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Comparative analysis of nutritional value and antioxidant activity in sweet and bitter almonds

Sara El Bernoussi [a], Ihssan Boujemaa [a], Chakir El Guezzane [a], Youssef Bou-Ouzoukni [a], Issmail Nounah [b], Abdelhakim Bouyahya [b,**], Riaz Ullah [c], Zafar Iqbal [d], Filippo Maggi [e], Giovanni Caprioli [e,*], Hicham Harhar [a], Mohamed Tabyaoui [a]

[a] Laboratory of Materials, Nanotechnology and Environment LMNE, Faculty of Sciences, Mohammed V University in Rabat, BP 1014, Rabat, Morocco
[b] Laboratory of Human Pathologies Biology, Faculty of Sciences, Mohammed V University in Rabat, BP 1014, Rabat, Morocco
[c] Department of Pharmacognosy College of Pharmacy King Saud University, Riyadh, Saudi Arabia
[d] Department of Surgery, College of Medicine, King Saud University P.O.Box 7805, Riyadh, 11472, Saudi Arabia
[e] Chemistry Interdisciplinary Project (ChIP) Research Center, School of Pharmacy, University of Camerino, Camerino, Italy

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ABSTRACT

In this study, four cultivars of almonds including bitter and sweet almonds from the northern regions of Morocco have been studied in terms of chemical composition, bioactive content, and antioxidant activity. Our research revealed that almonds are rich in minerals, and they displayed low levels of primary oxidation by-products and excellent stability. The fatty acid composition was dominated by oleic and linoleic acids, with slight variations between regions and almond cultivars. The analyses of unsaponifiable fraction revealed that the sterol component of almond oil was mainly composed by β-sitosterol and Δ-5-avenosterol (with regional differences), meanwhile α-tocopherol was the predominant among tocopherols. Furthermore, a significant presence of phenolic compounds was observed, particularly in Al Hoceima *Beldi* sweet almonds, with a gallic acid equivalent of 47.15 mg GAE/g in methanol extract and a total tocopherol content of 558.53 mg/kg. These results highlighted the strong antioxidant potential of Al Hoceima *Beldi* sweet almond oil, which showed good antioxidant activity for 2,2-Diphenyl-1-picrylhydrazyl (DPPH) with an IC_{50} value of 63.47 μg/mL and a high concentration of samples for 2,2′-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) (19.48 mg TE/g extract). In conclusion, the research supports the cultivation and consumption of these sweet almond cultivars in recognition of their significant contribution to human well-being. Bitter almonds have medicinal benefits but are toxic and unsafe for consumption.

1. Introduction

Almonds are an energizing food that is rich in lipids, proteins, carbohydrates, and vitamins. They are also high in fat (about 50% lipids), containing fatty acids such as oleic acid (ω 9), linoleic acid (ω 6), and palmitic acid (Hernandez, 2016). Almonds have a high content of antioxidants, with α-tocopherol being a notable contributor. In addition, almonds have a low sodium content (1 mg/100 g) and a high potassium content (700 mg/100 g), making them useful in low-sodium diets (Richardson et al., 2009). They also do not lead to weight gain and are beneficial for hypocholesterolemia (Richardson et al., 2009).

Sweet almonds have a pleasant taste and can be eaten whole (fresh or roasted) and in spreads like almond butter or they can be used in a wide range of food products and recipes (Richardson et al., 2009). Almond oil, which is extracted from almonds, can also be used in cosmetics and pharmaceuticals as a skin moisturizer, anti-wrinkle, and anti-aging lotion (Colic et al., 2019). Traditional medicine uses all parts of the almond tree, including the leaves, to reduce pain from bruises, burns, and wounds (Colic et al., 2019). Bitter almonds, on the other hand, are used in the production of flavors because of their high concentration of amygdalin, which gives them a bitter taste (de La Taille, 1985).

The almond [(*Prunus dulcis* (Miller) D.A. Webb, syn. *Prunus amygdalus* (L.) Batsch and *Prunus communis* L. as well as *Amygdalus communis* L.] is one of the oldest domesticated trees, native to south-central Asia,

* Corresponding author. Chemistry Interdisciplinary Project (ChIP) research center, School of Pharmacy, Via Madonna delle Carceri snc, Camerino, 62032, Italy.
** Corresponding author. Laboratory of Human Pathologies Biology, Faculté des Sciences, 4 Av. Ibn Battouta, B.P. 1014 RP, Rabat, Morocco.
E-mail addresses: a.bouyahya@um5r.ac.ma (A. Bouyahya), rullah@ksu.edu.sa (R. Ullah), zsyed@ksu.edu.sa (Z. Iqbal), giovanni.caprioli@unicam.it (G. Caprioli).

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but established in the United States since the mid-19th century, where it is now the world's largest producer of almonds (Silberfeld & Reeb, 2013). In Morocco, the almond tree is the second most cultivated species after the olive tree and plays an important socio-economic role. It generates thousands of working days and several million dirhams (Morocco's official monetary currency) in commercial value, with applications in the food, pharmaceutical and cosmetic industries (FAOSTAT, 2019). It includes two cultivars based on flavor: sweet almonds "*Prunus Amygdalus dulcis*" and bitter almonds "*Prunus Amygdalus amara*" (Yada et al., 2013).

In the literature, various studies have explored the nutritional value, chemical composition of almond oil, and genetic analysis (Kodad et al., 2011; Melhaoui et al., 2021; Vichi et al., 2020). However, none have compared the physicochemical parameters, chemical composition, phenolic compound contents, and antioxidant activity of polar and apolar extracts from four different almond cultivars— *Beldi* Bitter Almond "BA" and three sweet almond cultivars: *Beldi* "SA", *Fournat de Breznaud* "FN", and *Marcona* "M"—from different geographic origins (Taza, Al-Hoceima, Berkane, and Oujda) in the northern region of Morocco. Recent studies have focused on the pharmacological aspects of bitter almonds. Indeed, with Chahibakhsh et al. (2019) it has been demonstrated that bitter almond decreases insulin and HOMA-IR without affecting HbA1c. Additionally, amygdalin, one of the main active ingredients in bitter almonds, has been reported to have anti-tumor effects in solid tumors such as lung cancer, bladder cancer, and renal cell carcinoma (Shi et al., 2019).

Furthermore, the objective of this research was to comprehensively explore the effects of regional variations and different cultivars on the chemical composition (fatty acids, sterols, and tocopherols), pigment content (chlorophylls and carotenoids), and oil characteristics (free fatty acids, peroxide value, iodine value, specific extinction coefficients) of almonds from four specific cultivars in the northern region of Morocco. Additionally, this study aimed to evaluate the content of bioactive compounds (sugars, polyphenols, flavonoids) and the antioxidant activity (DPPH, ABTS) of these almonds. Special attention was given to the differences between bitter and sweet almonds and the identification of their potential health benefits. This work is distinguished by its innovative approach to address existing gaps in the literature on the chemical and bioactive characteristics of almonds from this specific region, thereby offering new insights into the nutritional advantages and antioxidant properties of these sweet local cultivars.

The benefits of bitter almond are used in medicine to combat problems, but they can not be eaten by consumers to combat health problems because they are toxic to humans. It has been suggested that the number of bitter almonds that can cause fatal poisoning due to cyanide release varies from 6 to 10 almonds (Zebbiche et al., 2013). However, under appropriate medical supervision, bitter almonds can be a good alternative for prevention or complementary treatment.

2. Material and methods

2.1. Materials and experimental design

2.1.1. Chemicals and reagents

All reagents and solvents utilized in this study were of analytical or HPLC grade. Specifically, ABTS (2,2′-azino-bis-3-ethylbenzothiazoline-6-sulphonic acid), DPPH (2,2-diphenyl-1-picrylhydrazyl), Folin-Ciocalteu reagent (for phenolic content), tocopherol isomer standards (with ≥98%), vitamin E homologues (α, β, and γ), and the standard fatty acid methyl ester (FAME) mixture for chromatographic analyses were obtained from Sigma-Aldrich Co. (St. Louis, MO, USA). Solvents such as methanol, hexane, isooctane, isopropanol, and cyclohexane were HPLC grade, while other solvents were of analytical grade, all sourced from Professional Lab (Casablanca). Additionally, all glassware, including Soxhlet extractors, condensers, round bottom flasks, funnels, and Erlenmeyer flasks, was made of borosilicate glass and purchased from Borosil Scientific Glassware, Mumbai, India.

2.1.2. Plant material

Almond is one of the most polymorphic cultivated fruit species, with two major cultivars based on taste: the bitter almond (*Prunus amygdalus "amara"*) and the sweet almond (*Prunus amygdalus "dulcis"*) (Martínez-Gómez et al., 2007, pp. 229–242). The sweet almond is the predominant type cultivated globally, while the bitter almond is recessive (Borràs et al., 2014). The bitterness of almonds is determined by the amount of amygdalin in the kernel, a cyanogenic glucoside that degrades into glucose, benzaldehyde (which imparts a bitter flavor), and hydrogen cyanide (a toxic compound) in response to crushing of the kernel and enzymatic hydrolysis (Dicenta et al., 2002). A single gene controls the bitter characteristic in almonds, with a sweet allele (Sweet Kernel, Sk) that is dominant over the bitter one (sk) (Heppner, 1923; 1926; Dicenta et al., 2007). The Sk gene has been mapped to linkage group five of the almond genome (Sánchez-Pérez et al., 2010), and its chromosome 5 position and function were recently elucidated (Arus et al., 2020; Sánchez-Pérez et al., 2010). After crossing, three genotypes are expected: homozygous SkSk (sweet), sksk (bitter), and heterozygous Sksk (sweet or semi-bitter) (Vichi et al., 2020). Indeed, Dicenta and García (1993) suggested that semi-bitter forms correspond to heterozygous trees (Sksk), where the recessive allele may induce a slightly bitter taste. All semi-bitter forms are heterozygous, but not all heterozygous forms are semi-bitter.

The almond groves of eastern Morocco primarily consist of seedlings known as the "*Beldi*" type, complemented by plantations of varying sizes featuring selected and productive introduced cultivars, mainly *Marcona* and *Fournat de Breznaud* (Mahhou & Dennis, 1992). For this study, four regions—Taza, Al-Hoceima, Berkane, and Oujda—were selected based on their reputation for producing high-quality almonds and their distinct geographic and environmental conditions. In January 2019, almonds were harvested and purchased from these regions.

