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Fatty acid and phytosterol contents in hazelnut (*Corylus avellana L.*) varieties grown in different regions: A comparative study of functional properties

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Abstract

Hazelnuts (*Corylus avellana L*) are among the most consumed nuts worldwide due to their high nutritional value and distinctive aroma. Hazelnuts are considered functional foods because of their nutritional and nutraceutical properties. The oils, fatty acids, phenolic compounds, and phytosterols they contain make them ideal for functional food production. The region and environmental conditions where hazelnuts are grown influence their chemical characterization and biological value. Many studies have been conducted on the nutritional composition of hazelnuts. However, no comprehensive study has been conducted on the effects of regional differences on the functional properties of cultivars. This study focused on determining the effects of regional differences on the functional properties of eight hazelnut cultivars grown most intensively in three different hazelnut-growing regions of Turkey (the Eastern Black Sea, Middle Black Sea, and Western Black Sea regions). The results were statistically evaluated at a confidence interval of $p<0.05$. As a result of comprehensive physicochemical analyses, it was determined that the oil contents of hazelnut varieties varied between 60.28±1.54% and 65.43±0.60%, and the iodine values varied between 92.43±1.74% and 95.35±2.81%, and these changes were found to be significant according to $p<0.05$. Regional differences were observed, especially in fatty acid compositions, notably oleic acid (C18:1) at 74.10±2.03% - 78.55±2.02% and linoleic acid (C18:2) at 12.18±1.52% - 16.12±1.85%. The phytosterol composition ranged from ß-sitosterol at 59.13±8.29% - 81.65±3.14% and stigmasterol at 6.89±0.86% - 12.50±7.25% ($p<0.05$), and shows that regional and variety differences also have a significant effect on phytosterol composition. In conclusion, when the data is evaluated holistically, it has been determined that while the functional composition of hazelnuts varies depending on the variety (genetic origin), the growing region conditions also have a significant effect on the functional composition. Furthermore, the data obtained will contribute to the correct sourcing of the most suitable raw materials according to variety and region in the food industry, where hazelnuts and hazelnut products are widely used.

Keywords: Fatty acids, Functional food, Hazelnut (Corylus avellana L.), Phytosterols, Turkish hazelnut varieties.

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1. Introduction

Hazelnut (*Corylus avellana L*) cultivation is concentrated on the northern slopes of mountain ranges native to all temperate regions of Türkiye and bordering the Black Sea. Türkiye is the leading producer globally and the largest exporter, with an annual yield of approximately 750,000 tons. Hazelnut, one of the most popular nuts worldwide, is typically consumed raw or roasted. It is also extensively used in products such as confectionery, chocolate, and in the development of functional foods. Due to its high nutritional value and unique aroma, hazelnut is an important raw material for the food industry. Additionally, hazelnut is used as a nutraceutical food in traditional Persian medicine, classified within the neuronutrient group that supports brain development [1]. In recent years, hazelnuts have gained significant value in the food industry, and hazelnut-like nuts have become increasingly widespread across many market segments.

This trend is driven by various factors such as changing consumer preferences for products that contribute to a healthy life and functional product development. In addition to the unique aroma that hazelnuts add to food products, awareness of their health-improving aspects has increased the demand for hazelnuts and hazelnut-derived products [2, 3]. Hazelnuts are rich in fats, generally low in saturated fatty acids (SFA), high in monounsaturated fatty acids (MUFA) (C18:1), and contain sufficient linoleic acid (C18:2). They also contain many vitamins, minerals, and minor compounds such as amino acids [4, 5]. Hazelnut oil is particularly notable for its oxidative stability compared to other vegetable oils [6-8]. The fatty acid composition of an oil can be an indicator of its oxidative stability and nutritional quality. It is generally accepted that the higher the degree of unsaturation of an oil, the more susceptible it is to oxidative degradation. However, the oxidative stability of oils is not only related to their fatty acid composition but also to the presence of minor components that may have antioxidant effects [9]. Evidence suggests that a diet rich in MUFAs may reduce the risk of coronary heart disease (CHD) and may also have preventive effects on atherosclerosis [10]. The increasing interest in the prevention of cardiovascular diseases is growing as numerous studies emphasize their potential to reduce the risk of CHD [11, 12]. Among the hazelnut species from a botanical perspective, commercial hazelnut varieties grown in Turkey are quite valuable. Hazelnuts consist of approximately 60% oil (fresh weight), and the dominant fatty acid is oleic acid. The fatty acid composition of hazelnut varieties shows fractions very similar to olive oil. Hazelnuts, beyond their favorable fatty acid profiles, are rich in phytosterols known for their cholesterol-lowering properties. Phytosterols have been reported to reduce plasma cholesterol concentrations by inhibiting cholesterol absorption in the intestinal tract [13]. In addition, phytosterols have been reported to possess anti-cancer and immunomodulatory effects [14]. Phytosterols (PS), as plant components, may protect against cancer in various ways. Long-term studies have shown a relationship between the amount of plant sterols consumed in the diet and the prevention of cancer development [15, 16]. These have been reported to include inhibiting cell division, stimulating tumor cell inhibition, and suppressing some hormones necessary for tumor development [17]. Considering that both variety and geographical origin play important roles in determining compositional characteristics, a comprehensive qualitative and quantitative characterization of hazelnut oil is essential. Such profiling provides important information about its chemical composition [18, 19]. Hazelnuts contain high levels of oil, usually ranging from 50% to 77%. The production of hazelnut oil can vary considerably depending on factors such as the physical and chemical properties of the oil, variety, geographical origin, climate, and growing conditions [18, 20]. Although some studies have investigated the fatty acid and sterol compositions of American, Italian, and Spanish hazelnuts [20-22] to date, only a few studies have been conducted on the fatty acid composition of commercial hazelnut varieties grown in Türkiye, but no comprehensive research has been conducted on the oil composition.

