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ORIGINAL PAPER

QbD-based chromatographic phenolic profiling of lentisk and apricot kernel oils with defined chemical composition and antioxidant properties

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Abstract

Lentisk (L) and apricot kernel (AKO) oils were characterized according to their phenolic, non-polar and antioxidant profiles. A quality by design (QbD) principles approach optimized phenolic analysis of samples through liquid chromatography coupled to diode array and mass spectrometry (LC-DAD-MS) analyses, firstly reporting catechol in L and vanillin and *p*-hydroxybenzoic acid in AKO oils. Non-polar fractions of L and AKO was featured by LC-DAD-MS analysis, determining 20 and 14 acylglycerols, respectively, most of them di- and tri-unsaturated acylglycerols. Moreover, analysis of fatty acids, tocopherols and phytosterols by GC-MS research unveiled high contents of unsaturated fatty acids (67% and 89% total content in L and AKO, respectively), mainly oleic, and relevant amounts of tocopherols (384 vs. 471 mg/kg) and physterols (1852 vs. 3511 mg/kg) in L and AKO samples, respectively. Spectrophotometric assays determined low carotenoid (2.18 vs. 0.18 mg luteolin/kg) and chlorophyll (1.51 vs. 0.08 mg pheophytine/kg) contents in L and AKO samples, but demonstrated their high antioxidant/antiradical capacity values. High quality nutritional value of lentisk and apricot kernel oils together to their relevant antioxidant/antiradical properties may favor their use as source of natural bioactive compounds by food and pharmaceutical industries, favoring circular economy through the reuse of agricultural by-products.

Keywords Lentisk oil · Apricot kernel oil · Quality-by-design · Optimized phenolic analysis · Antioxidant properties · Circular economy

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Introduction

Rising demand for edible oils driven by population growth and lifestyle changes necessitates the exploration of sustainable alternatives. Natural bioactive compounds from agricultural by-products represent a sustainable and affordable solution [1, 2]. Finding lentisk (*Pistacia lentiscus* L.) fruit drupes and apricot (Prunus armeniaca L.) kernels as interesting non-traditional alternative sources of edible oils. However, little is known about lipid and phenolic profiles of such abundant vegetal material. Lentisk is a wild evergreen shrub widely distributed throughout Mediterranean woodlands, maquis and garrigues traditionally valued for the aromatic and medicinal properties of its resins and leaves [3]. Lentisk essential oils and resin, known as mastic gum, showed promising antioxidant, antimicrobial, cardioprotective, and anti-ulcer activities [4].

Lentisk fruit oil was traditionally consumed in North Africa for its culinary and hepatoprotective properties, highlighting recent studies its richness in unsaturated fatty acids and minor bioactive antioxidant compounds [5]. Worldwide consumption of apricot fruits (fresh and processed) generates substantial by-products such as kernels, that are commonly used as a natural source of bioactive compounds (lipids, proteins and phytochemicals) by food, pharmaceutic and cosmetic industries [6–8]. In the particular case of Algeria, lentisk fruit is highly appreciated for its ancient medicinal properties, in contrast to apricot kernels that are mostly discarded as industry waste.

Apricot kernel oil (AKO) is valued for its high content of unsaturated fatty acids (mainly oleic acid), as well as, phenolics, carotenoids, tocopherols and phytosterols. Botanical variety, geographical origin, fruit maturity and extraction method are key factors influencing lipid profiling of AKO [7], determining its nutritional and industrial value. Surprisingly, few studies scarcely approached in detail chemical profiling, antioxidant capacity and industrial interest of lentisk fruit and apricot kernel oils [8].

This study investigates the phenolic profile of the polar fractions extracted from lentisk and apricot kernel oil using a chromatographic optimization software based on quality by design (QbD) principles [9]. The QbD approach include defining a target, identifying critical attributes, and creating a flexible Design-of-Experiments (DoE), which is used to simultaneously evaluate multiple variables and their interactions [10]. In this study, the phenolic profile of the polar fraction extracted from AKO and L was performed by RP-HPLC, whose separation parameters were determined by DryLab® (Molnár Institute, Berlin, Germany), which is a chromatographic optimization software based on analytical quality by design (QbD) principles [11]. This software allows to predict chromatographic conditions, such as column temperature, mobile phase composition, and gradient profile, requested to make predefined resolution thresholds of selected analytes in the shortest analysis time. DryLab® requires the execution of a limited number of experiments (twelve in this study) to generate color-coded resolution maps, representing the dependency of sample resolution on selected Design Space parameters, which allows the rapid in-silico optimization of HPLC methods, in a fraction of the time required by traditional one-parameter-at-a-time methods.

Hence, this study provides an optimized analytical approach and contributes to the characterization of these oils. Moreover, it proposes an affordable multidisciplinary analytical pipeline to investigate in detail composition of polar and non-polar fractions of lentisk fruit and apricot kernel oils. Polar metabolites were approached by a QbD optimized reverse-phase high-pressure liquid chromatography coupled to diode array and mass spectrometry (RP-HPLC-DAD-MS) analysis and gas chromatography mass spectrometry (GC-MS) research unveiled the lipid profile of samples. There were elucidated the phenolic, fatty acid, triacylglycerol, tocopherol and phytosterol profiles in samples assayed, establishing a solid foundation for reliability is chemical analysis of foodstuffs. Complementary assays powered by traditional methodologies addressing total phenolic and chlorophyll/carotenoid contents, as well as, oxidative stability and antioxidant properties of extracts studied were carried out for their complete characterization. The results of this research promotes interest about lentisk fruit and apricot kernel oils for industrial applications, favoring economic development of rural Algerian areas and sustainable activities addressing reuse of food industry by-products.

Materials and methods

Chemicals and reagents

Commercial standards of the phenolic compounds gallic acid, catechol, hydroxytyrosol, tyrosol, protocatechuic acid, *p*-hydroxybenzoic acid, *p*-hydroxyphenylacetic acid, vanillic acid, syringic acid, *p*-coumaric acid, sinapic acid, ferulic acid, catechin, vanillin, caffeic acid, chlorogenic acid, epicatechin, and cinnamic acid were obtained from Sigma-Aldrich (Milan, Italy). Analytical-reagent grade formic acid (FA), n-hexane, LC-MS grade methanol, ethanol (EtOH), isopropanol (IPA) and ultrapure water were purchased from Carlo Erba Reagents (Milan, Italy). Analytical reagent grade methanol, sodium carbonate, and calcium chloride were purchased from Panreac (Barcelona, Spain). Butylated hydroxytoluene (BHT) was purchased from Acros (Hampton, NH, USA). Folin–Ciocâlteu reagent, 2,20-azino-bis

(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS), methyl undecanoate and ascorbic acid, *N*,*O*-Bis(trimethylsilyl)trifluoroacetamide (BSTFA), pyridine, 2,2-diphenyl-1-picrylhydrazyl (DPPH$^{\bullet}$), β-carotene, potassium hexacyanoferrate [$K_3Fe(CN)_6$], trichloroacetic acid, and 3-*tert*-butyl-4-hydroxyanisole (BHA) were purchased from Sigma-Aldrich (St. Louis, MO, USA).

Oil samples

Freshly made lentisk edible oil, produced by a traditional homemade cold pressing extraction process practiced in rural areas of Algeria [12] was purchased from a local store in the province of Jijel, situated in Northeast Algeria (314 km East of Algiers, 9 m above the sea level, 36° 49′ 13″ N; 5° 46′ 00″ E). An in-house Apricot kernel oil was cold-extracted in our laboratories using intact apricot kernels (sweet variety), which were generously donated by N'Gaous Conserves SPA (Barika, Batna, Algeria). Kernels were released by manual crushing of apricot pits, featuring their separation from shells in a 10% sodium chloride brine solution, washed with tap water and dried at ambient conditions. Oil extraction was carried out using a KEK-P0101 hydraulic press (EGON Keller, Germany). Lentisk and apricot kernel oils were stored in amber glass flasks at 4 °C until use.

Extraction of the polar fraction

It was carried out in a glass flask by mixing 10 g of oil sample with 10 mL of 80:20 MeOH/water (v/v) solution, vigorously vortexed and centrifuged at 4000 rpm for 15 min. The process was repeated twice, combining all three recoveries (30 mL aprox) and dried in a rotary evaporator at 40 °C. The residue was re-dissolved in 3 mL of 80:20 MeOH/water (v/v) and polar extracts were stored in a glass flask at − 80 °C until analysis.

Chromatographic characterization of the extracted phenolic compounds in polar extracts supported by QbD approach

The chromatographic profiling and characterization of the phenolic compounds occurring in *Pistacia lentiscus* fruit and apricot kernel oils was carried out by RP-HPLC, employing a method developed by a modeling software based on Quality-by-Design principles (DryLa4®, Molnár-Institute, Berlin, Germany), which was used to predict the optimized gradient profile, column temperature, and pH of the aqueous component of the mobile phase, selected as critical parameters for gradient RP-HPLC separations of phenolic compounds.

Founded on former experiences and preliminary experiments, a 2 mm internal diameter (i.d.) Polaris C18-A column, which is specially designed for high-throughput analysis of polar compounds, was chosen to perform the chromatographic profiling, whereas water containing formic acid and methanol were selected as the starting eluent and the gradient former, respectively. The narrow-bore Polaris C18-A column (150 × 2.0 mm i.d., 5 µm particle size), coupled to a C18 (30 × 2 mm i.d., 5 µmparticle size) guard cartridge, was provided by Agilent (Milan, Italy). The column was eluted by a multi-segment gradient of increasing concentration of methanol in the hydro-organic mobile phase at pH 2.5 with formic acid, according to the following experimental conditions, which were optimized by DryLab4®. Column temperature, 25 °C; mobile phase flow rate, 0.2 mL/min; gradient elution program: 15 min linear gradient from 2 to 5% (v/v) methanol, followed by 30 min linear gradient from 5 to 20% (v/v) methanol, 10 min linear gradient from 20 to 34% (v/v) methanol, 3 min linear gradient from 34 to 42% (v/v) methanol, 12 min linear gradient from 42 to 55% (v/v) methanol, 8 min linear gradient from 55 to 80% (v/v) methanol, and subsequent 7 min isocratic elution with 80% (v/v) methanol to ensure complete elution of any strongly retained components of the injected samples. At the end of the gradient elution program described above, the composition of the mobile phase was brought to the initial conditions in 1 min, and the column was equilibrated for 20 min, before the next injection.

The optimized method was validated according to the Eurachem Guide [13]. Accordingly, sensitivity was assessed by determining the limit of detetion (LOD) for each expected analyte, precision was evaluated by intraday and interday repeatability of retention times and peak areas of phenolic compounds analyzed in triplicate during the same day and over three consecutive days, and the confirmation of identity was performed by ESI/MS detection in the selected ion monitoring (SIM) mode.