- **Aknoul** (34° 38′ 59″ N, 3° 52′ 00″ W): A town in northeastern Morocco, situated at an altitude of 955 m in the central-eastern part of the Rif region. It is in the province of Taza, on the road linking Taza to Nador.
- **Imzouren** (35° 09′ N, 3° 52′ W): Located in the province of Al Hoceima on the northern coast of Morocco along the Mediterranean Sea, in the Rif region, within the Tanger-Tétouan-Al Hoceima area. It is situated at an altitude of 129 m.
- **Sidi Bouhria** (34° 44′ 21″ N, 2° 21′ 44″ W): A town in Berkane Province, Oriental, Morocco. It is situated at an altitude of 720 m.
- **Aïn Sfa** (34° 45′ 0″ N, 2° 8′ 24″ W): A rural Moroccan commune in the prefecture of Oujda-Angad, in the Oriental region. It is situated at an altitude of 703 m.

Four different almond cultivars were studied: one bitter almond cultivar, *Beldi* 'BA', and three sweet almond cultivars, *Beldi* 'SA', *Fournat de Breznaud* 'FN', and *Marcona* 'M'. Samples were collected from each cultivar in the four selected regions, resulting in a total of 16 samples. The almonds were manually shelled, and the kernels were dried at 40 °C for 48 h before being finely ground using a mechanical grinder. The resulting almond powders were utilized immediately to produce extracts, which were then assessed for their chemical composition and antioxidant activity. For each almond cultivar, three samples were prepared and subjected to chemical analysis.

2.1.2.1. Determination moisture content. The water and volatile matter content of the almonds seeds was established by the drying procedure in an oven (VWR, Sheldon manufacturing, INC. Cornelius, Oregon, USA) at 105 °C ± 5 °C (Chatoui et al., 2020). This parameter is expressed in percentage by calculating it by the following formula (1):

$$M(\%) = \frac{m1 - m2}{m1} \times 100 \quad (1)$$

M: Moisture content (%)

m1: Weight of the test sample before drying (g)
m2: Weight of the test sample after drying (g)

2.1.2.2. Mineral content. The mineral content was determined using Inductively Coupled Plasma (ICP), which is used to measure the content of an inorganic element present in a sample. ICP sample analysis consists of several stages.

Firstly, mineralization involves the dissolution of the samples by using concentrated nitric acid HNO_3 (65%, Suprapur), followed by heating at 1200 W to accelerate the acid etching process. Afterwards, samples is vaporized in argon plasma and heated at high temperatures (190 °C). These thermal excitations lead to ionization and separation of the elements, making it possible to characterize and detect each element (Rehan et al., 2021).

The analysis technique used is Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES), with inductively coupled plasma comprising a computer-controlled atomic emission spectrometer with bacmeqround correction and a high-frequency generator.

The final concentration is calculated using the following formula (2):

$$C = \frac{(Cd - Cb) \times V \times F}{W} \quad (2)$$

C: Concentration of the element in the original sample (mg/kg).

Cd: Concentration of the element in the sample solution (mg/L)
Cb: Average concentration of the element in the reagent blanks (mg/L)
V: Dilution volume of digested solution (mL)
F: Dilution factor
W: Dry weight of sample (g)

2.1.3. Fat content determination

Fifty grams of powdered almond seeds were blended using an electric blender (Moulinex, model LM422125, Lyon, France), then transferred into a cellulose paper cone and extracted in a Soxhlet apparatus for 8 h with 250 mL of n-hexane at 60 °C. The lipid fraction was collected as the hot solvent cycled continuously through the matrix by boiling and condensation. After oil recovery, the same extraction thimble was used for a subsequent 8-h extraction with methanol to ensure complete extraction. The solvents were dehydrated by passing through a funnel containing Whatman No. 2 filter paper and anhydrous sodium sulfate, then removed under reduced pressure using a rotary evaporator (model VV 2000, Heidolph, Schwabach, Germany) under vacuum at 50 °C. The resultant extracts were stored in brown glass bottles at 4 °C until use (Chatoui et al., 2020). To calculate the yield, three separate extractions were performed for each type and cultivar of almond.

2.1.3.1. Determination of yields. The yields of oils and extracts derived from each extraction method were calculated utilizing this equation (3), as documented by El Ouafy et al., (2022).

$$\textit{Oil Yield}\ (\%) = \frac{\textit{weight of extract}\ (g)}{\textit{weight of almond seeds}\ (g)} \times 100 \quad (3)$$

2.2. Almond oil analysis

2.2.1. Physical and chemical oil parameters

The free fatty acids value (FFA) was determined according to the ISO 660 standard (ISO E.N. 5509: 2000, 2000). The peroxide value (PV) was established using the method described by El Bernoussi et al. (2020). The iodine value (IV) and specific extinction coefficients (K232 and K270) were measured following protocols recommended by the American Oil Chemists' Society (AOCS), specifically methods Cd 3a-94, Cd 1c-85, and Ch 5–91 (AOCS Official Method 7th Edition, n.d., p. 199). The FFA content was expressed as a percentage of oleic acid. The PV was measured by iodine titration of an almond oil solution in a 2:1 (v/v) iso-octane/acetic acid mixture with a sodium thiosulfate solution and represented as milliequivalents of active oxygen per kilogram of oil (meq O_2/kg oil). IV was calculated directly from fatty acid compositions and expressed in milligrams of iodine per 100 g of oil (mg I_2/100 g oil). K232 and K270 were measured in a 10 mm cuvette using an LLG-uniSPEC 2 spectrometer (LLG Labware, Meckenheim, Germany) at wavelengths of 232 and 270 nm, respectively, using a 1% (w/v) almond oil solution diluted in cyclohexane (Eddaoudi et al., 2023).

2.2.2. Determination of pigment content

The pigment content was determined according to the methodology of Minguez-Mosquera et al. (1991) and Gharby et al. (2018). In brief, 7.5 g of oil were dissolved in 25 mL of cyclohexane, and the absorbance values of chlorophyll and carotenoids were measured at 670 nm and 470 nm, respectively, using an LLG-uniSPEC 2 spectrophotometer (LLG Labware, Meckenheim, Germany). Chlorophyll and carotenoid contents were quantified as mg of pheophytin and lutein per kg of oil, respectively. The pigment content was calculated as follows:

$$\textit{Chlorophyll}(mg/kg) = \frac{A_{670} \times 10^6}{613 \times 100 \times d} \quad (4)$$

$$\textit{Carotenoid}(mg/kg) = \frac{A_{470} \times 10^6}{2000 \times 100 \times d} \quad (5)$$

A: Absorbance.

d: Spectrophotometer cell thickness (1 cm).

2.2.3. Fatty acid composition

According to ISO 12966–2 (2017), fatty acids (FAs) in the oils were converted to their methyl ester derivatives (FAMEs) by stirring a solution of 0.1 g of oil and 2 mL of n-hexane with 100 μL of 2 N methanolic potassium hydroxide. The hexane layer containing the methyl esters was then dehydrated with 1 g of anhydrous sodium hydrogen sulfate. The fatty acid composition was determined following ISO 12966–4 (2015). A Chromatec-Crystal 9000 gas chromatography system (Chromatec Company, Yoshkar-Ola, Russia) equipped with a flame ionization detector and a BPX70 capillary column (60 m × 0.32 mm inner diameter; 0.25 μm film thickness, Varian Inc., Middelburg, Netherlands) was used for FAME analysis. Helium served as the carrier gas at a flow rate of 1 mL/min. The injector and detector were operated at 250 °C. The oven temperature was initially set at 170 °C for 3 min, then programmed to increase to 230 °C at a rate of 4 °C/min, and maintained at this final temperature for 15 min. A 1 μL sample was injected in split mode at a ratio of 1:50. Peak identification was carried out by comparing the retention times with FAMEs from oils with known fatty acid profiles analyzed under the same conditions. The results were expressed as weight percentages (Lakhlifi El Idrissi et al., 2024).

2.2.4. Sterols composition

The content and composition of phytosterols were determined using gas chromatography (GC) following the procedure described by the International Olive Council (IOC, 2020). A total of 5 g of oil was saponified by boiling under reflux for 1 h with a 2 N ethanolic potassium solution. After saponification, 100 mL of water was added, and the unsaponifiable fraction was extracted three times with 200 mL of hexane. The solvent was evaporated, and 20 mg of the dry residue was dissolved in 0.5 mL of chloroform. This solution was then fractionated by thin-layer chromatography on silica gel, using a mixture of n-hexane and diethyl ether (65:35 v/v) as the eluent.

The plate was sprayed with a 0.2% solution of 2,7-dichlorofluorescein in ethanol, and the sterol band was carefully scraped off. The collected silica gel was suspended in 10 mL of chloroform and filtered to remove the silica. The solvent was evaporated under nitrogen, and the phytosterol composition was determined after trimethylsilylation using a Varian 3800 instrument equipped with a splitter injector type 1079 (T: 300 °C) and a flame ionization detector (FID) (T: 300 °C). Helium was used as the carrier gas at a flow rate of 1.6 mL/min. The analysis was conducted isothermally at 270 °C for 30 min on a VF-1ms capillary column (30 m × 0.25 mm i. d., 0.25 μm film thickness). An internal standard, α-cholestanol, was used for sterol quantification. Data were analyzed using Varian Star Workstation v 6.30 software (Varian Inc., Walnut Creek, CA, USA), and the results were expressed as milligrams of sterols per kilogram of oil (Lakhlifi El Idrissi et al., 2024).

2.2.5. Tocopherols composition

Tocopherol determination was performed according to ISO 9936 (2016) standards. The HPLC analysis utilized a Shimadzu LC-2050C 3D (Shimadzu, Kyoto, Japan) equipped with a fluorescence spectrophotometer detector (RF-20 A, Shimadzu, Japan) set to excitation and emission wavelengths of 290 nm and 330 nm, respectively. A LiChrospher Si-60 column (25 cm × 4.6 mm inner diameter, 5 μm film thickness, Merck, Darmstadt, Germany) was employed. A solution of 2 g of oil dissolved in 25 mL of n-heptane was filtered through a 0.45 μm PTFE membrane and injected directly using an autosampler. The mobile phase consisted of a mixture of isopropanol and isooctane (1:99, v/v) at a flow rate of 1.2 mL/min. Peak integration and quantitative calculations were performed with LabSolution software, using retention time for identification. The total and individual amounts of tocopherol were determined using external standards of tocopherol isomers, and results were expressed in milligrams of tocopherols per kilogram of oil (mg/kg) (Elouafy et al., 2022).