This study focuses on determining the effects of variety and regional differences on the functional properties of the eight most intensively cultivated hazelnut varieties in three distinct hazelnut-growing regions of Turkey: the Eastern Black Sea Region (Trabzon), the Middle Black Sea Region (Giresun and Ordu), and the Western Black Sea Region (Akçakoca). It also aims to serve as a reference for the selection of appropriate raw materials in the development of hazelnut-based functional products in the food industry.

2. Materials and Methods

2.1. Materials

A total of twelve samples belonging to eight different common varieties of hazelnuts (*Corylus avellana L.*) grown in three different geographical districts in the Black Sea Region of Türkiye were collected by experts (Figure 1). The samples were collected from the Western Black Sea (Akçakoca) (Mincane, Çakıldak, Karafındık, Fosa), Ordu (Palaz, Çakıldak), Middle Black Sea (Giresun/Ordu) (Sivri, Tombul, Kalınkara), and Eastern Black Sea (Trabzon) regions. The unshelled samples were stored at +20°C until the analyses were performed. All reagents used in the experimental studies were of analytical purity, and all analyses were performed in triplicate (n=3) to ensure the reproducibility of the results.

Figure 1.
Regions where hazelnut varieties are collected.

2.2. Physico-Chemical Analysis

Hazelnut samples were dried and stored at room temperature (+20°C) until analysis. The shells were physically separated from the kernels, and the outer surface of the hazelnuts was removed from the inner shells before analysis. Hazelnuts in shell were ground in a Waring commercial blender (Bosch MMB2111M Vita Power Serie 2, 450 W Blender, Germany) to 0.5-0.8 mm. Oils were pressed from the hazelnuts and extracted using light petroleum ether (b.p. 40-60°C) according to the modified method [23]. The oil was obtained in a Soxhlet apparatus for 8 hours. The chemical solvent used was removed in a rotary vacuum evaporator. The oil content was determined as the difference in amount between the samples weighed before and after extraction. The iodine and saponification values of the oil were determined according to the standard [23] IUPAC methods (1980).

2.3. Fatty Acid Analysis

Saponification of the oils was carried out using 0.1 N methanolic NaOH. The obtained fatty acids were esterified with 10% (v/v) boron trifluoride-methanol (BF_3-MeOH) reagent in accordance with standard procedures [23] IUPAC methods (1980). The formed fatty acid methyl esters (FAME) were analyzed using a Philips Pye Unicam PU 4500 gas-liquid chromatography (GLC) apparatus equipped with a flame ionization detector (FID) and a Carbowax 20M (25 m × 0.22 mm i.d.) capillary column. Helium served as the carrier gas in fatty acid analyses, with a flow rate set at 2 mL/min. The injector, column, and detector temperatures were maintained at 220 °C, 190 °C, and 250 °C, respectively. Fatty acid components were identified by comparing their relative retention times. The injection volume was 1 µL. Fatty acids were identified by comparing the retention times with those of known standards. Additionally, specific gravity and refractive index analyses were performed according to Walker [24] AOCS methods (1980).

2.4. Degree of Unsaturation

Degrees of unsaturation (DU) were calculated according to the formula [25] where ol, ln, and lno represented oleic, linoleic and linolenic acids, respectively.

$$DU = ol\,(\%) + ln\,(\%)\,x\,2 + lno\,(\%)\,x\,3 / 100 \quad (1)$$

2.5. Phytosterol Composition

For sterol analyses, saponification and extraction of unsaponifiable substances were carried out in accordance with Melhuish and Zander [23]. The unsaponifiable fraction was applied uniformly along a 1–1.5 cm line starting from the edge of 20 cm long chromatography plates completely covered with a 0.5 mm thick layer of silica gel (Kieselgel 60G, Merck, Germany). Development was performed using a mixture of hexane and ethyl ether (60:40, v/v) as the eluent. The plates were activated at 100 °C for 1 hour immediately before use. After development, the bands were visualized under ultraviolet light by spraying with 1% 2,7-dichlorofluoroscein solution in ethanol. The band corresponding to the sterol fraction was carefully scraped off the plate and transferred to a test tube. This fraction was extracted three times with 5 mL of diethyl ether each and centrifuged for 1 minute after each extraction. The ether phase was transferred to a new tube, and the solvent was completely removed by evaporation under a gentle flow of nitrogen (N_2).

As a silylation reagent, 0.1 mL of a mixture of bis-(trimethylsilyl)-trifluoroacetamide (BSTFA) and trimethylchlorosilane (TMCS) (0.8/0.2) was added to the sample. The tube was incubated at 65 °C for 30 min. Sterol fractions were analyzed by gas-liquid chromatography (GLC) using a SE 30 capillary column (30 m, 0.25 mm internal diameter). The detector temperature was set at 350 °C, and the injector temperature was set at 300 °C. The column temperature was initially held at 178 °C for 4 min and then increased to 260 °C at a rate of 6 °C/min. Nitrogen was used as the carrier gas at a flow rate of 20 mL/min. The injection volume was 0.1 µL. The extracted oil samples were stored at -30 °C until analysis.

