



OPEN Variability in seed oil content, fatty acids profile, phytochemical properties, mineral and proximate composition of Iranian cultivars of *Vitis vinifera* L

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Vitis vinifera L., a significant fruit species within the Vitaceae family, is extensively cultivated globally and finds diverse applications across the pharmaceutical, cosmetic, and food sectors. Notably, grape seeds are abundant in oils, phenolic compounds, and essential minerals, which may confer various health benefits. To enhance the value and optimize the use of grape seeds, recognized as a significant byproduct in industrial applications, this research investigated and compared ten Iranian grape cultivars regarding their oil content and composition, phenolic compounds, antioxidant properties, mineral content, and proximate analysis. The seed oil content ranged from 4.03 to 18.01%. The primary fatty acids identified in these cultivars were linoleic acid (varied from 17.9 to 59.4%) and margaric acid (from 1.6 to 33.2%). The seed oils were found to be rich in polyunsaturated fatty acids (PUFAs), which comprised between 17.9% and 62.1% of the total fatty acids, while monounsaturated fatty acids (MUFAs) and saturated fatty acids (SFAs) were present in proportions of 3.7–16.8% and 20.9–78.4%, respectively. The analyzed cultivars exhibited variations in carbohydrate (19.23 to 25.37 g/100 DW), fat (10.24 to 13.72 g/100 DW), protein (9.62 to 14.63 g/100 DW), and fiber (38.41 to 42.87 g/100 DW) contents. Notable mineral elements such as potassium (3.82–8.34 mg/g DW), phosphorus (2.34–3.74 mg/g DW), calcium (1.05–2.31 mg/g DW), magnesium (0.23–1.42 mg/g DW), and iron (0.01–0.03 mg/g DW) were detected across the cultivars analyzed. The primary phenolic compounds identified included gallic acid, quercetin, and kaempferol. Hosseini and Rashmiri cultivars were superior in terms of seed oil content and phenolic compounds, respectively. The significant variation observed among the different grape varieties concerning oil content and composition, phytochemical profiles, mineral content, and proximate composition indicates their potential as valuable sources of oil and nutritional components for application in food and cosmetic industries.

Keywords Grape, Seed oil, Gallic acid, Linoleic acid, GC, HPLC

Grape (*Vitis vinifera* L.) from the Vitaceae family is one of the most valuable fruit crops cultivated in various regions of the world, including Asia, Europe and America, and has wide applications in the cosmetic, pharmaceutical, and food industries¹. 80 million tons of grapes are produced every year, part of which is used as fresh grapes, juice and raisins². A significant part of it is also used for winemaking as one of the most popular alcoholic beverages³. In the winemaking process, 0.2 kg of pomace is produced from each kilogram of grape fruit, of which 8 to 52% are seeds⁴. The amount of seed production from the winemaking process in the world is about 0.4 to 2.4 million tons of seeds per year⁵. Sustainable utilization of food wastes appears essential due to increasing economic value, reducing environmental issues, and providing valuable bioactive compounds⁶.

Grape seeds contain 7–20% oil, which consists of 90% unsaturated fatty acids (USFA) (linoleic acid and oleic acid) and 10% saturated fatty acids (SFA). It is also rich in phenolic compounds, flavonoids, procyanidins, catechins and tannins⁷. In addition to oil, grape seeds have high nutritional value due to their high content

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of lipids, vitamins, phytosterols, proteins, fiber and minerals, and biological effects such as anti-inflammatory, antifungal, antibacterial and antioxidant have been reported to improve health^{7,8}. Grape seed extract and powder are used in the confectionery and bread industries and are added as an additive to biofilms (edible coatings) used to preserve food^{9,10}.

Oil content and composition are influenced by cultivar and genotype, ripening time, environmental factors, and agronomic practices^{8,11}. Studies of the effect of cultivar and cultivation region on olive oil content and composition showed that the fatty acid profile of the oil varies across cultivars and regions and is strongly influenced by these factors¹². Variation in oil content and composition and phytochemical traits has been reported in different populations and cultivars of *Xanthoceras sorbifolium*¹³, *Nigella sativa*¹⁴, *Ficus carica*¹⁵, and *Glycine max*¹⁶.

Different cultivars can vary in oil content and its composition as well as nutritional values, therefore, efforts to identify superior cultivars with high oil content and composition and nutritional value are essential in the cosmetic-health and food industries¹⁷. The aim of this study was to investigate the oil content and composition, phenolic compounds and nutritional value of seeds of diverse grape cultivars in Iran in order to identify the best cultivar for producing raw materials required by the pharmaceutical and food industries.

Materials and methods

Plant material

The fruits of ten grape varieties (Rashmiri, Rashe, Mambrayma, Taefi, Ghazeozum, Champagne, Hosseini, Sahebi, Dastchin, and Rishbaba) were collected from Malekan City, East Azerbaijan Province, Iran. The fruits were harvested at the ripe stage. The varieties Hosseini and Rishbaba were harvested on July 12 and the Sahebi variety on September 18. The varieties Rashe, Mambrayma, Dastchin, Champagne, and Taefi were harvested on September 15, and the Ghazeozum variety was harvested on October 15. Prof. Ali Sonboli identified the different grape varieties and voucher specimens were deposited at the Shahid Beheshti University herbarium (MPH3241-MPH3251). The authors confirm that the necessary permissions to collect and cultivate the samples have been obtained. In addition, the present study complies with the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora. The geographical characteristics and physicochemical features of the soil at the collection site are presented in Table 1.

Morphological features

Morphological and functional traits of ten grape cultivars were measured. Twenty fruits from each cultivar were randomly selected and various traits such as pericarp weight (g), fruit width (cm), fruit length (cm), fresh and dry seed weight (mg), and 1000 seed weight (g) were measured. Weight was measured using an electronic scale and digital caliper was used to measure fruit length and width¹⁸.

Oil extraction and fatty acid analysis

The crude oil content was assessed utilizing the maceration technique¹⁹. A sample of 1000 mg of dried and powdered seeds was combined with 10 ml of n-hexane and subjected to ultrasonication for a duration of 20 min (ultrasonication repeated three times). Then, the mixture was allowed to stand at a temperature of 23 ± 2 °C for 72 h and subsequently filtered using Whatman filter paper No. 1. The n-hexane solvent was then evaporated at ambient temperature. The extracted crude oil was stored in sealed, colored containers at -18 °C until further evaluation. Fatty acid analysis is performed according to previously reported work²⁰ as follows: 50 mg of the oil sample was mixed with a methanolic potassium hydroxide (KOH) solution at a ratio of 1:80 (w/v). The solution was prepared by dissolving 50 mg of KOH in 4 mL of methanol and added to the oil sample. The mixture was vortexed and centrifuged at 4000 rpm for 10 min. Fatty acids were first trans-esterified using KOH, followed by derivatization with boron trifluoride (BF₃) in methanol. This two-step process enabled the conversion of both free and esterified fatty acids into their corresponding methyl esters. Analyses were performed on an Agilent 7890 A Plus Gas Chromatograph (Agilent Technologies, Santa Clara, USA) equipped with a G4513A automatic liquid sampler and a flame-ionization detector (GC-FID). Separation was carried out on a 100-m capillary column (Agilent, CP-Sil 88 GC Columns, 100 m, 0.25 mm inner diameter, 0.20 μm thickness). Data acquisition and processing were performed using Agilent ChemStation software. The area percentages of each FAME were obtained. Finally, Peak identification was performed by comparing retention times with those of a commercial FAME standard mixture (GLC-462; Nu-Chek Prep, Elysian, MN, USA), which contains 28 known fatty acids. Due to the precise alignment of retention times between sample and standard chromatograms, peak identification was considered accurate without the need for calibration curves.

Geographic positions	Climatic data	Soil properties
Altitude (m): 1289 Longitude (E): 46° 07' Latitude (N): 37° 06'	Average maximum annual temperature (°C): 20.8 Average minimum annual temperature (°C): 10.5 Average annual temperature (°C): 15.6 Rainfall (mm): 420.5	Texture: silty loam EC (ds m ⁻¹): 2.94 pH : 7.4 Total N (%): 0.035 Available P (mg kg ⁻¹): 59.4 Available K (mg kg ⁻¹): 334.9

Table 1. Geographical positions, Climatic data, and soil properties of the cultivated region.

Quantification of phenolic compounds by HPLC

The extraction of phenolic compounds was performed according to the procedure outlined by Demir et al.²¹. In brief, 500 mg of powdered seeds underwent ultrasonication using an Elma S120H device from Germany, combined with 100 ml of a methanol/water solution (90:10, v/v) for a duration of 30 min. Subsequently, the mixture was centrifuged at 1,400 g for 10 min at a temperature of 4 °C using a Hettich Rotanta 460r centrifuge. The resulting extract was concentrated using a rotary evaporator at 35 °C. Finally, the extract was reconstituted in 1 ml of methanol and filtered through a 0.22 µm membrane.

Phenolic compounds were determined using a high-performance liquid chromatography (Knauer, Germany) photodiode array, with a Waters 2695 separations module equipped with a C18 column (250 × 4.6 mm) and a UV detector (Waters 2487). The mobile phase consisted of methanol (solvent A) and distilled water (solvent B). HPLC solvents both contained TFA (0.02%, v/v), and the flow rate was 0.5 ml/min. The gradient program was begun with 20%A: 80%B followed by 20:80 – 30:70 over 10 min, 30:70 – 50:50 over 10 min, 50:50 for 20 min, 50:50–100:0 over 2 min, 100:0 for 6 min, 100:0–20:80 over 7 min. The analysis was conducted under optimized conditions, with a 20 µl injection volume and a column temperature of 25 °C, to ensure accurate and reliable results. To detect phenolic compounds, the UV absorption peaks at 200–600 nm were investigated. Standard samples were used as references to identify compounds based on their characteristic retention times under equivalent analytical conditions. Pure standards of phenolic compounds were prepared from Sigma Aldric Co. (Buchs, Switzerland). Calibration curves were constructed by injecting standard mixture solutions at the seven concentrations of 2, 10, 50, 100, 250, 500, and 1000 ppm (Table 2). The results were presented in mg/g DW.

Evaluation of total phenol content (TPC) and flavonoid content (TFC)

Total phenolic compounds turned into quantified the usage of the approach described through Singleton et al.²², which includes the Folin-Ciocalteu reagent. In summary, 25 µl methanolic extract (1000 ppm) and 125 µl Folin-Ciocalteu reagent, 100 µl sodium carbonate (7.5%) were taken in a test tube. The final volume was made up to 6 ml with distilled water. The solution was stored for 30 min in the dark. The absorbance was recorded at 765 nm using a spectrophotometer (Bio-Tek Instruments, Inc., USA). The results are expressed as mg gallic acid equivalents (GAE)/per g of dry weight (mg GAE/g DW).

Total flavonoids compounds were assayed based at the technique mentioned with the aid of Dewanto et al.²³, utilising aluminium chloride. Initially, 20 µl methanolic extract, 3.4 ml methanol (30%), 80 µl distilled water, 6 µl sodium nitrite (0.5 M), 6 µl aluminum chloride h (0.3 M) and 80 µl sodium hydroxide (1.0 M) was taken in a test tube and mixed well. The absorbance of the solution was determined against the reagent blank at 510 nm wavelength. The data were expressed as mg of quercetin equivalents (QE) per g of dry weight (mg QE/g DW).

