Evaluation of nutritional and antioxidant properties of almond cultivars: A comprehensive analysis for health and industry applications

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Abstract

Almond (*Prunus amygdalus* L.), a species of the Rosaceae family, is valued for its high content of unsaturated fatty acids, proteins, minerals, and bioactive compounds with potent antioxidant activity. These nutritional qualities make almonds not only beneficial for human health but also a valuable resource for the food industry. This study aimed to evaluate the nutritional profile, fatty acid composition, antioxidant activity, and mineral content of five Iranian almond cultivars. The analysis was conducted using a completely randomized design. Proximate compositions (fat, protein, carbohydrate, ash, moisture, fiber, and energy), total oil content, fatty acid profiles (via GC-FID), antioxidant capacity (DPPH assay), and essential minerals (K, Ca, Mg, Na, and P) were measured. The highest fat content (33.23%), total energy (427.06 kcal/100g), and oil yield (28.74%) were found in Sangi Azar Shahr. Yamatga Shabestar exhibited the highest protein content (26.51%) and the lowest IC50 (13.45 µg/mL), indicating strong antioxidant capacity. Azar Tasuoj had the highest mineral content, particularly potassium (756 mg/100g), calcium (720 mg/100g), and magnesium (654 mg/100g). Oleic acid (up to 53.36%) and linoleic acid (17.5%) were the dominant fatty acids, followed by palmitic (9.3%) and stearic acids (3%). These results highlight significant variations among cultivars in their biochemical properties and suggest the potential of specific genotypes for use in health-oriented food products, pharmaceutical applications, and breeding programs.

Introduction

Almond (*Prunus amygdalus* L.), a member of the Rosaceae family, stands as one of the most economically valuable nut trees worldwide. Cultivated across temperate regions, almonds are known for their remarkable nutritional benefits and versatile applications in food, pharmaceutical, and cosmetic industries [1]. The almond fruit is an exceptional source of unsaturated fatty acids [2, 3], high-quality proteins [4], and essential vitamins, notably vitamin E [5]. Moreover, almonds are rich in minerals such as potassium, calcium, magnesium [6], and various bioactive compounds, including phenolic acids and flavonoids, which possess potent antioxidant properties [7].

Almonds offer a wide range of biological benefits due to their unique and rich composition of bioactive compounds. The high content of unsaturated fatty acids, including monounsaturated fatty acids (MUFA) like oleic acid and polyunsaturated fatty acids (PUFA) such as linoleic acid, contributes to their role in lowering LDL cholesterol, improving lipid profiles, and providing anti-inflammatory and antioxidant effects. These properties make almonds a functional food that can help in the prevention of heart disease, metabolic disorders, and oxidative damage [2, 3, 8].

Almonds also contain significant levels of phenolic compounds and vitamin E, both of which are powerful antioxidants that help neutralize free radicals in the body. These antioxidants protect cellular components from oxidative damage, which is associated with various chronic diseases such as cancer, Alzheimer's, and diabetes. In addition, the anti-inflammatory effects of almonds help reduce chronic inflammation, which is a key factor in the development of many diseases, including arthritis [9–11].

The biologically active compounds in almonds, including essential vitamins and minerals like calcium, magnesium, and potassium, further contribute to their health-promoting properties. These minerals support bone health, regulate blood pressure, and contribute to proper muscle and nerve function. Furthermore, almonds' high fiber content aids in digestive health and helps in weight management by promoting satiety and improving gut microbiota [12–14].

Almonds also play a critical role in the food industry, with almond oil, flour, and other by-products being widely used in products ranging from confectioneries to beverages and cosmetics [15]. In response to the increasing demand for plant-based functional ingredients, the assessment of almond cultivars' nutritional and bioactive components is crucial for both human health and industrial innovation. Understanding the diversity of these cultivars and their potential applications can help tailor products that meet specific health needs and market demands [16].

The global demand for plant-based functional foods is steadily increasing due to rising health consciousness and the growing prevalence of chronic diseases [17, 18]. Almonds, as one of the most nutritionally rich and widely consumed nuts, are positioned at the forefront of this trend. The unique nutritional composition of almonds, including healthy fats, bioactive compounds, and essential vitamins and minerals, has made them a key component in addressing global health challenges, such as cardiovascular diseases, diabetes, and obesity [19, 20]. This study not only contributes to the understanding of the nutritional and antioxidant properties of Iranian almond cultivars but also aligns with global efforts to identify sustainable and functional food sources that can improve public health worldwide. As almonds are increasingly recognized for their role in disease prevention and health promotion, the findings of this research have the potential to influence international almond production, market trends, and the development of value-added products, making it a valuable contribution to both the global food industry and public health initiatives.

Despite the widespread recognition of almonds' health benefits and their extensive industrial applications, research into local cultivars, particularly those grown in Iran, remains limited [21]. Iran, known for its favorable climatic conditions and rich agricultural history, is a key producer of almonds, yet there is a lack of comprehensive studies on the genetic diversity, nutritional profile, and antioxidant capacities of its local cultivars [22]. While several studies have investigated individual traits such as oil content or fatty acid composition in almonds, there is a clear gap in research that simultaneously evaluates the proximate composition, fatty acid profiles, mineral content, and antioxidant properties across various cultivars grown in Iran [23–25]. This lack of integrated research presents a challenge for cultivar selection, quality improvement, and the development of value-added almond products.

The aim of this study is to fill this gap by evaluating the nutritional and antioxidant properties of five Iranian almond cultivars. These comprehensive assessments will provide valuable insights into cultivar-specific health benefits and industrial potential. Additionally, the results of this study will serve as a basis for future breeding programs aimed at developing almonds with superior health-promoting characteristics, supporting both the growth of functional food products and innovations in the almond industry.

Material and methods

Chemicals and reagents

All chemicals and reagents used in this study were all of analytical grade and were obtained from trusted suppliers, including **Sigma-Aldrich** (Buchs, Switzerland), **Thermo Fisher** (USA), and **Merck** (Darmstadt, Germany).

Plant materials and sample collection

This study focused on five almond cultivars, which were collected from various orchards in the northwestern regions of Iran (Azar Shahr, Shabestar, Shahin Dej, Ilkhchi, Tasouj) . Sampling was conducted during the physiological maturity stage of the almonds in August 2024. At least 15 healthy almonds per cultivar were randomly selected from each orchard, ensuring that only fully mature nuts were collected. To ensure the integrity of the samples, almonds were harvested from healthy, mature trees with no visible signs of disease. After collection, the almonds were manually shelled, and the kernels were separated and naturally dried for further analysis. The samples were stored in dark, airtight containers at 4°C until chemical analysis was conducted. Sampling was repeated three times independently for each cultivar to ensure statistical reliability.

Fatty acid analysis

The total oil content of almond samples was determined using the Soxhlet extraction method with n-hexane as the solvent, following the AOAC Official Method 920.39. Approximately 5 g of almond powder was extracted in a Soxhlet apparatus for 6-8 hours. The extracted oil was evaporated to remove the solvent and expressed as a percentage of dry weight.