2.6. Statistical Analysis

Statistical analyses were conducted using one-way analysis of variance (ANOVA), the least significant difference (LSD) multiple range test, and correlation analyses at a 5% significance level ($P < 0.05$). The SPSS statistical software package (version 5.0) was used.

3. Results and Discussion

The obtained data revealed statistically significant differences in essential oil properties, including oil content, iodine value (IV), saponification value (SV), refractive index (RI), and specific gravity (SG), among hazelnut varieties and growing regions ($P < 0.00001$; Table 1). Furthermore, location-based differences in these parameters were also reported to be significant ($P = 0.0007$; Table 2).

The fat content in hazelnut samples varied between 58.85% and 69.50%. The highest oil concentration was found in the ‘‘Çakıldak’’ variety grown in Ordu, while the lowest concentration was found in the ‘‘Foşa’’ variety from the Trabzon region (Table 1). These findings are consistent with previous studies on Turkish hazelnut varieties [6, 25, 26]. Similar oil profiles have been reported for Spanish and Italian hazelnuts, including those grown in Tarragona (Catalonia), which show relatively higher oil content [21]. When the location means were evaluated, hazelnuts from Ordu showed the highest average oil content (65.43 ± 0.60%), outperforming those from Giresun and Trabzon (Table 2). This variation can be attributed not only to genetic differences but also to ecological parameters affecting lipid biosynthesis and accumulation, such as temperature, exposure to sunlight, and soil composition. The iodine value (IV), a key determinant of oxidative stability, degree of unsaturation, and shelf-life stability, varied between 90.60 and 97.90 among the samples. These values are within the accepted range (90-100) for cold-pressed vegetable oils (Table 1). Varieties with relatively lower iodine values (IV), such as ‘‘Mincane’’ (Akçakoca), ‘‘Foşa’’ (Akçakoca and Trabzon), and ‘‘Tombul’’ (Giresun), exhibit improved oxidative stability. Conversely, higher iodine values (IV), particularly in ‘‘Çakıldak’’ and ‘‘Palaz’’ varieties from Ordu, indicate increased susceptibility to lipid oxidation and a shorter shelf life (Table 1). Among the locations, Ordu hazelnuts recorded the highest iodine values (IV) (95.35 ± 2.81), while Akçakoca samples recorded the lowest IV (92.43 ± 1.74) (Table 2).

Saponification values (SV), which indicate the average molecular weight of fatty acids, ranged between 182 and 197 mg KOH/g. The highest SV was measured in the variety ‘‘Çakıldak’’ from Ordu (Table 1), suggesting the presence of shorter chain fatty acids, which are desirable for applications such as cosmetics and soap production. No statistically significant difference in refractive index (RI) was observed among the samples. The average value was 1.46845 ± 0.0048, characteristic of oils rich in unsaturated fatty acids, particularly oleic acid (Table 1). In terms of specific gravity (SG), the highest value (0.9213) was observed in the variety ‘‘Sivri’’ from Giresun, while the lowest value (0.9049) was determined in ‘‘Çakıldak’’ from Akçakoca. All measurements were within the accepted range for vegetable oils (0.90-0.92). The results of the study were found to be consistent with standardized physicochemical norms and the limit values established by food circulars (Table 1).

Hazelnut fat is considered a high-value dietary lipid due to its high content of monounsaturated fatty acids, especially oleic acid, which is associated with cardioprotective and anti-inflammatory properties. Recent studies have further emphasized its potential to regulate lipid metabolism and enhance antioxidant defense systems [27]. In this context, varieties from Ordu and Giresun can emerge as innovative and high-quality products in terms of nutritional composition, serving as functional candidates in the formulation of health-oriented and functional food products.

Table 1.
Fat Content, Iodine Value (IV), Saponification Value (SV), Refractive Index (RI) and Specific Gravity (SG) of Samples Belonging to Hazelnut Location Varieties[1].