Ferric reducing activity power (FRAP) assay

The approach outlined via Benzie and strain²⁴ turned into hired. The fresh FRAP reagent was prepared by mixing 300 mmol/l acetate buffer (pH 3.6), 10 mmol/l TPTZ in 40 mmol/l HCl, and 20 mmol/l FeCl₃ at 10:1:1 (v/v/v). The reaction mixture was kept for 30 min at 37 °C. The absorption was then measured at 593 nm. A standard curve was generated using ferrous sulfate solution in concentrations ranging from 0.25 to 8 mmol dm⁻³ (0.5–10 mg/ml). The result was expressed as µmol Fe⁺² per g of DW.

Elemental analysis

Initially, the seed samples of the studied grape varieties were digested using the Başgel and Erdemoğlu²⁵ method with hydrogen peroxide and pure nitric acid for 3 h at 140 °C. Then, mineral elements were evaluated by ICP-MS Agilent 7500 A series. The mineral content was determined using the values confirmed in the reference sample received from NIST (Gaithersburg, MD, USA).

Proximate composition analysis

The analysis of the samples for ash, protein, fat, and fiber was conducted following the AOAC guidelines²⁶. The ash content was quantified by subjecting the cultivars to high temperatures in a muffle furnace. Fat extraction was performed using a Soxhlet (SOX406, HANON Systems, South Korea) and its amount was determined. The micro-Kjeldahl method was employed to estimate protein levels, with the amount of protein calculated by multiplying the nitrogen content by a factor of 6.25. Fiber was derived following the digestion of samples with boiling solutions of diluted acid and alkali. The carbohydrate content was ascertained by deducting the combined weights of ash, protein, fiber, and fat from the overall dry matter. The energy value was achieved using the formula: energy value (kcal/100 g) = (4 × g of protein) + 9 × (g of fat) + (4 × g of carbohydrates)²⁷.

Compound	Range (ppm)	Equations	R
Gallic acid	5–250	Y = 123521X - 716,832	0.9971
Caffeic acid	5–250	Y = 200397X - 1,000,006	0.9978
Quercetin	5–250	Y = 70,624 X - 241,366	0.9997
<i>p</i> -Coumaric acid	5–250	Y = 259,208 X - 712,294	0.9953
vanillic acid	5–250	Y = 118,522 X - 263,440	0.9915
kaempferol	5–250	Y = 8966 X - 48,817	0.9981

Table 2. Information of standard calibration curves for phenolic compounds.

Data analysis

All experiments conducted in this research were carried out in triplicate. The results obtained are presented as means \pm standard deviation (SD). To assess significant disagreement among the cultivars regarding the measured traits, one-way analysis of variance (ANOVA) was performed using SAS 9.4. A post-hoc analysis was conducted employing Duncan's test with a significance level set at $p < 0.05$. The biplot was generated using Origin software version 2022, while cluster analysis was performed utilizing the Euclidean distance coefficient and Ward's method. Additionally, R software was utilized to create the correlation plot.

Results and discussion

Morphological characteristics

Significant diversity in morphological traits was observed among diverse Iranian grape cultivars. The coefficient of variation (CV %) for fruit width, number of seeds per fruit, and pericarp fresh weight were 57.04, 35.49, and 27.28%, respectively (Table 3). A high CV indicates higher variation in that trait, which allows for better selection for the breeder. The studied grape cultivars had significant differences in morphological traits ($P < 0.05$). The highest fresh (6.70 g) and dry (1.77 g) pericarp weights were observed in Dastchin cultivar, and the lowest fresh (1.68 g) and dry (0.44 g) pericarp weights were observed in Champagne cultivar. Dastchin cultivar had the highest fruit length (2.63 cm) and fruit width (2.23 cm), and the lowest were observed in Champagne cultivar. Rashe cultivar showed the highest fresh (78.00 mg) and dry (56.36) seed weights, while Mambrayma cultivar had the lowest fresh (36.73 mg) and dry (31.50 mg) seed weights. The highest number of seeds per fruit (3.36) was found in Rashmiri cultivar, although there was no significant difference with Rashe cultivar, but the minimum number of seeds per fruit (1.00) was observed in Mambrayma cultivar. The minimum (36.73 g) and maximum (78.00 g) thousand seed weights were obtained in Rasha and Mambrayma cultivars, respectively (Table 3). Grape fruit size and phenotypic variation as an inherent trait in all species is due to environmental, genetic interactions and their mutual effects²⁸. The variation in fruit and seed traits of grape cultivars has been previously explained by other studies^{29–31}, which is consistent with the results of this study. Differences in morphological and functional traits of different cultivars can be due to genetics, cultivar type, age, regional climatic conditions, and geographical region³⁰.

Oil content and fatty acid profile

The seed oil content of diverse grape cultivars is presented in Fig. 1. The oil content varied from 4.03 to 18.01% among the cultivars. The cultivars Hosseini, Ghazelozum, Sahebi, and Rashmiri had the highest oil content (18.01%, 14.66%, 13.12%, and 12.04%, respectively). The lowest oil content (4.03%) was observed in the cultivar Mambrayma. Consistent to the results of Beveridge et al.³², who investigated the oil content of grape seeds from eight Canadian wine varieties, revealing a range between 5.9% and 13.6%. Similarly, Sabir et al.³³ assessed the oil content of Turkish grape seed oils across 21 varieties, which varied from 7.3 to 22.4%. Ovcharova et al.³⁴ documented the seed oil content in Bulgarian grape varieties, noting white varieties yielded between 11.60% and 16.50% and red varieties yielded 15.70% and 13.90%. In a study conducted in China, Wen et al.³⁵ found that the Merlot variety produced the maximum yield of grape seed oil at 15.92%, while Chardonnay had the lowest yield at 13.71%. Furthermore, Harbeoui et al.³⁶ reported that nine Tunisian grape varieties exhibited seed oil content ranging from 6.31 to 12.7%. This suggests a potential variation in oil content due to factors, such as geographical location, environmental conditions, genetic diversity, and cultivation practices³⁷.

GC analyzed seed oil from diverse grape cultivars and the results are shown in Table 4. A representative chromatogram illustrating the fatty acid profiles across different cultivars is provided in Fig. 2. Eight fatty acids (palmitic acid, myristoleic acid, stearic acid, margaric acid, linoleic acid, oleic acid, arachidonic acid, arachidic acid) have been identified in the oil of different cultivars, constituting 99.5–100% of the seed oil. The SFA and USFA ranged from 20.9% (in Taefi cultivar) to 74.8% (in Sahebi cultivar) and from 21.6% (in Sahebi cultivar) to 78.7% (in Taefi cultivar), respectively. The proportion of monounsaturated fatty acids (MUFA) ranged from 3.7% to 16.8%, while the levels of polyunsaturated fatty acids (PUFA) fluctuated between 17.9% and 61.1%. Among

Cultivar	Pericarp fresh weight (g)	Pericarp dry weight (g)	Fruit length (cm)	Fruit width (cm)	Seed fresh weight (mg)	Seed dry weight (mg)	Seed number per fruit	1000 seed weight (g)
Rashmiri	2.95 \pm 0.11de	0.57 \pm 0.01e	1.96 \pm 0.15d	1.76 \pm 0.15a	42.40 \pm 2.75bc	34.76 \pm 2.00bcd	3.36 \pm 0.57a	42.40 \pm 2.75bc
Rasha	5.28 \pm 0.90bc	1.33 \pm 0.20b	2.20 \pm 0.10c	2.00 \pm 0a	78.00 \pm 14.48a	56.36 \pm 4.44a	3.33 \pm 1.15a	78.00 \pm 14.48a
Mambrayma	3.86 \pm 1.15 cd	0.99 \pm 0.29 cd	1.93 \pm 0.30d	3.03 \pm 3.43a	36.73 \pm 7.65c	31.50 \pm 7.90d	1.00 \pm 0c	36.73 \pm 7.65b
Taefi	6.24 \pm 1.11ab	1.18 \pm 0.19bc	2.53 \pm 0.05ab	2.03 \pm 0.15a	54.80 \pm 13.99b	43.16 \pm 2.87b	2.66 \pm 1.15abc	54.80 \pm 13.99b
Ghazelozum	4.98 \pm 0.64bc	1.00 \pm 0.11bcd	2.30 \pm 0.10bc	1.93 \pm 0.15a	47.96 \pm 0.80bc	32.36 \pm 1.33 cd	3.00 \pm 0ab	47.96 \pm 0.80bc
Champagne	1.68 \pm 0.45e	0.44 \pm 0.13e	1.53 \pm 0.05e	1.40 \pm 0.43a	55.46 \pm 5.95b	42.30 \pm 5.80bc	2.00 \pm 1.00abc	55.46 \pm 5.95b
Hosseini	4.80 \pm 0.52c	1.10 \pm 0.12bc	2.63 \pm 0.15a	1.70 \pm 0.10a	55.20 \pm 4.27b	39.60 \pm 2.26bcd	2.66 \pm 1.15abc	55.20 \pm 4.27b
Sahebi	4.58 \pm 0.62c	1.27 \pm 0.21bc	2.26 \pm 0.05c	1.80 \pm 0.10a	46.06 \pm 10.82bc	33.93 \pm 8.69bcd	1.33 \pm 0.57bc	46.06 \pm 10.82bc
Dastchin	6.70 \pm 1.07a	1.77 \pm 0.23a	2.63 \pm 0.05a	2.23 \pm 0.40a	50.96 \pm 5.02bc	35.16 \pm 4.09bcd	3.00 \pm 1.00abc	50.96 \pm 5.02bc
Rishbaba	3.12 \pm 0.08d	0.70 \pm 0.02de	2.33 \pm 0.05bc	1.50 \pm 0a	45.96 \pm 13.53bc	34.86 \pm 7.44bcd	2.00 \pm 1.00abc	45.96 \pm 13.53bc
CV (%)	27.28	17.23	5.95	57.04	17.97	13.84	35.49	22.97

Table 3. Comparison of different morphological traits among *Vitis vinifera* cultivars. Data are mean \pm standard deviation ($n = 3$). Values followed by the same letter within each column are significantly different ($p < 0.05$).

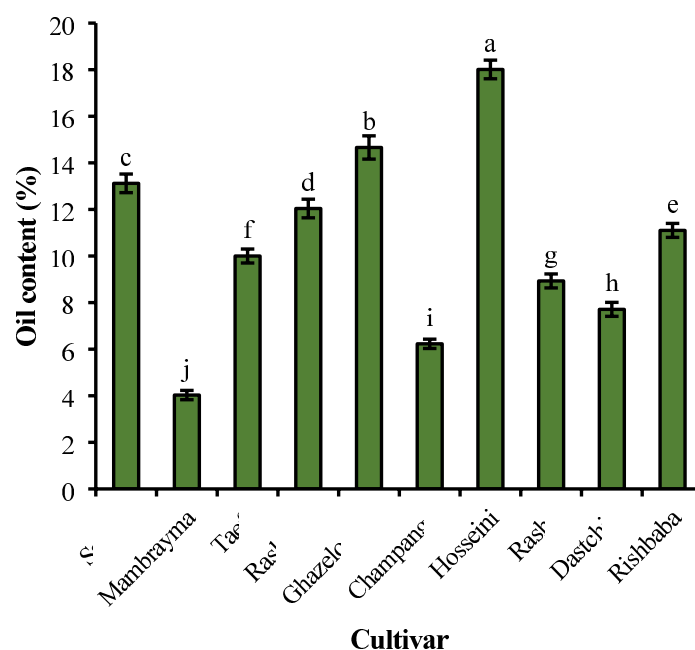


Fig. 1. Histogram of seed oil content among *Vitis vinifera* L. cultivars. The mean comparisons were performed using the Duncan test at $P \leq 0.05$ significant level. Means followed by the same letter(s) are not significantly different.