The HPLC instrument was a Shimadzu (Milan, Italy) Model LC-10A_{VP} system, consisting of a SCL-10A_{VP} system controller, two LC-10AD_{VP} solvent delivery units, a CTO-10AS_{VP} column oven, a DGU-14 A on-line vacuum membrane degasser, and an SPD-M10A spectrophotometric diode array (PDA) detector. The UV spectra of eluted samples were recorded in the 210–400 nm wavelength range and the chromatograms were acquired at 280 nm. A Rheodyne (Cotati, CA, USA) Model 8125 semi-micro valve with a 5 µL loop was employed for sample injection.

To confirm peak identification, the instrument was hyphenated with a Shimadzu single quadrupole Model LCMS-2010 mass spectrometer equipped with an electrospray ionization source (ESI), which was operated in the negative ionization mode at the following conditions:

nebulizing gas nitrogen at flow rate of 4.5 L/min; temperature of block heater, 200 °C; temperature of the curved desolvation line (CDL), 225 °C; probe voltage − 3.5 V; CDL voltage, 25 V; Q-array voltages, 0, − 35, − 360 V; Q-array RF, 150. The column effluent was first passed through the PDA detector before being introduced into the ESI interface without flow rate splitting. Instrument control and data acquisition and processing were performed by either the Shimadzu Class VP 5.6 HPLC data system or the Shimadzu LCMS Solution software, both running on a personal computer (Gigabyte, Milan, Italy). All solutions used as eluents were degassed by sonication before use and the pH of the aqueous component of the mobile phase was measured with a glass electrode Model 52-02 and Model Basic 20 pH-Meter, both from Crison (Alella, Spain).

Analysis of fatty acid methyl esters (FAME) of oils

It was performed according to a previously described method [14]. Briefly, 1 mL of 5% sulfuric acid methanolic solution was added to oil samples (5–10 mg), mixed with 200 µL of the internal standard toluene solution (IS, methyl undecanoate) and heated at 90 °C for 1 h. Then, 100 µL of water were added and FAMES formed were extracted with 400 µL of n-hexane and they were subsequently determined by an Agilent 7000 GC-MS system (Agilent Technologies, Palo Alto, CA, USA) loading a 25 m x 0.25 mm i.d. (0.2 µm thickness) 4MPy ionic liquid custom column (N-Propyl-4-methylpyridinium bistriflimide) described by Shashkov et al. [15]. Separation temperature ramp started at 90 °C (held for 3 min) finishing at 230 °C at a rate of 8 °C/min with a final hold time of 5 min. Other analytical conditions were: helium as carrier gas at a flow rate of 1 mL/min; injector operated in split mode (1:30) at 250 °C; transfer temperature set at 235 °C. The mass spectrometer operated in electron impact (EI) mode at 70 eV with a mass scan range of 40–400 *m/z*. Automated processing of GC-MS data was carried out by a program loading the 2011 NIST spectral library for tentative identification of components (National Institute of Standards and Technology, Gaithersburg, MD, USA). Results were appropriately normalized according to peak area ratios of matched FAMES with the IS for relative quantification.

Analysis of triacylglycerols (TAGs) of oils

Oil samples were analyzed using a Shimadzu HPLC-MS 2020 system (Shimadzu Co., Kyoto, Japan) equipped with a quaternary pump, vacuum degasser, thermostatic autosampler, and a single-quadrupole mass detector equipped with an electrospray ionization (ESI) interface operating in positive mode. Separation of TAGs was achieved as reported in Official Methods and Recommended Practices of the American Oil Chemists' Society [16] using a 250 mm × 4.6 mm; 5 µm particle size PerfectSil Target ODS-3 column (Agilent Technologies) and 70:30 (v/v) methanol/isopropanol as the mobile phase under isocratic conditions elution mode at 1 mL min^{-1}. Injection volume and column temperature were 5 µL and 50 °C, respectively. Mass spectrometry analysis was performed in positive ionization mode with ESI interface (mass scan range, 100–1000 *m/z*). Mass spectrometry analysis was performed considering 100–1000 *m/z* range using nitrogen as nitrogen was used as nebulizing and drying gas at flow rate of 1.5 L/min and 15 L/min, respectively. The LC-MS system and automated data processing were controlled by a personal computer loading the Shimadzu Lab Solution v. 5.53 program.

Analysis of tocopherols and phytosterols in oils

They were determined according to Du and Ahn 2002 [17] in where 2 mL of a 10% (w/v) KOH-ethanol solution and 0.5 mL of 20% (w/v) ascorbic acid solution in EtOH were added to oil samples (100 mg), gently mixed and heated at 60 °C for 1 h and cooled at room temperature. Two milliliters of water and 2 mL of n-hexane were added and centrifuged at 14,000 rpm for 3 min, collecting the upper organic phase containing tocopherols and phytosterols. The extraction was repeated once by adding 2 mL water and 2 mL n-hexane. The resultant unified organic solution was spiked with the internal standard (50 µg/mL tocopherol acetate). Water was removed from sample with sodium sulfate, achieving final desiccation of samples by argon purging. The residue was derivatized by adding 50 µL BSTFA (*N*,*O*-Bis(trimethylsilyl)trifluoroacetamide) and 100 µL of pyridine and heating at 60 °C for 1 h. The analysis of tocopherols and phytosterols was carried out using the same GC-MS system described above but considering an Agilent 30 m × 0.25 mm i. d. × 0.25 µm thickness HP-5MS column (Agilent Technologies, Palo Alto, CA, USA). Oven temperature was programmed from 140 °C (held for 3 min) to 300 °C at 10 °C/min. Helium was used as carrier gas at 1.2 mL/min flow-rate, the injector operated in split (1:5) mode at 300 °C, and the MS detection was performed in EI mode at 70 eV with mass scan range 40–600 *m/z*. Automated processing of GC-MS data was performed as for FAME analysis. Results were normalized according to peak area ratios of target analytes with the IS for relative quantification, calculating sensitivity coefficients by analyzing a mixture of tocopherol standards.

Spectrophotometric assays

Determination of the total phenolic content (TPC) in polar extracts

TPC was determined by the Folin-Ciocâlteu method, following the general methodology previously described by Silva et al. [18]. Briefly, 60 µL of water and 15 µL of Folin-Ciocâlteu reagent were added to 15 µL of the extracted polar fraction and gently mixed for 5 min. Then, 150 µL of a 7% sodium carbonate (w/v) aqueous solution were added and the mixture was incubated for 60 min in darkness. The absorbance at 750 nm was measured using a Microplate Reader (Synergy HTX microplate reader, Bio Tek, Winooski, USA) with water as blank. Samples were analyzed in triplicate and TPC was quantified employing a calibration graph constructed using gallic acid as the external standard. The results were expressed in mg of gallic acid equivalents per kg (mg_{GAE}/kg) of oil.

Determination of chlorophylls and carotenoids in oils

They were determined according to the method described by Minguez-Mosquera et al. [19]. Briefly, 0.2 g of oil was dissolved in 2 mL of cyclohexane and the absorbance was measured at 670 nm and at 470 nm for chlorophylls and carotenoids, respectively, using a Jenway Genova Plus Life spectrophotometer (Science, Bibby Scientific Ltd., Stone, Staffordshire, UK). The content of chlorophylls and carotenoids was calculated using the following equations:

$$\text{Chlorophylls (mg/kg of oil)} = (A670 \times 10^6) / (613 \times 100 \times d); \quad ((i))$$

$$\text{Carotenoids (mg/kg of oil)} = (A470 \times 10^6) / (2000 \times 100 \times d), \quad ((ii))$$

where A was the absorbance measured at the selected wavelength (either 670–470 nm) and d was the light path of the detection cell (1 cm).

Oxidative stability

Oxidative stability index of oils

Induction time was measured to determine the oxidative stability index of oils, as previously described by Chikhoune et al. [20], according to the ISO 6886 standard method [21], using a Metrohm Model 743 Rancimat instrument (Herisau, Switzerland). Briefly, a dry air stream of 10 Lh^{-1} was bubbled into the reaction vessel containing 3 g of oil maintained at 98 °C. The detector chamber containing deionized water measured and recorded volatile oxidation products that caused the changes in conductivity, determining the IP from the kinetics of conductivity versus time. Results were expressed as the time (in h) for the samples to reach their endpoints with a maximum of 48 h of assaying period.

Determination of quality parameters (peroxide value and free acidity)

They were determined according to ISO International Standard (1998) [22].

Determination of antioxidant activities in polar extracts

Free radical-scavenging activity determined by DPPH· method

The antioxidant activity was determined as described by Neto et al. [23], with slight modifications. Briefly, 100 µL of the methanol-water extract was mixed with 100 µL of a 60 µM 2,2-diphenyl-1-picrylhydrazyl (DPPH·) ethanolic solution. After 30 min of incubation, the absorbance was measured at 517 nm using a Microplate Reader (Synergy HTX microplate reader, Bio Tek, Winooski, USA) and ascorbic acid as the standard. Extract concentration providing 50% inhibition (IC_{50}) was determined and results expressed as mg equivalents of ascorbic acid per milliliter of oil.

Expression of results as the antiradical activity per milliliter of oil was chosen to directly correlate the volume of lipid matrix of samples used with their antiradical capacity, ensuring internal consistency with the experimental protocol.

Radical scavenging activity against the radical $ABTS^{\cdot+}$

It was determined using the method described by Neto et al. [23]. Briefly, $ABTS^{\cdot+}$ was generated by the oxidation of ABTS (7 mM) with potassium persulfate (2.45 mM) in darkness for 12–16 h. Prior to assay, the $ABTS^{\cdot+}$ stock solution was diluted with ethanol to achieve a final absorbance of 0.700 ± 0.020 at 734 nm (assay solution). Then, 50 µL of polar extracts were mixed with 250 µL of the $ABTS^{\cdot+}$ assay solution and the absorbance was measured after 20 min at 734 nm on a micro plate reader. The IC_{50} was evaluated and results expressed as mg Trolox equivalents per mL of oil.

β-carotene bleaching assay

Ability of polar fractions from oils assayed to inhibit bleaching of β-carotene linoleic acid emulsion was determined according to Silva et al. [18] with minor modification. Briefly, an emulsion was prepared by mixing 2 mg β-carotene dissolved in 1 mL chloroform, 50 mg of linoleic

acid and 1 g of tween 80. Chloroform was evaporated using a water bath at 50 °C and distilled water (100 mL) was then added and the reaction solution was obtained after vigorous shaking, transferring 800 µL of emulsion aliquots of this emulsion to glass tubes containing 200 µL of polar sample extracts. Samples were vortexed and incubated at 50 °C in a water bath. A blank emulsion was prepared without β-carotene whereas a control sample was prepared replacing the assayed methanolic fractions with a 8:2 water/MeOH (v/v) solution. Absorbance was recorded at 470 nm immediately after sample preparation (t = 0 min) and after 120 min (t = 120 min) using a Microplate Reader and 3-tert-butyl-4-hydroxyanisole (BHA) was used as the standard. The $IC_{50}$was calculated and the results are expressed in mg equivalents of BHA per milliliter of sample extract.