Locations	Varieties	Fat (g/100g)	IV	SV	RI	SG
Akçakoca	Mincane	$62.02 \pm 0.65^{b,c,d}$	90.60 ± 1.53^{a}	$193 \pm 4.00^{c,d}$	1.4678 ± 0.0086^{a}	$0.9080 \pm 0.0030^{a,b}$
	Çakıldak	$63.45 \pm 1.31^{d,e}$	$93.60 \pm 1.08^{d,e}$	183 ± 7.21^{a}	1.4687 ± 0.0080^{a}	0.9049 ± 0.002696^{a}
	Karafındık	66.08 ± 0.44^{f}	$94.10 \pm 0.39^{e,f}$	$189 \pm 2.65^{a,b,c,d}$	1.4687 ± 0.0078^{a}	$0.9088 \pm 0.0013^{a,b}$
	Foşa	$64.12 \pm 1.38^{e,f}$	$91.40 \pm 0.31^{a,b}$	$190 \pm 4.36^{a,b,c,d}$	1.4685 ± 0.0059^{a}	$0.9120 \pm 0.0028^{b,c,d}$
Ordu	Palaz	$61.35 \pm 1.41^{b,c}$	$92.80 \pm 0.47^{c,d}$	$193 \pm 2.65^{c,d}$	1.4691 ± 0.0013^{a}	$0.9172 \pm 0.0023^{e,f,g}$
	Çakıldak	69.50 ± 1.01^{g}	97.90 ± 0.18^{h}	197 ± 8.54^{d}	1.4688 ± 0.0079^{a}	$0.9173 \pm 0.0015^{e,f,g}$
Giresun	Sivri	$60.20 \pm 1.10^{a,b}$	97.50 ± 0.84^{h}	$192 \pm 5.29^{b,c,d}$	1.4687 ± 0.0041^{a}	0.9213 ± 0.0052^{g}
	Tombul	59.15 ± 1.96^{a}	$92.40 \pm 0.38^{b,c}$	182 ± 4.36^{a}	1.4688 ± 0.0060^{a}	$0.9202 \pm 0.0013^{f,g}$
	Kalınkara	$61.50 \pm 0.52^{b,c,d}$	$94.90 \pm 0.68^{f,g}$	$190 \pm 2.65^{a,b,c,d}$	1.4659 ± 0.0022^{a}	$0.9103 \pm 0.0036^{b,c}$
Trabzon	Sivri	$63.01 \pm 1.84^{c,d,e}$	$92.60 \pm 0.55^{c,d}$	$192 \pm 3.61^{b,c,d}$	1.4687 ± 0.0017^{a}	$0.9139 \pm 0.0025^{c,d,e}$
	Mincane	$61.50 \pm 0.60^{b,c,d}$	95.70 ± 0.33^{g}	$188 \pm 5.57^{a,b,c}$	1.4690 ± 0.0048^{a}	$0.9162 \pm 0.0021^{d,e,f}$
	Foşa	58.85 ± 1.46^{a}	$92.40 \pm 0.34^{b,c}$	$184 \pm 4.36^{a,b}$	1.4687 ± 0.0024^{a}	$0.9185 \pm 0.0004^{f,g}$
Mean ± SD		62.56 ± 3.09	93.82 ± 2.30	$189.42 \pm 6.00^{a,b,}$	1.46845 ± 0.0048^{a}	0.91405 ± 0.0056

Note: [1] Each value is an average of three determinations. Values in the same column with different lower-case letters (a-h) are significantly different at $p<0.05$.
Eastern Black Sea Region (Trabzon), Middle Black Sea Region (Giresun and Ordu), and Western Black Sea Region (Akçakoca).

Table 2.
Fat content, iodine value (IV), saponification value (SV), refractive index (RI) and specific gravity (SG) of samples from hazelnut locations[1].

Locations	Fat (g/100 g)	IV	SV	RI	SG
Akçakoca	63.92±1.76	92.43±1.74	188.75±5.61	1.4684±0.0065	0.9084±0.0035
Ordu	65.43±0.60	95.35±2.81	195.00±6.07	1.4690±0.0051	0.9173 ± 0.0017
Giresun	60.28±1.54	94.93±2.28	188.00±5.87	1.4678±0.0040	0.9173±0.0062
Trabzon	61.12±2.19	93.56±1.64	188.00±5.27	1.4688±0.0028	0.9162±0.0026

Note: [1] Each value is an average of three determinations. Values in the same column with different lower-case letters (a-h) are significantly different at $p<0.05$. Eastern Black Sea Region (Trabzon), Middle Black Sea Region (Giresun and Ordu), and Western Black Sea Region (Akçakoca).

According to Wang et al. [28], proteins obtained from hazelnut hydrolysate exhibit potential anti-obesity effects. Fatty acids, as essential components of the human body, play crucial structural and functional roles. In Turkish hazelnut varieties, palmitic (C16:0), stearic (C18:0), oleic (C18:1), and linoleic (C18:2) acids have been frequently identified. These fatty acids are major energy sources and fundamental constituents of phospholipids in cell membranes, influencing membrane fluidity, flexibility, and permeability [29]. Significant differences in fatty acid composition were observed among hazelnut varieties (Table 3) and cultivation regions, excluding palmitic acid ($P < 0.00001$; Table 4). However, no significant differences were found in total unsaturated fatty acid content across varieties or regions (Tables 3, 4). These results are largely consistent with previous literature [30, 31]. Notably, palmitoleic acid, which was absent in some earlier studies, was detected in Turkish hazelnut varieties in this research.

Table 3.

Fatty acid composition (%), total unsaturation/total saturation ratio and degree of unsaturation of hazelnut samples according to location and variety[1].