Fatty acid composition was analyzed by preparing fatty acid methyl esters (FAMEs) according to the method described by Milinsk et al. [26], with slight modifications. The FAMEs were prepared through esterification using methanolic KOH and analyzed using a gas chromatograph (GC-2010 Plus, Shimadzu, Japan) equipped with a flame ionization detector (FID) and a capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). The injector and detector temperatures were set at 250 °C, with nitrogen used as the carrier gas at a flow rate of 1.2 mL/min and a split ratio of 1:100. The initial column temperature was maintained at 150 °C for 3 minutes, then increased to 240 °C at a rate of 3 °C/min, holding for 20 minutes. Individual fatty acids were identified by comparing their retention times with those of standard FAME mixtures obtained from NU-CHEK-PREP (Code: GLC-462, USA). Each sample was analyzed in triplicate.

Proximate composition

The proximate composition of almond samples, including protein, fat, ash, crude fiber, moisture, and total carbohydrates, was determined using the official AOAC methods [27]. The protein content was measured by the Kjeldahl method [28], where nitrogen content was multiplied by a factor of 6.25 to calculate the crude protein. Moisture content was determined by drying approximately 5 g of the sample at 105°C until

a constant weight was achieved. Ash content was measured by incinerating 2 g of the ground almond sample in a muffle furnace at 550°C for 6 hours. For fat determination, the Soxhlet method was employed using hexane as the solvent. The crude fat content was calculated as a percentage of the dry matter after evaporating the solvent using a rotary evaporator. Crude fiber was measured through sequential acid and alkali digestion, and carbohydrate content was calculated by difference. The total carbohydrate content was calculated using the following formula:

Carbohydrate (%)=100−(Moisture+Protein+Fat+Ash+Fiber)

The gross energy value (kcal/100 g) of almond kernels was calculated as follows:

Energy value (kcal/100 g)=9×(g of fat)+4×(g of protein+g of carbohydrates) [29].

Mineral analysis

The concentrations of potassium (K), calcium (Ca), and magnesium (Mg) were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Agilent Technologies, USA). Approximately 1 g of almond samples was digested using concentrated nitric acid and hydrogen peroxide in a microwave digestion system (CEM MARS 6, USA) at 140°C for 3 hours. Following digestion, the sample solutions were analyzed using the ICP-OES method (Agilent Technologies, USA). The operating parameters of the ICP-OES system were as follows: plasma power: 1100 W, sampling depth: 2.5 mm, nebulizer flow rate: 1.06 L/min, plasma gas flow rate: 15 L/min, auxiliary gas flow rate: 1.2 L/min, and helium flow rate: 5.0 mL/min. The fog chamber temperature was maintained at 2°C, and a sampling rate of 0.5 L/min was used. Signal measurement was performed using peak hopping. Standard reference materials from the National Institute of Standards and Technology (NIST; Gaithersburg, MD, USA) were employed to validate the analytical procedure [30].

Antioxidant activity

Antioxidant activity was assessed by the DPPH method, following the protocol described by Akhlaghi and Najafpour-Darzi [31]. A 0.1 mM DPPH solution was prepared in methanol, and the decrease in absorbance at 515 nm was measured after 30 minutes of incubation in the dark. Butylated hydroxytoluene (BHT) was used as the positive control. The DPPH scavenging effect (%) was calculated using the following formula:

DPPH Scavenging Effect (%)=(Abs $_{Control}$−Abs $_{Sample}$/Abs $_{Control}$)×100

The IC50 value, which represents the concentration of the sample required to scavenge 50% of the DPPH radicals, was calculated from the dose-response curve.

Statistical analysis

All experiments were performed in triplicate, and the data were expressed as mean ± standard deviation (SD). Statistical analysis was conducted using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). One-way analysis of variance (ANOVA) was applied to test for significant differences between the

groups. If significant differences were found, Duncan's multiple range test was used for post-hoc comparisons at a significance level of $p < 0.05$. Data visualization was performed using OriginPro 2022 (SR1) software.

Results

Oil content and fatty acid composition

The results showed significant variation in the oil content among the almond cultivars. The highest oil content was observed in the Sangi Azar Shahr cultivar, with an average oil percentage of 18.33%. The Yamatga Shabestar cultivar followed closely with 26.76%, while the Sahand Ilkhchi cultivar exhibited the lowest oil content at 16.58% (Fig. 1A).

In terms of fatty acid composition, the most notable variation was observed in the levels of both saturated and unsaturated fatty acids, which together accounted for the majority of the total composition (Table 1). The total number of fatty acid compounds identified in each cultivar ranged from 22 to 27, reflecting genetic and metabolic differences across the cultivars. In the Yamatga Shabestar cultivar, the predominant fatty acid was Oleic acid methyl ester, which accounted for 36.53%, indicating the high quality of the oil in this cultivar. Following this, Palmitic acid methyl ester (31.9%) and Linoleic acid methyl ester (29.8%) were the next most abundant fatty acids. Similarly, in the Sangi Azar Shahr cultivar, the highest levels of fatty acid compositions were observed in Oleic acid methyl ester (37.02%) and Linoleic acid methyl ester (22.97%), making this cultivar one of the richest in beneficial fatty acids. The Azar Tasuoj cultivar showed the highest amount of Methyl 11-octadecenoate at 35.33%, reflecting a distinctive metabolic pathway for this cultivar, with Linoleic acid methyl ester (17.51%) and Palmitic acid methyl ester (14.51%) also being significant contributors. The Sahand Ilkhchi cultivar exhibited the highest concentration of Phthalic acid, bis(2-ethylhexyl) ester (42.5%), followed by Elaidic acid, methyl ester at 23.73%, which may contribute to unique biological and industrial properties for this cultivar. Lastly, in the Sangi Shahindezh cultivar, the most prominent fatty acids were Oleic acid methyl ester (28.87%) and Elaidic acid methyl ester (23.68%). Fatty acids like Palmitic acid methyl ester were present in all cultivars at levels ranging from 5.4–10.2%, which play an important role in oil stability and its physical properties.

Table 1
Fatty acid profiles of the studied almond cultivars

			Area %				
	RI	Compound	Shahin Dej	Shabestar	Kuj	Ilkhchi	Azar Shahr
1	3250	1-Heptatriacotanol	-	-	1.43^{g}	1^{h}	-
2	1687	1-Hydroxycyclohexyl phenyl ketone	0.59	0.64	0.57	0.52	0.63
3	2104	11-Octadecenoic acid, methyl ester	-	-	-	0.63	-
4	1502	2,4-Di-tert-butylphenol	-	-	1.24^{h}	0.9	1.29^{h}
5	2045	2,6,10,14-Tetramethylheptadecane	-	-	-	-	0.18
6	2055	2,6,10,15-Tetramethylheptadecane	-	-	-	0.21	-
7	1275	2,6,10-Trimethyltetradecane	0.09	-	-	-	-
8	1452	2,6,10-Trimethyltridecane	-	0.33	-	0.13	-
9	1544	2,6,11-Trimethyldodecane	-	0.27	0.19	0.13	0.19
10	1864	2-Methyloctadecane	-	0.42	-	-	-
11	1850	4-Azido-2-nitrobutyric acid, 2,6-di-t-butyl-4-methoxyphenyl ester	0.27	0.29	-	-	-
12	3060	9-(2',2'-Dimethylpropanoilhydrazono)-3,6-dichloro-2,7-bis-[2-(diethylamino)-ethoxy]fluorene	-	-	-	0.57	-
13	2104	9-Octadecenoic acid, (E)	-	-	-	1.36^{f}	-
14	1770	Benzenepropanoic acid, 3,5-bis(1,1-dimethylethyl)-4-hydroxy-, methyl ester	-	0.27	-	-	-
15	1024	D-Limonene	-	-	-	0.18	-
16	3056	Docosyl octyl ether	0.1	-	-	-	-
17	2086	Elaidic acid, methyl ester	23.68^{b}	-	-	23.73^{b}	-
18	2120	Glycidyl oleate	5.53^{e}	5.18^{e}	7.21^{d}	5.89^{d}	3.5^{e}

Each value is expressed as the mean ± SD (n = 3). The letters indicate the highest values in each row.