Determination of the ferric reducing antioxidant power (FRAP)

FRAP of the methanol-water extract was carried out as described by Neto et al. [23]. Briefly, 200 µL of samples were mixed with 200 µL of 200 mM phosphate buffer (pH 6.6) and 200 µL of potassium hexacyanoferrate [$K_3Fe(CN)_6$] aqueous solutions (1%, w/v). After 20 min of incubation at 50 °C, 200 µL of 4% (w/v) trichloroacetic acid in water was added and vigorously stirred. Then, the UV absorbance was measured at 690 nm and 3-tert-butyl-4-hydroxyanisole (BHA) was used as the standard.

For the FRAP assay, the reported EC_{50} values correspond to the extract concentration required to reach 50% of the maximal reducing capacity measured under the experimental conditions.

Statistical analysis

All determinations were carried out in triplicate and the results were expressed as mean values ± standard deviation, calculated using Excel spread sheet software (Microsoft Office, USA), which was also used to perform linear regression analysis for the construction of calibration graphs.

Results and discussion

Phenolic profiling

Many phenolic compounds among those occurring in *Pistacia lentiscus* and apricot kernel oils are phenolic acids, either derived from cinnamic or benzoic acid [24–26]. The RP-HPLC method employed in this study for their separation was developed by DryLab®, which is a chromatographic optimization software based on analytical quality by design (QbD) principles [27]. This software allows to predict gradient profile, column temperature, and pH of the aqueous component of the mobile phase, requested to obtain the baseline separation of all components of a given sample mixture in the shortest analysis time.

Twelve experiments were carried out to conduct the design of experiment (DoE) depicted in panel A of Fig. 1. These experiments consisted in separating a mixture of commercially available phenolic standards, selected among

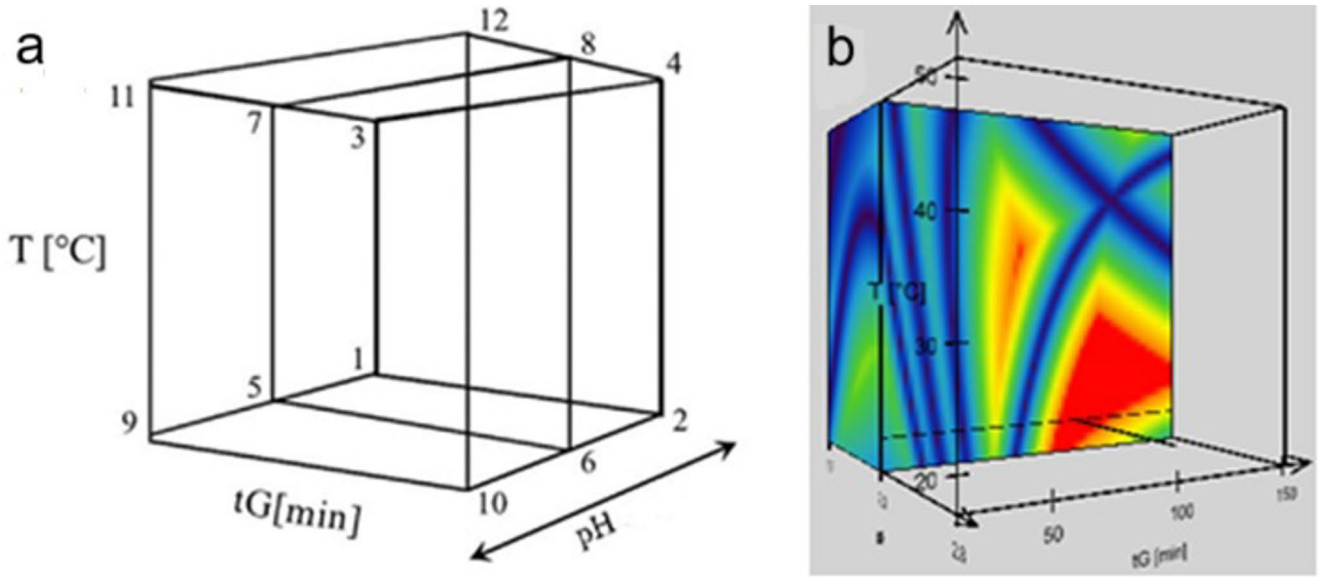


Fig. 1 Design of experiments (DoE) used in this study (**a**) to obtain a three-dimensional resolution map (**b**) showing the influence of gradient time (t_G), pH of aqueous component of the mobile phase (pH), and temperature of the HPLC column (T°C) on the resolution of phenolic compounds occurring in *Pistacia lentiscus* oil and apricot kernel oil

those previously identified in *Pistacia lentiscus* and apricot kernel oils [24–26], plus the addition of catechol that we have identified in Algerian L by HPLC-MS. Retention times and area of individual peaks from the above experiments were used as inputs for DryLab® analysis. Experiments 1,3,5,7, 9, and 11 of the planned DoE (see panel A, Fig. 1) were carried out by running 30 min linear gradients, whereas experiments 2, 4, 6, 8, 10, and 12 by running 90 min linear gradients. All gradients were run from 2 to 62% (v/v) methanol (eluent B) in water containing formic acid at three different pH values (eluent A). Accordingly, the pH of eluent A employed in experiments 1, 2, 3, and 4 was pH 1.8, in experiments 5, 6, 7, and 8 was pH 2.3, and in experiments 9, 10, 11, and 12 was pH 2.8. The temperature of the column was either 20 °C (experiments 1, 2, 5, 6, 9, and 10) or 50 °C (experiments 3, 4, 7, 8, 11, and 12).

The elaboration by DryLab® software of the retention times and peak areas of the individual phenolic compounds, separated according to DoE, generated the 3-D resolution model depicted in panel B of Fig. 1, which is referred to as "3D resolution map". The "red space" of the 3D resolution map indicated the predicted values of column temperature, pH of eluent A and gradient time requested for the baseline separation of all selected phenolic compounds. The elaboration by DryLab® software of the above data generated simulated chromatograms corresponding to all possible combinations of column temperature, pH of eluent A, and steepness and duration of the elution gradient, which included those of the optimized HPLC method described in the Experimental section, allowing the baseline separation of all phenolic compounds comprising the mixture of authentic standards shown in Fig. 2. The method was validated as described in the Experimental session. For all tested standard phenolic compounds, the limit of detection (LOD) at 280 nm was lower than 0.05 µg/mL, while the relative standard deviation (RSD) of their retention times and peak areas, assed during the same day and over three consecutive days, were lower than 0.7% and 2.0%, respectively, indicative of the reliability of the optimized qualitative analytical method [13].

The optimized RP-HPLC method was then applied to explore the phenolic profile of the polar fraction extracted from Algerian lentisk and apricot kernel oil, obtaining the well resolved chromatograms displayed in Figs. 3 and 4, respectively. The identification of the separated phenolic compounds was performed based on the comparison of their retention times and UV spectra, acquired in the 210–400 nm wavelength range, with those of the authentic standards of Fig. 2. The identity of each chromatographic peak was further confirmed by ESI/MS detection in the selected ion monitoring (SIM) mode, which resulted in the appearance of signals at *m*/*z* values corresponding to the main negative ion of the searched compounds corresponding to the peaks

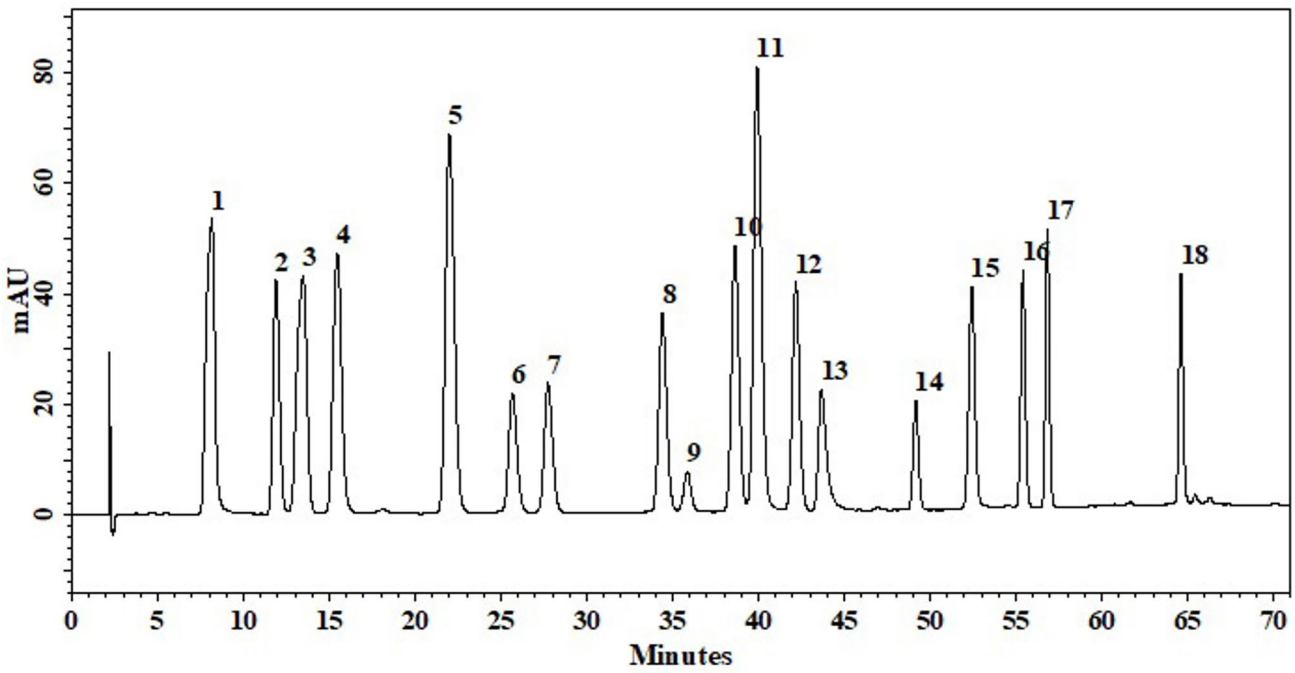


Fig. 2 Standard phenolic compounds separated by the DryLa4® optimized RP-HPLC method described in Sect. "Materials and Methods". Peak identification, (1) gallic acid, (2) catechol, (3) hydroxytyrosol, (4) protocatechuic acid, (5) tyrosol, (6) *p*-hydroxybenzoic acid, (7) *p*-hydroxyphenylacetic acid, (8) vannilic acid, (9) catechin, (10) vanillin, (11) caffeic acid, (12) syringic acid, (13) chlorogenic acid, (14) epicatechin, (15) *p*-coumaric acid, (16) ferulic acid, (17) sinapic acid, (18) cinnamic acid

