3) with different letters within the same column are significantly (p < 0.05) different.

4.3. Effect of Roasting on Texture of Hazelnuts

Textural properties including hardness, elasticity, and fracturability are important parameters that must be monitored during the roasting process. The hardness of hazelnuts decreased significantly (p < 0.05) with increasing roasting temperature and time (**Table 4.3**). The hardness of unroasted hazelnuts decreased from 99.46 to 19.75 N after roasting at 180 °C for 15 min. The decrease in hardness with increasing roasting temperature and time was attributed to the reduction in moisture content and the loss of structural integrity in the hazelnuts [Mohammadi Moghaddam et al., 2016]. Roasting causes partial disintegration of the cell walls and intercellular spaces, as well as partial disruption of the cytoplasmic network, resulting in swollen and aggregated protein masses. These structural changes lead to a softer and more brittle texture. The increase in the volume of intercellular spaces further contributes to the reduction in hardness while enhancing crispness and brittleness [Saklar et al., 2003]. Similarly, elasticity and fracturability values decreased significantly (p < 0.05) with increasing roasting temperature and time. These findings are consistent with those reported by Kita et al. [2006], and Mohammadi Moghaddam et al.

[2016], who observed that more intensive thermal processing produces softer and less elastic nut textures with lower fracturability due to structural weakening.

Table 4.3: Effect of roasting conditions on the textural properties of hazelnuts.

		Hardness (N)	Elasticity (mm)	Fracturability (mm)
Unroasted		99.46±0.64 ^a	1.82±0.26 ^a	1.82±0.26 ^a
120 °C	5 min	59.65±0.85 ^b	1.87±0.24 ^a	1.87±0.24 ^a
	10 min	54.14±0.84 ^c	1.69±0.46 ^{ab}	1.69±0.46 ^{ab}
	15 min	49.51±0.90 ^d	1.42±0.31 ^{abc}	1.42±0.31 ^{abc}
150 °C	5 min	40.26±0.67 ^e	1.35±0.20 ^{abcd}	1.35±0.20 ^{abcd}
	10 min	35.77±0.82 ^f	1.02±0.08 ^{bcd}	1.02±0.08 ^{bcd}
	15 min	31.11±0.57 ^g	0.87±0.16 ^{cde}	0.87±0.16 ^{cde}
180 °C	5 min	26.95±0.65 ^h	0.74±0.02 ^{cde}	0.74±0.02 ^{cde}
	10 min	24.13±0.54 ⁱ	0.65±0.02 ^{de}	0.65±0.02 ^{de}
	15 min	19.75±0.25 ^j	0.72±0.25 ^e	0.72±0.25 ^e

Values (mean ± SD, n = 3) with different letters within the same column are significantly (p < 0.05) different.

4.4. Effect of Roasting on Hazelnut Oil Yield

The total oil content and oil yield of hazelnuts increased significantly (p < 0.05) with rising roasting temperature and time (**Table 4.4**). The total oil content of unroasted and roasted hazelnuts ranged from 66.23% to 72.65%, while the oil yield varied between 52.56% and 67.40%. The highest oil yield and total oil content were obtained at the roasting condition of 180 °C for 15 min.

Table 4.4: Effect of roasting conditions on oil yield and total oil content of hazelnuts.

		Total Oil Content (%)	Oil Yield (%)
Unroasted		66.23±0.64 ^a	52.56±0.68 ^a
120 °C	5 min	67.48±0.58 ^{ab}	54.20±0.64 ^{ab}
	10 min	67.22±0.43 ^{ab}	54.60±0.66 ^{bc}
	15 min	67.54±0.55 ^{ab}	54.72±0.57 ^{bcd}
150 °C	5 min	68.37±0.54 ^b	54.56±0.59 ^{bc}
	10 min	67.70±0.40 ^{ab}	56.35±0.63 ^{cd}
	15 min	70.14±0.46 ^c	56.52±0.60 ^d
180 °C	5 min	71.86±0.24 ^{de}	55.52±0.64 ^{bcd}
	10 min	70.49±0.55 ^{cd}	61.37±0.73 ^e
	15 min	72.65±0.70 ^e	67.40±0.66 ^f

Values (mean ± SD, n = 3) with different letters within the same column are significantly ($p < 0.05$) different.