			Area %				
19	2055	Heptadecane, 2,6,10,15-tetramethyl-	-	0.12	-	-	-
20	1231	Isoxylaldehyde	0.5	0.44	0.65	0.4	0.69
21	2098	Linoleic acid, methyl ester	9.57^{c}	8.29^{c}	17.51^{b}	7.51^{c}	22.97^{b}
22	2103	Methyl 11-octadecenoate	-	-	35.33^{a}	-	-
23	1890	Methyl palmitoleate	1.02^{j}	0.67	0.62	0.48	0.88
24	2130	Octadecanoic acid, methyl ester	-	3.15^{f}	-	-	-
25	2104	Oleic acid, methyl ester	28.87^{a}	53.34^{a}	-	-	37.02^{a}
26	1904	Palmitic acid, methyl ester	9.86^{c}	9.31^{b}	9	5.44^{d}	10.21^{d}
27	1519	Phenol, 2,4-di-tert-butyl	1.12^{i}	1.36^{h}	-	0.27	-
28	2519	Phthalic acid, bis(2-ethylhexyl) ester	-	-	14.51^{c}	42.5^{a}	12.16^{c}
29	2475	Phthalic acid, bis(6-methylheptyl)ester	6.02^{d}	6.77^{d}	-	-	-
30	2130	Stearic acid, methyl ester	2.85^{f}	-	3.12^{e}	1.88^{e}	2.85^{f}
31	1350	Terpinyl acetate	0.2	-	-	-	-
32	2140	cis-Vaccenic acid	1.15^{i}	0.97	1.65^{f}	-	-
33	1600	n-Cetane	1.57^{g}	1.51^{g}	1.27^{h}	1.1^{g}	1.37^{h}
34	1203	n-Dodecane	0.31	0.33	0.22	0.19	0.26
35	2000	n-Eicosane	0.74	0.78	0.76	0.75	0.78
36	2100	n-Heneicosane	0.67	0.69	0.62	0.88	0.61
37	2700	n-Heptacosane	0.7	-	-	0.45	0.27
38	1703	n-Heptadecane	0.35	0.4	0.3	0.34	0.31
39	1805	n-Octadecane	1.3^{h}	1.34^{h}	1.14^{i}	1.06^{g}	1.93^{g}
40	1510	n-Pentadecane	0.95	0.98	0.73	0.55	-
41	1402	n-Tetradecane	0.98	1.05^{i}	0.86	0.72	0.97

Each value is expressed as the mean ± SD (n = 3). The letters indicate the highest values in each row.

			Area %				
42	1300	n-Tridecane	0.13	0.14	-	0.08	0.12
43	2130	trans-13-Octadecenoic acid, methyl ester	-	-	0.96	-	-
44	2250	β-Monolinolein	0.71	0.82	-	-	0.68
		Total	100	100	100	100	100
Each value is expressed as the mean ± SD (n = 3). The letters indicate the highest values in each row.							

The heatmap in Fig. 2 provides a visual representation of the relative proportions of key fatty acids in each almond cultivar. Based on the observed patterns, natural clustering among cultivars is evident. The cluster analysis indicated that Yamatga Shabestar and Sangi Azar Shahr, due to their high levels of Oleic acid methyl ester and low levels of Linoleic acid methyl ester, form a common cluster and have a stable and desirable fat composition for industrial uses. Conversely, Azar Tasuoj and Sahand Ilkhchi, with higher percentages of Linoleic acid methyl ester and greater polyunsaturated fatty acid content, grouped into a separate cluster. These two cultivars are more suitable for nutritional value, but due to lower stability, they are recommended for fresh consumption or health-focused products. The Sangi Shahindezh cultivar, with intermediate characteristics, lies between the two clusters and displays a balanced fat composition.

Proximate composition

Significant differences ($p < 0.05$) were observed among the cultivars in terms of proximate composition. This indicates that there are significant differences in these components across the different cultivars. The coefficient of variation (CV) for various compositions indicated the dispersion of the data and diversity among the cultivars, with the highest CV being observed for fiber (1.95%) and the lowest for energy (0.13%).

According to the mean comparison results (means ± SD), the Sangi Azar Shahr cultivar exhibited the highest energy content (427 kcal/100 g) (Fig. 1B) and fat content (28.7 g/100 g dry weight) (Fig. 1C). In contrast, the Sangi Shahindezh cultivar showed the lowest energy content (368.38 kcal/100 g) and Yamatga Shabestar had the lowest fat content (21.42 g/100 g dry weight). For protein, Yamatga Shabestar had the highest value (26.5 g/100 g dry weight), while Azar Tasuoj had the lowest protein content (19.47 g/100 g dry weight) (Fig. 1D). The highest fiber content was found in the Azar Tasuoj and Sangi Shahindezh cultivars (14.32 g and 14.18 g per 100 g dry weight, respectively) (Fig. 1E).

Regarding carbohydrates, the Sahand Ilkhchi cultivar showed the highest content (22.41 g/100 g dry weight), while the Sangi Shahindezh cultivar had the lowest content (17.88 g/100 g dry weight) (Fig. 1F). Sangi Shahindezh also had the highest total ash content (11.35 g/100 g dry weight), while Sangi Azar Shahr had the lowest ash content (9.32 g/100 g dry weight) (Fig. 1G). In terms of moisture, significant differences were observed across the cultivars, with Yamatga Shabestar showing the highest moisture

content (13.24 g/100 g dry weight) and Sangi Azar Shahr having the lowest moisture content (8.33 g/100 g dry weight) (Fig. 1H).

Mineral analysis

Significant differences ($p < 0.05$) were observed between the almond cultivars in the mineral content of P ,Na ,K ,Ca, and Mg (Fig. 3A-E). The CV for the studied elements ranged from 0.7–1.83%, indicating high precision and stability of the data.

According to the mean comparison results, the Azar Tasuoj cultivar exhibited significantly higher values of phosphorus (556.67 mg/100 g DW), sodium (643 mg/100 g DW), calcium (716.33 mg/100 g DW), potassium (749 mg/100 g DW), and magnesium (651.33 mg/100 g DW) compared to the other cultivars. Following this, the Yamatga Shabestar cultivar showed high levels of potassium (664.67 mg/100 g DW), sodium (565.67 mg/100 g DW), and magnesium (589 mg/100 g DW), while the Sahand Ilkhchi cultivar had higher phosphorus (505.33 mg/100 g DW) and calcium (658.67 mg/100 g DW) contents. Conversely, the Sangi Azar Shahr and Sangi Shahindezh cultivars contained the lowest concentrations of these minerals.