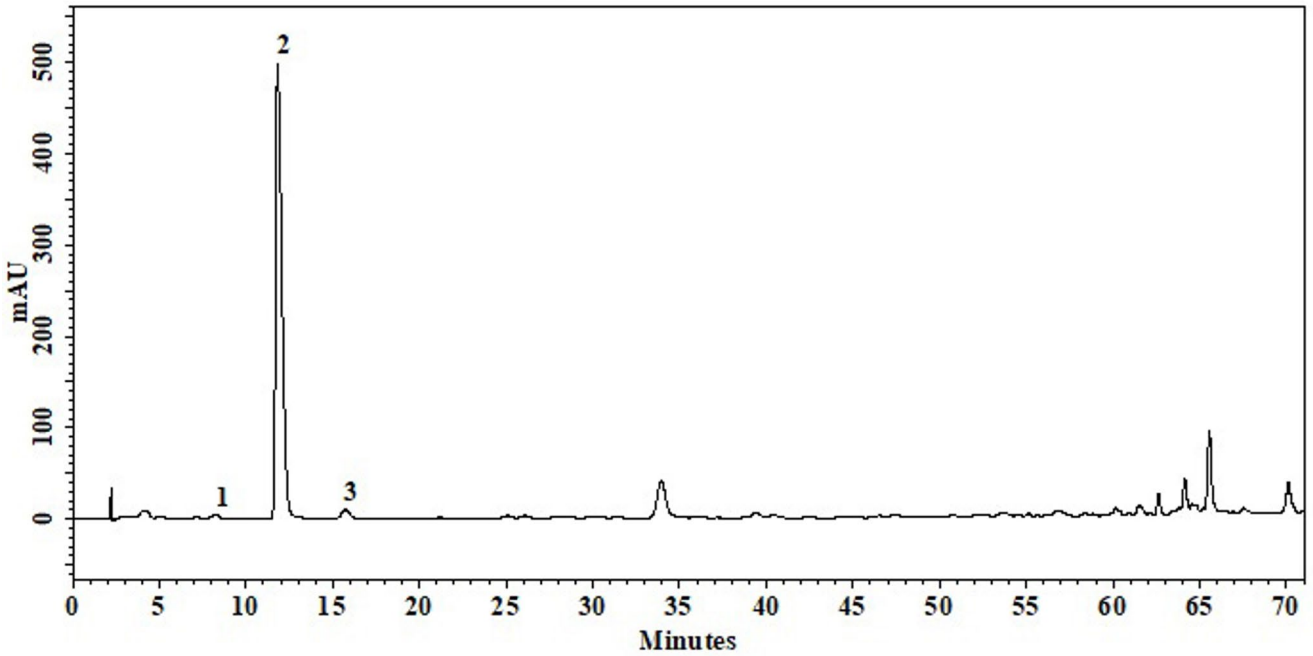


Fig. 3 Phenolic profile of polar fraction extracted from Algerian lentisk oil. Peak identification, (1) gallic acid; (2) catechol; (3) protocatechuic acid. HPLC column and experimental condition as in Fig. 2

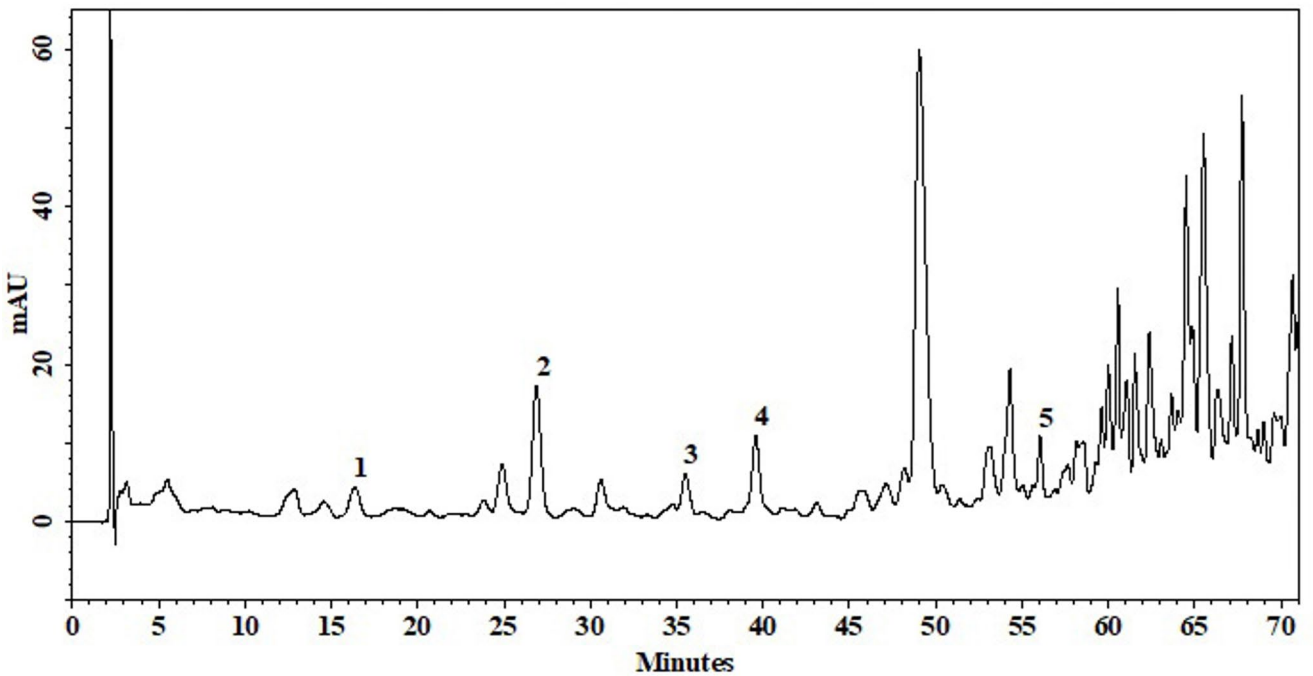


Fig. 4 Phenolic profile of polar fraction extracted from Algerian apricot kernel (AKO) oil. Peak identification, (1) protocatechuic acid; (2) p-hydroxybenzoic acid; (3) vanillic acid; (4) vanillin; (5) ferulic acid. HPLC column and experimental condition as in Fig. 2

of the PDA chromatograms, whose structures are displayed in Fig. 5.

Previous investigations have shown significant differences in the phenolic profile of the polar fraction extracted from either *Pistacia lentiscus* oil or apricot kernel oil of diverse origin, most of which, however, displayed the predominance of phenolic acids [12, 24–26, 28]. Similar results were also obtained in this study, which produced phenolic profiles slightly comparable with those reported in literature. The identified components of the polar fraction

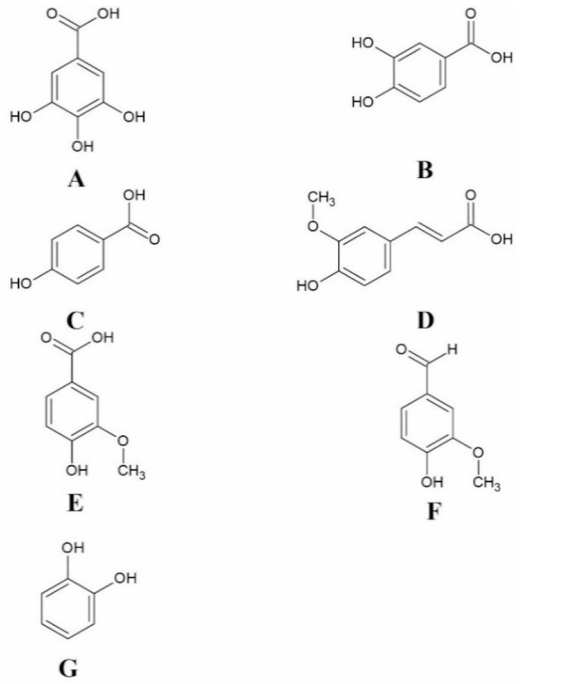


Fig. 5 Chemical structure of phenolic compounds identified in L and AKO. A, gallic acid; B, ferulic acid, C, p-hydroxybenzoic acid; D, protocatechuic acid; E, vanillic acid; F, vanillin; G, catechol

extracted from *Pistacia lentiscus* oil were gallic acid, catechol, and protocatechuic acid (see Fig. 3). Catechol, which has previously reported in edible and cosmetic argan oils by Rojas et al. [29] and in apricot kernels [30], was identified in the polar fraction extracted from *Pistacia lentiscus* oil for the first time in this study. Gallic acid and protocatechuic acid were earlier identified by Siano et al. in the polar fractions extracted from Italian lentisk oil [24], whereas protocatechuic acid was recently reported as the only phenolic compound occurring in an Algerian *Pistacia lentiscus* seed oil [12].

Our investigation allowed the identification in AKO of protocatechuic acid, p-hydroxybenzoic acid, vanillic acid, vanillin, and ferulic acid (see Fig. 5). Vanillin and p-hydroxybenzoic acid were identified for the first time in this study, whereas protocatechuic acid, ferulic acid and vanillic acid, together with other phenolic compounds, have already been reported in the polar fractions extracted from apricot kernel oils produced in Turkey by cold press and Soxhlet extraction [26]. Moreover, protocatechuic acid and ferulic acid were identified, in addition to gallic acid, amygdalin and dimethoxyflavone, in ethyl acetate and ethanol fractions obtained by subsequent reflux hot extraction of Tunisian apricot kernels, using, in the order, dichloromethane, chloroform, ethyl acetate and ethanol [28].

Hence, the results of our investigation are consistent with the reported prevalence of phenolic acids in the polar fractions extracted from other *Pistacia lentiscus* and apricot kernel oils. Also confirmed are the expected differences in their chemical composition, which is well known to be affected by botanical and geographical origin of the plant, the process of oil extraction and condition and time of oil storage, as well as by the methods employed to extract and analyze the phenolic compounds.

Table 1 Fatty acid composition (FAC) of lentisk (P. lentiscus) oil (L) and apricot kernel (Prunus armeniaca) oils (AKO)

FAC	L (% ±SD[a])	AKO (% ±SD[a])
C16:0	31.88±0.08	9.45±0.01
C16:1	3.40±0.14	1,27±0.01
C18:0	1.38±0.01	1.16±0.01
C18:1 (9-octadecenoic acid)	38.94±0.10	61.86±2.61
C18:1 (7-octadeceno	2.00±0.01	n.d.
C18:2	20.64±0.33	26.26±2.62
C18:3	1.78±0.01	n.d.
SFA	33.26±0.08	10.62±0.02
MUFA	44.34±0.25	63.14±2.61
PUFA	22.41±0.33	26.26±2.62
UFA	66.75±0.08	89.39±0.88
UFA/SFA	2.01±0.01	8.42±0.07

SFA saturated fatty oil, *MUFA* monounsaturated fatty acids, *PUFA* polyunsaturated fatty acids, *UFA* unsaturated fatty acids

[a]% ± standard deviation

Fatty acid profile of lentisk and apricot kernel oils

Table 1 shows the results of fatty acid (FA) analysis (% of total GC-MS peak areas of detected signals). The percentage of saturated fatty acid (SFA) detected in AKO was 10.62%, composed of palmitic (C16:0) and stearic acid (C18:0), while the amount of monounsaturated fatty acids (MUFA) was 63.14% (consisting of oleic (9-octadecenoic, C18:1) and palmitoleic acid (C16:1). Linoleic acid (C18:2) was the only detected polyunsaturated fatty acid (PUFA), accounting for 26.26% of total peak area. Hence, the whole amount of unsaturated fatty acids (UFA), which are renowned for their nutritional value and health promoting properties, was 89.39% and the ratio of unsaturated fatty acid to saturated fatty acid (UFA/SFA) was 8.42. The most abundant FAs were oleic acid (61.86%), followed by linoleic (26.26%) and palmitic acid (9.45%). The less abundant ones were palmitoleic (1,27%) and stearic acid (1.16%). No evidences of 7-Octadecanoic acid (C18:1) and linolenic acid (C18:3) were found in AKO.