The increase in oil yield with rising roasting temperature and time was attributed to enhanced lipid extraction resulting from more extensive cell wall damage and greater protein denaturation caused by higher temperatures and longer exposure during roasting [Amaral et al., 2006]. Suri et al. [2019] also observed an increase in peanut oil yield following air-fryer roasting and cold pressing. The enhancement in oil extraction yield from roasted peanuts was attributed to the formation of permanent pores and disruption of cell walls, which occurred as a result of the roasting treatment. These structural changes improved oil flow within the cellular matrix, thereby facilitating its release and enhancing the overall extraction efficiency. Li et al. [2023] reported that the roasting of walnut kernels induced a series of structural changes, including the disruption of oil-containing cells, enhanced protein denaturation, reduction in oil viscosity, and increased suitability for mechanical pressing, all of which contributed to improved oil extraction efficiency. Jokić et al. [2016] observed that hazelnuts subjected to different pressing temperatures, oil yield increased considerably with increasing pressing temperature. Similar observations were reported for apricot kernels, where thermal damage to the cell walls caused membrane rupture and the formation of large pores that enhanced oil flow [Mirzaei et al., 2019; Wu et al., 2024].

4.5. Hazelnut Oil Analysis

The FFAC, AV, PV, pAV, and TV of hazelnut oil samples are presented in **Table 4.5**.

Table 4.5: Effect of roasting conditions on FFAC, AV, PV, pAV, and TV of hazelnut oils.

		FFAC (%)	AV (mg KOH/g oil)	PV (mEq O ₂ /kg oil)	pAV	TV
Unroasted		0.35±0.011 ^a	0.69±0.021 ^a	1.46±0.055 ^a	0.46±0.192 ^a	3.38±0.177 ^a
	5 min	0.37±0.000 ^{ab}	0.75±0.001 ^{ab}	1.59±0.094 ^a	0.50±0.283 ^{ab}	3.69±0.263 ^a
120 °C	10 min	0.38±0.011 ^{abc}	0.76±0.022 ^{abc}	2.06±0.059 ^b	0.54±0.039 ^{abc}	4.66±0.082 ^b
	15 min	0.39±0.022 ^{bcd}	0.77±0.043 ^{bcd}	2.09±0.255 ^b	0.60±0.171 ^{abcd}	4.77±0.512 ^b
	5 min	0.40±0.000 ^{bcd}	0.79±0.000 ^{bcd}	2.13±0.156 ^b	0.64±0.073 ^{abcd}	4.89±0.238 ^b
150 °C	10 min	0.40±0.028 ^{bcd}	0.80±0.056 ^{bcd}	2.19±0.101 ^b	1.04±0.074 ^{abcd}	5.43±0.274 ^{bc}
	15 min	0.41±0.011 ^{bcd}	0.81±0.022 ^{bcd}	2.40±0.169 ^{bc}	1.08±0.036 ^{bcd}	5.88±0.346 ^{cd}
	5 min	0.41±0.012 ^{bcd}	0.82±0.025 ^{bcd}	2.61±0.016 ^c	1.12±0.133 ^{cd}	6.33±0.165 ^d
180 °C	10 min	0.42±0.012 ^{cd}	0.83±0.025 ^{cd}	2.66±0.060 ^c	1.20±0.194 ^d	6.51±0.077 ^d
	15 min	0.43±0.011 ^d	0.85±0.021 ^d	2.70±0.099 ^c	3.01±0.469 ^e	8.39±0.271 ^e

Values (mean ± SD, n = 3) with different letters within the same column are significantly (p < 0.05) different.

The FFAC of hazelnut oils extracted from unroasted and roasted hazelnuts varied from 0.35% to 0.43% (**Table 4.5**). Significant differences (p < 0.05) were observed in the FFAC values of hazelnut oils extracted from hazelnuts roasted under different conditions, with FFAC increasing as roasting temperature and time increased. The FFAC of hazelnut oil began to rise after roasting at 120 °C for 10 min, compared to that of unroasted hazelnuts, and reached the highest value (0.43%) at 180 °C for 15 min. The increase in FFAC value is attributed to the thermal degradation of lipid compounds into free fatty acids as roasting temperature and time increase [Suri et al., 2019]. Li et al. [2023] also reported slight differences in FFAC of oils extracted from walnut roasted at different temperatures (120, 150, and 180 °C) and times (10, 20, and 30 min). Ciemniewska-Żytikiewicz et al. [2015] investigated the quality parameters of hazelnut oils at different roasting temperatures, where the highest FFAC was attained at roasting of 160 °C for 60 min, attributing the increase to triglyceride hydrolysis.