FA (%)	Rashmiri	Rashe	Mambrayma	Taefi	Ghazelozum	Champagne	Hosseini	Sahebi	Dastchin	Rishbaba
Myristoleic acid (C14:1)	3.5 ± 0.01	1.6 ± 0.00	3.2 ± 0.01	0.8 ± 0.00	0.9 ± 0.00	1.0 ± 0.01	1.0 ± 0.01	0.2 ± 0.00	0.9 ± 0.01	1.5 ± 0.02
Palmitic acid (C16:0)	9.3 ± 0.02	11.1 ± 0.41	13.7 ± 0.23	10.7 ± 0.34	14.5 ± 0.20	11.3 ± 0.15	25.2 ± 0.14	2.8 ± 0.03	11.6 ± 0.67	10.5 ± 0.05
Margaric acid (C17:0)	33.2 ± 1.04	28.2 ± 0.61	20.3 ± 0.70	5.0 ± 0.02	6.8 ± 0.03	11.5 ± 0.09	14.7 ± 0.11	1.6 ± 0.07	8.6 ± 0.06	28.6 ± 0.61
Stearic acid (C18:0)	5.7 ± 0.01	6.2 ± 0.06	5.8 ± 0.21	4.4 ± 0.22	6.9 ± 0.02	5.2 ± 0.01	5.0 ± 0.05	73.8 ± 0.16	5.2 ± 0.02	6.2 ± 0.13
Oleic acid (C18:1c)	5.6 ± 0.01	7.9 ± 0.15	9.5 ± 0.18	16.6 ± 0.77	16.8 ± 0.56	14.8 ± 0.73	14.6 ± 0.97	3.7 ± 0.04	13.1 ± 0.01	6.3 ± 0.01
Linoleic acid (C18:2)	37.4 ± 1.21	39.4 ± 1.12	42.8 ± 1.74	59.4 ± 1.82	52.2 ± 1.46	52.9 ± 1.15	33.9 ± 1.02	17.9 ± 0.97	56.8 ± 1.46	39.7 ± 0.36
Arachidic acid (C20:0)	0.3 ± 0.03	0.4 ± 0.41	0.3 ± 0.12	0.4 ± 0.63	0.2 ± 0.06	0.5 ± 0.37	0	0	0	0
Arachidonic acid (C20:4)	4.5 ± 0.01	4.7 ± 0.01	3.9 ± 0.01	2.3 ± 0.01	1.2 ± 0.00	2.6 ± 0.00	5.2 ± 0.01	0	3.5 ± 0.01	7 ± 0.01
Others	0.5 ± 0.03	0.5 ± 0.01	0.5 ± 0.00	0.4 ± 0.00	0.5 ± 0.02	0.2 ± 0.01	0.4 ± 0.00	0	0.3 ± 0.01	0.2 ± 0.0
SFA	51.7 ± 1.15	47.1 ± 1.17	43.0 ± 1.23	20.9 ± 0.85	29.1 ± 0.91	29.0 ± 0.89	45.9 ± 1.14	78.4 ± 1.81	26.3 ± 0.92	46.8 ± 1.24
USFA	47.8 ± 1.42	52.4 ± 1.70	56.5 ± 0.93	78.7 ± 1.63	70.4 ± 1.52	70.8 ± 1.32	53.7 ± 1.29	21.6 ± 0.95	73.4 ± 1.69	53.0 ± 1.47
MUFA	5.6 ± 0.29	7.9 ± 0.41	9.5 ± 0.53	16.6 ± 0.29	16.8 ± 0.63	14.8 ± 0.62	14.6 ± 0.37	3.7 ± 0.21	13.1 ± 0.23	6.3 ± 0.21
PUFA	42.2 ± 1.58	44.5 ± 1.21	47.0 ± 1.11	62.1 ± 1.84	53.6 ± 1.05	56.0 ± 1.29	39.1 ± 1.02	17.9 ± 0.55	60.3 ± 1.68	46.7 ± 1.26

Table 4. Fatty acid profiles of the studied *Vitis vinifera* cultivars. Data are mean ± standard deviation ($n = 3$). Values followed by the same letter within each row are significantly different ($p < 0.05$). FA, fatty acids; SFA, saturated fatty acids; USFA, unsaturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids.

the SFA examined, margaric acid and palmitic acid were predominant, with a concentration ranging from 1.6 to 33.2% and from 2.8 to 25.2%, respectively, particularly prevalent in the Rashmiri and e Hosseini cultivars. Additionally, linoleic acid, a significant PUFA, exhibited concentrations from 17.9 to 59.4%, with the highest levels recorded in the Taefi cultivar. Göktürk Baydar et al.³⁸ reported the linoleic, oleic, palmitic and stearic contents of grape seed oil as 63.33–71.37%, 16.15–21.63%, 7.42–10.24%, and 2.95–4.68%, respectively. Harbeoui et al.³⁵ reported linoleic acid (64.77–75.37%) as the topmost fatty acid in the seed oil of Tunisian grape cultivars, which is consistent with our results. To et al.³⁹ stated that MtWRI transcription factor homolog regulates fatty acid biosynthesis in *M. orbicularis*. Tang et al.⁴⁰ also reported that overexpression of some genes and their mRNA levels are involved in oil accumulation and regulating of fatty acid biosynthesis in peanut seeds. The obtained variations in the fatty acid profile of the studied samples can be related to the transcription factors controlling the biosynthesis of these compounds.

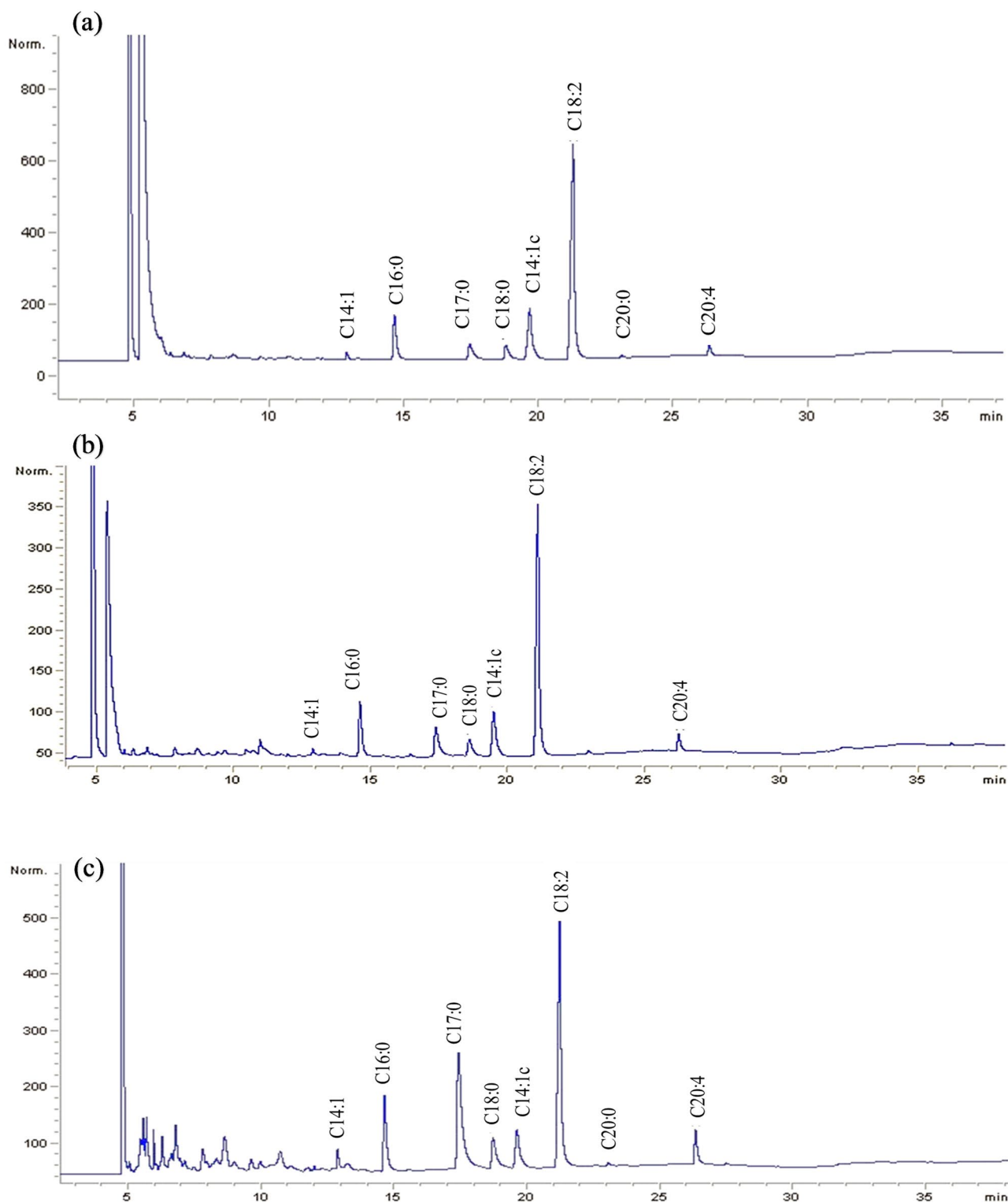


Fig. 2. A typical chromatogram of the fatty acids from Taefi (a), Dastchin (b), and Rashe (c) cultivars of *Vitis vinifera* L.

Phenolic compound profile

Phenolic compounds have traditionally been considered in preventing and treating many diseases as antioxidants due to their important biologically active materials that are good for human health⁴¹. The main phenolic compounds of the seed extracts of different grape cultivars were gallic acid, quercetin, *p*-coumaric acid, vanillic acid, caffeic acid, and kaempferol (Fig. 3). The maximum level of gallic acid (1.53 mg/g DW) was obtained in the Mambrayma cultivar, while the minimum level (0.23 mg/g DW) was obtained in the Rishbaba cultivar. The