2.3. Almond polar extracts assays

2.3.1. Determination of phenolic content

Total phenols were quantified following the Folin-Ciocalteu spectrophotometric method described by Ait Bouzid et al. (2023). Solutions were prepared by dissolving the extract in methanol to achieve a concentration of 1 mg/mL (Eddahhaoui et al., 2022). A 0.5 mL extract solution was first mixed with 2.5 mL Folin-Ciocalteu (1/10), then sodium carbonate Na_2CO_3 (7.5%) was added. Following a 30 min incubation period at 45 °C. The absorbance was measured using an LLG-uniSPEC 2 spectrophotometer (LLG Labware, Meckenheim, Germany) at 765 nm. TPC content was calculated using gallic acid as a standard of 1–200 mg GA/100 mL in methanol. Results were expressed as mg gallic acid (GAE)/g extract.

2.3.2. Determination of flavonoids content

The flavonoid assay followed the same extraction method as the phenols. The colorimetric method outlined by El Kourchi et al. (2024). Solutions were prepared by dissolving the extract in methanol to achieve a concentration of 1 mg/mL. A 1 mL extract solution was first diluted with 6.4 mL distilled water was then diluted with 0.3 mL $NaNO_2$ solution (5%) to form the solution. After 5 min, 0.3 mL aluminum trichloride solution (10%) was mixed in, followed by 2 mL NaOH (1 M) after a further 5 min. The absorbance was measured using an LLG-uniSPEC 2 spectrophotometer (LLG Labware, Meckenheim, Germany) at 510 nm. A standard curve of Quercetin was constructed using various concentrations (2–200 μg/mL). The total flavonoid content (TFC) was determined and expressed as milligrams of Quercetin equivalents per gram of extract (mg QE/g of extract).

2.3.3. Determination of total sugar content

Quantification of the total sugar content of the five extracts was performed by the phenolic sulfuric acid method according to the protocol described by El Moudden et al., 2020. Briefly, 1 mL of each sample (1 mg/mL) was added to 1 mL of phenol (5%) and 5 mL of concentrated sulfuric acid. The mixture was left for 10 min and then incubated for 20 min in a water bath at 30 °C (Elouafy et al., 2023). Total sugar content (TSC) was determined by measuring the yellow-orange color using an LLG-uniSPEC 2 spectrophotometer (LLG Labware, Meckenheim, Germany) at 488 nm and subsequently calculated using the regression equation derived from the calibration range established with glucose (5–100 μg/mL) under identical conditions as the samples. Results are expressed as milligrams of D-Glucose equivalents per gram extract (mg D-GluE/g of extract).

2.3.4. DPPH free radical scavenging activity

The antioxidant capacity was assessed by the DPPH (1,1-diphenyl-2-picrylhydrazyl) assay. In brief, 0.2 mM DPPH solution in methanol was prepared; of this 0.5 mL was mixed with 2.5 mL of the extract at different concentrations (0.1–1 mg/mL). The mixture was vigorously mixed and was allowed to stand at room temperature (22–25 °C) for 30 min in the dark. The absorbance was then recorded at 517 nm using an LLG-uniSPEC 2 spectrophotometer (LLG Labware, Meckenheim, Germany), compared to blank samples (El-Guezzane et al., 2021). Both DPPH and methanol were used as controls. A lower absorbance of the reaction mixture correlated with a stronger free radical-scavenging activity. This scavenging activity was quantified by IC_{50} values (the extract concentration necessitating a 50% inhibition of the initial DPPH free radical) (Agbangnan et al., 2013), with results expressed in micrograms per milliliter (μg/mL).

2.3.5. ABTS radical scavenging test

The ABTS assay was performed to complement the results obtained in the DPPH assay. Preparation of the ABTS radical scavenging test began with stock solutions of 2 mM ABTS and 70 mM $K_2S_2O_8$ mixed in equal volumes and allowed to stand in the dark for 12–16 h at room temperature (22–25 °C) (Nounah et al., 2017). Prior to assay, the ABTS solution was diluted with methanol to achieve an absorbance of 0.70 ± 0.02 at 734 nm. Subsequently, 2 mL of this prepared solution was introduced to 200 μL of the almond extracts at different concentrations [1–3 μg/mL]. The reaction mixture was vortexed, and after a 30-min reaction period in the dark, the absorbance was measured at 734 nm using an LLG-uniSPEC 2 spectrophotometer (LLG Labware, Meckenheim, Germany) (Brand-Williams et al., 1995). The same was done for the Trolox standard. The results are reported as milligrams of Trolox equivalents per gram of extract (mg TE/g).

2.4. Statistical analysis

2.4.1. Data analysis

Analysis of variance was performed for the checking of the statistical significance by Tukey test at a confidence level of 95.0 % as well as the data were presented as means ± standard error of the mean using the software IBM SPSS Statistics 21. The correlation between all the results of the variables from the extracts of this study was made by the Pearson correlation. The association of the variables with the extracts from this study was carried out by PCA in the form of a graphic representation by the software XLSTAT 2014.

2.4.2. Correlation matrix

The PCA was performed out on a matrix that resumes all the data of the different physicochemical parameters of the quality (IV, PV, FFA, K270, and K232) and phenolic compounds (TPC, TTC, TFC), antioxidant activity, carotenoid content, polyunsaturated fatty acids (Linoleic (C18:2)), and total phytosterol composition. The individuals are represented by the 16 samples of almond seeds oils originating from different regions.

2.4.3. Principal component analysis (PCA)

In this work, the main component analysis (PCA) aims to establish the existence of a correlation between the different physicochemical parameters of the quality used of the almond seeds oil on the one hand, and between the phenolic compounds, antioxidant activity, chlorophyll content, carotenoid content, fatty acid, and phytosterol composition on the other hand. The main component analysis was realized on the results of physicochemical parameters quality (IV, PV, FFA, K270, and K232) and the chlorophyll content, phenolic compounds (TPC, TTC, TFC), antioxidant activity, carotenoid content, polyunsaturated fatty acids (Linoleic (C18:2)) and total phytosterol composition which represented the 14 variables and those of the 16 samples of almond seeds originating from different regions. This method facilitates the interpretation of the fundamental factors contributing most to explain the variation in physicochemical parameters quality according to geographic region of the almond seeds samples, and to investigate whether there was a correlation between the phenolic compounds (TPC, TTC, TFC), antioxidant activity, carotenoid content, polyunsaturated fatty acids (Linoleic (C18:2)), phytosterol composition, and the parameters quality.

2.4.4. Hierarchical cluster analysis (HCA)

The Pearson correlations between phenolic compounds, antioxidant capacity by two assays ABTS and DPPH, and the parameters of the quality were performed by PCA. In which PCA had expressed the 16 samples according to their response values in a graph in order to facilitate the comprehension of the variations of data depending on the origin of HCA was done to pursue the interrelatedness between extracts a cluster characteristic; moreover, the dendrogram was determined by the cluster technical of Ward and the Squared Euclidean Distance, which are considered as coefficients of similarity (El-Guezzane et al., 2021).

3. Results and discussion

3.1. Proximate composition

3.1.1. Moisture content

The moisture content was determined to assess the water content of the almond kernels, as water significantly contributes to the risk of oil oxidation (Cheftel & Cheftel, 1984). The results, listed in Table 1S, reveal that SA from Al-Hoceima had the lowest moisture content, while FN almonds from Aknoul had the highest. This variation in moisture content among different regions and cultivars can be attributed to the drying process post-harvest. Importantly, the moisture content of all almond kernels in this study did not exceed 6.12%, which is lower than the 8% threshold recommended by Brooker and Patterson for the storage of oil seeds (Brooker et al., 1992; Patterson, 1989). The lower moisture content values observed in the present study indicate that the almond kernels were adequately dried, thereby reducing the risk of microbial growth and maintaining product quality during storage (Zambrano et al., 2019).

Comparatively, the study by Ibourki et al. (2022) showed moisture content variations ranging from 2.55 ± 0.38% in BA from Tafraout to 4.34 ± 1.16% in SA from Tiznit, with an average of 3.32 ± 0.23%. Similar moisture content ranges (2.25–3.70%) were observed in Turkish almond genotypes by Simsek et al. (2018). These findings suggest that the moisture content of almonds can be influenced by geographic factors and almond type.

3.1.2. Mineral composition

The mineral content (MC) of almond kernels was determined using ICP-AES, focusing on six elements (Fe, Mn, Zn, Cr, Cd, Al) that could impact the nutritional quality of the almonds. The results from the analysis of the cultivars studied across four regions are illustrated in Fig. 1, expressed in mg/kg of almonds on a dry weight basis.

The analysis revealed that almond kernels are rich in iron (Fe), manganese (Mn), and zinc (Zn) (Fig. 1), with very low values of aluminum (Al) and no detectable chromium (Cr). Specifically, the M, BA, SA, and FN cultivars from the four regions of Morocco showed high iron levels, while the quantities of Mn, Zn, and Al did not exceed 45 mg/kg. These elements are classified as essential micronutrients required for the development of plants and animals in low doses but can be toxic at higher concentrations. Zinc (Zn) is crucial in the human diet due to its role in various biological functions, including enzyme activity and redox processes (Hayes, 1997).

In Morocco, almonds exhibit elevated zinc concentrations across all cultivars and regions. The FN cultivar from Oujda and Berkane displayed the highest concentrations, at 46.27 mg/kg and 43.48 mg/kg, respectively. These values surpass those found in walnuts (31 mg/kg), pistachios (22 mg/kg), and macadamia nuts (13 mg/kg), according to Alasalvar and Shahidi (2008). Additionally, the zinc levels in long stalk almonds (460 mg/kg) are significantly higher than those of other edible nuts (Wang et al., 2019).

Wei Wang's study noted that almond kernels are rich in various minerals, except for Fe (44.3 mg/kg), which is present in lower concentrations compared to Moroccan almonds, ranging from 25.36 mg/kg in the FN cultivar to 113.50 mg/kg in the BA cultivar from the Oujda region (Wang et al., 2019). In the study, (Cu) ranged from 9.37 mg/kg in FN Aknoul to 38.57 mg/kg in FN Berkane, while (Mn) ranged from

Table 1
Quality characteristics and pigments content of almond vegetable oils of the four regions.