Antioxidant activity

Antioxidant activity primarily depends on the ability to donate electrons that neutralize free radicals. The antioxidant capacity of the almond cultivars was evaluated using the DPPH method. Significant differences were observed in the antioxidant activity across the different cultivars (Fig. 3F). According to the results, the Azar Tasuoj cultivar exhibited the highest IC50 value of 26.97 µg/ml, indicating the lowest antioxidant activity among the cultivars. The Sangi Shahindezh cultivar followed with an IC50 value of 24.19 µg/ml. On the other hand, the Yamatga Shabestar cultivar demonstrated the lowest IC50 value of 13.88 µg/ml, which corresponds to the highest antioxidant capacity. This suggests that Yamatga Shabestar has the strongest ability to scavenge free radicals among the tested cultivars.

Correlation, principal component analysis (PCA), and cluster analysis

The correlation analysis revealed significant positive and negative associations between various traits, including proximate composition, antioxidant capacity, oil content, and mineral elements in the almond cultivars. As shown in Fig. 4, positive correlations are depicted in blue, while negative correlations are represented in red. These significant correlations were observed at the 5% probability level ($p < 0.05$).

A notable negative correlation was observed between fat and carbohydrates, suggesting that higher fat content may be inversely related to carbohydrate levels. This could be attributed to differences in the metabolic pathways and biosynthesis of these compounds. Additionally, a positive correlation between antioxidant activity and oil content was found, indicating that cultivars with higher antioxidant capacity tend to have higher oil content. This relationship may arise from the synergistic effects of phytochemicals, which contribute to both antioxidant activity and fat absorption. Furthermore, a negative and significant correlation between moisture content and antioxidant activity was identified, implying that

higher moisture levels may adversely affect antioxidant capacity. This may suggest the detrimental effect of elevated moisture on antioxidant activity in almonds. In contrast, protein and fiber exhibited a significant positive correlation with certain other traits, such as energy content, implying that almonds with higher protein content also tend to have higher fiber content. Additionally, oil content showed a negative correlation with several mineral elements, including potassium and calcium, suggesting that cultivars with higher oil content typically contain lower levels of these minerals. This could be explained by competition in biosynthetic pathways and mineral absorption in almonds.

Principal Component Analysis (PCA) was conducted to reduce the dimensionality of the data and identify the underlying patterns of variation among the cultivars. Figure 5 illustrates the PCA biplot, which clearly separates the cultivars based on their fatty acid composition and other proximate traits. The first two principal components (PC1 and PC2) accounted for 70.22% of the total variance, with PC1 explaining 39.97% and PC2 explaining 30.25%. The biplot emphasizes key factors such as oil content, fatty acid composition, and moisture, highlighting the differences among the cultivars. Cultivars like Yamatga Shabestar and Sangi Azar Shahr clustered closely, indicating similar profiles in fatty acid composition, while cultivars such as Sangi Shahindezh and Sahand Ilkhchi exhibited distinct characteristics.

Cluster analysis, based on phytochemical traits, grouped the cultivars into distinct clusters. As shown in Fig. 6, the analysis identified a clear division between the cultivars. Yamatga Shabestar, Sangi Azar Shahr, and Sangi Shahindezh formed a common cluster, sharing similar fatty acid profiles and oil content, while Azar Tasuoj and Sahand Ilkhchi were placed into separate groups due to their unique fatty acid compositions and other biochemical traits. Notably, the Azar Tasuoj cultivar showed a strong positive correlation with oil content and antioxidant activity, which distinguished it from the other cultivars.

The results from PCA and cluster analysis confirm the grouping of the cultivars based on key characteristics such as oil content, fatty acid composition, and antioxidant activity, offering valuable insights into the genetic and chemical diversity of these almond cultivars.

Discussion

The present study provides an in-depth analysis of the nutritional and biochemical diversity among five Iranian almond cultivars, shedding light on how genetic factors, cultivation conditions, and environmental variables play a significant role in shaping the chemical composition and functional properties of almonds. The variation observed in proximate composition, oil yield, fatty acid profiles, antioxidant activity, and mineral content suggests that these cultivars offer substantial potential for both enhancing nutrition and expanding industrial applications. This finding aligns with previous studies on almond germplasm from Spain, California, and the Mediterranean basin, where environmental factors such as temperature, soil composition, and seasonal changes, along with inherent genetic traits, have been shown to influence the quality and quantity of bioactive compounds in almonds [32–34].

In terms of proximate composition, Sangi Azar Shahr was identified as a high-energy cultivar, with the highest oil content (33.23%) and a gross energy value of 427.06 kcal per 100 g. This positions it among

the richest varieties in terms of oil content, comparable to or even surpassing well-known cultivars like Marcona and Desmayo Largueta from Spain, where oil content typically ranges from 28–32% [35]. The high energy content of Sangi Azar Shahr is an important factor for its potential use in both human nutrition and industrial oil production. In contrast, Yamatga Shabestar showed the highest protein content (26.51%), exceeding the typical protein levels found in California almonds, which range from 21–23%. This higher protein content is of particular significance in light of the growing global demand for plant-based protein sources [35]. Since energy and protein are two key indicators of the nutritional value of plant products, the results suggest that cultivars with higher levels of these compounds play an important role in human and animal nutrition. The higher protein content not only enhances nutritional value but may also improve nutrient digestibility and absorption, making these cultivars valuable in nutritional and industrial applications. Furthermore, protein diversity can serve as a foundation for genetic improvement aimed at developing cultivars with better nutritional performance [36]. Additionally, the fiber content in these cultivars varied between 5.26% in Azar Tasuoj and 7.82% in Sangi Shahindezh, suggesting the potential of these cultivars for use in fiber-enriched snacks or digestive health products. Significant changes in fiber and carbohydrates are also of great importance. Fiber is recognized as a key factor in digestive health and the reduction of chronic disease risks, such as diabetes and cardiovascular diseases [37].

Regarding oil yield and fatty acid profiles, the biochemical analysis confirmed that each cultivar has distinct characteristics. Sangi Azar Shahr exhibited the highest oil yield (28.74%) and a lipid profile that was primarily dominated by oleic acid methyl ester (53.3%), followed by linoleic acid, palmitic acid, and stearic acid. The MUFA/PUFA ratio of 3.1 in this cultivar is strongly linked to oxidative stability and cardiovascular health benefits, as high MUFA content is known to reduce the risk of cardiovascular diseases. The oleic acid levels in Sangi Azar Shahr are comparable to, or even exceed, those found in Mediterranean and Californian almonds, suggesting that Iranian almonds, particularly Sangi Azar Shahr, have the potential to compete globally in terms of oil quality and nutritional value [38]. The results of fatty acid analysis in different almond cultivars showed that the composition and percentage of these acids are influenced by a combination of genetic factors and environmental conditions, including temperature, humidity, and altitude. For instance, at higher altitudes, lower temperatures and air pressure lead to changes in fatty acid metabolism, typically resulting in an increase in the percentage of unsaturated fatty acids in plant oils [39, 40].

In the context of antioxidant activity, significant differences were observed among the cultivars using DPPH assay. Yamatga Shabestar exhibited the strongest antioxidant activity, with the lowest IC_{50} value (13.88 µg/ml), suggesting a rich presence of phenolic compounds and tocopherols that are known to enhance antioxidant potential. These Phenolic compounds, through mechanisms such as electron transfer and free radical scavenging, can help reduce oxidative damage in plant cells and preserve food quality [41, 42]. Additionally, enhancing the antioxidant capacity in food products can have multiple positive effects on human health, including reducing the risk of chronic diseases such as cardiovascular diseases, diabetes, and cancer [43, 44].