The AV of hazelnut oils extracted from unroasted and roasted hazelnuts ranged from 0.69 to 0.85 mg KOH/g oil (**Table 4.5**). All AV values remained below 4 mg KOH/g oil, indicating that the extracted oils meet the criteria for classification as “cold-pressed oils” according to the Codex Standard [**Codex Alimentarius, 2024**]. Roasting temperature and time were found to have a significant ($p < 0.05$) effect on the AV of hazelnut oils, with the highest AV (0.85 mg KOH/g oil) observed at 180 °C for 15 min of roasting.

The PV of hazelnut oils extracted from unroasted and roasted hazelnuts varied between 1.46 and 2.70 mEq O₂/kg oil (**Table 4.5**). All PV values remained below 15 mEq O₂/kg oil, indicating that the extracted oils meet the criteria for classification as “cold-pressed oils” according to the Codex Standard [**Codex Alimentarius, 2024**]. Roasting temperature and time were found to have a significant ($p < 0.05$) effect on the PV of hazelnut oils, with the highest PV (2.70 mEq O₂/kg oil) obtained at 180 °C for 15 min of roasting. **Li et al. [2023]** reported that the highest PV for walnut oils were obtained when walnuts were roasted at 180 °C for 30 min, with the increase in PV attributed to the elevated formation of peroxides and hydroperoxides during the roasting process.

The pAV of hazelnut oils extracted from unroasted and roasted hazelnuts changed from 0.46 to 3.01 (**Table 4.5**). pAV rose with increasing roasting temperature and time, reaching its highest level at 180 °C for 15 min. A similar trend was reported by **Cienniewska-Żytkiewicz et al. [2015]**, who observed that pAV of hazelnut oil increased with temperature, reaching a peak at 160 °C after 60 min of roasting. At elevated temperatures and longer roasting times, hydroperoxides decompose into low-molecular-weight carbonyl compounds, including unsaturated aldehydes, resulting in higher pAV [**Cienniewska-Żytkiewicz et al., 2015; Rabadán et al., 2018**].

TV, which combines PV and pAV, provides a comprehensive measure of the total oxidation status of oils, reflecting the progression of both primary and secondary oxidation products [**Cienniewska-Żytkiewicz et al., 2015; Król et al., 2021**]. The TV of hazelnut oils extracted from unroasted and roasted hazelnuts changed between 3.38 and 8.39 (**Table 4.5**), with the highest value at 180 °C for 15 min of roasting condition. Roasting temperature and time significantly ($p < 0.05$) affected TV. **Ciou et al. [2021]** evaluated the oxidative stability of peanuts roasted at various

temperatures (120, 140, and 160 °C for 10 min) and noted that TV of peanut oils increased with roasting temperature, reaching the highest TV at 160 °C for 10 min.

The CD and CT values of unroasted and roasted hazelnut oils ranged from 3.83 to 12.03% and 4.56 to 11.56%, respectively (**Table 4.6**). Significant differences ($p < 0.05$) were observed in the CD and CT values of hazelnut oils extracted from hazelnuts roasted under different conditions. Both CD and CT values consistently increased with rising roasting temperature and time, reaching their highest levels at 180 °C for 15 min. The results obtained in the present study are consistent with the findings of **Zhang et al. [2022]**, who reported increases in CD and CT values in peanut oils roasted at various temperatures (160-190 °C) and times (10-30 min). An increase in CD and CT values can be attributed to lipid oxidation, during which non-conjugated double bonds in fatty acids are transformed into conjugated double bonds, resulting in the formation of conjugated diene hydroperoxides [**Nielsen, 2010**]. Consequently, higher roasting temperatures and longer roasting times promote greater formation of these oxidation products, reflected in the elevated CD and CT values.

Table 4.6: CD and CT values of hazelnut oils.

		CD (%)	CT (%)
Unroasted		3.83±0.193 ^a	4.56±0.107 ^a
120 °C	5 min	4.25±0.194 ^{ab}	4.63±0.184 ^a
	10 min	4.72±0.201 ^{abc}	5.06±0.148 ^{ab}
	15 min	5.05±0.152 ^{abc}	5.32±0.128 ^{abc}
150 °C	5 min	5.24±0.158 ^{bc}	5.36±0.159 ^{abc}
	10 min	5.42±0.159 ^{bc}	5.39±0.219 ^{abc}
	15 min	5.55±0.244 ^c	5.91±0.449 ^{bc}
180 °C	5 min	5.80±0.526 ^c	6.36±0.654 ^{cd}
	10 min	7.55±0.829 ^d	7.21±0.817 ^d
	15 min	12.03±0.758 ^e	11.56±0.571 ^e

Values (mean ± SD, n = 3) with different letters within the same column are significantly ($p < 0.05$) different.