Locations	Varieties	$C_{16:0}$	$C_{18:0}$	$C_{18:1}$	$C_{18:2}$	$C_{18:1}+C_{18:2}$	∑MUFA+∑PUFA / ∑SFA	DU
Akçakoca	Mincane	$6.60 \pm 0.20^{b,c}$	3.05 ± 0.13^{e}	$77.60 \pm 0.53^{d,e,f}$	12.75 ± 0.35^{d}	$90.35 \pm 0.72^{a,b}$	$9.37 \pm 0.26^{b,c}$	$1.03 \pm 0.03^{a,b}$
	Çakıldak	6.80 ± 0.14^{c}	2.45 ± 0.14^{c}	$77.10 \pm 0.18^{d,e}$	13.65 ± 0.25^{e}	$90.75 \pm 0.14^{a,b}$	$9.82 \pm 0.23^{c,d}$	$1.04 \pm 0.03^{a,b}$
	Karafındık	5.90 ± 0.16^{a}	2.10 ± 0.08^{a}	79.50 ± 0.12^{g}	12.50 ± 0.21^{d}	92.0 ± 0.31^{b}	11.50 ± 0.10^{f}	$1.05 \pm 0.03^{a,b}$
	Foşa	7.40 ± 0.20^{d}	2.80 ± 0.13^{d}	80.00 ± 3.61^{g}	9.80 ± 0.11^{a}	89.80 ± 3.57^{a}	8.80 ± 0.35^{a}	1.00 ± 0.03^{a}
Ordu	Palaz	6.30 ± 0.45^{b}	3.60 ± 0.09^{g}	$75.90 \pm 0.54^{c,d}$	14.20 ± 0.20^{f}	$90.10 \pm 0.35^{a,b}$	$9.12 \pm 0.51^{a,b}$	$1.04 \pm 0.04^{a,b}$
	Çakıldak	6.90 ± 0.10^{c}	3.20 ± 0.13^{e}	72.30 ± 0.58^{a}	17.60 ± 0.18^{h}	89.90 ± 0.71^{a}	$8.90 \pm 0.17^{a,b}$	1.08 ± 0.04^{b}
Giresun	Sivri	6.90 ± 0.11^{c}	3.00 ± 0.12^{e}	$72.40 \pm 0.10^{a,b}$	17.70 ± 0.24^{h}	$90.10 \pm 0.32^{a,b}$	$9.10 \pm 0.08^{a,b}$	1.08 ± 0.06^{b}
	Tombul	6.30 ± 0.16^{b}	$2.40 \pm 0.10^{b,c}$	$77.60 \pm 0.20^{d,e,f}$	13.70 ± 0.12^{e}	$91.30 \pm 0.31^{a,b}$	10.50 ± 0.10^{e}	1.05 ± 0.04^{b}
	Kalınkara	$6.60 \pm 0.13^{b,c}$	$2.25 \pm 0.07^{a,b}$	$74.20 \pm 0.54^{b,c}$	16.95 ± 0.21^{g}	$91.15 \pm 0.51^{a,b}$	$10.30 \pm 0.17^{d,e}$	1.08 ± 0.03^{b}
Trabzon	Sivri	6.95 ± 0.23^{c}	2.80 ± 0.08^{d}	$79.10 \pm 0.87^{f,g}$	11.15 ± 0.11^{b}	$90.25 \pm 0.97^{a,b}$	$9.26 \pm 0.27^{a,b}$	1.01 ± 0.05^{a}
	Mincane	6.35 ± 0.43^{b}	2.90 ± 0.15^{d}	76.25 ± 0.08^{d}	14.50 ± 0.18^{f}	$90.75 \pm 0.24^{a,b}$	$9.84 \pm 0.60^{c,d}$	$1.05 \pm 0.04^{a,b}$
	Foşa	$6.60 \pm 0.20^{b,c}$	3.40 ± 0.10^{f}	$78.15 \pm 0.41^{e,f,g}$	11.85 ± 0.11^{c}	90.00 ± 0.31^{a}	$9.00 \pm 0.08^{a,b}$	$1.02 \pm 0.06^{a,b}$
Mean ± SD		6.63 ± 0.43	2.83 ± 0.46	76.68 ± 2.68	13.86 ± 2.45	90.54 ± 1.14	9.63 ± 0.82	1.04 ± 0.04

Note: [1] Each value is an average of three determinations. Values in the same column with different lower-case letters (a-h) are significantly different at $p<0.05$. [2] Unsaturation/saturation ratio. Eastern Black Sea Region (Trabzon), Middle Black Sea Region (Giresun and Ordu), and Western Black Sea Region (Akçakoca)

The average saturated fatty acid (SFA) content was approximately 10%, which is lower than that reported for olive oil (15%) [30]. Oleic acid (C18:1) was the dominant unsaturated fatty acid, with an average content of 76.68 ± 2.68%. The total unsaturated fatty acid (MUFA + PUFA) content averaged 90.54 ± 1.14%, which is comparable to Italian hazelnut varieties [21] but lower than values reported for hazelnuts grown in Tarragona, Spain, and higher than some other studies [30, 31].

Unsaturated fatty acids, particularly oleic acid, are known to contribute significantly to oxidative stability. However, their susceptibility to autoxidation can limit the shelf life of hazelnut products [32-34]. Nevertheless, factors such as high natural antioxidant capacity, low water activity (aw), and limited enzymatic activity help counterbalance this limitation [32]. The average UFA/SFA ratio was 9.63 ± 0.82, with the highest value in Akçakoca Karafındık (11.50%) and the lowest in Akçakoca Foşa (8.80%) (Table 3). Among regions, Giresun had the highest average ratio (9.97 ± 0.66%) and Ordu the lowest (9.01 ± 0.36%) (Table 4). The degree of unsaturation (DU), calculated using Equation 1, averaged 1.04 ± 0.04. Among varieties, DU ranged from 1.00 (Akçakoca Foşa) to 1.08 (Giresun Kalınkara, Giresun Sivri, Ordu Çakıldak). Regionally, higher DU values were observed in Giresun (1.07 ± 0.04) and Ordu (1.06 ± 0.04) compared to Akçakoca and Trabzon (1.03 ± 0.03 and 1.03 ± 0.05) (Table 4). Phytosterols naturally present in hazelnut oil, structurally similar to cholesterol, contribute to oxidative inhibition and provide functional health benefits [35]. These compounds enhance both the nutritional quality and shelf life of hazelnut oil.