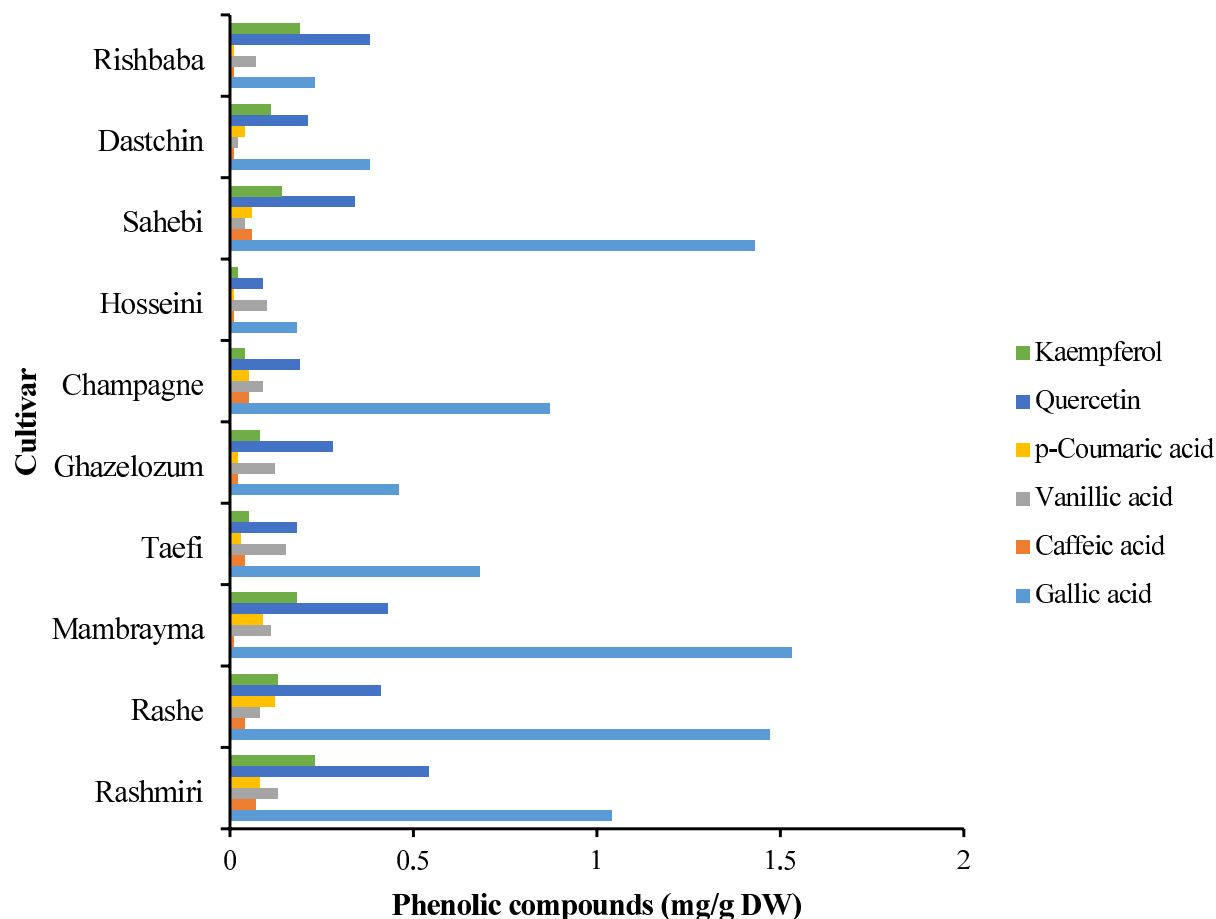


Fig. 3. The phenolic compound profiles of *Vitis vinifera* L. cultivars.

maximum levels of caffeic acid, quercetin and kaempferol were obtained in the Rashmiri cultivar, 0.07, 0.54 and 0.23 mg/g DW, respectively. The minimum levels of quercetin (0.09 mg/g DW) and kaempferol (0.02 mg/g DW) were obtained in the Hosseini cultivar. The level of vanillic acid varied between 0.02 and 0.15 mg/g DW, with the Maximum and lowermost levels being in the Taefi and Dastchin cultivars, respectively. Rasha cultivar had the highest (0.12 mg/g DW) *p*-coumaric acid and Hosseini and Rishbaba cultivars had the lowest (0.01 mg/g DW). The compounds *p*-coumaric acid, caffeic acid, vanillic acid, ferulic acid, kaempferol and quercetin in grape seed extract have been expressed by other studies^{42,43}. The degree of variation in phenolic compounds of the different grape cultivars studied may be due to the type of cultivar or genetics, extraction and analysis method, location of seed preparation and climatic factors⁴⁴.

TPC, TFC and antioxidant activity

The figure shows the TPC, TFC and antioxidant activity content of seed extracts of different grape cultivars. There was a significant disagreement among the cultivars in terms of the mentioned traits ($p < 0.05$). The maximum TPC (8.83 mg GAE/g DW) and TFC (4.64 mg QE/g DW) was obtained in Rashmiri cultivar, followed by Rasha cultivar with the maximum TPC (8.79 mg GAE/g DW) and TFC (3.15 mg QE/g DW). The lowermost TPC (2.21 mg GAE/g DW) and TFC (0.97 mg QE/g DW) were obtained in Hosseini and Ghazelozum cultivars, respectively (Fig. 4a, b). Krasteva et al.⁴³ reported the TPC of seeds of different grape cultivars to be between 70.06 and 111.2 mg GAE/g DW. Castro-Lopez et al.⁴⁵ reported the TPC of seed extracts of different grape varieties as 107.8–10.7 mg GAE/g DW. In addition, in another study, the TPC of seed extracts of different grape varieties was determined as 8.79–11.27 mg GAE/g⁴⁶. The TFC of seed extracts of different grape varieties was reported as 40.05–52.01 mg QE/g DW in one study⁴⁴ and in another study, as 6.9–1.25 mg QE/g DW⁴⁷. The results of evaluating the antioxidant activity of seed extracts of different cultivars by FRAP method showed that the maximum antioxidant activity was determined in Rashmiri (59.63 $\mu\text{mol Fe}^{2+}$ /g DW) and Rasha (49.95 $\mu\text{mol Fe}^{2+}$ /g DW) cultivars, and the lowest (7.17 $\mu\text{mol Fe}^{2+}$ /g DW) was related to Ghazelozum cultivar (Fig. 4c). Seed extracts of different grape cultivars showed different antioxidant activity, which is consistent with the study of Guaita and Bosso⁴⁸ and Ghouila et al.⁴⁹. Based on the results, seed extracts that contained more compounds also had higher antioxidant power. Polyphenolic compounds can capture free radicals due to their chemical structure

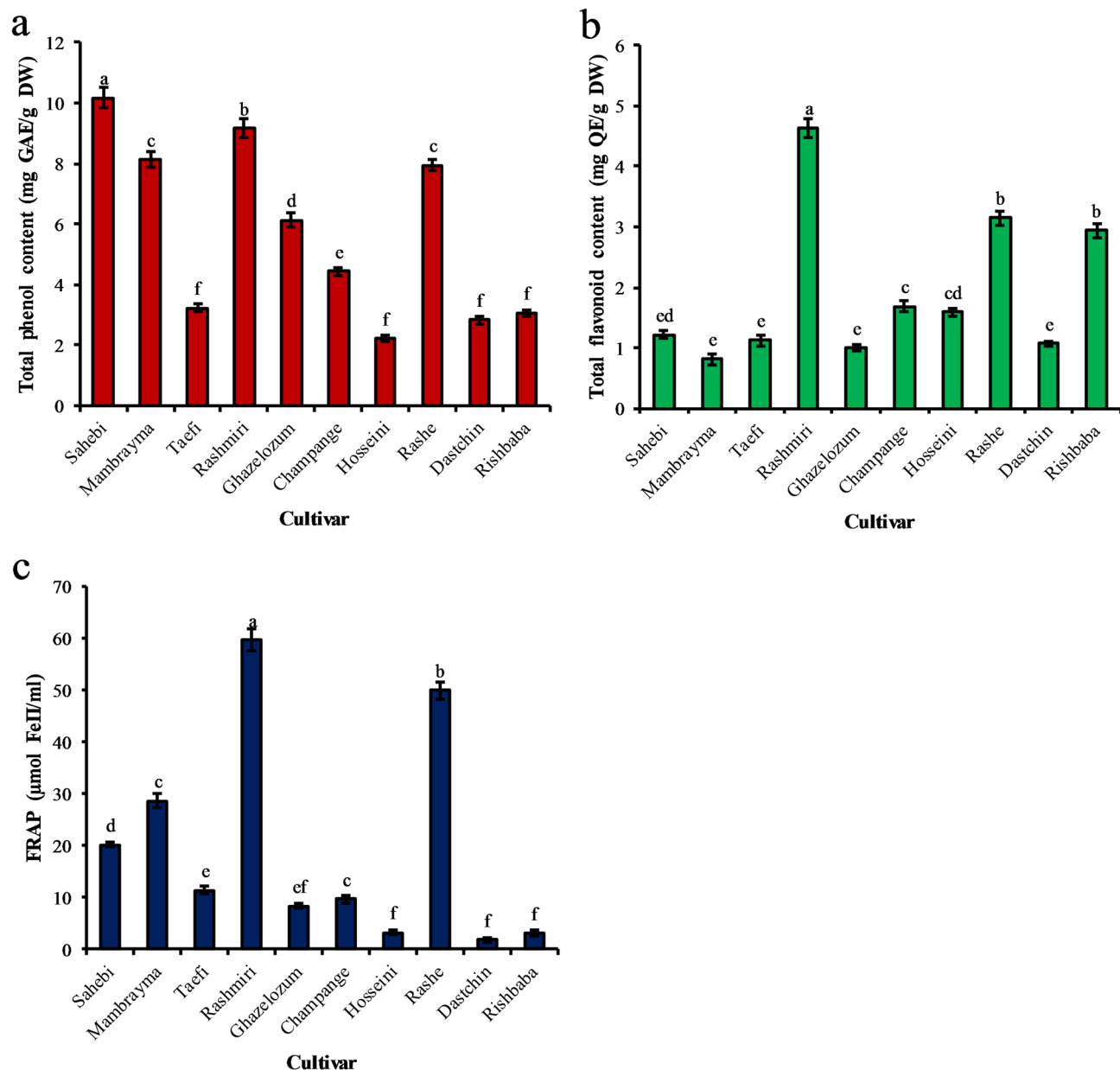


Fig. 4. Histogram of total phenol content (a), total flavonoid content (b), and antioxidant activity (c) among *Vitis vinifera* L. cultivars. The mean comparisons were performed using the Duncan test at $P \leq 0.05$ significant level. Means followed by the same letter(s) are not significantly different. .

and form complexes with metal ions. Therefore, these compounds showed good antioxidant activity. A positive and significant correlation among phenolic compounds and antioxidant activity has been expressed in other studies⁵⁰. There are some methods to produce polyphenolic compounds in plants and various mechanisms for their distribution across different plant structures. Genetics, environmental conditions, climatic conditions, and the solvent used in extraction are some factors that influence the level of phenolic and flavonoid compounds derived from plants⁵¹.

Proximate composition

Figure 5 shows the approximate composition of seeds including carbohydrates, protein, fat, fiber and energy value of different grape varieties. Significant disagreement were observed between different grape cultivars in terms of approximate composition content of seeds. The carbohydrate varied from 13.23 g/100 g DW in Hosseini to 19.37 g/100 g DW in Rashmiri. The seed protein content of different varieties varied from 6.24 to 9.72 g/100 g DW, with the lowest and maximum being determined in Ghazelozum and Rishbaba cultivars, respectively. Hosseini cultivar showed the highest (15.40 mg/100 g DW) fat content and Mambrayma cultivar showed the lowest (9.62 mg/100 g DW) fat content. The maximum (42.87 mg/100 g DW) and lowest (38.41 mg/100 g DW) fiber content was determined in Mambrayma and Rishbaba cultivars, respectively. The maximum energy value