Profiles obtained in AKO were similar to those previously reported in where there was also explained relevance of apricot genotype, ripening stage and extraction methods greatly affects FA profile of this cultivar [31–33]. Compared to results achieved in this research regarding Algerian AKO, Pavlović et al. [31] demonstrated how FA profile from cold pressed extracts of sweet Hungarian apricots was slightly

higher for oleic (62.73%) and linoleic acid (29.18%), lower for palmitic acid (5.79%) and almost identical for stearic acid (1.24%). These authors also stated that FA composition of same AKOs obtained from the same kernels of sweet apricots by supercritical carbon dioxide extraction resulted in a lower content of oleic acid (57.33%) and significantly higher percentage of linoleic acid (33.81%), not varying palmitic (5.93%) and stearic (1.46%) contents that were similar than values found in current research. In this line and considering other apricot cultivars, higher levels (69.79–71.43% range) of oleic acid were found in samples of AKO produced by Soxhlet extraction with n-hexane from the kernels of five cultivars of apricot grown in Southeastern Poland with lower contents of linoleic (22.41%) and palmitic acids (3.17%) and similar stearic results (1.40%) [34].

In lentisk oil, predominant FAs were oleic acid (38.94%), palmitic acid (31.88%) and linoleic acid (20.64%), whereas the lowest contents were found for 7-octadecenoic (2.00%), linolenic (1.78%) and stearic acid (1.38%). The levels of SFA, MUFA, PUFA, and UFA were 33.26, 44.34, 22.41, and 66.75%, respectively, whereas the ratio UFA/SFA was 2.01 (see Table 1). Results partially agree those reported Brahmi et al., (2020) [12] in a different Algerian lentisk oil obtained by using the same traditional cold pressing process considered in this study. Such authors reported a comparable abundance of linoleic (19.94%) and stearic (1.66%) acids, significantly lower content of palmitic, palmitoleic and linolenic acids (20.34, 1.77and 0.43%, respectively) and slightly higher content of oleic acid (41.22%), not reporting 7-octadecenoic acid. In agreement with our results, former studies using Sohlet extraction with n-hexane confirmed that main (even at different %) FAs were oleic, palmitic and linoleic acids in lentisk oil [35], as well as, oleic acid was the largest constituent in *Pistacia lentiscus* grown in eight different Tunisian geographical areas [36]. In this line, higher oleic acid levels (≈45%) were reported in different cold pressed Italian lentisk oils with also lower (≈23%) and similar (≈25%) palmitic and linoleic acid contents, respectively [24]. The levels of oleic acid in these cold-pressed oils were in the range 44.22–44.88%, whereas the abundance of palmitic and on linoleic acid was ranging from 22.42 to 23.82% and from 24.83 to 25.33%, respectively. It is yet to be determined whether the differences in FA composition observed for these oils are a consequence of the extraction process or depend on other influencing factors, such as genotype, pedo-climatic conditions and growing areas.

Table 2 Triacylglycerols (TAG) composition of lentisk (P. lentiscus) oil (L) and apricot kernel (*Prunus armeniaca*) oil (AKO)

TAG	L (% ± SD[a])	AKO (% ± SD[a])
O	0.37±0.07	1.26±0.01
LL	1.48±0.01	3.71±0.01
OL	2.51±0.07	7.58±0.33
PL	1.46±0.01	n.d.
PO	2.4±0.01	n.d.
OO	1.78±0.01	9.12±0.02
LLPo	1.54±0.01	1.17±0.01
LLL	4.73±0.01	5.58±0.23
PLPo	3.32±0.00	1.66±0.03
PLP	6.59±0.01	n.d.
OSP	1.54±0.00	2.93±0.01
LLP	9.92±0.01	12.41±0.39
LLO	8.21±0.01	1.76±0.00
POPo	3.07±0.00	n.d.
LOP	10.51±0.37	7.60±0.02
LOO	10.58±0.08	17.15±0.04
POP	5.88±0.01	n.d.
OOP	10.03±0.01	6.83±0.02
OOO	9.10±0.34	18.32±0.33
SOO	2.42±0.01	2.90±0.01
SOL	2.90±0.01	n.d.
MAG	0.37±0.07	1.26±0.01
DAG	9.63±0.06	20.42±0.30
StUSt/StStU	14.00±0.02	2.93±0.01
StUU/UUSt	42.17±0.40	31.42±0.32
UUU	33.80±0.25	43.97±0.61

n.d not determined, *P* palmitic acid, *Po* palmitoleic acid, *L* linoleic acid, *O* oleic acid, *S* stearic acid, *Ln* linolenic acid, *St* saturated acid, *U* unsaturated acid, *StStSt* trisaturated acid, *StUSt/StStU* disaturated acids, *StUU/UUSt* monosaturated acids, *UUU* triunsaturated acids.

[a]% ± standard deviation

Acylglycerols profile of lentisk and apricot kernel oils

A total of 20 and 14 acylglycerol species, most of which were triacylglycerols in di- and tri-unsaturated forms, were identified in L and AKO, respectively (see Table 2). They were composed of six predominant fatty acids (P, palmitic acid C16:0; Po, palmitoleic acid C16:1; O, oleic acid *cis*C18:1; L, linoleic acid C18:2; Ln, linolenic acid C18:3, and S, stearic acid C18:0. The number of diacylglycerols(DAGs) and triacylglycerols (TAGs) occurring in AKO were 3 and 11, respectively, whereas the total DAGs and TAGs occurring in L were 5 and 15, respectively.

The fourteen acylglycerol species detected in AKO were identified as, LL, OL, OO, LLPo, LLL, PLPo, OSP, LLP, LLO, LOP, LOO, OOP, OOO, SOO and the predominant triacylglycerols were trioleyl glycerol (OOO, 18.32%), linoleoyl-dioleyl glycerol (LOO, 17.15%), dilinoleoyl-palmitoyl glycerol (LLP, 12.41%), linoleoyl-oleyl-palmitoyl glycerol (LOP, 7.60%), dioleoyl-palmitoyl glycerol (OOP, 6.83%), and trilinoleoyl glycerol (LLL, 5.58%), indicative of the high content of linoleic and oleic acid and, consequently, of the nutritional quality of AKO. Similar findings were observed for Macedonian "sweet" and "bitter" apricot kernel oil that displayed eight TAGs (LOO, OOO, LOL,

POO, LLL, PLL, SLL, and SOO) [33]. As in our study, the most abundant TAGs were linoleoyl-dioleyl glycerol (LOO), accounting for 27.30 and 26.70% in "sweet" and "bitter" AKO, respectively, and trioleyl glycerol (OOO), whose abundance was 25.31 and 39.90% in "sweet" and "bitter" AKO, respectively. These findings are consistent with the results of previous studies indicating in OOO and LOO the major TAGs occurring in AKO [37, 38].

Similar results were reported by Hrichi et al. [28] for samples obtained from Tunisian apricot kernels by subsequent reflux extraction with four different organic solvents of increasing polarity (dichloromethane, chloroform, ethyl acetate, and ethanol). This work reported the detection of six diacylglycerols and eighteen triacylglycerols and indicated the predominance of dioleyl-linoleoyl glycerol (OOL), oleyl-dilinoleoyl glycerol (OLL), and triolein glycerol (OOO), with percentages in the four different extracts within the ranges 20.3–23.6%, 19.0–32.8%, and 12.1–20.1%, respectively.

The identification of the 20 acylglycerols occurring in lentisk oil evidenced the absence of tri-saturated species such as tri palmitoyl glycerol (PPP) and dipalmitoyl-stearoyl glycerol (PPS) described in oils from plants belonging to the closely related Anacardiaceae family [39, 40]. The most abundant triacyl glycerols were linoleoyl-dioleyl glycerol (LOO, 10.58%), linoleoyl-oleyl-palmitoyl glycerol (LOP, 10.51%), dioleyl-palmitoyl glycerol (OOP, 10,03%), dilinoleoyl-palmitoyl glycerol (LLP, 9.92%), trioleylglycerol (OOO, 9.10%), dilinoleoyl-oleylglycerol (LLO, 8.21%), palmitoyl-linoleoyl-palmitoylglycerol (PLP, 6.59), palmitoyl-oleyl-palmitoyl glycerol (POP, 5.88%), and trilinoleoyl glycerol (LLL, 4.73%).

The abundance of acylglycerols in the tri unsaturated forms accounted for 33.80% of total TAGs, which was comparable with the content of 33.94% recently reported for a Tunisian cold-pressed lentisk oil [41]. Lower content of tri unsaturated TAGS (28.86%) was previously reported for hexane extracted Tunisian L [09] whereas a higher content (38.10%) was found in an Algerian cold pressed *Pistacia atlantica* fruit oil [40].

Table 3 Unsaponifiable fraction (tocopherols and phytosterols) occurring in lentisk (*P. lentiscus*) oil (L) and apricot kernel (*Prunus armeniaca*) oil (AKO)

Compounds	L (mg/kg ± SD[a])	AKO (mg/kg ± SD[a])
Tocopherols		
α-tocopherol	354.94 ± 0.03	335.67 ± 1.27
β-tocopherol	5.92 ± 1.42	n.d.
γ-tocopherol	17.91 ± 1.49	97.64 ± 3.87
δ-tocopherol	3.09 ± 0.02	37.36 ± 5.03
Total	383.92	470.68
Phytosterols		
Cholesterol	50.76 ± 1.68	26.04 ± 1.32
Campesterol	90.39 ± 2.91	157.01 ± 16.12
Stigmasterol	34.59 ± 1.19	23.33 ± 11.15
β-sitosterol	1337.44 ± 28.75	2957.00 ± 26.74
Stigmastanol	19.62 ± 0.52	127.49 ± 19.17
d5-avenasterol	59.64 ± 1.94	175.95 ± 27.56
Lupeol	97.15 ± 3.15	n.d.
Cycloartenol	109.08 ± 3.61	n.d.
24-methylenecycloartanol	52.94 ± 15.57	n.d.
γ-sitosterol	n.d.	13.89 ± 0.02
d5-24-stigmastadienol	n.d.	30.09 ± 0.05
Total	1851.63	3510.81

[a]mg/kg oil ± standard deviation

Tocopherols and phytosterols of lentisk and apricot kernel oils

Table 3 summarizes the content of tocopherols (all L-form) and phytosterols determined in the unsaponifiable fraction of samples assayed.