Roasting temperatures and times significantly ($p < 0.05$) affected L*, a*, b*, and ΔE values of hazelnut oils (**Table 4.7**). L* and b* values of hazelnut oils decreased with increasing roasting temperature and time, while the a* value increased under the

same conditions. The highest ΔE value (4.80) was observed at the roasting condition of 180 °C for 15 min. The decrease in L^* value is attributed to the formation of some pigments such as melanoidins as a result of Maillard reactions, which darken the oil color [Suri et al., 2019; Zhang et al., 2022]. Similar findings were reported by Zhang et al. [2022], who observed that the ΔE values of peanut oils from peanuts roasted at various temperatures (160-190 °C) and times (10-30 min) increased with both roasting temperature and time, a change they attributed to the accumulation of roasting-induced compounds that intensify oil color.

Table 4.7: L^* , a^* , b^* and ΔE values of hazelnut oils.

		L^*	a^*	b^*	ΔE
	Unroasted	25.38±0.01 ^a	0.85±0.04 ^a	7.62±0.02 ^{ab}	-
120 °C	5 min	25.08±0.02 ^b	0.83±0.04 ^a	7.69±0.03 ^a	0.31±0.03 ^b
	10 min	24.72±0.01 ^c	1.02±0.01 ^b	7.56±0.05 ^b	0.68±0.02 ^c
	15 min	24.31±0.03 ^d	1.21±0.02 ^c	6.49±0.00 ^c	1.60±0.01 ^d
150 °C	5 min	24.27±0.09 ^d	1.26±0.04 ^{cd}	6.40±0.01 ^d	1.70±0.06 ^e
	10 min	24.05±0.01 ^e	1.36±0.04 ^{de}	6.40±0.03 ^d	1.87±0.04 ^f
	15 min	23.77±0.01 ^f	1.41±0.05 ^e	6.20±0.02 ^e	2.22±0.01 ^g
180 °C	5 min	23.55±0.01 ^g	1.69±0.04 ^f	5.88±0.05 ^f	2.66±0.03 ^h
	10 min	22.90±0.02 ^h	2.06±0.06 ^g	4.77±0.03 ^g	3.97±0.04 ⁱ
	15 min	22.42±0.02 ⁱ	2.73±0.01 ^h	4.35±0.01 ^h	4.80±0.03 ^j

Values (mean ± SD, n = 3) with different letters within the same column are significantly ($p < 0.05$) different.

Effect of roasting on fatty acid composition of cold-press extracted hazelnut oils from unroasted and roasted hazelnuts is shown in **Table 4.8**. The major fatty acids identified in hazelnut oil were oleic, linoleic, palmitic, and stearic acids, while other acids were present in minor quantities. The most significant ($p < 0.05$) changes occurred in oleic and linoleic acid contents of hazelnut oils as a result of roasting whereas the levels of other fatty acids showed only slight changes with increasing roasting temperature and time. The decrease in oleic and linoleic acids can be attributed to their unsaturated structures containing double bonds, which are more vulnerable to thermal degradation and oxidation [Amaral et al., 2006]. Suri et al. [2019] reported similar findings in cold-pressed peanut oils from peanuts roasted in

an air fryer at 140, 160, and 180 °C for 5 and 10 min, where oleic and linoleic acid content of the peanut oil decreased after roasting at 180 °C for 10 min.



Table 4.8: Fatty acid composition of oils extracted from unroasted and roasted hazelnuts at different roasting conditions.