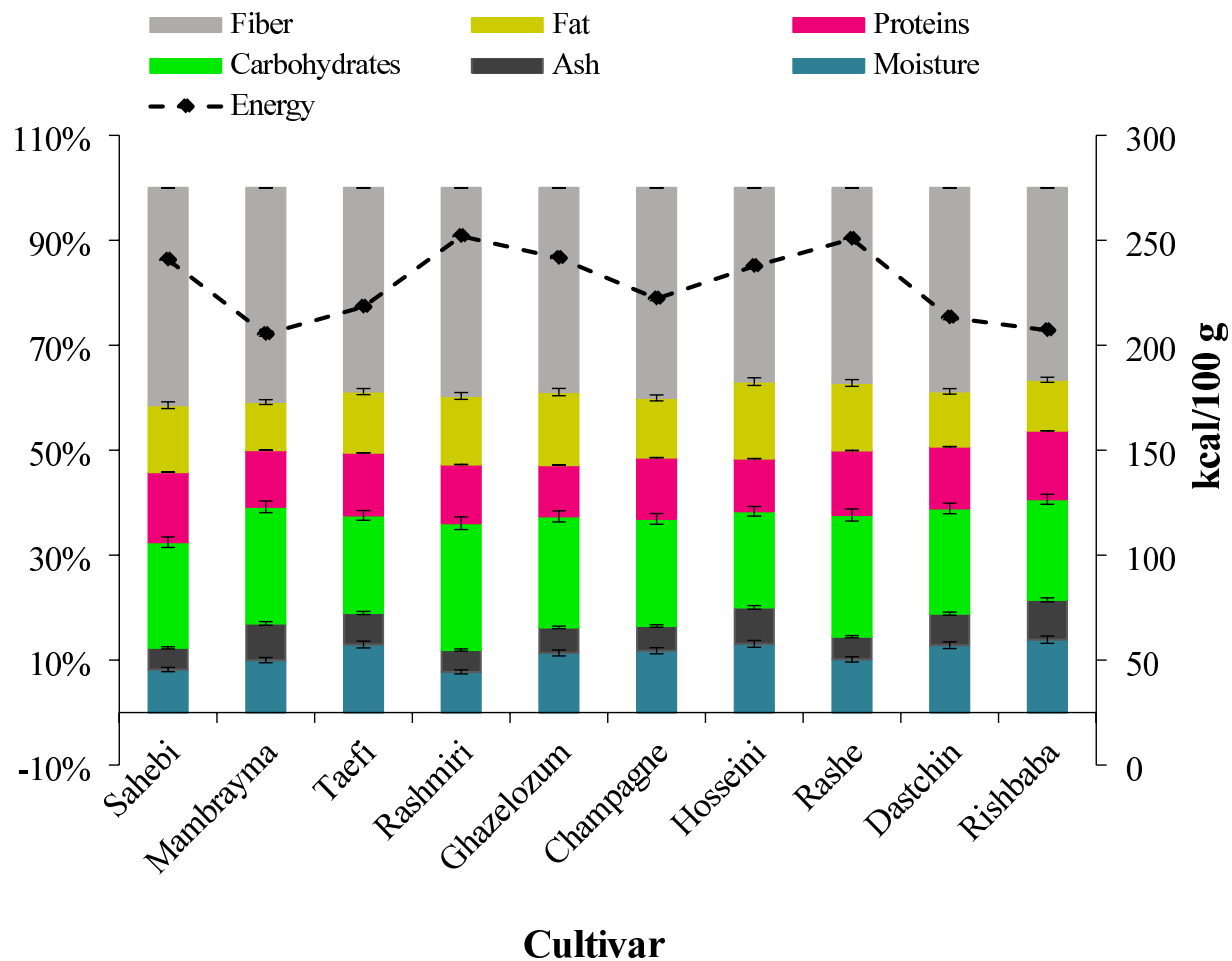


Fig. 5. Histogram of proximate composition for ten cultivars of *Vitis vinifera* L.

was achieved in Rashmiri cultivar (231.96 Kcal/100 g), followed by Rasha (230.63 Kcal/100 g), Ghazelozum (221.55 Kcal/100 g), and Hosseini (217.68 Kcal/100 g). In previous research, the protein, lipid, carbohydrate and fiber content of grape seeds were reported to be 8.7–9.8, 10.45–16.73, 18.2–19.8 and 40.2–43.7 g/100 g, respectively^{52,53}. Nikolidaki et al.⁵⁴ reported the protein and lipid content of grape seeds to be 2.2% and 0.43%, respectively. Fiber, which plays a substantial role in the prevention of cardiovascular diseases, gastrointestinal diseases, diabetes and some cancers, is about 9 times higher in this study than the amount found in the US Food Database (4.5 g/100 g)⁵⁵. The fiber content of grape seeds cultivated in Morocco was reported by Kalili et al.⁵⁶ to be 13.93 g/100 g.

Mineral composition

There was a significant difference among different grape cultivars in terms of seed mineral content ($p < 0.05$). The amount of mineral elements in the seeds of different cultivars is shown in the Fig. 6. Macro elements such as potassium, phosphorus and calcium and micro elements such as magnesium and iron were identified in the seeds of diverse cultivars. The highest amount of potassium was found in the Champagne cultivar (8.34 mg/g dry weight) followed by Rashmiri (7.32 mg/g dry weight), mambrayma (6.61 mg/g dry weight) and Rasha (6.40 mg/g dry weight). The lowest amount (3.82 mg/g dry weight) of potassium was found in the Taefi cultivar. The amount of phosphorus varied from 2.34 mg/g dry weight in the Sahebi cultivar to 3.74 mg/g dry weight in the Champagne cultivar. The cultivars Mambrayma, Rashmiri and Rasha had the maximum calcium amount with 2.31, 2.17 and 2.04 mg/g DW respectively and the lowest calcium content (1.05 mg/g DW) was observed in the cultivar Hosseini. The highest magnesium and iron content was determined in the cultivar Champagne. The lowermost magnesium amount (0.23 mg/g DW) was in the cultivar Rishbaba and the cultivars Sahebi, Taefi and Rishbaba had the lowest iron content (0.01 mg/g dry weight). The diversity of mineral elements in the seeds of Turkish grape cultivars (B, Al, Co, Ca, Cr, Mo, K, Fe, Mg, Na, Mn, S, P, Se, S, and Zn) showed that the content of potassium, calcium, magnesium, sodium, phosphorus and S in Turkish grape seed samples was generally very high⁵⁷. In addition, Vrcek et al.⁵⁸ reported that the uttermost microelements in grape seeds were iron, copper, zinc, manganese and aluminum. Several factors such as soil type, pH, the amount of mineral compounds in

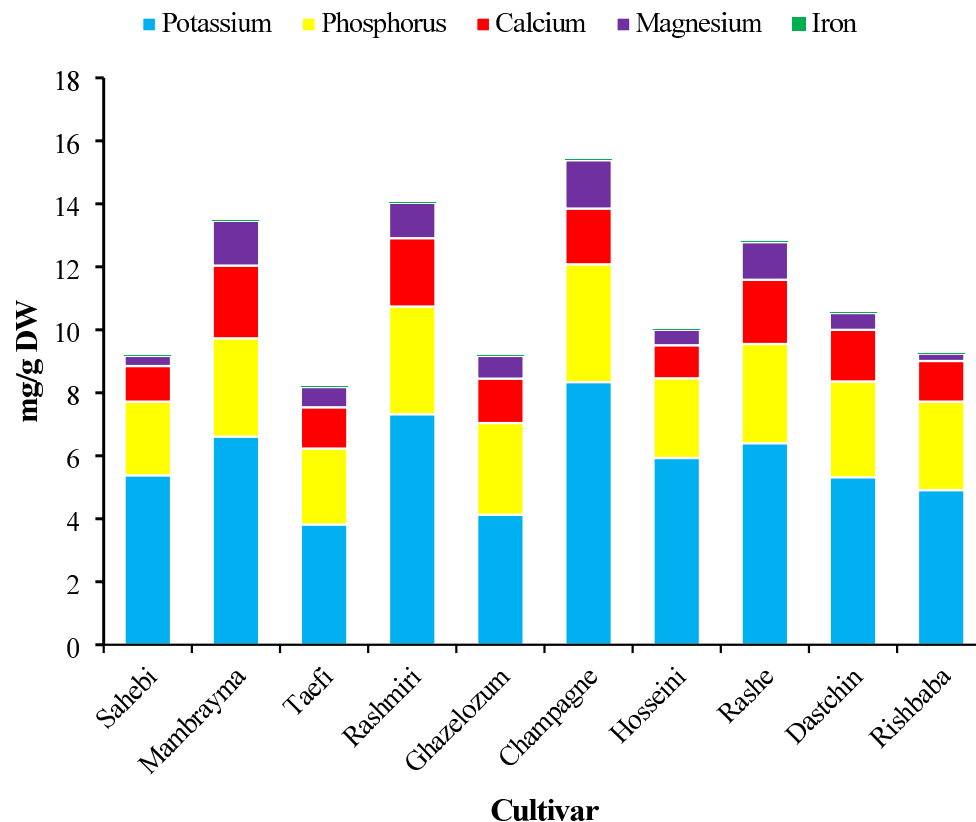


Fig. 6. Histogram of mineral composition for ten cultivars of *Vitis vinifera* L.

the soil and the plant's ability to absorb can affect the amount of mineral compounds in the plant⁵⁹. This study showed that grape seeds, due to their appropriate nutrients, could play a substantial role in the diet and prevent various diseases.

Correlation, cluster analysis and PCA

The outcomes of the analysis concerning the interrelations among traits, as determined by the Pearson correlation coefficient, are illustrated in the accompanying Fig. 7. Positive communication are depicted in blue, while negative correlations are indicated in red. Notably, a positive and statistically significant relationship was observed between fat and carbohydrates with energy. Conversely, oil content demonstrated a negative and statistically significant relationship with fiber, phosphorus, calcium, magnesium, iron, gallic acid, and p-coumaric acid. Additionally, a significant positive relationship was identified among oil content, fat, and energy. The dry weight of seeds had a positive and significant correlation with fiber, potassium, calcium, magnesium, iron, and fresh seed weight. Furthermore, carbohydrates, energy, calcium, TPC, TFC, gallic acid, and caffeic acid all showed a positive and significant correlation with antioxidant activity. Numerous research have documented a significant positive association among antioxidant activity and phenolic compounds, aligning with the findings of this investigation^{50,60}.

Principal component Analysis (PCA) is a widely utilized statistical technique in metabolomics aimed at reducing dataset dimensionality while highlighting significant variance and patterns⁶¹. It transforms correlated variables into a smaller set of orthogonal variables known as principal components (PCs), which serve as axes in a new coordinate system where the first PC captures the greatest variance. PCA results are often visualized through "scores plots," which display sample similarities and differences, and "loadings plots," which identify the variables contributing to sample separation. As an unsupervised method, PCA finds application across various research fields, including agricultural science⁶². In this research, PCA was conducted focusing on oil content and composition, phenolic compounds, as well as mineral and proximate composition across various grape cultivars. Table 5 illustrates the relationships among the cultivars and the studied traits. The analysis revealed that the first eight PC accounted for 98.42% of the variance among the cultivars. Specifically, PC1, PC2, and PC3 contributed 26.52%, 19.82%, and 16.08% of the total variance, respectively. The first component was predominantly influenced by traits such as calcium, magnesium, carbohydrates, potassium, phosphorus, iron, FRAP, seed dry weight, moisture content, fiber, TFC, caffeic acid, and oil content. The second component was primarily affected by quercetin, kaempferol, oleic acid, myristoleic acid, p-coumaric acid, gallic acid, proteins, margaric acid, fruit length, and palmitic acid. The third component highlighted traits such as energy, ash content, fat content, stearic