Concentration of total tocopherols determined in lentisk sample was 383.92 mg/kg, higher than that determined in different Tunisian *Pistacia lentiscus* oils from different Tunisian growing areas (62.4–273 mg/kg range) [36, 42]. In contrast, our values were lower than other reported in Iranian *Pistacia atlantica* cold-pressed oil (409.97 mg/kg) [41] and Tunisian cold-pressed *Pistacia lentiscus* fruit oil (1249.16 mg/kg) [41]. Occurrence of α-tocopherol as the predominant isomer (92.5% of total tocopherols) was consistent with previous findings featured in comparable lentisk oils whose contribution was in the 70–93% range [36, 39, 41, 43].

Total tocopherol content found in AKO sample was 470.68 mg/kg (Table 3), very conparable to the reported value (476.0 mg/kg) in two cold-pressed Macedonian apricot kernel oils [33] and also for hexane-extracted Polish AKOs (466.2 mg/kg) [34] and those from different Tunisian regions assayed at three different ripening stages (304–707 mg/kg range) [43]. Again, differences can be understood according to botanical and geographical considerations. Evidently, total tocopherol content can be significantly affected by extraction methods considered as stated by Pavlovic et al. reporting values at 940 and 2520 mg/kg in AKOs produced from Hungarian sweet apricot by cold pressing and supercritical carbon dioxide extraction, respectively [31]. Although there were other studies indicating that γ-tocopherol was the main isomer in AKO [33, 34, 43], in contrast to our findings (Table 3), there is a general agreement about the absence of β-tocopherol in this matrix together with the scarce presence of δ-tocopherol [24].

Among phytosterols found in lentisk oil, β-sitosterol was the most abundant specie representing 72.23% of total amount (Table 3), finding similar contributions in Tunisian (≈ 81%) [41] and Italian (≈ 93%) [24] oil samples even

having different concentration levels. In the case of AKO, β-sitosterol presence was double than in its lentisk counterpart (2957 vs. 1337 mg/kg, Table 3) and again, it was the preponderant phytosterol representing about 84% of total content. Comparison of β-sitosterol content achieved by the assayed AKO sample is diverse. Thus, lower values were found in Tunisian AKOs (2853 mg/kg) [44] and higher (3394–4244 mg/kg) contents were stated in Macedonian samples [33], but in any case, such isomer was the largest one among total phytosterol contents determined (71% and 80%, respectively), in concordance with results yielded in current research. Results about contribution of minor phytosterols (i. el. Campesterol) to total content in AKO sample assayed were comparable to other studies [33].

Total phenolic content, chlorophylls and carotenoids determined in lentisk and apricot kernel oils

Table 4 collects TPC, carotenoid and chlorophyll findings in samples assayed. Compared to other approaches, TPC value of lentisk sample was 2-times higher than that reported in an Iranian cold-pressed oil (57.6 mg_{GAE}/kg) [39] and significantly lower than results stated in Tunisian (598.5 mg_{GAE}/kg) [41] and in Italian (435–616 mg_{GAE}/kg range) [24] cold-pressed oils. Interestingly, results were similar to those reported in extra virgin olive oil produced from two endemic Algerian olive cultivars (115.4 to 226.9 mg_{GAE}/kg) [45] and higher than found in olive oils from Pakistan (23.6–92.4 mg_{GAE}/kg) [46]. It must be noted that outside genetic and growing conditions, TPC is also affected by handling practices during processing and storage of oils. In AKO sample, TPC (19.6 mg_{GAE}/kg) was higher than other values found in solvent-extracted oils from Bebeko variety (7.94–8.18 mg_{GAE}/kg) [47] and lower than reported in cold-pressed and solvent extracted oild (25–50 mg_{GAE}/kg) [46, 48].

The carotenoids level determined in this study for lentisk oil (2.18 mg/kg) was significantly lower than reported (6–11 mg/kg range) in Tunisian varieties from different growing regions [36, 42]. A similar trend was observed in the case of chlorophylls in where value found (1.51 mg/kg, Table 4) was smaller than described in Tunisian (8.91 mg/kg) [44] and Moroccan samples (4.69–24.43 mg/kg range) [49]. Regarding AKO sample assayed, carotenoid and chlorophyll contents were 0.18 and 0.08 mg/kg, respectively, finding similar values (0.10 and 0.12 mg/kg, respectively) in other Algerian cold-pressed oils [50]. However, carotenoid results achieved were rather different than those reported in hexane-extracted Latvian (1.5 to 5.3 mg/kg range) [51] and shoxlet-extracted Polish (42.3 to 66.8 mg/kg range) [34] AKOs.

Table 4 Total phenolic content, total carotenoids and chlorophylls contents, antioxidant activity by the IC_{50} evaluation, oxidative stability and quality parameters (peroxide value and free acidity) of lentisk (*P. lentiscus*) oil (L) and apricot kernel (*Prunus armeniaca*) oil (AKO)

Assay	L	AKO
TPC[a]	140.00 ± 9.64	19.60 ± 1.22
Carotenoids[b]	2.18 ± 0.09	0.18 ± 0.01
Chlorophylls[c]	1.51 ± 0.08	0.08 ± 0.02
DPPH[d]	0.05 ± 0.00	5.94 ± 0.87
ABTS[e]	0.04 ± 0.00	0.75 ± 0.13
β-Carotene bleaching[f]	0.16 ± 0.02	1.78 ± 0.08
FRAP[f]	0.06 ± 0.00	0.59 ± 0.02
Induction time[g]	15.81 ± 0.71	4.27 ± 0.18
Peroxide value[h]	1.43 ± 0.04	1.21 ± 0.02
Acidity[i]	0.76 ± 0.03	1.51 ± 0.01

All results are mean values of triplicate analysis ± standard deviation

[a]Expressed in mg of gallic acid equivalents per kg of oil

[b]Expressed in mg of luteolin equivalents per kg of oil

[c]Expressed in mg of pheophytine equivalents per kg of oil

[d]Expressed in mg/mL (ascorbic acid as standard)

[e]Expressed in mg/mL (trolox as standard)

[f]Expressed in mg/mL (butylhydroxyanisole (BHA) as standard)

[g]Hours (h)

[h]Expressed in mg of active O_2 per kg of oil

[i]Expressed in %

Oxidative stability of lentisk and apricot kernel oils

The induction periods (IP) in hours, determined to evaluate the oxidative stability of the investigated oils by Rancimat analysis, carried out at 98° C, are reported in Table 4. The IP values determined for Algerian L and AKO were 15.81 h and 4.27 h, respectively. These values are in the range of the oxidative stability determined at comparable temperature (100 °C) for some edible oils obtained from other unconventional raw materials [52–54]. As we can see from Table 1, *Pistacia lentiscus* oil had longer IP than apricot kernel oil, which had a high content of unsaturated fatty acids (UFA 89.40%), which are known to have a negative impact on the oxidative stability [22], whereas UFA in L accounted for 66.75% (see Table 1).

The IP obtained for AKO in this study was significantly longer than that reported by [52] for cold pressed apricot kernel oil (IP of 0.2 h), but shorter than that determined at 120 °C for a cold pressed Macedonian AKO (IP of 7.6 h) [55], which, however, displayed TPC (37.95 mg_{GAE}/kg) and content of total tocopherols (588 mg/Kg) higher than those found in the investigated AKO (19.6 mg_{GAE}/kg and 470.68 mg/kg, respectively).

In Lentisk oil, peroxide value (1.43 mg O_2/kg oil) and free acidity (0.76%) were lower than those reported for Lybian Lentisk fruits (4.00 mg O_2/kg oil and 2.05%, respectively) [56], clearly emphasizing relevance of the geographical

variability. In AKO, its peroxide value (1.21) was lower than values commonly determined in cold pressed oils (2.09–5.62 mg O_2/kg oil) [7], finding how free acidity (1.51, Table 4) met the standards claimed for virgin oils (< 2.00%) in the Codex Alimentarius.

Antioxidant activity of polar extracts

Table 4 summarizes in-vitro antioxidant capacity of methanolic fractions from the investigated oils assessed by different methods. Results of IC_{50} determined by DPPH$^{\bullet}$ (IC_{50} =0.05 mg/mL), ABTS$^{\bullet+}$ (IC_{50} =0.04 mg/mL), FRAP (IC_{50} =0.06 mg/mL) and β-carotene bleaching (0.16 mg/mL) assays were comparable with those reported in Moroccan *Pistacia lentiscus* [57] and Chinese olive [58] oils. Lentisk oil assayed exhibited higher antioxidant activity compared to previous DPPH$^{\cdot}$ (5.34 mg/mL) and β-carotene bleaching (7.42 mg/mL) assays in similar lentisk samples [59] and of the scavenging activity previously reported for another Algerian lentisk oil (IC_{50} = 20.61 mg/mL) [60]. It must be highlighted that investigated AKO displayed IC_{50} values for DPPH$^{\cdot}$ (5.94 mg/mL), ABTS$^{\cdot}$+ (0.75 mg/mL), FRAP (0.59 mg/mL) and β-carotene bleaching (1.78 mg/mL) assays clearly higher than those reported for oils obtained from kernels of different apricot varieties, achieving up to a 5-fold difference [61].

The differences in antioxidant activity observed between lentisk oil and apricot kernel oil can be attributed to variations in their phenolic composition and to well-established structure–activity relationships of phenolic compounds. The antioxidant efficiency of phenolic acids is strongly influenced by the number and position of hydroxyl groups on the aromatic ring, as well as by their electron-donating capacity. Compounds bearing ortho-dihydroxyl or multiple hydroxyl substitutions exhibit enhanced radical scavenging activity due to improved stabilization of phenoxyl radicals [62]. Accordingly, phenolic acids such as gallic acid, protocatechuic acid, and ferulic acid act as primary antioxidants by donating hydrogen atoms to neutralize free radicals and interrupt oxidation reactions [63].

However, the antioxidant behavior of edible oils cannot be explained solely by the presence of individual phenolic compounds. It reflects the combined and potentially synergistic interactions among minor bioactive constituents within the lipid matrix. Tocopherols, phytosterols, and carotenoid pigments contribute to oxidative stability through chain-breaking mechanisms and by protecting unsaturated fatty acids against peroxidation [64]. Comprehensive compositional profiling of vegetable oils further demonstrates that the interaction between fatty acids and minor antioxidants plays a decisive role in determining overall antioxidant capacity and oxidative stability [65].

Beyond their contribution to oxidative stability, these phenolic compounds and minor lipid constituents may also contribute to the potential health-promoting properties of lentisk and apricot kernel oils. Phenolic acids have been associated with anti-inflammatory, cardioprotective, and cytoprotective effects, mainly through modulation of oxidative stress–related pathways and cellular redox signaling. Their capacity to scavenge reactive oxygen species and inhibit lipid peroxidation is particularly relevant in the context of cardiovascular health, where oxidative modification of lipids is a key pathogenic factor [66].