Fatty acid (g/100 g)							
Temperature (°C)	Time (min)	Oleic Acid (C18:1n9c)	Linoleic Acid (C18:2n6t)	Palmitic Acid (C16:0)	Stearic Acid (C18:0)	Palmitoleic Acid (C16:1)	Cis-11-Eicosenoic Acid (C20:1n9)
unroasted		85.070±0.026 ^a	7.460±0.037 ^a	5.840±0.060 ^{ab}	1.785±0.009 ^a	0.162±0.002 ^a	0.160±0.003 ^a
120	5	84.980±0.036 ^{ab}	7.450±0.005 ^a	5.820±0.011 ^{ab}	1.730±0.010 ^{bc}	0.160±0.003 ^{ab}	0.152±0.002 ^b
	10	84.920±0.128 ^{abc}	7.187±0.007 ^b	5.840±0.032 ^{ab}	1.710±0.022 ^c	0.160±0.002 ^{ab}	0.151±0.002 ^b
	15	84.870±0.105 ^{abc}	7.130±0.010 ^{bc}	5.810±0.011 ^{abc}	1.520±0.009 ^e	0.159±0.003 ^{ab}	0.150±0.004 ^b
150	5	84.830±0.092 ^{abc}	7.097±0.009 ^{bc}	5.740±0.020 ^{bc}	1.780±0.018 ^{ab}	0.159±0.004 ^{ab}	0.150±0.003 ^b
	10	84.813±0.136 ^{abc}	7.050±0.036 ^{cd}	5.870±0.027 ^a	1.426±0.012 ^f	0.158±0.001 ^{ab}	1.149±0.002 ^b
	15	84.760±0.079 ^{bcd}	6.950±0.056 ^{de}	5.860±0.023 ^{ab}	1.640±0.036 ^d	0.157±0.002 ^{ab}	0.149±0.003 ^b
180	5	84.643±0.121 ^{cde}	6.910±0.040 ^{ef}	5.840±0.015 ^{ab}	1.544±0.020 ^e	0.157±0.003 ^{ab}	0.148±0.005 ^b
	10	84.520±0.075 ^{de}	6.830±0.011 ^{fg}	5.790±0.013 ^{bc}	1.710±0.017 ^c	0.157±0.002 ^{ab}	0.148±0.002 ^b
	15	84.360±0.131 ^e	6.770±0.029 ^g	5.850±0.008 ^{ab}	1.541±0.015 ^e	0.154±0.003 ^b	0.148±0.002 ^b

Values (mean ± SD, n = 3) with different letters within the same column are significantly (p < 0.05) different.

Table 4.8: Continued.

Fatty acid (g/100 g)						
Temperature (°C)	Time (min)	Arachidic Acid (C20:0)	Alfa-Linolenic Acid (C18:3n3)	Cis-10-Heptadecenoic Acid (C17:1)	Heptadecanoic Acid (C17:0)	Myristic Acid (C14:0)
unroasted		0.134±0.002 ^{ab}	0.089±0.001 ^a	0.070±0.020 ^a	0.048±0.002 ^a	0.031±0.002 ^a
120	5	0.138±0.002 ^a	0.089±0.003 ^a	0.070±0.033 ^a	0.049±0.004 ^a	0.031±0.002 ^a
	10	0.133±0.003 ^{ab}	0.087±0.004 ^a	0.069±0.002 ^a	0.048±0.001 ^a	0.031±0.003 ^a
	15	0.129±0.002 ^b	0.086±0.003 ^a	0.069±0.003 ^a	0.047±0.003 ^a	0.030±0.003 ^a
150	5	0.130±0.003 ^b	0.086±0.002 ^a	0.068±0.003 ^a	0.048±0.005 ^a	0.030±0.002 ^a
	10	0.136±0.003 ^{ab}	0.085±0.002 ^a	0.068±0.002 ^a	0.050±0.003 ^a	0.030±0.003 ^a
	15	0.129±0.003 ^b	0.085±0.003 ^a	0.068±0.002 ^a	0.048±0.003 ^a	0.032±0.003 ^a
180	5	0.133±0.003 ^{ab}	0.085±0.003 ^a	0.067±0.003 ^a	0.048±0.002 ^a	0.034±0.003 ^a
	10	0.129±0.003 ^b	0.084±0.003 ^a	0.067±0.003 ^a	0.048±0.005 ^a	0.032±0.002 ^a
	15	0.131±0.004 ^{ab}	0.083±0.003 ^a	0.067±0.004 ^a	0.049±0.003 ^a	0.030±0.003 ^a

Values (mean ± SD, n = 3) with different letters within the same column are significantly ($p < 0.05$) different