This is consistent with findings by El Bernoussi et al., who reported that phenolic content is a critical factor in determining the antioxidant capacity of almonds. Interestingly, the high protein content in Yamatga Shabestar may also indirectly contribute to its antioxidant properties through bioactive peptides, as observed in studies focusing on the interaction between protein-derived compounds and oxidative stability. This adds another layer of potential health benefits to this cultivar, making it particularly useful for functional foods and nutraceutical applications aimed at combating oxidative stress [3, 45].

The mineral content analysis revealed that Azar Tasuoj had the highest concentrations of potassium (756 mg/100g dry weight), calcium (716 mg/100g dry weight), and magnesium (651 mg/100g dry weight) compared to other cultivars. Similar studies have shown that different almond cultivars exhibit significant variations in their mineral composition. For instance, almonds from France, Italy and Greece are reported to have potassium levels between 5000 and 8000 mg/kg, calcium content varying from 1000 to 3000 mg/kg, and magnesium between 1000 and 2000 mg/kg [46]. In a study, the mineral content of almond kernels was reported, with potassium ranging from 4817.31 to 7218.58 mg/kg, calcium from 924.51 to 1970.86 mg/kg, and magnesium from 744.58 to 2909.45 mg/kg [47]. The results from the present study, particularly with Azar Tasuoj, which demonstrated higher levels of potassium, calcium, and magnesium, further reinforce the importance of Iranian almond germplasm in contributing to high-mineral-content almond products. This cultivar’s mineral richness suggests it could be particularly beneficial for fortification purposes, such as in almond-based milks or dietary supplements, which are essential for addressing mineral deficiencies in human diets.

The diversity observed across all traits, including fatty acid composition, oil yield, antioxidant activity, and mineral content, suggests that Iranian almond cultivars hold substantial promise for targeted breeding programs. The positive correlation between oil yield and oleic acid content indicates that the quality and quantity of oil can be enhanced simultaneously through selection, providing opportunities to improve both the commercial value and health benefits of these almonds. Moreover, the correlation between protein content and antioxidant activity suggests that cultivars with higher protein levels might also have superior functional properties, which are crucial for developing superior genotypes that combine both nutritional value and industrial suitability [48, 49].

In comparison with international studies, the results of this research demonstrate that Iranian almond cultivars are not only competitive but, in some cases, superior in terms of nutritional quality. For example, Sangi Azar Shahr's oleic acid levels and Yamatga Shabestar’s protein content exceed those of several well-known European cultivars, while Yamatga Shabestar's antioxidant potential is comparable to or higher than that of almonds cultivated in California and Spain. These findings highlight the untapped potential of Iranian almond germplasm in meeting global demands for high-value, health-oriented almond products. The observed variability among these cultivars emphasizes the importance of preserving local almond germplasm and investing in detailed compositional studies. This approach will not only help select superior cultivars for immediate industrial applications but also provide valuable insights for future breeding programs that focus on improving specific traits such as oil stability, antioxidant activity, and mineral content. The integration of nutritional profiling with molecular and genetic studies will further

enhance breeding strategies and contribute to the sustainable development of almonds as a functional food ingredient in both local and international markets.

Conclusions

The increasing demand for almonds as a nutrient-rich food ingredient and a source of high-quality oil and bioactive compounds is evident in both the food and cosmetic industries. This study provides a comprehensive analysis of the proximate composition, fatty acid profiles, antioxidant capacities, and mineral contents of five Iranian almond cultivars: Sangi Shahindezh, Yamatga Shabestar, Sahand Ilkhchi, Azar Tasuoj, and Sangi Azar Shahr. The results revealed substantial diversity among these cultivars, with Sangi Azar Shahr excelling in oil content and lipid quality, Yamatga Shabestar standing out for its high protein content and antioxidant activity, and Azar Tasuoj distinguished by its rich mineral composition. This significant variability highlights the diverse genetic and biochemical properties of Iranian almond germplasm, positioning it as a valuable resource for breeding programs aimed at improving specific nutritional and functional traits. Cultivars with high oleic acid content and strong antioxidant capacity are ideal candidates for the production of premium-quality oils and functional foods. In contrast, cultivars with enriched mineral content hold promise for use in fortified products and dietary supplements, addressing essential nutrient deficiencies. The findings suggest that Iranian almond cultivars not only meet but, in some aspects, surpass the nutritional quality of well-known international varieties, such as those from Spain and California. These results underscore the untapped potential of Iranian almonds in global markets and their significant role in the development of healthy, high-value products. Consequently, Iranian almond germplasm offers critical advantages for the selection of superior genotypes with desirable nutritional profiles, high adaptability, and industrial applicability. Future research should aim to integrate the compositional data obtained in this study with genetic and molecular studies, enabling more effective breeding strategies and fostering the development of innovative, health-oriented almond-based products.

Declarations

Acknowledgments

Author contributions

M.B.A. conceptualized the study, designed the experiments, drafted the manuscript. A.Y.D. performed the experiments, analyzed the data, and contributed to writing the manuscript. E.F.M.T supervised the research, provided critical revisions, and approved the final of the manuscript

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Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Figures