	Var	FFA (%)	PV (meq O_2/kg)	IV (g I_2/100 g)	K232	K270	Car (mg/kg)	Chl (mg/kg)
Aknoul	**BA**	0.68 ± 0.08^{a}	5 ± 0.02^{a}	99.91 ± 0.09^{a}	0.614 ± 0.03^{a}	0.052 ± 0.003^{a}	0.07 ± 0.01^{a}	0.35 ± 0.12^{a}
	SA	0.56 ± 0.15^{b}	4 ± 0.06^{b}	101.55 ± 0.04^{b}	0.507 ± 0.01^{b}	0.06 ± 0.009^{b}	0.18 ± 0.01^{a}	0.35 ± 0.01^{a}
	FN	0.56 ± 0.15^{b}	2.5 ± 0.03^{c}	99.86 ± 0.08^{c}	0.859 ± 0.02^{c}	0.085 ± 0.02^{c}	0.19 ± 0.01^{a}	0.37 ± 0.04^{a}
	MA	0.51 ± 0.08^{c}	2.5 ± 0.08^{c}	99.88 ± 0.08^{c}	0.853 ± 0.02^{d}	0.076 ± 0.01^{d}	0.21 ± 0.02^{a}	0.39 ± 0.05^{a}
Al- Hoceima	**BA**	0.23 ± 0.08^{a}	1.5 ± 0.06^{a}	99.06 ± 0.04^{a}	0.506 ± 0.02^{a}	0.058 ± 0.004^{a}	0.58 ± 0.01^{b}	0.26 ± 0.04^{b}
	SA	0.23 ± 0.08^{a}	2.5 ± 0.03^{b}	99.18 ± 0.09^{b}	0.483 ± 0.02^{b}	0.038 ± 0.006^{b}	0.16 ± 0.03^{b}	0.40 ± 0.02^{b}
	FN	0.51 ± 0.08^{b}	2 ± 0.04^{c}	101.49 ± 0.01^{c}	0.577 ± 0.03^{c}	0.068 ± 0.006^{c}	0.30 ± 0.01^{b}	0.81 ± 0.06^{b}
	MA	0.4 ± 0.15^{c}	2 ± 0.07^{c}	103.05 ± 0.07^{d}	0.531 ± 0.01^{d}	0.06 ± 0.006^{d}	0.20 ± 0.01^{b}	0.51 ± 0.02^{b}
Berkane	**BA**	0.23 ± 0.08^{a}	2 ± 0.04^{a}	101.13 ± 0.06^{a}	0.55 ± 0.03^{a}	0.039 ± 0.003^{a}	0.18 ± 0.01^{c}	0.39 ± 0.07^{c}
	SA	0.28 ± 0.08^{b}	1.5 ± 0.04^{b}	100.69 ± 0.01^{b}	0.748 ± 0.02^{b}	0.045 ± 0.01^{b}	0.28 ± 0.01^{c}	0.75 ± 0.02^{c}
	FN	0.73 ± 0.08^{c}	1.5 ± 0.05^{b}	105.61 ± 0.09^{c}	0.945 ± 0.09^{c}	0.042 ± 0.005^{c}	0.17 ± 0.04^{c}	0.5 ± 0.01^{c}
	MA	0.45 ± 0.08^{d}	2.5 ± 0.06^{c}	103.83 ± 0.09^{d}	0.469 ± 0.01^{d}	0.048 ± 0.02^{d}	0.17 ± 0.04^{c}	0.69 ± 0.06^{c}
Oujda	**BA**	0.28 ± 0.08^{a}	3 ± 0.04^{a}	101.45 ± 0.02^{a}	0.907 ± 0.02^{a}	0.072 ± 0.006^{a}	0.25 ± 0.01^{d}	0.51 ± 0.02^{d}
	SA	0.45 ± 0.15^{b}	1.5 ± 0.01^{b}	103.65 ± 0.07^{b}	0.543 ± 0.01^{b}	0.057 ± 0.006^{b}	0.09 ± 0.02^{d}	0.16 ± 0.02^{d}
	FN	0.51 ± 0.15^{c}	2 ± 0.07^{c}	103.18 ± 0.04^{c}	0.689 ± 0.01^{c}	0.057 ± 0.006^{b}	0.28 ± 0.01^{d}	0.66 ± 0.01^{d}
	MA	0.45 ± 0.15^{b}	2 ± 0.04^{c}	101.01 ± 0.02^{d}	0.454 ± 0.01^{d}	0.046 ± 0.009^{c}	0.38 ± 0.01^{d}	0.94 ± 0.01^{d}

Data are presented as the mean of three individual replicates (n = 3rd ± SEM), means followed by similar superscript lowercase letters in the same column are not different ($P < 0.05$). Bitter Almond "BA," Sweet Almond "SA," Fournat "FN," and Marcona "M". Var: Variety; FFA: Free Fatty Acid; PV: Peroxide Value; IV: Iodine Value; K232 & K270: Specific Extinction; Car: Carotenoids; Chl: Chlorophyll.

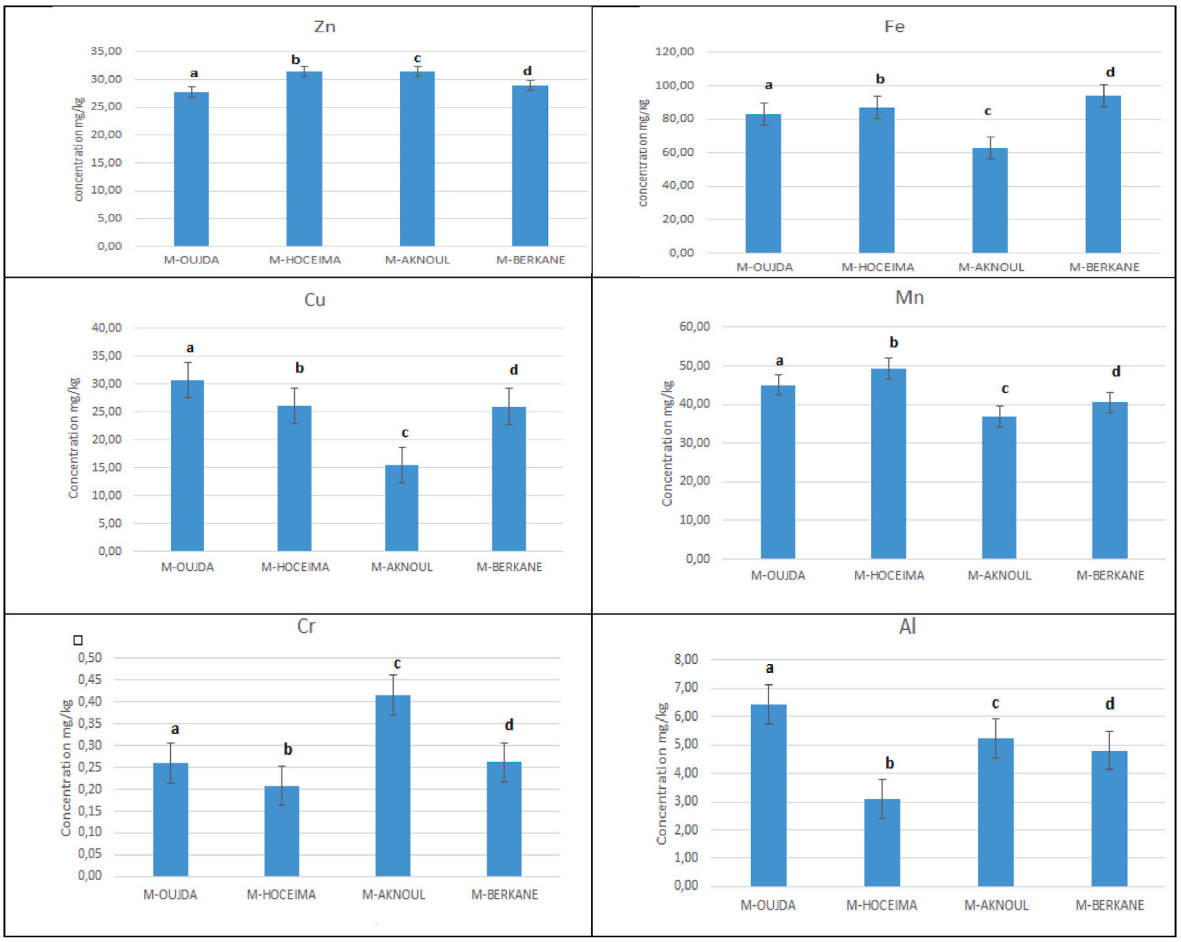

Fig. 1. Mineral elements contents in the different varieties of M, BA, SA and FN samples (mg/kg).
Data are presented as the mean of three individual replicates (n = 3rd ± SEM), means followed by similar superscript lowercase letters in the same graph are not different ($P < 0.05$).

17.43 mg/kg in FN Aknoul to 53.27 mg/kg in FN Oujda. These results are like those reported by Ibourki et al. (2022), who found that the major elements in BA and SA from different regions included K, Ca, P, and Mg, with other minerals such as Na, Cu, Fe, Zn, and Mn present in smaller amounts.

The cadmium (Cd) content in these extracts was below the detection limit (<0.002 mg/L), indicating negligible levels. Significant differences in mineral content were observed based on geographical origin, consistent with findings by other researchers for different plants and foods (Faez et al., 2013; Ibourki et al., 2022). These variations can be attributed to factors such as soil mineral composition, ecological conditions, agronomic practices, water sources, irrigation methods, fertilizer composition (Simsek et al., 2018), and the ripening stage (Schirra et al., 1994; Yada et al., 2013).

The high mineral content in almonds offers various health benefits, including improved bone health and a reduced risk of hypertension (Cockell, 2011).

3.1.3. *Extract yield*

Table 2 shows the results of the extractions yields obtained by the Soxhlet method.