Significant differences ($p < 0.05$) were observed in the FRAP values of hazelnut oils extracted from hazelnuts roasted under different conditions, with antioxidant activity increasing as roasting temperature and time increased (**Table 4.9**). The antioxidant activity of hazelnut oils obtained from unroasted and roasted hazelnuts ranged from 8 to 16.82 mg TE/100 mL, as determined by the FRAP method. The highest antioxidant activity was observed at 180 °C for 15 min. **Zhang et al. [2022]** reported similar findings on roasted peanut oils, attributing the increased antioxidant activity to the thermal release of bioactive compounds such as phytosterols, polyphenols, and tocopherols, as well as the formation and migration of Maillard reaction products into the oil phase. **Suri et al. [2019]** and **Zou et al. [2018]** made similar observations, reporting that the increased antioxidant activity was due to the transfer of phenolic compounds and Maillard reaction products, such as hydroxymethylfurfural (HMF), into the oil, both known for their strong antioxidant properties. **Ciou et al. [2021]** also reported that the FRAP antioxidant activity of peanut oils increased with higher roasting temperatures, which they attributed to the release of phenolic compounds and the formation of Maillard reaction products. **Li et al. [2023]** reported similar increases in antioxidant activity in cold-pressed walnut oils from walnuts roasted at different temperatures (120, 150, and 180 °C) and times (10, 20, and 30 min), concluding that roasting may promote the release of bound phenolics, convert heat-labile antioxidants into heat-stable forms, and generate new antioxidant compounds through Maillard reactions, collectively enhancing the overall antioxidant activity of the oils.

Table 4.9: Effect of roasting on antioxidant activities of hazelnut oils.

FRAP (mg TE/100 mL)		
Unroasted		8.01±0.21 ^a
120 °C	5 min	9.95±0.21 ^b
	10 min	11.05±0.47 ^{bc}
	15 min	11.31±0.37 ^{cd}
150 °C	5 min	11.52±0.55 ^{cd}
	10 min	11.84±0.53 ^{cde}
	15 min	12.31±0.48 ^{de}
180 °C	5 min	12.51±0.45 ^{de}
	10 min	12.77±0.23 ^e
	15 min	16.82±0.50 ^f

Values (mean ± SD, n = 3) with different letters within the same column are significantly ($p < 0.05$) different.

4.6. Pearson Correlation Analysis

The Pearson correlation coefficients between process parameters (temperature and time) and the hazelnut color, hazelnut texture, hazelnut oil content, hazelnut oil yield, physicochemical properties of hazelnut oil, hazelnut oil color, fatty acid composition of hazelnut oil and antioxidant activity of hazelnut oil are presented in **Table 4.10**.

Table 4.10: Pearson correlation coefficients*.

Correlations		Temperature		Time	
		r-value	p-value	r-value	p-value
Hazelnut color	L*	-0.733	0.000	-0.508	0.004
	a*	0.676	0.000	0.431	0.017
	b*	0.686	0.000	0.362	0.049
	ΔE	0.736	0.000	0.497	0.005
Hazelnut texture	Hardness	-0.981	0.000	-0.628	0.000
	Elasticity	-0.710	0.000	-0.448	0.013
	Fracturability	-0.710	0.000	-0.448	0.013
	Oil Content	0.745	0.000	0.394	0.031
	Oil Yield	0.590	0.001	0.553	0.002
Physicochemical properties of hazelnut oil	FFAC	0.841	0.000	0.566	0.001
	AV	0.842	0.000	0.566	0.001
	PV	0.838	0.000	0.569	0.001
	pAV	0.522	0.003	0.493	0.006
	TV	0.762	0.000	0.589	0.001
	CD	0.573	0.001	0.521	0.003
	CT	0.536	0.002	0.491	0.006
Hazelnut oil color	L*	-0.803	0.000	-0.589	0.001
	a*	0.677	0.000	0.503	0.005
	b*	-0.723	0.000	-0.520	0.003
	ΔE	0.765	0.000	0.556	0.001
Fatty acid composition of hazelnut oil	Oleic Acid	-0.730	0.000	-0.487	0.006
	Linoleic Acid	-0.824	0.000	-0.615	0.000
	Palmitic Acid	-0.083	0.663	0.224	0.234
	Stearic Acid	-0.449	0.013	-0.557	0.001
	Palmitoleic Acid	-0.588	0.001	-0.499	0.005
	Eicosenoic Acid	-0.824	0.000	-0.541	0.002
	Arachidic Acid	-0.280	0.134	-0.446	0.013
	Alfa-Linolenic Acid	-0.506	0.004	-0.387	0.035
	Heptadecenoic Acid	-0.091	0.632	-0.056	0.769
	Heptadecanoic Acid	0.051	0.788	-0.008	0.968
	Myristic Acid	0.088	0.644	-0.121	0.523
	Antioxidant Activity	0.789	0.000	0.664	0.000

*A significance level of $p < 0.05$ was considered statistically significant.