Table 4.
Fatty acid composition (%), total unsaturation/total saturation ratio and degree of unsaturation of hazelnut samples according to their locations[1].

Locations	$C_{16:0}$	$C_{18:0}$	$C_{18:1}$	$C_{18:2}$	$C_{18:1}+C_{18:2}$	∑MUFA+∑PUFA /∑SFA	DU
Akçakoca	6.68±0.58	2.60±0.39	78.55±2.02	12.18±1.52	90.73±1.77	9.87±1.07	1.03±0.03
Ordu	6.60±0.44	3.40±0.24	74.10±2.03	15.90±1.87	90.00±0.51	9.01±0.36	1.06±0.04
Giresun	6.60±0.28	2.55±0.35	74.73±2.31	16.12±1.85	90.85±0.66	9.97±0.66	1.07±0.04
Trabzon	6.63±0.37	3.03±0.30	77.83±1.35	12.50±1.54	90.33±0.62	9.37±0.50	1.03±0.05

Source: Eastern Black Sea Region (Trabzon), Middle Black Sea Region (Giresun and Ordu), and Western Black Sea Region (Akçakoca).

Phytosterols are bioactive compounds that, although structurally similar to cholesterol, cannot be synthesized by the human body and are naturally found only in plant sources. One of the most important functions of these compounds is the inhibition of cholesterol absorption by reducing its solubility in the intestinal lumen, thereby lowering plasma cholesterol levels. In our study, the main components isolated from the phytosterol fraction were campesterol, stigmasterol, β-sitosterol, Δ5-avenasterol, and Δ7-stigmasterol, with the corresponding data presented in Table 5. The proportion of unidentified components varied among samples, ranging from 1.70% to 17.00%. While campesterol and β-sitosterol were detected in all samples, Δ5-avenasterol was identified only in the Mincane, Foşa, Çakıldak, and Sivri varieties, and Δ7-stigmasterol was found exclusively in Mincane samples from the Akçakoca and Trabzon locations (Tables 5 and 6).

β-sitosterol constituted the largest proportion of the total sterol content, with an average of 71.84 ± 12.92%. Campesterol, Δ5-avenasterol, and Δ7-stigmasterol were present at 5.52 ± 1.60%, 11.24 ± 12.58%, and 6.21 ± 3.82%, respectively. Each sterol compound showed significant differences among the varieties ($P < 0.00001$). When evaluated by location, significant differences were observed in the levels of campesterol, stigmasterol, and β-sitosterol, whereas Δ7-stigmasterol and Δ5-avenasterol levels did not differ significantly ($P < 0.0001$) (Table 5).

When Turkish and Italian hazelnuts were compared, β-sitosterol was the dominant compound in both groups; however, its proportion was higher in Italian hazelnuts (91.3%) [14]. In Turkish hazelnuts, the average was 71.84 ± 12.92%. The campesterol level was similar between Turkish (5.52 ± 1.60%) and Italian (5.90%) hazelnuts. In contrast, stigmasterol content was significantly higher in Turkish hazelnuts (9.09 ± 4.18%) compared to Italian hazelnuts (1.23%) [36, 37]. Likewise, the Δ7-stigmasterol level was higher in the Akçakoca Mincane sample (9.70 ± 0.10%) than in the Trabzon Mincane sample (2.72 ± 0.10%), both of which exceeded the average value reported in Italian hazelnuts (1.36%).

Overall, the dominant phytosterols detected in hazelnut oil are similar to those found in olive oil. Hazelnuts, being rich in oil, contain substantial amounts of cholesterol-lowering phytosterols, distinguishing them as significant dietary sources of these bioactive components. In particular, β-sitosterol plays a crucial role in cardiovascular protection due to its potential to lower serum cholesterol levels [38]. Additionally, it has been reported in the literature that phytosterols not only regulate cholesterol metabolism but also possess anticarcinogenic, anti-inflammatory, antifungal, antibacterial, and antioxidant properties [39-41]. These findings clearly demonstrate the potential of phytosterols derived from hazelnuts as functional food ingredients with cardiometabolic health benefits when consumed as part of a balanced diet.

Table 5.
Phytosterol compositions of hazelnut samples according to location and variety (%)[1].