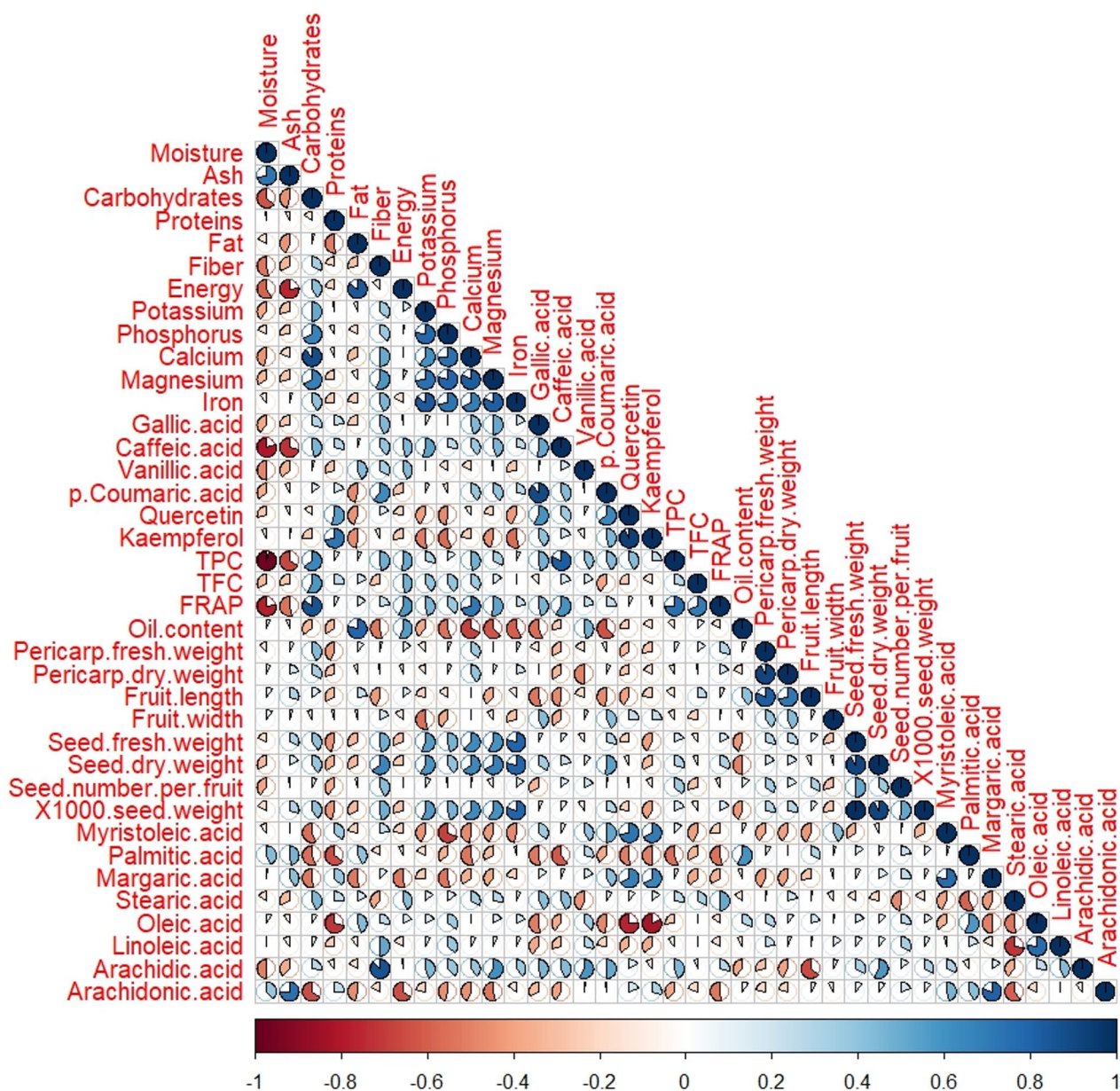


Fig. 7. Pearson correlation representation of morphological traits, seed oil content, proximate and mineral composition of *Vitis vinifera* L. cultivars.

acid, seed fresh weight, arachidonic acid, and TFC with the highest coefficients (Table 4). This analysis serves to elucidate the key differentiating factors among the populations under study. However, according to the PCA and despite the same cultivation conditions, the similarity of the phytochemical composition values among the cultivar, and the difference in the composition values in the cultivars are more influenced by genetic factors and less related to their geographical origin. The results can provide useful information for breeding program and exploitation of these potential compounds in the field of food, pharmaceutical, cosmetic and health industries⁶³.

The results of the cluster analysis conducted on various cultivars based on oil content and composition, phenolic compounds, as well as mineral and proximate composition are presented in Fig. 8. The cluster analysis revealed that the cultivars could be classified into four primary groups. The Rashah cultivar was allocated to the first group (I), while the Rashmiri and Mambrayma cultivars were grouped together in the second group (II). The third group (III) comprised the Dastchin, Champagne, Hosseini, and Ghazelozum cultivars. Lastly, the fourth group (IV) included the Rishbaba, Taefi, and Sahebi cultivars. A biplot generated from PC1 and PC2 illustrated the diversity among the cultivars and corroborated their classification into four distinct groups (Fig. 9). In the study of Shakuri et al.⁴¹, PCA was used to evaluate different ecotypes of Iranian oak, in which the studied phytochemical and morphological traits were classified into the first two principal components, which together accounted for 68.53% of the total variance. In another study on *Medicago* species, morphological and phytochemical traits were classified into the first two principal components using PCA, which accounted for

Traits	Component							
	1	2	3	4	5	6	7	8
Calcium	0.913	0.102	0.093	-0.309	0.132	0.114	0.143	0.117
Magnesium	0.904	0.127	0.129	0.118	-0.226	-0.235	-0.202	0.112
Carbohydrates	0.856	-0.118	-0.309	-0.143	0.206	0.104	0.192	0.104
Potassium	0.770	-0.156	0.141	0.148	-0.469	0.227	0.116	0.132
Phosphorus	0.769	-0.306	0.101	-0.155	-0.429	-0.129	0.275	0.145
Iron	0.743	-0.225	0.440	-0.190	-0.250	0.141	-0.217	0.162
FRAP	0.736	0.127	-0.488	0.162	0.249	0.133	0.116	0.343
Seed dry weight	0.681	0.131	0.624	0.124	0.141	0.154	-0.206	0.225
Moisture	-0.648	0-0.303	0.339	-0.425	-0.304	-0.280	0.122	0.118
Fiber	0.633	0.240	0.434	0.457	0.173	-0.260	0.121	-0.176
Total phenol content	0.629	0.428	-0.334	0.310	0.304	0.319	0.113	0.141
Caffeic acid	0.619	0.521	-0.341	0.201	-0.161	0.277	-0.117	-0.226
Oil content	-0.555	-0.393	-0.453	0.448	0.118	0.269	-0.184	0.105
Quercetin	-0.138	0.933	0.131	0.115	0.238	0.139	0.129	0.116
Kaempferol	-0.351	0.862	0.117	-0.169	0.220	0.109	0.186	0.121
Oleic acid	0.105	-0.782	0.124	0.491	0.108	-0.316	0.137	0.108
Myristoleic acid	-0.410	0.720	0.198	0.436	0.190	0.138	0.107	0.102
p-Coumaric acid	0.385	0.720	0.338	0.087	0.307	-0.202	-0.270	0.147
Gallic acid	0.448	0.709	0.123	-0.113	0.179	-0.335	-0.337	0.156
Proteins	-0.172	0.683	-0.177	-0.343	-0.280	0.114	0.430	0.141
Margaric acid	-0.357	0.632	0.514	0.195	0.112	0.396	0.121	0.105
Fruit length	-0.174	-0.626	-0.119	-0.286	0.577	0.344	0.0143	0.121
Palmitic acid	-0.457	-0.584	0.355	0.387	0.101	0.127	-0.361	0.172
Energy	0.240	-0.204	-0.847	0.350	0.100	0.110	-0.180	0.129
Ash	-0.456	-0.177	0.666	-0.407	0.126	0.176	0.131	0.294
Fat	0.105	-0.474	-0.646	0.423	0.141	0.134	-0.406	0.172
Stearic acid	0.282	0.169	-0.642	-0.602	0.131	0.121	-0.328	0.149
1000 seed weight	0.616	-0.235	0.635	0.107	0.114	0.326	-0.163	0.126
Seed fresh weight	0.616	-0.235	0.635	0.172	0.114	0.326	-0.163	0.123
Arachidonic acid	-0.549	0.144	0.609	0.118	0.112	0.426	0.149	0.292
Total flavonoid content	0.312	-0.183	-0.550	-0.125	-0.149	0.252	0.420	0.537
Vanillic acid	0.117	0.121	-0.145	0.899	0.132	0.119	0.131	0.366
Arachidic acid	0.577	0.300	0.295	0.610	-0.141	-0.265	0.120	0.148
Pericarp fresh weight	0.191	-0.513	0.151	-0.234	0.782	0.121	0.160	0.134
Pericarp dry weight	0.168	-0.396	0.139	-0.526	0.687	-0.133	0.143	-0.102
Fruit width	-0.169	0.174	0.127	0.172	0.615	-0.691	0.131	0.258
Seed number	0.157	-0.188	0.353	0.402	0.389	0.509	0.134	-0.476
Linoleic acid	0.113	-0.378	0.318	0.439	0.108	-0.360	0.639	-0.106
Eigenvalues	10.07	7.53	6.11	4.49	3.30	2.59	1.94	1.33
% of variance	26.52	19.82	16.08	11.89	8.70	6.82	5.11	3.51
Cumulative variance %	26.52	46.34	62.42	74.26	82.96	89.79	94.91	98.42

Table 5. Eigenvalues of the principal component axes from the multiple regression analysis of the studied parameters in *Vitis vinefera* cultivars.

78.06% of the total variance⁶³. This biplot reinforced that the findings related to oil content and composition, phenolic compounds, as well as mineral and proximate composition were largely consistent with those derived from the cluster analysis.

Conclusion

The current investigation revealed significant variation among Iranian grape cultivars regarding their morphological characteristics, mineral and proximate composition, as well as phytochemical properties, including phenolic acids and fatty acids. This research provides new insights into the fatty acid profiles of grape seeds and the oils extracted from them, along with detailed information on the mineral and nutritional composition and phenolic amount of seeds from Iranian grape varieties. Among the cultivars examined, Hosseini, Ghazelozum, Sahebi, and Rashmiri exhibited the highest levels of oil content. Linoleic and margaric acids were identified as the uttermost fatty acids present in these cultivars. Additionally, the seeds of the Iranian