Tocopherols contribute not only to lipid-phase antioxidant protection but also to the preservation of cell membrane integrity against peroxidative damage, Phytosterols are linked to cholesterol-lowering effects via inhibition of intestinal cholesterol absorption, supporting cardiovascular health [67]. Moreover, the unsaturated fatty acid profile, particularly oleic and linoleic acids, may further promote cardiometabolic health when protected from oxidative degradation by endogenous antioxidants in the oil matrix [68].

Overall, the potential health benefits of lentisk and apricot kernel oils should not be attributed to a single bioactive compound but rather to the combined and synergistic effects of phenolic compounds, lipid-soluble antioxidants, phytosterols, and the unsaturated fatty acid composition [64].

Conclusions

There was demonstrated relevance of *Pistacia lentiscus* and Apricot (*Prunus armeniaca L.*) kernel oils as natural sources of a wide variety of phytochemicals. Detailed bioactive profiles of both matrices were elucidated through a multidisciplinary analytical approach, highlighting efficiency of a quality-by-design initiative to firstly report the presence of chatecol and vanillin/*p*-hydroxybenzoic acid in polar fractions of lentisk and AKO oils, respectively. Moreover, health-promoting interest of oils assayed was confirmed according to their lipid profiles elucidated that were mainly contributed by unsaturated fatty acids and heterogeneous tri-, di- and mono-acylglycerols. Presence of other health promoters with antioxidant/antiradical capacity such as tocopherols, phytosterols, carotenoids and chlorophylls was also confirmed in samples assayed. Nutritional benefits of lentisk and AKO oils can promote their interest by industry addressing commercialization of dietary supplements, cosmetics and food ingredients, favoring the reduction of agricultural waste through the exploitation of food industry by-products.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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References

1. Brennan CS (2024) Regenerative food innovation: the role of agro-food chain by-products and plant origin food to obtain high-value-added foods. Foods 13:427. https://doi.org/10.3390/foods13030427
2. Srivastava Y, Semwal AD, Dhiman A (2021) A comprehensive review on processing, therapeutic benefits, challenges, and economic scenario of unconventional oils. J Food Process Pres 45:e15152. https://doi.org/10.1111/jfpp.15152
3. Gardeli C, Vassiliki P, Athanasios M, Kibouris T, Komaitis M (2008) Essential oil composition of Pistacia lentiscusL. and Myrtus communis L.: Evaluation of antioxidant capacity of methanolic extracts. Food Chem 107:1120–1130. https://doi.org/10.1016/j.foodchem.2007.09.036
4. Derradji L, Benkhaled A, Yıldız K, Özbek ZA, Nouasri A, Ergönül PG (2025) Influence of extraction method on physicochemical properties, fatty acid profile, and tocol content of *Pistacia lentiscus* oil from the Hodna Subarid Region (Algeria). Chem Biodivers 22:e01018. https://doi.org/10.1002/cbdv.202501018
5. Górnaś P, Mišina I, GrāvīteI, Soliven A, Kaufmane E, Segliņa D (2015) Tocochromanols composition in kernels recovered from different apricot varieties: RP-HPLC/FLD and RP-UPLC-ESI/MSn study. Nat Prod Res 29:1222–1227. https://doi.org/10.1080/14786419.2014.997727
6. Pawar KR, Nema PK (2023) Apricot kernel characterization, oil extraction, and its utilization: a review. Food Sci Biotechnol 32:249–263. https://doi.org/10.1007/s10068-022-01228-3
7. Tian M, Bai Y, Tian H, Zhao X (2023) The chemical composition and health-promoting benefits of vegetable oils—a review. Molecules 28(17):636393. https://doi.org/10.3390/molecules28176393
8. Cherif AO, Aderrabba M, Moussa F, Ben Messaouda M (2025) Fatty acids profile in three cultivars of Tunisian apricot oil seeds (*Prunus armeniaca* L.): impact of maturity. Nat Prod Res 39:2734–2750. https://doi.org/10.1080/14786419.2024.2309659
9. Jayaraman K, Rajendran AK, Kumar GS, Bhutani H (2021) A methodology employing retention modeling for achieving control space in liquid chromatography method development using quality by design approach. J Chromatogr A 1635:461658. https://doi.org/10.1016/j.chroma.2020.461658
10. Zöldhegyi A, Horváth K, Kormány R (2024) Revisiting column selectivity choices in ultra-high performance liquid chromatography—using multidimensional analytical Design Spaces to identify column equivalency. J Chromatogr A 1719:464738. https://doi.org/10.1016/j.chroma.2024.464738
11. Rácz N, Kormány R, Fekete J, Molnár I (2015) Establishing column batch repeatability according to quality by design (QbD) principles using modeling software. J Pharm Biomed Anal 137:60–69. https://doi.org/10.1016/j.jpba.2017.01.013
12. Brahmi F, Haddad S, Bouamara K, Yalaoui-Guellal D, Prost-Camus E, Pais de Barros J-P, Prost M, Atanasov AG, Madani K, Boulekbache-Makhlouf L, Lizardi G (2020) Comparison of chemical composition and biological activities of Algerian seed oils of *Pistacia lentiscus* L., *Opuntia ficusindica* (L.) mill. and *Argania spinosa* L. Skeels. Ind Crops Prod 151:112456. https://doi.org/10.1016/j.indcrop.2020.112456
13. Bettencourt da Silva R, Ellison S L R (eds) (2021) Eurachem/CITAC guide: assessment of performance and uncertainty in qualitative chemical analysis, Eurachem, 1st edn. https://www.eurachem.org
14. Lim DKY, Garg S, Timmins M, Zhang ESB, Thomas-Hall SR, Schuhmann H, Li Y, Schenk PM (2012) Isolation and evaluation of oil-producing microalgae from subtropical coastal and brackish waters. PLoS ONE 7:e40751. https://doi.org/10.1371/journal.pone.0040751
15. Shashkov MV, Sidelnikov VN, Zaikin PA (2014) Selectivity of stationary phases based on pyridinium ionic liquids for capillary gas chromatography. Russ J Phys Chem A 88:717–721. https://doi.org/10.1134/S0036024414040268
16. Firestone D (1994) Official methods and recommended practices of the American Oil Chemists' Society, 4th edn. AOCS Press, Champaign
17. Du M, Ahn D (2002) Simultaneous analysis of tocopherols, cholesterol, and phytosterols using gas chromatography. J Food Sci 67:1696–1700. https://doi.org/10.1111/j.1365-2621.2002.tb08708.x
18. Silva AF, Abreu H, Silva A, Cardoso SM (2019) Effect of oven-drying on the recovery of valuable compounds from Ulva rigida, *Gracilaria* sp. and *Fucus vesiculosus*. Mar Drugs. https://doi.org/10.3390/md17020090
19. Minguez-Mosquera MI, Rejano-Navarro L, Gandul-Rojas B, SanchezGomez AH, Garrido-Fernandez J (1991) Color-pigment correlation in virgin olive oil. J Am Oil Chem Soc 68:332–336. https://doi.org/10.1007/BF02657688
20. Chikhoune A, DamjanPavleca J, Shashkov M, Berroua Z, Chebbi K, Bougherra H, Zeroual B, Aliane K, Gagaoua M, Boudjellal A (2017) Antioxidant effect induced by the essential oil of *Pituranthos scoparius* in a formulation of a whey spread emulsion. J Food Process Preserv 41:e13163. https://doi.org/10.1111/jfpp.13163