The color parameters of hazelnuts were significantly ($p < 0.05$) influenced by both roasting temperature and time. The L^* value showed a strong negative correlation with roasting temperature ($r = -0.733$, $p < 0.001$) and a moderate negative correlation with roasting time ($r = -0.508$, $p = 0.004$), indicating that higher temperatures and longer times produced darker samples. The a^* value was strongly correlated with roasting temperature ($r = 0.676$, $p < 0.001$) and moderately with roasting time ($r = 0.431$, $p = 0.017$), suggesting intensified red tones under more severe roasting conditions. The b^* value exhibited strong and weak but significant positive correlations with roasting temperature ($r = 0.686$, $p < 0.001$) and roasting time ($r = 0.362$, $p = 0.049$), respectively, reflecting increased yellow coloration. The ΔE value showed strong ($r = 0.736$, $p < 0.001$) and moderate ($r = 0.497$, $p = 0.005$) positive correlations with roasting temperature and time, confirming that roasting led to more pronounced overall color changes.

The textural properties of hazelnuts were significantly affected by both roasting temperature and time. Hardness exhibited a very strong negative correlation with roasting temperature ($r = -0.981$, $p < 0.001$) and a moderate negative correlation with time ($r = -0.628$, $p < 0.001$), indicating that higher temperatures and longer roasting times substantially reduced the hardness of hazelnuts, leading to a more brittle texture. Elasticity showed a strong negative correlation with roasting temperature ($r = -0.710$, $p < 0.001$) and a moderate negative correlation with time ($r = -0.448$, $p = 0.013$), suggesting that prolonged roasting decreased the elasticity and structural integrity of hazelnuts. Similarly, fracturability was negatively correlated with both roasting temperature ($r = -0.710$, $p < 0.001$) and time ($r = -0.448$, $p = 0.013$), confirming that hazelnuts became more fragile and easier to break as roasting conditions intensified.

Oil content showed a strong positive correlation with roasting temperature ($r = 0.745$, $p < 0.001$) and a moderate positive correlation with time ($r = 0.394$, $p = 0.031$), indicating that higher roasting temperatures and longer roasting times increased the oil content. Similarly, oil yield was moderately correlated with both roasting temperature ($r = 0.590$, $p = 0.001$) and time ($r = 0.553$, $p = 0.002$), suggesting that both roasting conditions positively influenced the efficiency of oil extraction.

FFAC, AV and PV exhibited very strong positive correlations with roasting temperature ($r = 0.841$, 0.842 , and 0.838 , respectively, $p < 0.001$) and moderate

positive correlations with time ($r = 0.566$, 0.566 , and 0.569 , respectively, $p = 0.001$), revealing that higher roasting temperatures and longer roasting times substantially increased the acidity of the hazelnut oil, and enhanced primary oxidation. The pAV was moderately correlated with both roasting temperature ($r = 0.522$, $p = 0.003$) and time ($r = 0.493$, $p = 0.006$), suggesting an increase in secondary oxidation products under more severe roasting conditions. The TV exhibited a strong positive correlation with roasting temperature ($r = 0.762$, $p < 0.001$) and a moderate correlation with time ($r = 0.589$, $p = 0.001$), while CD and CT exhibited moderate positive correlations with both roasting temperature ($r = 0.573$ and 0.536 , respectively, $p < 0.01$) and time ($r = 0.521$ and 0.491 , respectively, $p < 0.01$). Overall, these results indicate that roasting temperature has a more pronounced effect on the physicochemical deterioration of hazelnut oil than roasting time, although prolonged roasting also contributes significantly ($p < 0.05$) to increases in oxidation and acidity-related parameters.

The color parameters of hazelnut oil were significantly ($p < 0.05$) influenced by roasting conditions. The L^* value exhibited a strong negative correlation with roasting temperature ($r = -0.803$, $p < 0.001$) and a moderate negative correlation with time ($r = -0.589$, $p = 0.001$), indicating that higher temperatures and longer roasting times produced darker oil. The a^* value was strongly correlated with roasting temperature ($r = 0.677$, $p < 0.001$) and moderately with time ($r = 0.503$, $p = 0.005$), reflecting enhanced red tones under more intense roasting conditions. The b^* value showed strong negative correlations with roasting temperature ($r = -0.723$, $p < 0.001$) and moderate negative correlations with time ($r = -0.520$, $p = 0.003$), suggesting a decrease in yellow coloration under more severe roasting conditions. The ΔE value demonstrated strong ($r = 0.765$, $p < 0.001$) and moderate ($r = 0.556$, $p = 0.001$) positive correlations with roasting temperature and time, confirming that roasting induces pronounced overall color changes in hazelnut oil.