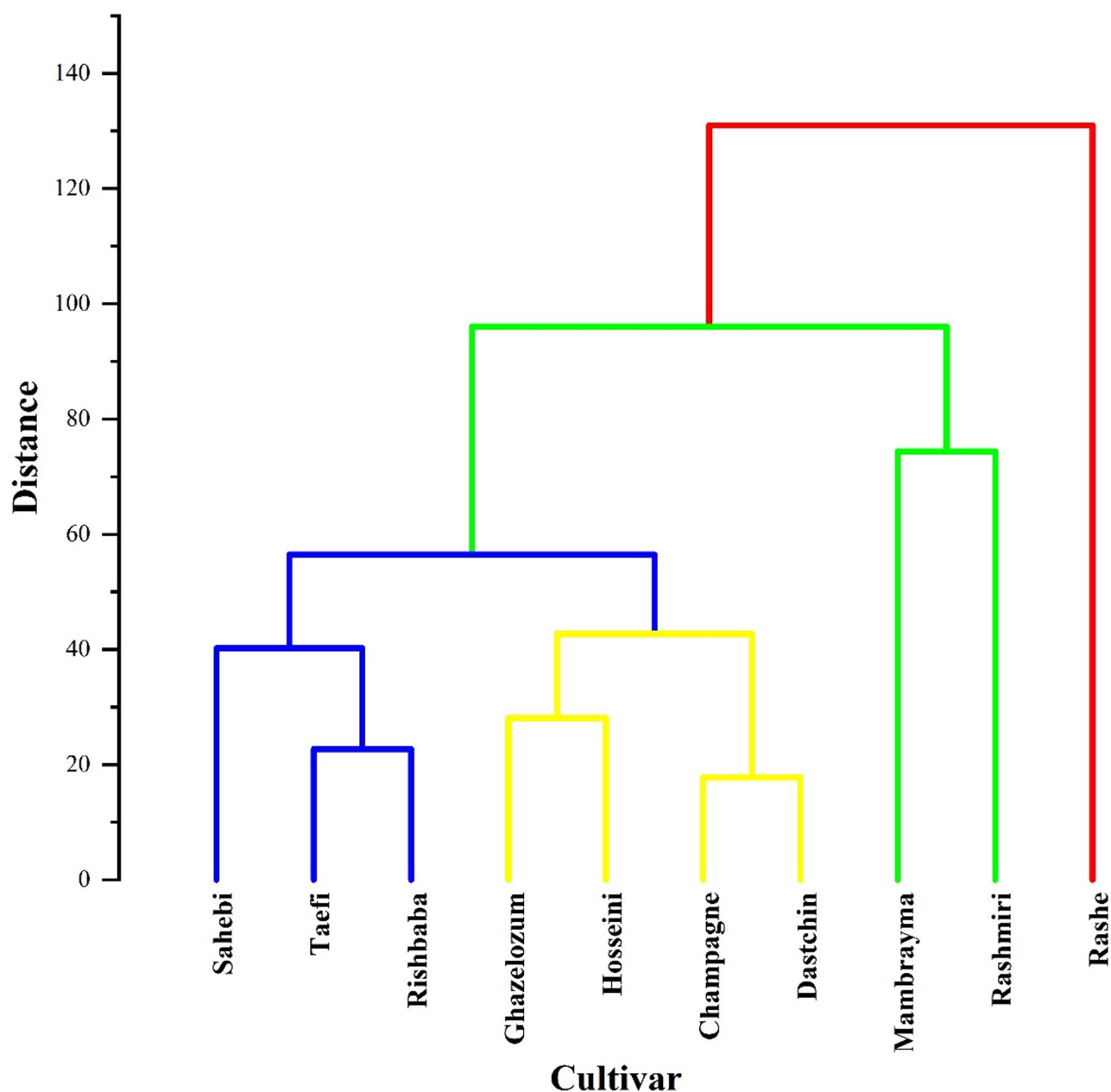


Fig. 8. Cluster analysis of *Vitis vinifera* L. cultivars based on morphological traits, seed oil content, proximate and mineral composition using Euclidean distances.

grape varieties demonstrated a commendable level of minerals, fats, proteins, and carbohydrates. Furthermore, the TPC, TFC, and phenolic compounds in the seeds significantly contributed to their antioxidant potential. The high genetic diversity among the studied grape cultivars allows us to use superior genotypes in future breeding programs to achieve proper cultivars with desirable growth parameters, high adaptability, and rich secondary metabolite contents.

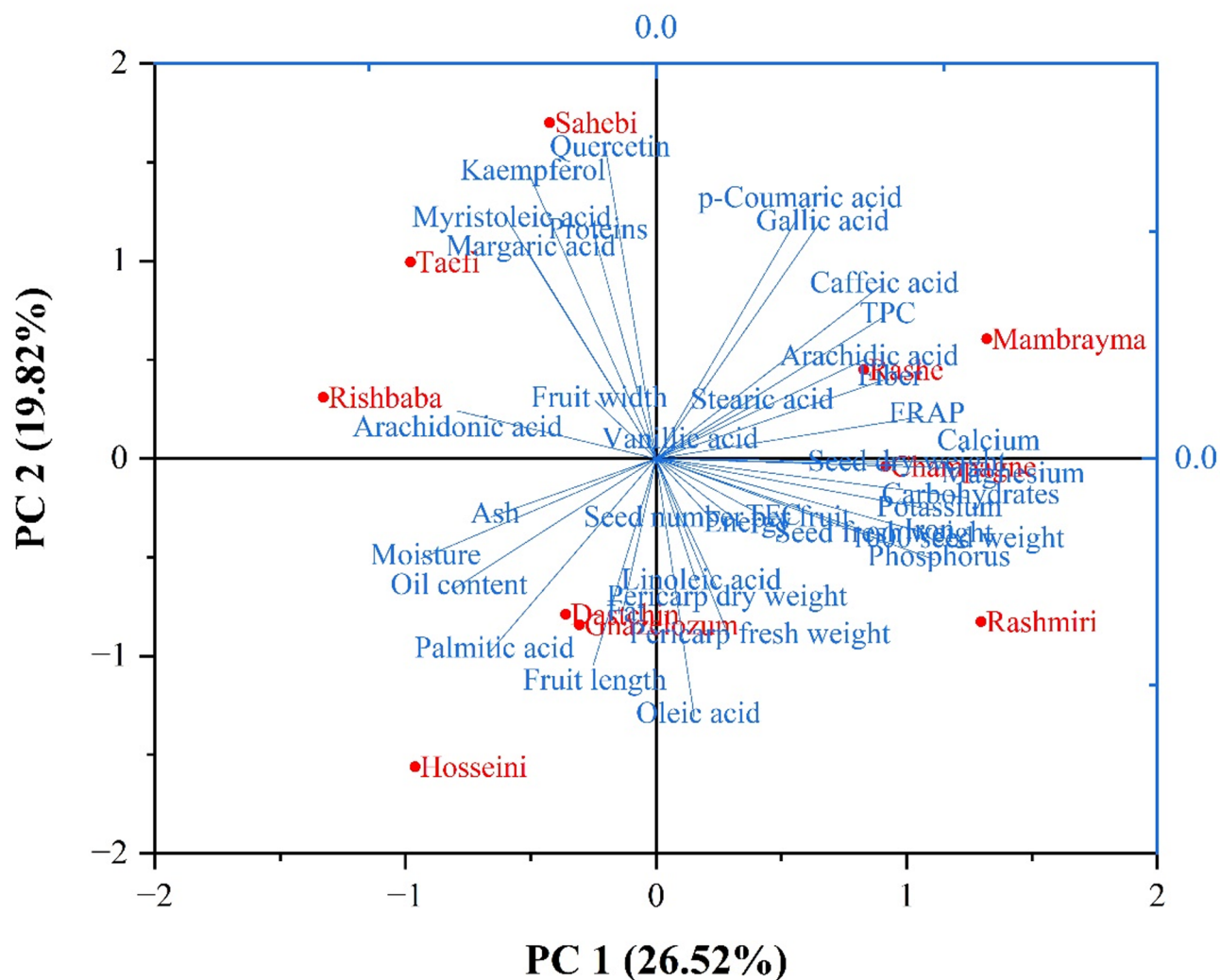


Fig. 9. Bi-plot graph for the first and second principal components based on morphological traits, seed oil content, proximate and mineral composition for ten cultivars of *Vitis vinifera* L.

Data availability

All data generated or analyzed during this study are included in this article. Further enquiries can be directed to the corresponding author.

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References

- Malinowska, M. A., Ekiert, H., Kwaśniak, B., Sikora, E. & Szopa, A. *Vitis vinifera* (Vine Grape) as a valuable cosmetic Raw material. *Int. J. Pharm.* **15**, 1372. <https://doi.org/10.3390/pharmaceutics15051372> (2023).
- OIV. State of the World Vine and Wine Sector in 2022. *Int. Org. Vine Wine*. Available online (accessed on 8 December 2024). (2022).
- Teixeira, A. et al. Natural bioactive compounds from winery by-products as health promoters: A review. *Int. J. Mol. Sci.* **15** (9), 15638–15678 (2014).
- Yang, C. et al. Processing technologies, phytochemical constituents, and biological activities of grape seed oil (GSO): A review. *Trends Food Sci. Technol.* **116**, 1074–1083 (2021).
- Pozzo, L. et al. Characterization of antioxidant and antimicrobial activity and phenolic compound profile of extracts from seeds of different *Vitis* species. *Molecules* **28**, 4924. <https://doi.org/10.3390/molecules28134924> (2023).
- Rao, M., Bast, A. & de Boer, A. Valorized food processing By-Products in the EU: finding the balance between safety, nutrition, and sustainability. *Sustainability* **13**, 4428 (2021).
- Di Fernandes, P. et al. Nutraceutical potential of grape (*Vitis vinifera* L.) seed oil in oxidative stress, inflammation, obesity and metabolic alterations. *Molecules* **28**, 7811. <https://doi.org/10.3390/molecules28237811> (2023).
- Dimić, I. et al. Innovative and conventional valorizations of grape seeds from winery by-products as sustainable source of lipophilic antioxidants. *Antioxidants* **9**, 568 (2020).
- Kapcsándi, V., Lakatos, E. H., Sik, B., Linka, L. Á. & Székelyhidi, R. Antioxidant and polyphenol content of different *Vitis vinifera* seed cultivars and two facilities of production of a functional bakery product. *Chem. Pap.* **75**, 5711–5717 (2021).