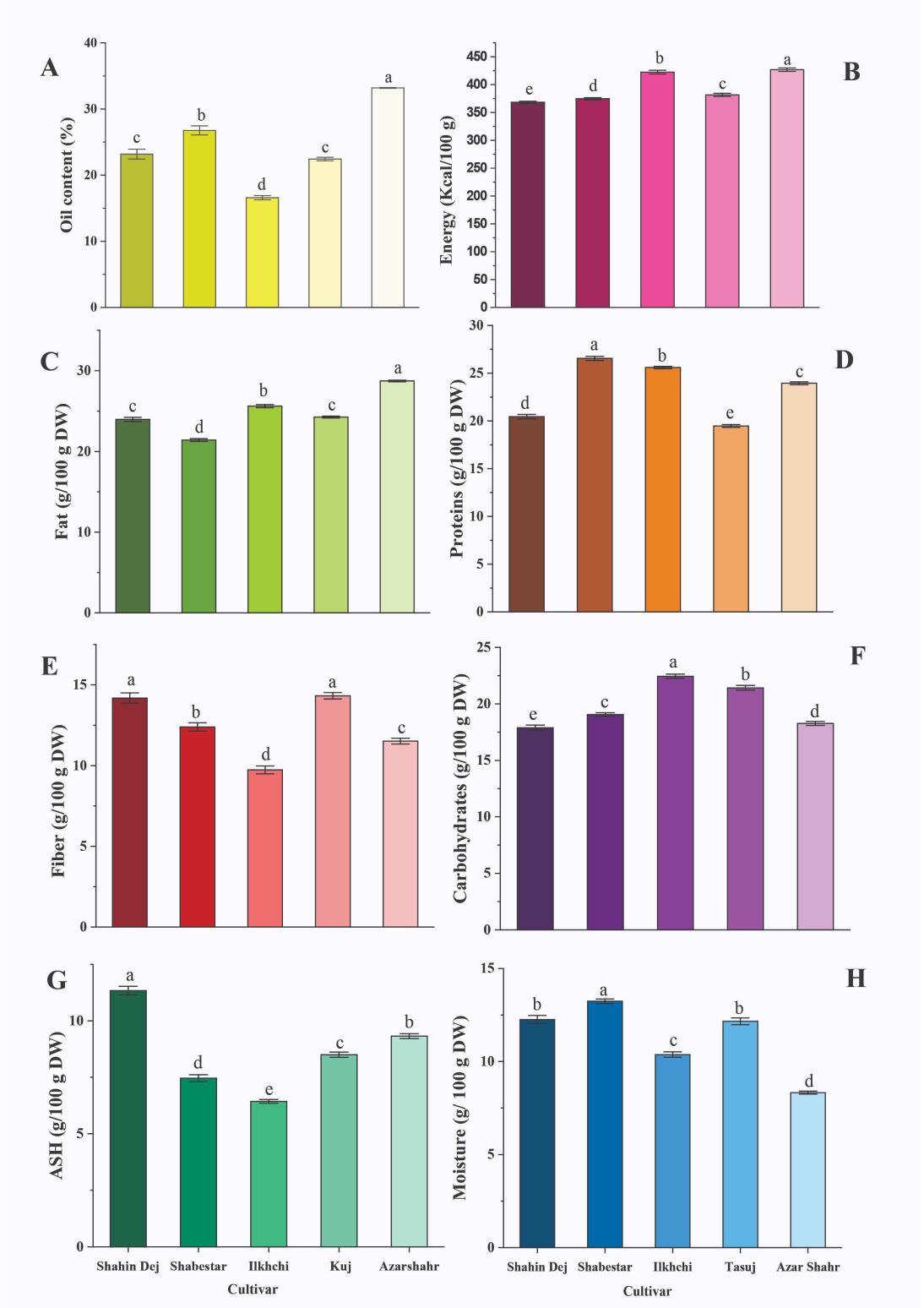

Figure 1

Proximate composition and oil content in five Iranian almond cultivars: (A) Oil content (%), (B) Energy (Kcal/100 g), (C) Fat (g/100 g DW), (D) proteins (g/100 g DW), (E) Fiber (g/100 g DW), (F) Carbohydrates (g/100 g DW), (G) ASH (g/100 g DW), (H) Moisture (g/100 g DW).

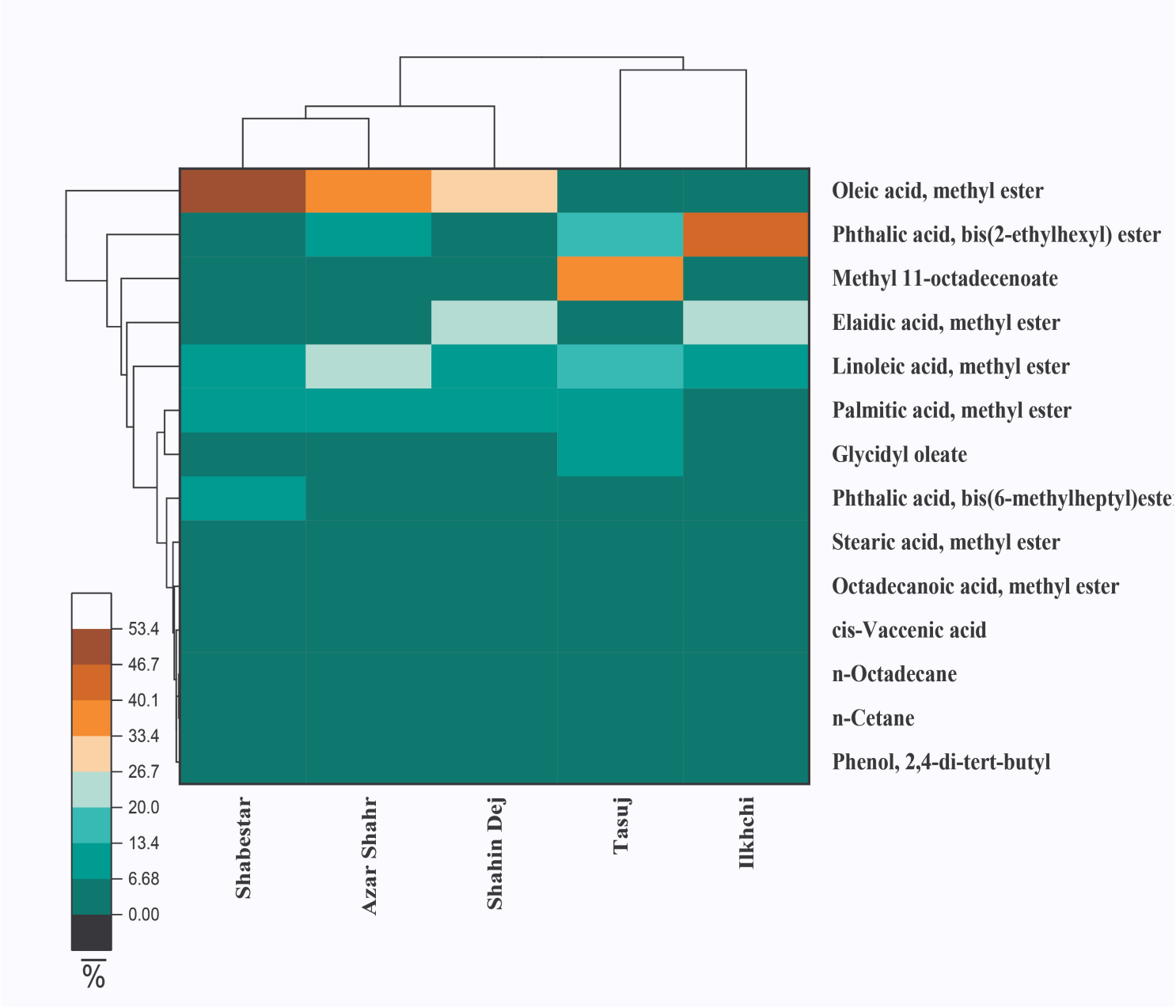

Figure 2

Heat map of the fatty acid composition profiles of five Iranian almond cultivars.