The study's results indicate variations in yield among different almond cultivars and regions. The highest yield was observed in the FN cultivar from Aknoul (56.58%), followed by M from Aknoul (55%), and the SA cultivar from Al-Hoceima and M from Oujda (54.36% and 49.49%, respectively). In contrast, the lowest yield was found in the M cultivar from Al-Hoceima (40.22%). These findings align with a study by Roncero et al. (2016), which also reported that the lipid content in almonds ranges from 30% to 60%, depending on the cultivar and factors such as soil and climate conditions (Kodad, Estopanan, et al., 2014; Sathe, 1992; Yada et al., 2013). The outcomes are consistent with other studies on almonds from Turkey (43.50–55.70 g/100 g) as noted by Simsek and Demirkiran (2010) and Özcan et al. (2011), Portugal (30.00–51.00 g/100 g) as documented by Martins et al. (2000), and Morocco (52.6–58.7 g/100 g) as reported by Kodad et al. 2014.

Regarding the yield of methanolic extract, it was observed that BA had the highest yield, followed by SA, FN, and M in all regions. The BA of Berkane exhibited the highest value (14.29%), while the highest value for SA was recorded in Aknoul (10.93%). Conversely, the lowest values were found in FN and M almonds from Aknoul (3.95% and 3.94%), respectively.

These findings are consistent with the notion that different almond cultivars and growing regions can significantly influence the yield of lipids and methanolic extracts. Factors such as genetic variation, environmental conditions, and cultivation practices can all contribute to these variations. Understanding these factors can be valuable for almond growers and researchers in selecting the most suitable cultivars and optimizing cultivation practices to achieve desirable yields and extract qualities.

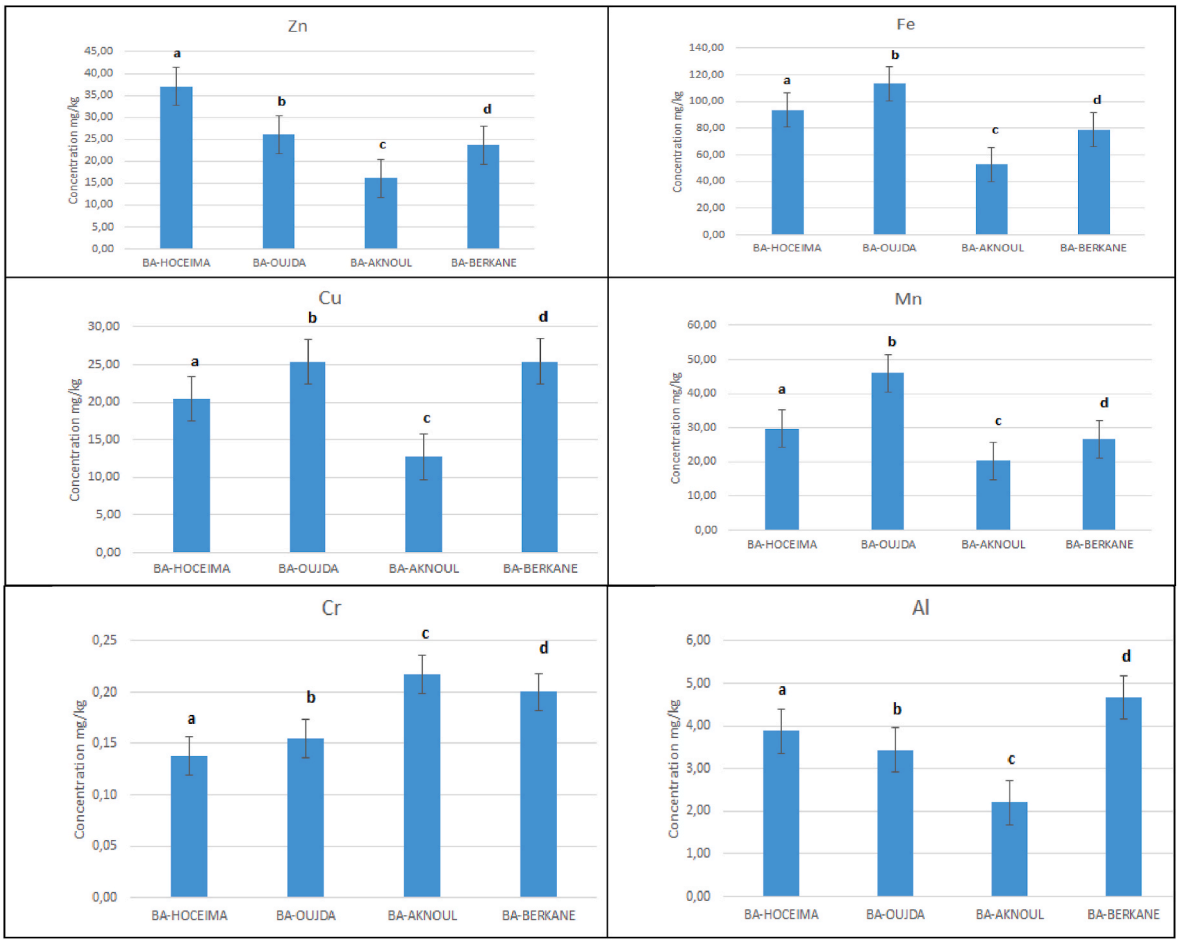

Fig. 1. (*continued*).

3.2. Non-polar extract analysis

3.2.1. Quality characteristics

Each vegetable oil is characterized by the free fatty acid, iodine value, peroxide value, extinction coefficient and other parameters to evaluate its qualities and use. In addition, the quantification of the carotenoids and the chlorophylls are necessary because of the nutritional and sanitary changes caused by their variations. The natural pigments of fats are carotenoids, chlorophylls, and their derivate. A trace of chlorophylls (670) and carotenoids (470) was found in the samples.

Table 1 summarizes the free fatty acid, peroxide value, iodine value, K232 and K270, carotenoid and chlorophyll contents of almond oils from the four cultivars in different regions of northern Morocco.

Free acidity determines the free fatty acid quantity, expressed by oleic acid. The results show that FN Berkane (0.73%) represents the cultivar with the highest FFA, and the lowest value (0.23%) was obtained in SA Al-Hoceima and BA Al-Hoceima and Berkane. These values do not exceed the recommended 5% by Codex Alimentarius for unrefined oils (Alimentarius, 1999). Lower acidity values indicate a good oil quality and the absence or inexistence of enzymatic hydrolysis of acylglycerols (Álvarez-Ortí et al., 2012). These results differ slightly from those reported by Melhaoui et al. (2021), where values ranging from 0.33% to 0.32% for M and FN from Sidi Bouhria were noted, compared to the results from Berkane in the study. The FFA% for BA oil ranges from 1.389 to 3.559% for almonds produced in the Algarve, Portugal (Martins et al., 2000), and for Bouhadi et al. (2021), it is 6.148 ± 1.212% in the Béjaïa region of eastern Algeria. These values are higher than those found in this study across all regions and cultivars. This discrepancy may be attributed to differences in seed conservation and moisture levels, as well as the influence of solvent extraction and environmental conditions.

The peroxide value is a quantitative measure of the level of primary oxidation products (hydroperoxides) in oils and fats (Gharby et al., 2018). The oils produced by the four cultivars from the four regions were of good quality in terms of hydroperoxide levels. All values obtained were below the Codex Alimentarius recommendation of not exceeding 15 meq (meq O_2/kg) (Alimentarius, 1999). The Aknoul region had the highest value 5 (meq O_2/kg) for BA, while the lowest value 1.5 (meq O_2/kg) was recorded for BA al Hoceima, SA Oujda, SA and FN from Berkane. Melhaoui et al. (2021) observed significant differences in the peroxide index ($p < 0.05$) among the four almond cultivars tested in Sidi Bouhria in eastern Morocco. The M variety had the lowest value (1.88 meq O_2/kg), followed by Ferraduel (2.44 meq O_2/kg) and FN (2.75 meq O_2/kg), while the Ferragnes variety had the highest value (3.18 meq O_2/kg). The results differ from Melhaoui's findings, where FN de Berkane (Sidi Bouhria) had the lowest peroxide value (1.5) and M had the highest (2.5) (Melhaoui et al., 2021). For BA, the peroxide value in the Béjaïa region of eastern Algeria is 19.538 ± 4.987 (Bouhadi et al., 2021), significantly higher than the values found in this study. These results suggest that the peroxide value of almonds can be influenced by environmental conditions.

The iodine values of the oils extracted from the four cultivars in the four regions were almost identical, ranging from 99 g I_2/100 g–105 g I_2/100 g oil for (BA from Al-Hoceima) and (FN from Berkane) respectively. These values fall within the range established by the Codex Alimentarius (between 85 and 106 g I_2/100 g oil) (Alimentarius, 1999). All the almond oils studied are more stable due to their high content of monounsaturated fatty acids (MUFA). The antioxidant compounds in