Locations	Varieties	Campesterol (%)	Stigmasterol (%)	β-sitosterol (%)	Δ_5Avenasterol (%)	Δ_7Stigmasterol (%)	~~Unidentifed (%)~~
Akçakoca	Mincane	3.70 ± 0.13^{b}	8.20 ± 0.14^{d}	66.80 ± 0.81^{d}	7.64 ± 0.01	9.70 ± 0.10	~~X3.96~~
	Çakıldak	7.50 ± 0.27^{ý}	6.95 ± 0.12^{b}	72.35 ± 0.22^{e}	nd[2]	nd	~~X12.90~~
	Karafındık	4.70 ± 0.21^{d}	6.30 ± 0.10^{a}	86.90 ± 0.41^{k}	nd	nd	~~X2.10~~
	Foşa	6.50 ± 0.24^{g}	6.10 ± 0.10^{a}	49.80 ± 0.26^{b}	20.60 ± 0.10	nd	~~X17.00~~
Ordu	Palaz	8.01 ± 0.08^{j}	8.04 ± 0.17^{d}	78.80 ± 0.41^{g}	nd	nd	~~X5.15~~
	Çakıldak	2.80 ± 0.11^{a}	10.30 ± 0.13^{h}	84.50 ± 0.22^{ý}	0.70 ± 0.10	nd	~~X1.70~~
Giresun	Sivri	4.15 ± 0.11^{c}	9.90 ± 0.18^{f}	81.40 ± 0.29^{h}	0.70 ± 0.05	nd	~~X4.40~~
	Tombul	5.60 ± 0.28^{e}	8.25 ± 0.07^{d}	78.00 ± 0.40^{f}	nd	nd	~~X8.15~~
	Kalınkara	4.02 ± 0.10^{c}	7.50 ± 0.13^{c}	86.08 ± 0.28^{j}	nd	nd	~~X2.40~~
Trabzon	Sivri	6.10 ± 0.10^{f}	22.10 ± 0.27^{ý}	60.40 ± 0.25^{c}	nd	nd	~~X11.40~~
	Mincane	7.00 ± 0.07^{h}	8.60 ± 0.18^{e}	68.00 ± 0.46^{d}	3.77 ± 0.153	2.72 ± 0.10	~~X9.70~~
	Foşa	6.10 ± 0.10^{f}	6.80 ± 0.21^{b}	49.00 ± 0.19^{a}	34.00 ± 1.00	nd	~~X4.10~~
Mean ± SD		5.52 ± 1.60	9.09 ± 4.18	71.84 ± 12.92	11.24 ± 12.58	6.21 ± 3.82	~~X6.91~~

Note: [1] Each value is a average of three determinations. Values in the same column with different lower-case letters (a-k) are significantly different at $p<0.05$. [2] n.d., Not detected. Eastern Black Sea Region (Trabzon), Middle Black Sea Region (Giresun and Ordu), and Western Black Sea Region (Akçakoca).

Table 6.
Phytosterol composition association between locations (%).

Locations	Campesterol (%)	Stigmasterol (%)	β-sitosterol	Δ_5-Avenasterol	Δ_7-Stigmasterol
Akçakoca	5.60 ± 1.56	6.89 ± 0.86	68.96 ± 13.87	14.12 ± 7.10	9.70 ± 1.41
Ordu	5.41 ± 2.86	9.17 ± 1.25	81.65 ± 3.14	0.70 ± 0.71	nd
Giresun	4.59 ± 0.78	8.55 ± 1.07	81.83 ± 3.53	0.70 ± 0.05	nd
Trabzon	6.40 ± 0.46	12.50 ± 7.25	59.13 ± 8.29	18.88 ± 16.57	2.72 ± 0.21

Source: East Black Sea Region (Trabzon), Middle Black Sea Region (Giresun and Ordu), and Western Black Sea Region (Akçakoca).

As shown in Table 6, β-sitosterol was found to be the predominant phytosterol in hazelnut varieties and regions. However, the β-sitosterol ratio in hazelnut varieties in the Middle Black Sea region was determined to be 81.65 ± 3.14% and 81.83 ± 3.53%, which is higher than in other regions.

A statistical correlation analysis was conducted among various parameters, including oil content, iodine value (IV), saponification value (SV), refractive index (RI), specific gravity (SG), fatty acid profile, and phytosterol composition. Correlation coefficients (r) and significance levels (P) are presented in Table 7. A strong negative correlation was observed between iodine value and oleic acid ($r = -0.7388$, $P < 0.0001$), and between iodine value and campesterol ($r = -0.3841$, $P < 0.021$). Conversely, iodine value showed a strong positive correlation with linoleic acid ($r = 0.8060$, $P < 0.0001$). The total iodine value was found to decrease with increasing oleic acid content.

Oleic acid was negatively correlated with linoleic acid ($r = -0.9040$, $P < 0.0001$), supporting the inverse relationship between these two major unsaturated fatty acids. Linoleic acid levels were higher in samples with greater unsaturation, reflecting the sensitivity of IV to unsaturated fatty acids. Regarding phytosterol composition, campesterol showed a moderate positive correlation with Δ5-avenasterol ($r = 0.5297$, $P < 0.024$) and a strong negative correlation with Δ7-stigmasterol ($r = -0.9973$, $P < 0.0001$). Similarly, stigmasterol was negatively correlated with both Δ5-avenasterol ($r = -0.8485$, $P < 0.0001$) and Δ7-stigmasterol ($r = -0.8516$, $P = 0.031$). β-Sitosterol exhibited strong negative correlations with Δ5-avenasterol ($r = -0.9056$, $P < 0.0001$) and Δ7-stigmasterol ($r = -0.7482$, $P = 0.087$), although the latter was not statistically significant.

A particularly strong positive correlation was identified between Δ5-avenasterol and Δ7-stigmasterol ($r = 0.9985$, $P < 0.0001$), suggesting that these two sterols are synthesized via the same biosynthetic pathway. The positive correlation between SV and Δ5-avenasterol ($r = 0.5267$, P = N.S.) was not statistically significant but noteworthy, indicating a possible relationship between this sterol and fatty acid chain structure. Other correlation coefficients and their statistical significance are provided in Table 7.