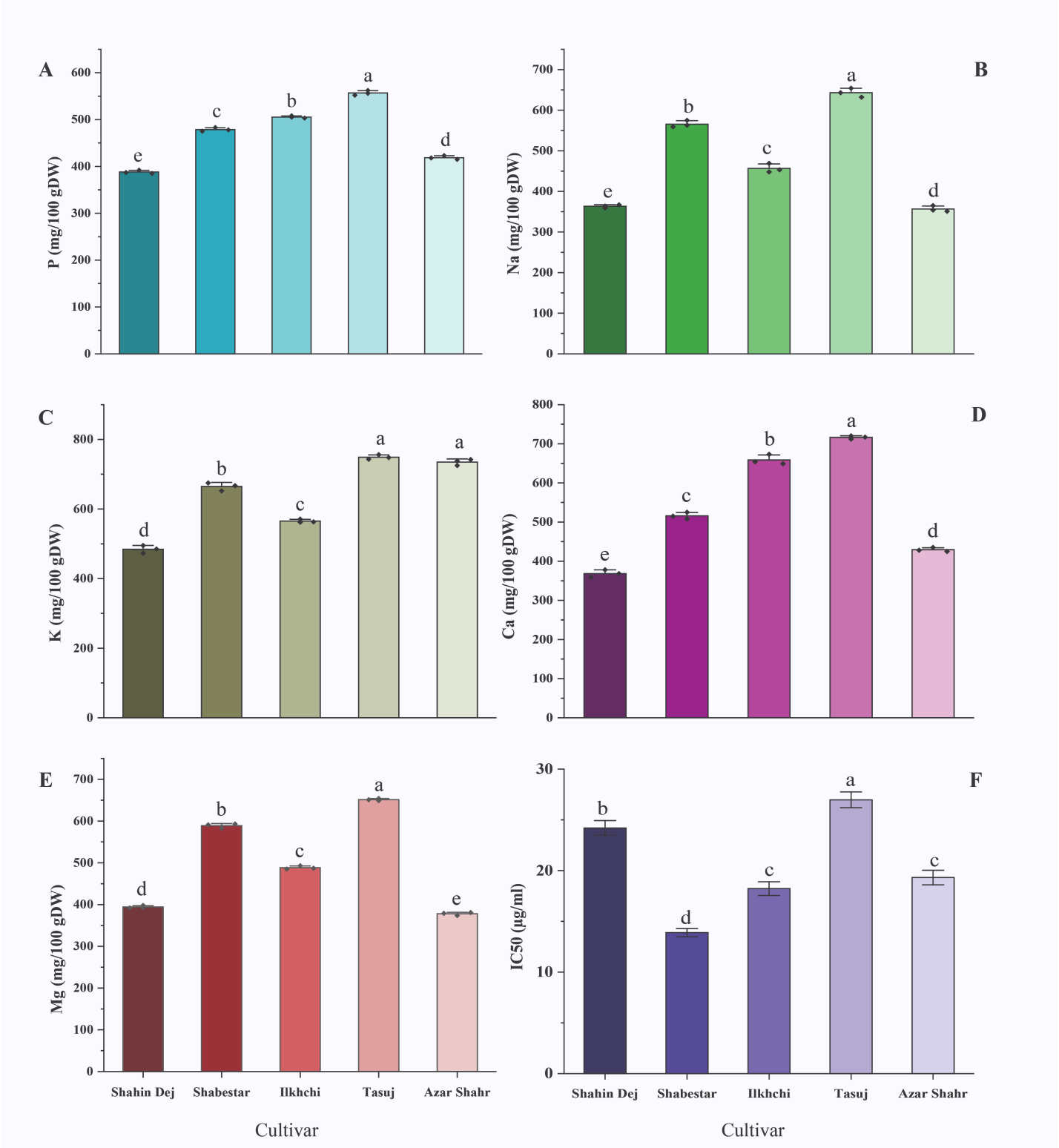

Figure 3

Levels of mineral and antioxidant activity in five Iranian almond cultivars: (A) Phosphorus (g/100 g DW), (B) Sodium (g/100 g DW), (C) Potassium (g/100 g DW), (D) Calcium (g/100 g DW), (E) Magnesium (g/100 g DW), (F) DPPH (IC_{50})

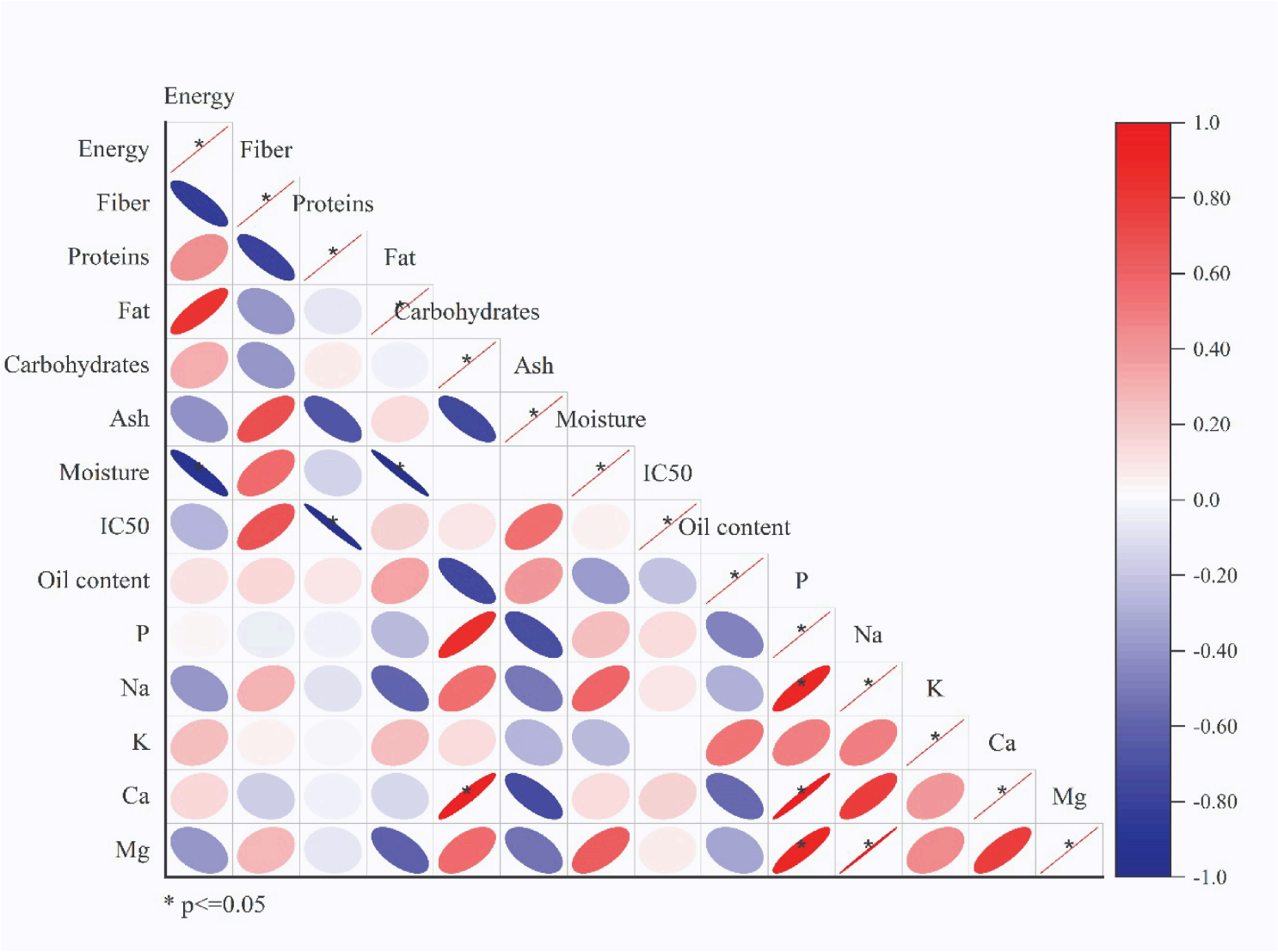

Figure 4

Network correlation representation of proximate composition (energy, fiber, proteins, fat, carbohydrates, ASH, moisture) , antioxidant activity (DPPH), oil content and mineral elements (P, Na, K, Ca, Mg) of five Iranian almond cultivars.