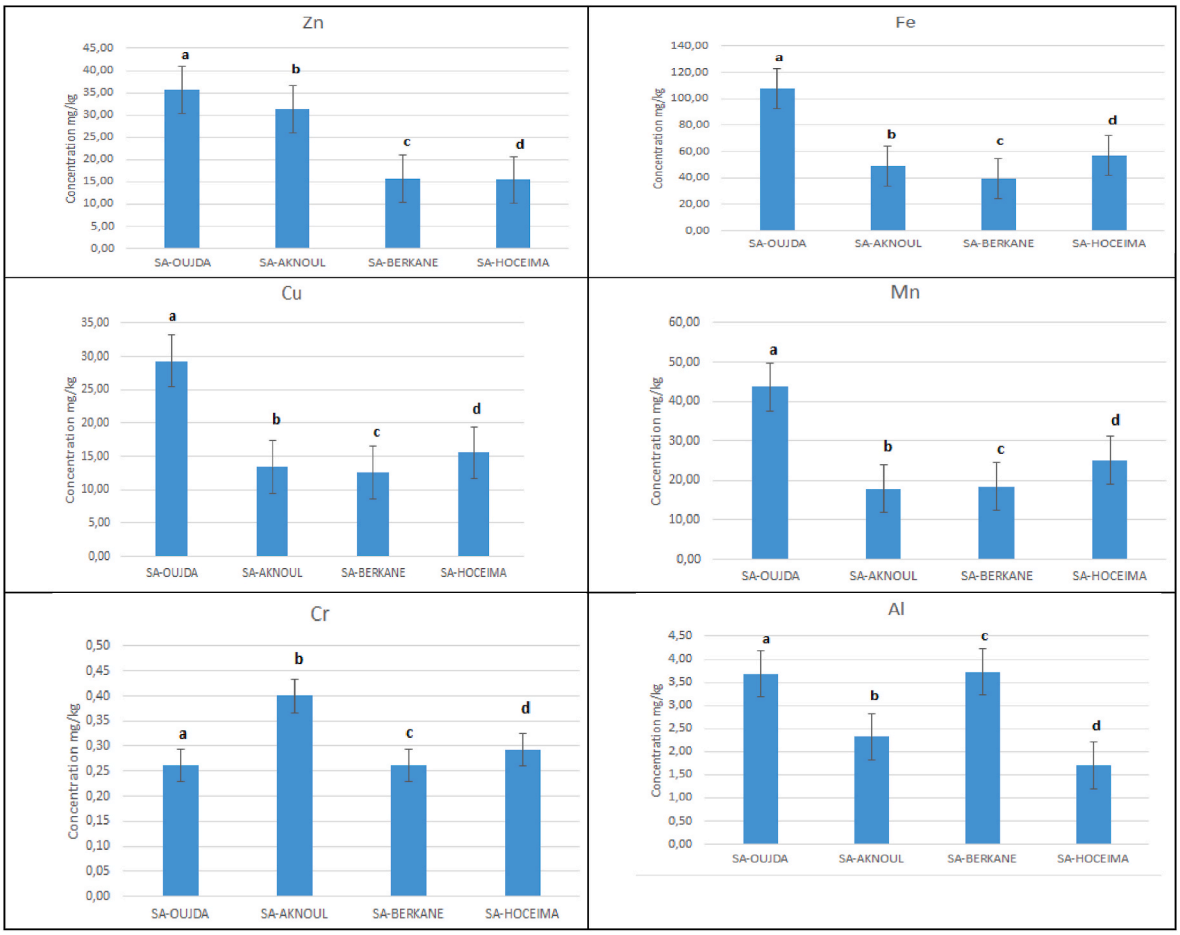

Fig. 1. (*continued*).

the oils appear to protect them from the degradation of unsaturated fatty acids (El Bernoussi et al., 2020).

Table 1 illustrates the absorption values at 232 nm (K232) and 270 nm (K270), respectively, which can be considered as an image of the oxidation state of vegetable oils, indicating the evolution of the formation of primary and secondary oxidation products (El Moudden et al., 2020). All oils studied had almost similar K232 and K270 values. For K232 they ranged from 0.454 for MA Oujda to 0.945 for FN Berkane. This is less than the 2.5 required by the 2011 International Olive Oil Council for olive oils. K270 values ranged from 0.038 for SA Al Hoceima to 0.085 for FN Aknoul. These values are well below the 0.25 value required by the standards for Argan oil and olive oil (IMANOR, 2003; COI 2011). These results agree with Boujemaa et al. (Boujemaa et al., 2020) where, whatever the species of pumpkin seed oils, quality indices vary very slightly. Bouhadi et al. (2021) demonstrated high values for both the optical density at 270 nm (0.278) and 232 nm (1.869) in BA, which were higher than all BAs in this study for specific extinction. The low values of K232 and K270 indicate that the analyzed oil is not degraded, as it was freshly extracted.

Pigment content is an essential indicator of vegetable oil quality. Carotenoids, chlorophylls, and their derivatives are the most common natural pigments present in oils (Borello & Domenici, 2019). As shown in Table 1, Al-Hoceima BA has a high carotenoid content (0.58 mg/kg), followed by Oujda M (0.38 mg/kg). Aknoul BA and Oujda SA have the lowest carotenoid contents (0.07 mg/kg and 0.09 mg/kg) respectively. Higher chlorophyll content was observed in M from Oujda and FN from Al-Hoceima. The four Aknoul cultivars gave similar values (from 0.35 mg/kg to 0.39 mg/kg). The results do not suggest a systematic effect of region and cultivar on chlorophyll content.

3.2.2. *Chemical composition*

3.2.2.1. Fatty acids composition. In almond samples, the most abundant fatty acids are oleic, linoleic, palmitic, and stearic acids, which account for approximately 95% of the total fatty acid concentration. The remaining 5% is made up of other fatty acids. Almond oil is primarily composed of oleic and linoleic acids, which make up approximately 90% of the unsaturated fatty acids present. The quantity of saturated fatty acids, particularly palmitic, palmitoleic, and stearic acids, is relatively low (Čolić et al., 2019).

Table 2 shows the fatty acid composition of almond oil from four regions (Aknoul, Al-Hoceima, Berkane, and Oujda) across the studied cultivars. Palmitic acid is the primary saturated fatty acid, with values ranging from 5.52% in M from Oujda to 7.54% in FN from Berkane. Oleic acid, the main monounsaturated fatty acid, had the highest values in BA cultivars across all regions, ranging from 73.63% in Al-Hoceima to 69.66% in Oujda. Linoleic acid, which is more prone to oxidation than monounsaturated fatty acids (Kenar et al., 2017, pp. 23–82), was highest in the FN Berkane variety (28.33%) and lowest in the BA Al-Hoceima variety (17.84%). The minor fatty acids, palmitoleic acid, and stearic acid, also varied slightly among the different oils.

Comparing results with similar studies, we find alignment with the research by Kodad and Socias i Company (2008) on the M cultivar from Spain, which reported no qualitative variation. However, the oleic acid content in M cultivars from the four regions in this study was lower than the high content (72.1%) reported by Kodad. Except for M from Oujda, the palmitic acid and palmitoleic acid content in all cultivars was higher than the findings of Kodad and Socias i Company. Additionally, the levels of stearic acid and linoleic acid in M from the four regions were

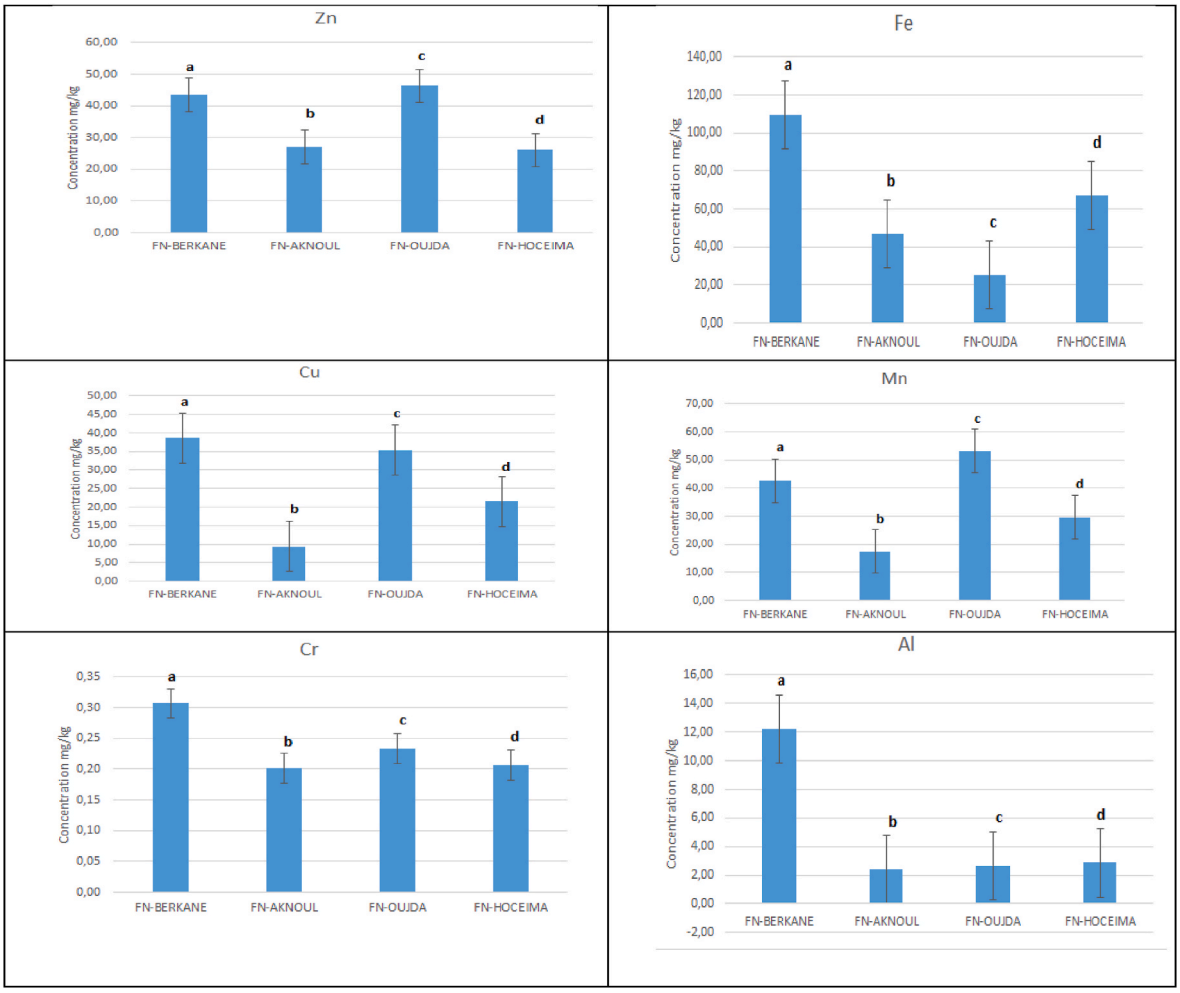

Fig. 1. (*continued*).

Table 2
Fatty acid composition (%) of almond oil from the four regions.