Table 7.
Correlations between the fat content, iodine value (IV), saponification value (SV), refractive index (RI) and specific gravity (SG), fatty acid composition, degree of unsaturation (DU) and phytosterol composition.

Composition		IV	SV	RI	SG	C16:0	C18:0	C18:1	C18:2	DU	Campe sterol	Stigma sterol	β-Sito sterol	Δ_5-Avena sterol	Δ_7-Stigma sterol
Fat	r	0.3197	0.3334	-0.122	-0.316	0.1424	-0.1389	-0.0729	0.0987	0.1064	-0.341	0.0748	0.2706	-0.4107	0.4648
	p	N.S.	0.047	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	0.042	N.S.	N.S.	N.S.	N.S.
IV	r		0.2091	0.0704	0.2716	-0.0069	-0.0189	-0.7388	0.806	0.4909	-0.3841	0.0416	0.5779	-0.637	-0.9488
	p		N.S.	N.S.	N.S.	N.S.	N.S.	< 0.0001	< 0.0001	0.002	0.021	N.S.	< 0.0001	0.004	0.004
SV	r			0.2023	0.0629	0.2105	0.3088	-0.3092	0.2262	0.1766	-0.3763	0.2428	0.1795	-0.5065	0.5267
	p			N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	0.024	N.S.	N.S.	0.032	N.S.
RI	r				0.0651	0.0358	0.1159	-0.054	-0.0278	-0.1322	0.0738	0.027	-0.0333	-0.0084	-0.1143
	p				N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
SG	r					-0.0081	0.4551	-0.3291	0.283	0.1446	-0.0345	0.1467	0.0002	-0.064	-0.8809
	p					N.S.	0.005	0.050	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	0.020
C16:0	r						0.1969	-0.0916	-0.0928	-0.1639	-0.0454	0.2378	-0.4405	0.1061	0.4125
	p						N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	0.007	N.S.	N.S.
C18:0	r							-0.231	0.0396	-0.0577	0.1584	0.0942	-0.3462	0.3529	0.5533
	p							N.S	N.S	N.S	N.S	N.S	0,039	N.S	N.S
C18:1	r								-0.904	-0.4264	0.427	0.033	-0.5611	0.6765	0.902
	p								<0.0001	0.009	0.009	N.S.	< 0.0001	0.002	0.014
C18:2	r									0.59	-0.4861	-0.0929	0.7534	-0.7694	-0.9664
	p									<0.0001	0.003	N.S.	<0.0001	<0.0001	0.002
DU	r										-0.3526	-0.1084	0.529	-0.4897	-0.3303
	p										0.035	N.S.	0.001	0.039	N.S.
Campe sterol	r											-0.0323	-0.4173	0.5297	-0.9973
	p											N.S.	0.011	0.024	<0.0001
Stigma sterol	r												-0.1261	-0.8485	-0.8516
	p												N.S.	< 0.0001	0.031
β–Σιτο στερολ	r													-0.9056	-0.7482
	p													<0.0001	0.087
Δ_5–Αϖενα στερολ	r														0.9985
	p														< 0.0001

4. Conclusions

In conclusion, hazelnuts are a rich source of oleic acid, comprising approximately 80% of their fatty acid profile, and are associated with beneficial health effects. They also typically contain high levels of various phytosterols (β-sitosterol: 71.84 ± 12.92, stigmasterol: 9.09 ± 4.18, campesterol: 5.52 ± 1.60%). These compounds are regarded as important bioactive constituents due to their ability to inhibit the intestinal absorption of LDL cholesterol. A comparative analysis of hazelnut varieties from different regions has revealed that oil content varies depending on both genetic diversity and geographical origin. Hazelnut samples taken from the middle and western Black Sea region were found to contain higher oil content than those from the Eastern Black Sea region. Iodine values also showed significant differences between varieties. In the Middle Black Sea region (Giresun and Ordu), the iodine content in hazelnut varieties was found to be higher than in other regions, at 94.93 ± 2.28 and 95.35 ± 2.81, respectively.

The fatty acid composition varied between varieties and showed variation between regions. Oleic acid (C 18:1) was low in varieties grown in the Middle Black Sea region (74.10 ± 2.03% - 74.73 ± 2.31%), high in the Eastern (77.83 ± 1.35%) and Western (78.55 ± 2.02%) regions. Linoleic acid (C 18:2) was found to be high in varieties from the Middle Black Sea region and low in varieties from the Eastern and Western Black Sea regions. Similarly, the phytosterol composition of β-sitosterol was high in the Middle Black Sea region (81.65 ± 3.14% - 81.83 ± 3.53%) and lower in the Eastern and Western regions. The degree of unsaturation did not show any variation depending on the variety or region. It remained consistent.

In this study, key parameters defining the functional properties of hazelnut varieties, including oil content and biochemical composition (saponification number, iodine value, fatty acid and phytosterol composition), were comprehensively examined in a comparative manner based on variety and region. The results of this study can guide producers seeking to develop functional products in selecting the appropriate raw materials for new product designs based on variety and region. It was determined that regional and variety differences have a significant effect on biochemical parameters. These results were found to have significant potential not only to assist in the selection of suitable raw materials for the food industry but also to enrich foods with low nutritional value and to develop new functional food products that support healthy living.

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