10. Kaynarca, G. B., Kamer, D. D. A., Yucel, E. & Gümüő, T. Proposed use of a Polyvinyl alcohol with grape pomace extract as an edible coating for strawberries. *Pol. J. Food Nutr. Sci.* **73**, 151–162 (2023).
11. Martin, M. E., Grao-Cruces, E., Millan-Linares, M. C. & Montserrat-de la Paz, S. Grape (*Vitis vinifera* L.) seed oil: a functional food from the winemaking industry. *Foods* **9** (10), 1360 (2020).
12. Kritiotti, A., Menexes, G. & Drouza, C. Chemometric characterization of Virgin Olive oils of the two major Cypriot cultivars based on their fatty acid composition. *Int. Food Res.* **103**, 426–437. <https://doi.org/10.1016/j.foodres.2017.10.064> (2018).
13. Zhang, Z., Zhang, Y., Ao, Y., Saunders, M. R. & Wang, X. Diversity of seed and seed oil physicochemical traits of *Xanthoceras sorbifolium* bunge. *J. Food Compos. Anal.* **96**, 103705. <https://doi.org/10.1016/j.jfca.2020.103705> (2021).
14. Ravi, Y. et al. Guesstimate of thymoquinone diversity in *Nigella sativa* L. genotypes and elite varieties collected from Indian States using HPTLC technique. *Open. Life Sci.* **18** (1), 20220536. <https://doi.org/10.1515/biol-2022-0536> (2023).
15. Irchad, A. et al. Lipidomic profiling reveals phenotypic diversity and nutritional benefits in *Ficus carica* L. (Fig.) seed cultivars. *Front. Plant. Sci.* **14**, 1229994. <https://doi.org/10.3389/fpls.2023.1229994> (2023).
16. De Meyer, E. et al. Evaluating genetic diversity and seed composition stability within Pan-African soybean variety trials. *Crop Sci.* **64** (6), 3272–3292. <https://doi.org/10.1002/csc2.21356> (2024).
17. Lucarini, M. et al. Grape seeds: chromatographic profile of fatty acids and phenolic compounds and qualitative analysis by FTIR-ATR spectroscopy. *Foods* **9**, 10 (2019).
18. Abiri, K., Rezaei, M., Tahanian, H., Heidari, P. & Khadivi, A. Morphological and Pomological variability of a grape (*Vitis vinifera* L.) germplasm collection. *Sci. Hort.* **266**, 109285. <https://doi.org/10.1016/j.scienta.2020.109285> (2020).
19. Popovic-Djordjevic, J. et al. Fatty acids in seed oil of wild and cultivated rosehip (*Rosa Canina* L.) from different locations in Serbia. *Ind. Crops Prod.* **191**, 115797. <https://doi.org/10.1016/j.indcrop.2022.115797> (2023).
20. Hosseini, S. S., Rezadoost, H., Nadjafi, F. & Asareh, M. S. Comparative essential oil composition and fatty acid profiling of some Iranian black Cumin landraces. *Ind. Crops Prod.* **140**, 111628. <https://doi.org/10.1016/j.indcrop.2019.111628> (2019).
21. Demir, N., Yildiz, O., Alpaslan, M. & Hayaloglu, A. A. Evaluation of volatiles, phenolic compounds and antioxidant activities of Rose hip (*Rosa* L.) fruits in Turkey. *LWT Food Sci. Technol.* **57**, 126–133. <https://doi.org/10.1016/j.lwt.2013.12.038> (2014).
22. Singleton, V. L. & Rossi, J. A. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *Am. J. Enol. Vitic.* **16** (3), 144–158. <https://doi.org/10.5344/ajev.1965.16.3.144> (1965).
23. Dewanto, V., Wu, X., Adom, K. K. & Liu, R. H. Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. *J. Agric. Food Chem.* **50** (10), 3010–3014. <https://doi.org/10.1021/jf0115589> (2002).
24. Benzie, I. F. & Strain, J. J. The ferric reducing ability of plasma (FRAP) as a measure of antioxidant power: the FRAP assay. *Anal. Biochem.* **239** (1), 70–76. <https://doi.org/10.1006/abio.1996.0292> (1996).
25. Baőgel, S. & Erdemoőlu, S. B. Determination of mineral and trace elements in some medicinal herbs and their infusions consumed in Turkey. *Sci. Total Environ.* **359** (1–3), 82–89. <https://doi.org/10.1080/15538362.2020.1735601> (2006).
26. AOAC. *Official Methods of Analysis* 15th edn, Vol. 1 (Association of Official Analytical Chemists, 1990).
27. FAO. Food energy—methods of analysis and conversion factors. Report of a technical workshop. *Food Nutr.* **77**. (2003).
28. Bigard, A. et al. *Vitis vinifera* L. fruit diversity to breed varieties anticipating climate changes. *Front. Plant. Sci.* **9**, 455. <https://doi.org/10.3389/fpls.2018.00455> (2018).
29. Rasouli, M., Mohammadparast, B. & Eyni, M. Study on phenotypic diversity of some grape (*Vitis vinifera* L.) cultivars and genotypes using morphological traits in Hamedan Province. *Appl. Crop Breed.* **2** (2), 241–260 (2014).
30. Riaz, S. et al. Genetic diversity analysis of cultivated and wild grapevine (*Vitis vinifera* L.) accessions around the mediterranean basin and central Asia. *BMC Plant. Biol.* **18**, 137. <https://doi.org/10.1186/s12870-018-1351-0> (2018).
31. Zahedi, M., Rasouli, M., Imani, A., Khademi, O. & Jari, S. K. Evaluation of quantitative, qualitative, and biochemical traits of almond offspring from controlled reciprocal crosses between ‘mamaei’ and ‘marcona’ cultivars. *Erwerbs-Obstbau* **65** (5), 1525–1543. <https://doi.org/10.1007/s10341-023-00900-0> (2023).
32. Beveridge, T. H. J., Girard, B., Kopp, T. & Drover, J. C. G. Yield and composition of grape seed oils extracted by supercritical carbon dioxide and petroleum ether: varietal effects. *J. Agric. Food Chem.* **53**, 1799–1804 (2005).
33. Sabir, A., Unver, A. & Kara, Z. The fatty acid and Tocopherol constituents of the seed oil extracted from 21 grape varieties (*Vitis spp*). *J. Sci. Food Agric.* **92**, 1982–1987 (2012).
34. Ovcharova, T., Zlatanov, M. & Dimitrova, R. Comparative study of seed composition of white and red grape varieties. *Eur. J Food Sci. Technol.* **4**, 37–51 (2016).
35. Wen, X. et al. Characterisation of seed oils from different grape cultivars grown in China. *J. Food Sci. Technol.* **53**, 3129–3136 (2016).
36. Harbeoui, H. et al. Biochemical characterization and antioxidant activity of grape (*Vitis vinifera* L.) seed oils from nine Tunisian varieties. *J. Food Biochem.* **42**, e12595. <https://doi.org/10.1111/jfbc.12595> (2018).
37. Ambaw, Y. D., Abitea, A. G., Olango, T. M. & Molla, M. B. Genetic variation in Ethiopian mustard (*Brassica carinata* A. Braun) germplasm based on seed oil content and fatty acid composition. *Genet. Resour. Crop Evol.* **72**, 3249–3263. <https://doi.org/10.1007/s10722-024-02155-4> (2025).
38. Baydar, N. G., Özkan, G. & Çetin, E. S. Characterization of grape seed and pomace oil extracts. *Grasas Aceites.* **58** (1), 29–33. <https://doi.org/10.3989/gya.2007.v58.i1.5> (2007).
39. To, A. et al. WRINKLED transcription factors orchestrate tissue-specific regulation of fatty acid biosynthesis in Arabidopsis. *Plant. Cell.* **24** (12), 5007–5023. <https://doi.org/10.1105/tpc.112.106120> (2012).
40. Tang, G. et al. Seed-specific expression of AtLEC1 increased oil content and altered fatty acid composition in seeds of peanut (*Arachis hypogaea* L.). *Front. Plant. Sci.* **9**, 260. <https://doi.org/10.3389/fpls.2018.00260> (2018).
41. Shakuri, F., Eghlima, G., Behboudi, H. & Babashpour-Asl, M. Phytochemical variation, phenolic compounds and antioxidant activity of wild populations of Iranian oak. *Sci. Rep.* **15**, 6534. <https://doi.org/10.1038/s41598-025-90991-4> (2025).
42. Pantelic, M. M. et al. Identification and quantification of phenolic compounds in berry skin, pulp, and seeds in 13 grapevine varieties grown in Serbia. *Food Chem.* **211**, 243–252 (2016).
43. Peixoto, C. M. et al. Grape pomace as a source of phenolic compounds and diverse bioactive properties. *Food Chem.* **253**, 132–138 (2018).
44. Krasteva, D., Ivanov, Y., Chengolova, Z. & Godjevargova, T. Antimicrobial potential, antioxidant activity, and phenolic content of grape seed extracts from four grape varieties. *Microorganisms* **11**, 395 (2023).
45. Castro-Lopez, L., Castillo-Sanchez, G., Diaz-Rubio, L. & Cordova-Guerrero, I. Total content of phenols and antioxidant activity of grape skins and seeds Cabernet Sauvignon cultivated in Valle de Guadalupe, Baja California, México. In Proceedings of the BIO Web of Conferences, 42nd World Congress of Vine and Wine, Geneva, Switzerland, 15–19 July; 15, 04001. (2019).
46. Sochorova, L. et al. Health effects of grape seed and skin extracts and their influence on biochemical markers. *Molecules* **25**, 5311. <https://doi.org/10.3390/molecules25225311> (2020).
47. Rockenbach, I. I. et al. Phenolic compounds and antioxidant activity of seed and skin extracts of red grape (*Vitis vinifera* and *Vitis labrusca*) pomace from Brazilian winemaking. *Food Res. Int.* **44**, 897–901 (2011).
48. Guaita, M. & Bosso, A. Polyphenolic characterization of grape skins and seeds of four Italian red cultivars at harvest and fermentative maceration. *Foods* **8**, 395 (2019).
49. Ghouila, Z. et al. Rich extract on total polyphenols and antioxidant activity obtained by conventional and non-conventional methods from ahmeur Bouamer grape seed. *J. Appl. Fundam Sci.* **8**, 692–711 (2016).

50. Moshari-Nasirkandi, A. et al. Chemometrics-based analysis of the phytochemical profile and antioxidant activity of *Salvia* species from Iran. *Sci. Rep.* **14**, 17317. <https://doi.org/10.1038/s41598-024-68421-8> (2024).
51. Pourhosseini, S. H. et al. Diversity of phytochemical components and biological activities in *Zataria multiflora* boiss. (Lamiaceae) populations. *S Afr. J. Bot.* **135**, 148–157. <https://doi.org/10.1016/j.sajb.2020.08.024> (2020).
52. Fernandes, L., Casal, S., Cruz, R., Pereira, J. A. & Ramalhosa, E. Seed oils of ten traditional Portuguese grape varieties with interesting chemical and antioxidant properties. *Food Res. Int.* **50**, 161–166 (2013).
53. Lachman, J. et al. Evaluation of oil content and fatty acid composition in the seed of grapevine varieties. *LWT Food Sci. Technol.* **63**, 620–625 (2015).
54. Nikolidaki, E. K. et al. Sun dried corinthian currant (*Vitis vinifera* L., var. Apyrena) simple sugar profile and macronutrient characterization. *Food Chem.* **221**, 365–372. <https://doi.org/10.1016/j.foodchem.2016.10.070> (2017).
55. Food Data Central (FDC). Available at: <https://fdc.nal.usda.gov/fdc-app.html#/fooddetails/168165/nutrients> (Accessed 1 Dec 2021).
56. Kalili, A. et al. Nutritional composition and bioactive compounds in a local grape variety *Vitis vinifera* L. cultivated in Morocco. *Rocz Panstw Zakl Hig.* **74** (1), 41–48. <https://doi.org/10.32394/rpzh.2023.0244> (2023).
57. Ozcan, M. M. Mineral contents of several grape seeds. *Asian J. Chem.* **22**, 6480–6488 (2010).
58. Vrcek, I. V., Bojic, M., Zuntar, I., Mendas, G. & Medic-Saric, M. Phenol content, antioxidant activity and metal composition of Croatian wines deriving from organically and conventionally grown grapes. *Food Chem.* **124**, 354–361 (2011).
59. Harmankaya, M., Özcan, M. M. & Gezgin, S. Variation of heavy metal and micro and macro element concentrations of bread and durum wheats and their relationship in grain of Turkish wheat cultivars. *Environ. Monit. Assess.* **184**, 5511–5521. <https://doi.org/10.1007/s10661-011-2357-3> (2012).
60. Grzegorzczak-Karolak, I., Kuźma, L. & Wysokińska, H. Study on the chemical composition and antioxidant activity of extracts from shoot culture and regenerated plants of *Scutellaria altissima* L. *Acta Physiol. Plant.* **37**, 1–9. <https://doi.org/10.1007/s11738-014-1736-0> (2015).
61. Iaccarino, N. et al. Impact of phytosterols on liver and distal colon metabolome in experimental murine colitis model: an explorative study. *J. Enzyme Inhib. Med. Chem.* **34**, 1041. <https://doi.org/10.1080/14756366.2019.1611802> (2019).
62. Granato, D., Santos, J. S., Escher, G. B., Ferreira, B. L. & Maggio, R. M. Use of principal component analysis (PCA) and hierarchical cluster analysis (HCA) for multivariate association between bioactive compounds and functional properties in foods: A critical perspective. *Trends Food Sci. Technol.* **72**, 83–90. <https://doi.org/10.1016/j.tifs.2017.12.006> (2018).
63. Bakhtiar, Z., Hassandokht, M., Fallah, M., Rezadoost, H. & Mirjalili, M. H. Oil content, fatty acids profile, phenolic compounds and biological activity of the seeds from wild *Medicago* species growing in Iran. *Chem. Biol. Technol. Agric.* **12**, 40. <https://doi.org/10.1186/s40538-025-00758-2> (2025).

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Author contributions

FP: lab work, analysis data; GE: methodology, sample collection, conceptualization, supervision, data curation, data analysis and writing-original draft, DK: reviewing, and editing; HE: methodology and editing; MHM: methodology, conceptualization, data curation, reviewing, and editing.

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Declarations

Competing interests

The authors declare no competing interests.

Declaration of competing interest

The authors declare no conflict of interest.

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