	Variety	Palmitic Acid	Palmitoleic Acid	Stearic Acid	Oleic Acid	Linoleic Acid
Aknoul	**BA**	6.31 ± 0.04^{a}	0.57 ± 0.05^{a}	2.19 ± 0.01^{a}	71.13 ± 0.09^{a}	19.47 ± 0.03^{a}
	SA	6.30 ± 0.09^{a}	0.48 ± 0.03^{b}	2.73 ± 0.03^{b}	68.33 ± 0.06^{b}	21.82 ± 0.06^{b}
	FN	6.89 ± 0.04^{b}	0.57 ± 0.02^{a}	2.41 ± 0.01^{c}	69.61 ± 0.01^{c}	20.18 ± 0.02^{c}
	M	6.71 ± 0.03^{c}	0.67 ± 0.06^{c}	2.41 ± 0.06^{c}	69.87 ± 0.10^{d}	20.03 ± 0.09^{d}
Al- Hoceima	**BA**	5.66 ± 0.07^{a}	0.42 ± 0.01^{a}	2.08 ± 0.04^{a}	73.63 ± 0.08^{a}	17.84 ± 0.05^{a}
	SA	6.44 ± 0.08^{b}	0.53 ± 0.09^{b}	2.01 ± 0.02^{b}	72.17 ± 0.11^{b}	18.58 ± 0.10^{b}
	FN	7.05 ± 0.10^{c}	0.68 ± 0.07^{c}	1.83 ± 0.03^{c}	68.56 ± 0.05^{c}	21.55 ± 0.08^{c}
	M	7.32 ± 0.09^{d}	0.76 ± 0.03^{d}	2.26 ± 0.06^{d}	65.39 ± 0.06^{d}	23.92 ± 0.07^{d}
Berkane	**BA**	5.65 ± 0.05^{a}	0.49 ± 0.02^{a}	1.59 ± 0.05^{a}	72.32 ± 0.05^{a}	19.59 ± 0.03^{a}
	SA	6.78 ± 0.04^{b}	0.68 ± 0.08^{b}	2.43 ± 0.07^{b}	68.74 ± 0.09^{b}	21.01 ± 0.01^{b}
	FN	7.54 ± 0.06^{c}	0.73 ± 0.03^{c}	3.59 ± 0.06^{c}	59.39 ± 0.01^{c}	28.33 ± 0.07^{c}
	M	6.83 ± 0.02^{d}	0.76 ± 0.04^{d}	2.3 ± 0.04^{d}	65.50 ± 0.02^{d}	24.32 ± 0.06^{d}
Oujda	**BA**	6.36 ± 0.03^{a}	0.42 ± 0.02^{a}	2.34 ± 0.07^{a}	69.66 ± 0.06^{a}	20.88 ± 0.04^{a}
	SA	6.99 ± 0.08^{b}	0.73 ± 0.09^{b}	2.36 ± 0.01^{a}	65.69 ± 0.12^{b}	23.85 ± 0.03^{b}
	FN	7.46 ± 0.11^{c}	0.68 ± 0.04^{c}	2.89 ± 0.03^{b}	62.04 ± 0.07^{c}	25.96 ± 0.07^{c}
	M	5.52 ± 0.06^{d}	0.33 ± 0.02^{d}	3.36 ± 0.06^{c}	68.75 ± 0.03^{d}	21.62 ± 0.09^{d}

Data are presented as the mean of three individual replicates (n = 3rd ± SEM), means followed by similar superscript lowercase letters in the same column are not different ($P < 0.05$). Bitter Almond "BA," Sweet Almond "SA," Fournat "FN," and Marcona "M"

higher than those reported by Kodad and Socias i Company.

The results align with Melhaoui et al. (2021), where the fatty acid profile of almond oil from Sidi Bouhria is approximately the same as that from Berkane in this study, showing three major fatty acids: oleic acid (C18:1) varied from 56.64% to 64.03% for FN and M, respectively; linoleic acid (C18:2) varied from 24.57% to 29.8% for M and FN, respectively; and palmitic acid (C16:0) varied from 7.22% to 8.60% for M and FN, respectively.

Another study by Matthäus et al. (2018) on local almonds in Turkey showed quantitative variations in fatty acid composition. The levels of palmitic acid (5.04%), palmitoleic acid (0.39%), stearic acid (1.99%), and linoleic acid (12.02%) were lower in the Turkish study compared to

the *Beldi* SA cultivars from the four regions of Morocco in this study. Conversely, the oleic acid level (78.86%) was higher in the Turkish study than in the *Beldi* SA cultivars from the four regions of Morocco.

In summary, findings are consistent with previous studies but also demonstrate variations in the fatty acid composition of almond oils from different regions. These variations may be attributed to genetic factors, environmental conditions, and other factors specific to each study location.

3.2.2.2. Phytosterols composition. Plant sterols, also known as phytosterols, are the main unsaponifiable constituents of vegetable oils, accounting for around 60–80% (Deme et al., 2021). These compounds are a useful parameter for detecting adulteration or proving authenticity (Oubannin et al., 2022). In addition, their identification is crucial due to their antioxidant properties and health benefits (El Moudden et al., 2020).

The chemical composition of sterols from the four regions studied (Aknoul, Al-Hoceima, Berkane and Oujda) is shown in Table 3. Analysis of the sterol fraction of the kernel revealed that it ranged from 196.34 mg/100 g to 334.13 mg/100 g for Aknoul, and from 258.10 mg/100 g to 283.05 mg/100 g for Al Hoceima, and from 264.63 mg/100 g to 310.1 mg/100 g for Berkane, and finally from 151.91 mg/100 g to 267.87 mg/100 g for Oujda. These values were similar to those reported by Kodad, with an average oil phytosterol concentration of 2600 mg/kg of oil for Al Hoceima and 2320 mg/kg of oil for Aknoul (Kodad et al., 2015).

The study carried out on the various samples showed that the sterol fraction of almond oil is constitute of two major sterols: β-sitosterol and Δ-5-Avenosterol. Two minority sterols are also found in the composition of almond oils: Campesterol and Stigmasterol.

The β-sitosterol in samples ranged from 80.97% (M Al-Hoceima) to 70.50% (M Oujda), and the Δ-5-Avenosterol from 21.81% (M Oujda) to 9.51% (M Al-Hoceima), which together accounted for >90% of phytosterols, similar to other reports on almond (Dulf et al., 2010; Normén et al., 2007; Robbins et al., 2011). Studies have shown that β-sitosterol has promising effects on normalizing T-cell function and reducing hyperactive antibody responses. On its own or in combination with other phytosterols, β-sitosterol reduces blood cholesterol levels. Lastly, numerous studies have demonstrated the value of β-sitosterol in the treatment of prostate hyperplasia (Piironen et al., 2000).

The two minority phytosterols detected were campesterol (1.99–3.82%) and stigmasterol (0.53–1.96%; Table 3). Kodad et al., 2015) also found similar campesterol values in other almonds, but their stigmasterol values were lower (0.04–0.36%) than those obtained in this study.

These results support the idea that edapho-climatic factors and cultivars can influence the sterol composition of almond oils from different geographical origins.

3.2.2.3. Tocopherols composition. Tocopherols are natural fat-soluble antioxidants that protect cells against the damaging effects of free radicals and other reactive oxygen species (Szewczyk et al., 2021). These components inhibit lipid oxidation in foods, ensuring lipid stability during shelf life and determining the nutritional values of processed foods (Oracz et al., 2014).

Total tocopherols in BA oils were higher than those determined for SA oils, except for the Aknoul region (326.81 mg/kg), which was the lowest value compared with the other cultivars. The highest value was attributed to the Oujda region (848.7 mg/kg). For SA oils, the results showed that the highest tocopherol levels were found in the SA and M cultivars for the Al Hoceima and Aknoul regions (558.5 and 513.91 mg/kg) and (489.1 and 493.7 mg/kg) respectively. For the FN variety, the highest levels were recorded in the Al Hoceima and Oujda regions (666.27 mg/kg and 574.36 mg/kg) respectively. The tocopherol concentration in almonds is reported to be affected by the climatic conditions (Kodad et al., 2006; López-Ortiz et al., 2008) and the location (Kodad et al., 2011).

Table 4
Tocopherol composition of almond vegetable oils from four regions studied (%).

	Var	T.T (mg/kg)	Alpha	Beta	Gamma
Aknoul	**BA**	326.8 ± 5 ^{a}	88.8 ± 3 ^{a}	2.23 ± 0.3^{a}	5.65 ± 0.5^{a}
	SA	513.9 ± 7 ^{b}	90.6 ± 5 ^{a}	2.16 ± 0.7^{a}	6.11 ± 0.2^{a}
	FN	391.2 ± 8 ^{c}	88.8 ± 2 ^{a}	0.79 ± 0.7^{b}	7.59 ± 0.1^{b}
	M	493.7 ± 6 ^{d}	88.9 ± 5 ^{a}	1.46 ± 0.6^{c}	6.33 ± 0.2^{a}
Al-Hoceima	**BA**	656.4 ± 10 ^{a}	94.02 ± 2 ^{a}	1.8 ± 0.1^{a}	2.59 ± 0.3^{a}
	SA	558.5 ± 7 ^{b}	93.1 ± 5 ^{a}	1.09 ± 0.9^{a}	3.75 ± 0.4^{b}
	FN	666.2 ± 5 ^{a}	84.1 ± 1 ^{b}	1.47 ± 0.7^{a}	5.86 ± 0.9^{c}
	M	489.1 ± 7 ^{c}	89.04 ± 6 ^{b}	1.58 ± 0.5^{a}	3.9 ± 0.6^{b}
Berkane	**BA**	583.4 ± 10 ^{a}	93.56 ± 3 ^{a}	1.73 ± 0.8^{a}	1.44 ± 0.6^{a}
	SA	486.3 ± 9 ^{b}	94.73 ± 2 ^{a}	1.75 ± 0.7^{a}	2.24 ± 0.8^{b}
	FN	395.1 ± 10 ^{c}	91.75 ± 7 ^{a}	1.61 ± 0.6^{a}	1.8 ± 0.1^{a}
	M	406.1 ± 7 ^{d}	94.5 ± 2 ^{a}	1.3 ± 0.6^{a}	2.37 ± 0.3^{b}
Oujda	**BA**	848.7 ± 8 ^{a}	91.2 ± 6 ^{a}	2.4 ± 0.9^{a}	4.1 ± 0,1^{a}
	SA	425.8 ± 6 ^{b}	94.4 ± 6 ^{a}	0.38 ± 0.1^{b}	2.27 ± 0.2^{b}
	FN	574.3 ± 9 ^{c}	93.8 ± 5 ^{a}	0.73 ± 0.7^{b}	3.17 ± 0.6^{c}
	M	381.8 ± 8 ^{d}	86.5 ± 1.2 ^{b}	1.06 ± 0.8^{b}	4.42 ± 0.6^{a}

Data are presented as the mean of three individual replicates (n = 3rd ± SEM), means followed by similar superscript lowercase letters in the same column are not different (P < 0.05). Bitter Almond "BA," Sweet Almond "SA," Fournat "FN," and Marcona "M". Var: Variety; T.T: Total Tocopherols.