The fatty acid composition of hazelnut oil was significantly ($p < 0.05$) affected by roasting temperature and time. Oleic acid exhibited a strong negative correlation with roasting temperature ($r = -0.730$, $p < 0.001$) and a moderate negative correlation with time ($r = -0.487$, $p = 0.006$). Linoleic acid showed even stronger negative correlations with roasting temperature ($r = -0.824$, $p < 0.001$) and time ($r = -0.615$, $p < 0.001$), indicating a reduction of polyunsaturated fatty acids under more severe

roasting conditions. Stearic acid decreased moderately with roasting temperature ($r = -0.449$, $p = 0.013$) and time ($r = -0.557$, $p = 0.001$). Palmitoleic and eicosenoic acids exhibited moderate to strong negative correlations with both roasting temperature ($r = -0.588$ and -0.824 , respectively, $p = 0.001$) and time ($r = -0.499$ and -0.541 , respectively, $p < 0.01$). Alpha-linolenic acid decreased moderately with roasting temperature ($r = -0.506$, $p = 0.004$) and time ($r = -0.387$, $p = 0.035$). Arachidic acid was not significantly ($p \geq 0.05$) affected by roasting temperature but decreased moderately with roasting time ($r = -0.446$, $p = 0.013$). In contrast, palmitic, heptadecenoic, heptadecanoic, and myristic acids were not significantly ($p \geq 0.05$) influenced by roasting conditions. Overall, the results suggest that higher roasting temperatures and longer roasting times decrease the content of unsaturated fatty acids in hazelnut oil, whereas saturated fatty acids remain relatively stable.

Antioxidant activity showed a strong positive correlation with roasting temperature ($r = 0.789$, $p < 0.001$) and time ($r = 0.664$, $p < 0.001$), indicating that higher temperatures and longer roasting durations significantly ($p < 0.05$) improve the antioxidant activity of hazelnut oil.

5. CONCLUSIONS

Tombul variety hazelnuts harvested in 2024 from Giresun province of Türkiye were used to investigate the effect of air fryer roasting conditions on the oil yield and quality of cold-pressed hazelnut oil. Hazelnuts were roasted at 120, 150, and 180 °C for 5, 10, and 15 min, and their color (L, a*, b* values and ΔE) and texture were measured. The overall color difference (ΔE) increased with both roasting temperature and time, reaching a maximum of 26 at 180 °C for 15 min. Hardness decreased significantly as roasting intensity increased, with the lowest hardness (19.75 N) recorded at 180 °C for 15 min. The extracted oils were analyzed for oil yield, free fatty acids (FFAC), acid value (AV), peroxide value (PV), p-anisidine value (pAV), totox value (TV), conjugated dienes (CD), conjugated trienes (CT), color, fatty acid composition, and antioxidant activity to assess their quality in detail. Oil yield increased with roasting temperature and time, with the lowest yield (52.56%) from raw nuts and the highest (67.40%) from nuts roasted at 180 °C for 15 min. FFAC and AV gradually rose with roasting temperature and time, peaking at 0.43% and 0.85 mg KOH/g oil, respectively, under the same roasting conditions. PV also increased with temperature and time, reaching 2.70 mEq O₂/kg oil, indicating some oxidation, but both PV and AV remained within Codex limits for cold-pressed oils (PV < 15 mEq O₂/kg; AV < 4 mg KOH/g). Secondary oxidation indicators, including pAV and TV, increased with roasting temperature and time, reaching maxima of 3.01 and 8.39, while CD and CT followed a similar trend, reaching peak values at 12.03% and 11.56%, respectively. The ΔE values of the hazelnut oils also increased, reaching 4.80 at 180 °C for 15 min. Fatty acid analysis showed that higher roasting temperatures and times caused notable reductions in oleic and linoleic acids, with minor changes in other fatty acids. Antioxidant activity, measured via the FRAP assay, increased from 8.01 mg TE/100 mL in oil from raw hazelnuts to 16.82 mg TE/100 mL in oil from hazelnuts roasted at 180 °C for 15 min. In conclusion, although roasting at 180 °C for 15 min considerably increases the oil yield and antioxidant activity, lower roasting temperatures and times may be preferred to limit oxidation. Air fryer roasting proves to be a practical roasting treatment that enhances oil yield and quality of hazelnut oil when combined with cold pressing.

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BIOGRAPHY

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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