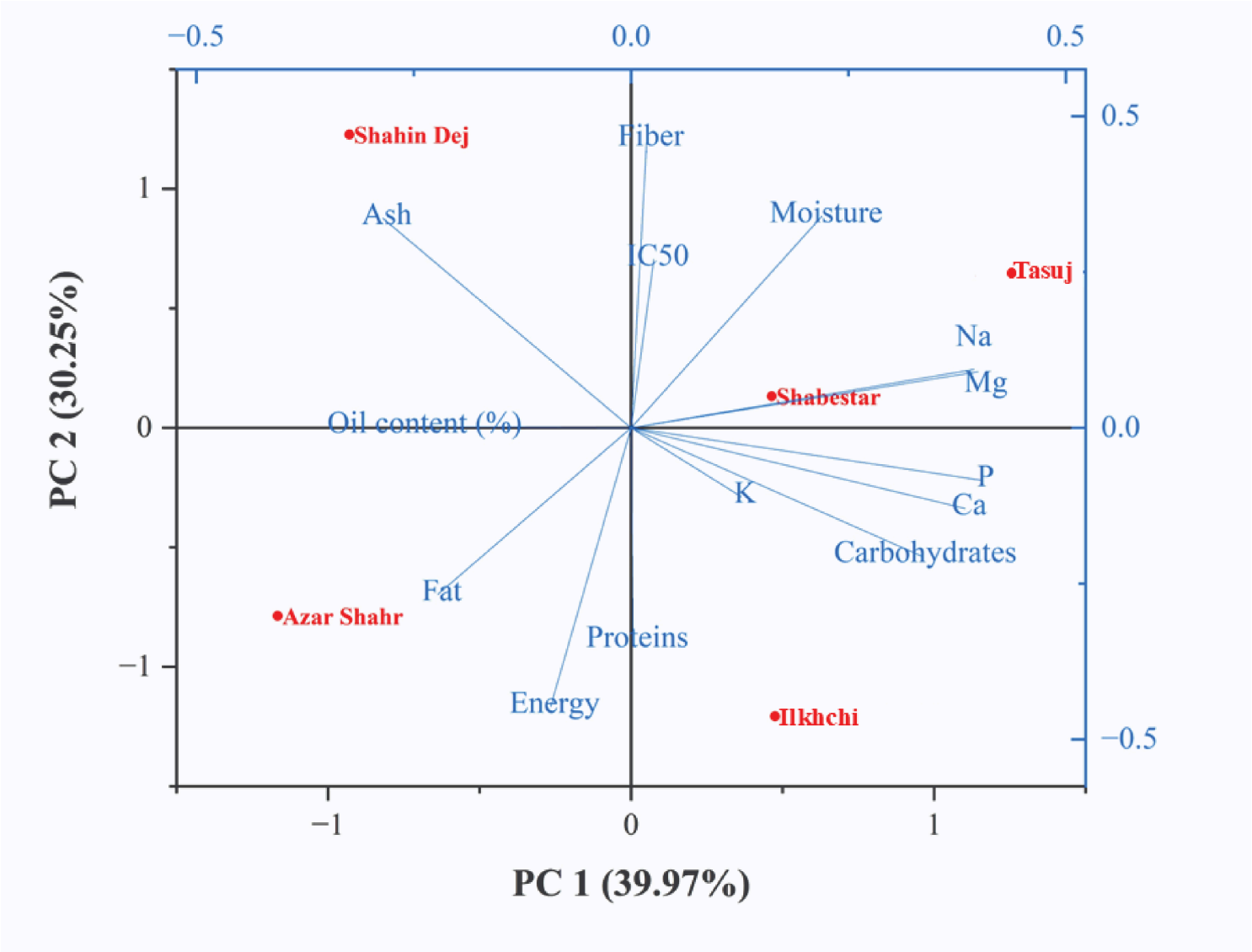

Figure 5

Biplot analysis of five Iranian almond cultivars based on phytochemical traits.

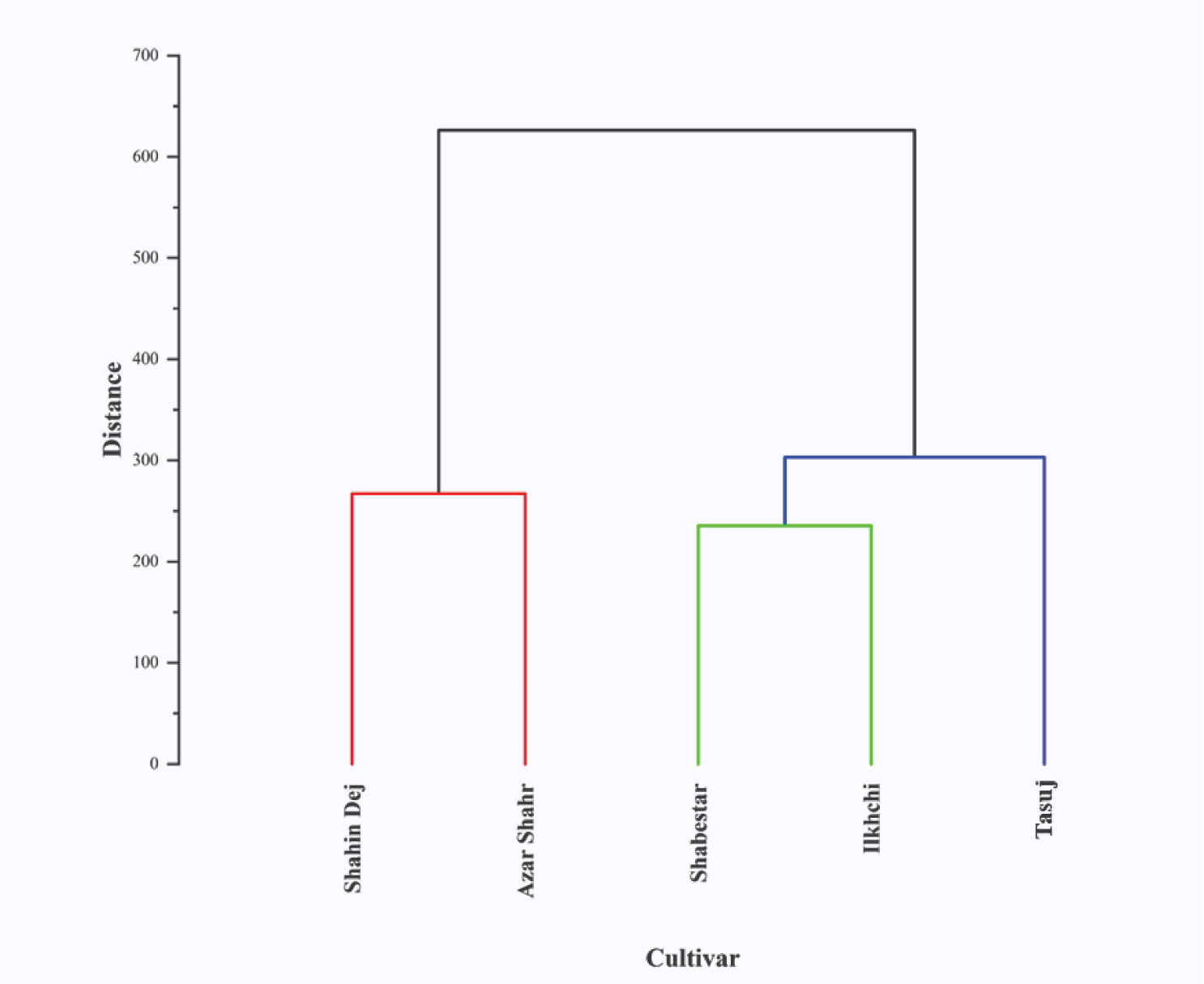

Figure 6

Ward cluster analysis of five Iranian almond cultivars based on phytochemical traits using Euclidean distances