21. ISO International Standard (2006) Method 6886. Animal and vegetable fats and oils. Determination of the oxidative stability (accelerated oxidation test), 2nd ed, pp 1–14
22. ISO International Standards (1998) Method 3960, animal and vegetable fats and oils. Determination of peroxide index/ISO international standards (1998). Animal and vegetable fats and oils. Determination of acid value and acidity
23. Neto RT, Marçal C, Queirós AS, Abreu H, Silva A, Cardoso SM (2018) Screening of *Ulva rigida*, Gracilaria sp., *Fucus vesiculosus* and *Saccharina latissima* as functional ingredients. Int J Mol Sci 19:2987. https://doi.org/10.3390/ijms19102987
24. Siano F, Cutignano A, Moccia S, Russo GL, Volpe MG, Picariello G (2020) Phytochemical characterization and effects on cell proliferation of lentisk (*Pistacia lentiscus*) berry oil: a revalued source of phenolics. Plant Foods Hum Nutr 75:487–494. https://doi.org/10.1007/s11130-020-00835-x
25. Mezni F, Slama A, Ksouri R, Hamdaouri G, Khouja ML, Khaldi A (2018) Phenolic profile and effect of growing area on *Pistacia lentiscus* seed oil. Food Chem 257:206–210. https://doi.org/10.1016/j.foodchem.2018.03.019
26. Al Juhaimi a F A, Özcan MM, Ghafoor K, Babiker EE, Hussain S (2018) Comparison of cold-pressing and soxhlet extraction systems for bioactive compounds, antioxidant properties, polyphenols, fatty acids and tocopherols in eight nut oils. J Food Sci Technol 55(8):3163–3173. https://doi.org/10.1007/s13197-018-3244-5
27. Molnár I, Rieger HJ, Kormány R (2017) Modeling of HPLC methods using QbD principles in HPLC. In: Grushka E, Grinberg N (eds) *Advances in chromatography*, vol 53. CRC, Boca Raton, pp 331–350
28. Hrichi S, Rigano F, Chaabane-Banaoues R, Oulad El Majdoub Y, Mangraviti D, Di Marco D, Babba H, Dugo P, Mondello L, Mighri Z, Cacciola F (2020) Identification of fatty acid, lipid and polyphenol compounds from *Prunus armeniaca* L. Kernel extracts. Foods 9:896. https://doi.org/10.3390/foods9070896
29. Rojas LB, Quideau S, Pardon P, Charrouf Z (2005) Colorimetric evaluation of phenolic content and GC-MS characterization of phenolic composition of alimentary and cosmetic argan oil and press cake. J Agric Food Chem 53:9122–9127. https://doi.org/10.1021/jf051082j
30. Al Juhaimi b F A, Özcan MM, Ghafoor K, Babiker EE (2018) The effect of microwave roasting on bioactive compounds, antioxidant activity and fatty acid composition of apricot kernel and oils. Food Chem 243:414–419. https://doi.org/10.1016/j.foodchem.2017.09.100
31. Pavlović N, Vidović S, Vladić J, Popović L, Moslavac T, Jakobović S, Jokić S (2018) Recovery of tocopherols, amygdalin, and fatty acids from apricot kernel oil: cold pressing versus supercritical carbon dioxide. Eur J Lipid Sci Technol 120:1800043. https://doi.org/10.1002/ejlt.201800043
32. Savchenko L (2021) Determination and comparison of fatty acids composition of apricot and peach oils. Farmacia 69(5):941–947. https://doi.org/10.31925/farmacia.2021.5.17
33. Kostadinović-Veličkovska S, Mot AC, Mitrev S, Gulaboski R, Brühl L, Mirhosseini H, SilaghiDumitrescu R, Matthäus B (2018) Bioactive compounds and in vitro antioxidant activity of some traditional and non-traditional cold-pressed edible oils from Macedonia. J Food Sci Technol 55:1614–1623. https://doi.org/10.1007/s13197-018-3050-0
34. Stryjecka M, Kiełtyka-Dadasiewicz A, Michalak M, Rachoń L, Głowacka A (2019) Chemical composition and antioxidant properties of oils from the seeds of five apricot (*Prunus armeniaca* L.) cultivars. J Oleo Sci 68:729–738. https://doi.org/10.5650/jos.ess19121
35. Mezni b F, Labidi A, Msallem M, Boussaid M, Khouja M, Khaldi A (2014) Influence of harvest date on fatty acid composition and antioxidant activity of *Pistacia lentiscus* L. edible oils. J Mater Environ Sci 5:1703–1708. https://doi.org/10.1080/14786419.2014.895724
36. Mezni AF, Khouja M, Gregoire S, Martine L, Khaldi A, Berdeaux O (2014) Effect of growing area on tocopherols, carotenoids and fatty acid composition of *Pistacia lentiscus* edible oil. Nat Prod Res 28:1225–1230. https://doi.org/10.1080/14786419.2014.895724
37. Turan S, Topcu A, Karabulut I, Vural H, Hayaloglu AA (2007) Fatty acid, triacylglycerol, phytosterol, and tocopherol variations in kernel oil of Malatya apricots from Turkey. J Agric Food Chem 55:10787–10794. https://doi.org/10.1021/jf071801p
38. Hassanien MM (1999) Studies on non-traditional oils: l. Detailed studies on different lipid profiles of some Rosaceae kernel oils. Grasas Aceites 50:379–384. https://doi.org/10.3989/gya.1999.v50.i5.682
39. Saber-Tehrani M, Givianrad M, Aberoomand-Azar P, Waqif-Husain S, Jafari Mohammadi S (2013) Chemical composition of Iran's *Pistacia atlantica* cold-pressed oil. J Chem 2013:1–6. https://doi.org/10.1155/2013/126106
40. Yousfi M, Nadjemi B, Belal R, Bombarda I, Gaydou E (2005) Triacylglycerol composition of oil from *Pistacia atlantica* fruit growing in Algeria. J Amer Oil Chem Soc 82:93–96. https://doi.org/10.1007/s11746-005-1048-7
41. Ben Ameur R, Hadjkacem B, Ayadi M, Ikram B, Feki A, Gargouri J, Gargouri A, Allouche N (2024) Phytochemical profile of Tunisian *Pistacia lentiscus* fruits oil: antioxidant, antiplatelet, and cytotoxic activities assessment. Eur J Lipid Sci Technol 126:1–16. https://doi.org/10.1002/ejlt.202300274
42. Karoui IJ, Ayari J, Ghazouani N, Abderrabba M (2020) Physicochemical and biochemical characterizations of some Tunisian seed oils. OCL 27:29. https://doi.org/10.1051/ocl/2019035
43. Cherif AO, Messaouda MB, Abderrabba M, Moussa F (2021) The content of carotenoids and tocochromanols in bitter, semi-sweet and sweet apricots depending on different harvest times and geographical regions. Eur Food Res Technol 247:1609–1615. https://doi.org/10.1007/s00217-021-03688-z
44. Vadalà R, Nava V, Turco VL, Potortì AG, Costa R, Rando R, Ben Mansour H, Ben Amor N, Beltifa A, Santini A, Di Bella G (2023) Nutritional and health values of Tunisian edible oils from less-used plant sources. Agriculture 13:1096. https://doi.org/10.3390/agriculture13051096
45. Faci M, Douzane M, Hedjal M, Daas MS, Fougere L, Lesellier E (2021) Changes in secoiridoids content and chemical characteristics of cultivated and wild Algerian olive oil, in term of fruit maturation. PLoS ONE 16(11):e0260182. https://doi.org/10.1371/journal.pone.0260182
46. Gulfraz M, KasuarR, Arshad G, Mehmood S, Minhas N, Asad MJ, Ahmad A, Siddique F (2009) Isolation and characterization of edible oil from wild olive. Afr J Biotechnol 8:3734. https://doi.org/10.5897/AJB2009.000-9373
47. Makrygiannis I, Athanasiadis V, Chatzimitakos T, Bozinou E, MantzouraniC, Chatzilazarou A, Makris DP, Lalas SI (2023) Exploring the chemical composition and antioxidant properties of apricot kernel oil. Separations 10:332. https://doi.org/10.3390/separations10060332
48. Uluata S (2016) Effect of extraction method on biochemical properties and oxidative stability of apricot seed oil. Akad Gida 14:904333–904340
49. Ait Mohand B, Antari AE, Benkhalti F (2022) Influence of maturity stage on chemical composition and antioxidant activity of *Pistacia lentiscus* seed oils. AJMAP 8:171–186. https://doi.org/10.48347/IMIST.PRSM/ajmap-v8i1.27039
50. Brahmi F, Chennit B, Batrouni H, Benallaoua K, Madani K, Boulekbache-Makhlouf L (2023) Valorization of apricot, melon, and watermelon by-products by extracting vegetable oils from

their seeds and formulating margarine. OCL 30:11. https://doi.org/10.1051/ocl/2023009
51. Górnaś P, Radziejewska Kubzdela E, Mišina I, Biegańska Marecik R, Grygier A, Rudzińska M (2017) Tocopherols, tocotrienols and carotenoids in kernel oils recovered from 15 apricot (*Prunus armeniaca* L.) genotypes. J Am Oil Chem Soc 94:693–699. https://doi.org/10.1007/s11746-017-2978-y
52. Ying Q, Wojciechowska P, Siger A, Kaczmarek A, Rudzińska M (2018) Phytochemical content, oxidative stability, and nutritional properties of unconventional cold-pressed edible oils. J Food Nutr Res 6:476–485. https://doi.org/10.12691/jfnr-6-7-9
53. Karrar E, Sheth S, Navicha WB, Wei W, HinawiHassanin H, Mohammed Abdalla M, Xingguo Wang X (2019) A potential new source: nutritional and antioxidant properties of edible oils from cucurbit seeds and their impact on human health. J Food Biochem 43:e12733. https://doi.org/10.1111/jfbc.12733
54. Symoniuk E, Ksibi E, Wroniak M, Lefek M, Ratusz K (2022) Oxidative stability analysis of selected oils from unconventional raw materials using Rancimat apparatus. Appl Sci 12:10355. https://doi.org/10.3390/app122010355
55. KostadinovićVeličkovska S, Brühl L, Mitrev S, Mirhosseini H, Matthäus B (2015) Quality evaluation of cold-pressed edible oils from Macedonia. Eur J Lipid Sci Technol 117:2023–2035. https://doi.org/10.1002/ejlt.201400623
56. Belgasim SM, Boubrig SY, Zaed MS (2025) Physical and chemical properties of fruit oil of *Pistacia lentiscus* L. growing wild in Libya. Alex Sci Exch J 46(2):279–289. https://doi.org/10.21608/asejaiqjsae.2025.426484
57. Boudieb K, Ait Slimane-Ait Kaki S, Amellal-Chibane H (2019) Traditional uses, phytochemical study and morphological characterization of *Pistacia lentiscus* L. fruits from three areas of northern Algeria. J Appl Biosci 135:13788–13797. https://doi.org/10.4314/jab.v135i0.5
58. Xiang C, Xu Z, Liu J, Li T, Yang Z, Ding C (2017) Quality, composition, and antioxidant activity of virgin olive oil from introduced varieties at Liangshan. LWT 78:226–234. https://doi.org/10.1016/j.lwt.2016.12.029
59. Daoued K, Chouaibi M, Gaout N, Haj O (2016) Chemical composition and antioxidant activities of cold pressed lentisk (*Pistacia lentiscus* L.) seed oil. Riv Ital Sostanze Grasse 93:31–38
60. Belyagoubi-Benhammou N, Belyagoubi L, El Zerey-Belaskri A, Zitouni A, Ghembaza N, Benhassaini H, Atik-Bekkara F, Piras A, Falconieri D, Rosa A (2018) Fatty acid composition and antioxidant activity of *Pistacia lentiscus* L. fruit fatty oil from Algeria. J Food Meas Charact 12:1408–1412. https://doi.org/10.1007/s11694-018-9755-y
61. Korekar G, Stobdan T, Arora R, Yadav A, Singh S (2011) Antioxidant capacity and phenolics content of apricot (*Prunus armeniaca* L.) kernel as a function of genotype. Plant Foods Hum Nutr 66:376–383. https://doi.org/10.1007/s11130-011-0246-0
62. Moazzen A, Öztinen N, Ak-Sakalli E, Koşar M (2022) Structure-antiradical activity relationships of 25 natural antioxidant phenolic compounds from different classes. Heliyon 8:e10467. https://doi.org/10.1016/j.heliyon.2022.e10467
63. Lu A, Yuan SM, Xiao H, Yang DS, Ai ZQ, Li QY, Zhao Y, Chen ZZ, Wu XM (2022) QSAR study of phenolic compounds and their anti-DPPH radical activity by discriminant analysis. Sci Rep 12:7860. https://doi.org/10.1038/s41598-022-11925-y
64. Wang G, Liu L, Peng F, Ma Y, Deng Z, Li H (2024) Natural antioxidants enhance the oxidation stability of blended oils enriched in unsaturated fatty acids. J Sci Food Agric 104:2907–2916. https://doi.org/10.1002/jsfa.13183
65. Kamińska W, Grygier A, Rzyska-Szczupak K, Przybylska-Balcerek A, Stuper-Szablewska K, Neunert G (2025) Nutritional quality, fatty acids profile, and phytochemical composition of unconventional vegetable oils. Molecules 30:3269. https://doi.org/10.3390/molecules30153269
66. Zhu C, Lin Z, Jiang H, Wei F, Wu Y, Song L (2024) Recent advances in the health benefits of phenolic acids in whole grains and the impact of processing techniques on phenolic acids: a comprehensive review. J Agric Food Chem 72:24131–24157. https://doi.org/10.1021/acs.jafc.4c05245
67. Aboutaleb AS, Mahdy ES, Khamies SM, Hal DM, El-Dessouki AM, El-Shiekh RA, Hassan M, Elshazly AM, Salman A, Sayed GA, Abd El Hafeez MS, Reda AM, El-Alfy AN, Allam S (2025) Health benefits of phytosterols in the management of several non-communicable disorders. Chem Biodivers 22:e00983. https://doi.org/10.1002/cbdv.202500983
68. Vera-Candioti L, Negro E, Mancini SI, Bernal CA (2026) Oxidative stability of flaxseed oil: effects of tocopherols, phytosterols and extraction conditions. Food Chem 502:147708. https://doi.org/10.1016/j.foodchem.2025.147708

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