Table 3
Composition of the sterol fraction, of the almond oils from the four regions studied (%).

	Var	S.T (mg/100 g)	Camp	Stigma	β-sito	Δ-5-Aven
Aknoul	BA	334.13 ± 0.56^{a}	2.89 ± 0.05^{a}	1.34 ± 0.03^{a}	73.95 ± 0.50^{a}	14.52 ± 0.12^{a}
	SA	219.42 ± 0.34^{b}	2.78 ± 0.03^{b}	0.73 ± 0.10^{b}	76.38 ± 0.20^{b}	14.69 ± 0.05^{b}
	FN	196.34 ± 0.87^{c}	3.30 ± 0.12^{c}	1.46 ± 0.10^{c}	76.37 ± 0.10^{b}	13.80 ± 0.08^{c}
	M	198.36 ± 0.65^{d}	3.14 ± 0.50^{d}	1.22 ± 0.06^{d}	77.74 ± 1.02^{c}	12.62 ± 0.08^{d}
Al-Hoceima	BA	258.10 ± 1.03^{a}	2.97 ± 0.20^{a}	1.96 ± 0.10^{a}	77.38 ± 0.90^{a}	11.31 ± 0.09^{a}
	SA	283.05 ± 0.27^{b}	2.88 ± 0.08^{b}	1.32 ± 0.09^{b}	73.61 ± 0.60^{b}	15.85 ± 0.25^{b}
	FN	268.40 ± 0.54^{c}	3.09 ± 0.10^{c}	1.81 ± 0.07^{c}	76.95 ± 0.90^{c}	12.67 ± 0.02^{c}
	M	259.10 ± 0.73^{d}	3.01 ± 0.06^{d}	1.24 ± 0.05^{d}	80.97 ± 0.06^{d}	9.51 ± 0.13^{d}
Berkane	BA	310.1 ± 1.12^{a}	2.78 ± 0.30^{a}	1.86 ± 0.08^{a}	79.31 ± 0.60^{a}	10.83 ± 0.06^{a}
	SA	266.44 ± 0.96^{b}	3.20 ± 0.12^{b}	1.44 ± 0.07^{b}	78.91 ± 0.81^{b}	9.88 ± 0.15^{b}
	FN	279.93 ± 1.03^{c}	3.82 ± 0.07^{c}	0.89 ± 0.06^{c}	78.94 ± 0.15^{c}	10.42 ± 0.10^{c}
	M	264.63 ± 0.73^{d}	3.14 ± 0.20^{d}	1.07 ± 0.06^{d}	80.13 ± 0.36^{d}	10.38 ± 0.09^{d}
Oujda	BA	151.91 ± 0.85^{a}	2.77 ± 0.06^{a}	1.86 ± 0.09^{a}	78.36 ± 0.10^{a}	11.41 ± 0.03^{a}
	SA	267.87 ± 0.67^{b}	3.46 ± 0.09^{b}	1.44 ± 0.1^{b}	78.46 ± 0.25^{b}	11.04 ± 0.08^{b}
	FN	239.24 ± 0.98^{c}	3.74 ± 0.15^{c}	1.21 ± 0.07^{c}	81.71 ± 0.06^{c}	7.98 ± 0.05^{c}
	M	266.50 ± 0.82^{d}	1.99 ± 0.12^{d}	0.53 ± 0.08^{d}	70.50 ± 0.63^{d}	21.81 ± 0.08^{d}

Data are presented as the mean of three individual replicates (n = 3rd ± SEM), means followed by similar superscript lowercase letters in the same column are not different (P < 0.05). Bitter Almond "BA," Sweet Almond "SA," Fournat "FN," and Marcona "M". Var: Variety; S.T: Total sterol; Camp: Campesterol; Stigma: Stigmasterol. β-Sito: β-sitosterol; Δ-5 avena: Δ-5 avenasterol.

Table 4 distinguishes three tocopherols: α-tocopherol, which is the major homologue, followed by γ-tocopherol and β-tocopherol. These results confirm those reported in other almond cultivars and selections (Kodad et al., 2006; López-Ortiz et al., 2008).

The α-tocopherol content varies, with values ranging from 84.1% for FN from Al Hoceima to 94.73% for SA from Berkane. Kodad's results (2014; 2011) for α-tocopherol in Aknoul ranged from 411 (mg/kg oil) in 2010 to 439 (mg/kg oil) in 2009, while for M, they varied from 393.9 (mg/kg oil) in 2008 to 340.9 (mg/kg oil) in 2009. Findings align with these results, with the α-tocopherol values for SA cultivars in Aknoul ranging from 347.46 (mg/kg) for FN, 439.12 (mg/kg) for M, and 466.01 (mg/kg) for SA *Beldi*. According to Melhaoui et al. (2021), the α-tocopherol content for FN from Sidi Bouhria is 473.55 mg/kg and 456.64 mg/kg for M, while in this study, the α-tocopherol content from Berkane slightly differs from previous findings, with 362.56 mg/kg for FN and 383.73 mg/kg for M. Furthermore, the α-tocopherol content for M and FN differs from those found in Spain (470 mg/kg), with the highest rate (595 mg/kg) recorded for M in Argentina.

For BAs, γ-tocopherol levels range from 1.44% in Berkane to 5.65% in Aknoul, while β-tocopherol ranges from 1.73% in Berkane to 2.4% in Oujda. In SA, γ-tocopherol content varies from 1.8% in FN from Berkane to 7.59% in FN from Aknoul. Conversely, β-tocopherol exhibits lower levels, averaging from 0.38% in SA from Oujda to 2.16% in SA from Aknoul. Melhaoui et al. (2021) reported γ-tocopherol ranging from 2.29 mg/kg to 14.77 mg/kg, and β-tocopherol ranging from 1.67 mg/kg to 3.43 mg/kg for M and FN, respectively.

Several factors can affect tocopherol content, such as the oil extraction process, drying maturity, storage conditions, climate, variety as well as region and method of tocopherol determination (Murkovic et al., 1996; Rabrenović et al., 2014). It is noteworthy that tocopherols and their isomers have very significant antioxidant capacity and may, therefore, play an important role in the control or prevention of pre-diabetes, insulin, and vascular damage (Boujemaa et al., 2020; de Oliveira et al., 2012; Manchanda et al., 2018, pp. 773–831).

3.3. Polar extract analysis

The quantitative analysis of the total sugars (TSC) as well as the polyphenols (TPC), and flavonoids (TFC) of the different extracts of sweet and bitter almonds was carried out by spectrophotometer. The results obtained are shown in Table 5.

3.3.1. Quantification of sugar

Calculation of the total amount of carbohydrates present in a sample by means of the "total sugar method". According to the results, the highest sugar content was reported in BA and SA from Aknoul with a value of 593.89 and 577.89 (mg D-GluE/g), followed by FN from Berkane and M from Al-Hoceima with a content of 570.78 and 525.89 (mg D-GluE/g) respectively. The lowest levels were found in samples from FN and M Aknoul, with values of 149.11 and 163.22 (mg D-GluE/g), respectively. These results are twice high as those found in Argan seeds (336.30 mg D-GluE/g) (Idrissi et al., 2023). It can be said that sugar content is strongly influenced by plant species and choice of solvent (Idrissi et al., 2023), and by cultivar and region for the almonds.

3.3.2. Total phenolic content

Phenolic compounds are natural secondary metabolites that present many biological effects, where the antioxidant capacity is the most important characteristic mainly for its beneficial impact on health (Rahman et al., 2021).

The results of the total polyphenol assay show that SA Al-Hoceima extract is the richest in polyphenols, with a value of 47.15 (mg EGA/g extract), followed by M of Oujda 25.18 (mg EGA/g extract). The lowest levels were recorded in BA from Oujda and Al-Hoceima and M from Berkane with 3.52 and 3.53 and 3.59 (mg EGA/g extract) respectively. Bouhadi et al. (2021) quantified total polyphenols in BA oil using the Folin Ciocalteu method, finding a value of 0.137 mg gallic acid/mL. Qi et al. (2019) reported that the total phenol content in extracted almond oil ranged from 4.71 mg/100 g to 11.75 mg/100 g. According to Melhaoui et al. (2021), the total phenolic content in almond oils ranged from 85.33 mg/kg for FN to 141.66 mg/kg for M in Sidi Bouhria. Findings indicate higher phenolic compound levels than those in both BA (3.18–10.9 mg EGA/g extract) and SA (3.59–47.15 mg EGA/g extract).

Phenolic compounds contribute significantly to the oxidation stability of oils. It is important to consider various factors that can influence polyphenolic content, including climatic and environmental conditions, genetic factors, and experimental procedures. Additionally, differences in extraction methods, evaluation, and expression of results between studies should be considered (Bouhadi et al., 2021).

The results obtained show that flavonoid content follows the same logic as that of polyphenols. Similar to polyphenols, the total flavonoid content varies between different cultivars and regions of the plant. Quantitative assay of total flavonoids reveals that FN extracts from Al-Hoceima and Oujda are more abundant in flavonoids, with contents of 10.56 and 10.26 (mg EQE/g extract), as are SA and FN extracts from Berkane, with 8.18 and 7.66 (mg EQE/g extract). Cultivars in the Aknoul region, except for M, do not exceed 1 (mg EQE/g extract). This could be due to environmental factors (high altitude (955 m), high rainfall and cold winter).

3.3.3. Evaluation of the antioxidant activity

The antioxidant activity of the almond extract was assessed using the DPPH method, which measures the reduction of the DPPH radical resulting in a color change from violet to yellow at 517 nm, with results expressed as the IC_{50} value. Representing the concentration corresponding to 50% inhibition.

In addition to the DPPH method, we employed the ABTS test as a

Table 5
Sugars (mg D-GluE/g), polyphenols (mg EGA/g) and flavonoids (mg EQE/g) contents of methanol extracts of almond in the four regions studied.

		BA	*SA*	*FN*	*M*
Aknoul	TSC	593.89 ± 1.49^{a}	577.89 ± 0.08^{b}	149.11 ± 0.47^{c}	163.22 ± 1.96^{d}
	TPC	10.9 ± 2.42^{a}	9.78 ± 2.14^{b}	10.57 ± 2.33^{c}	13.99 ± 0.66^{d}
	TFC	0.39 ± 0.18^{a}	0.91 ± 0.37^{b}	0.52 ± 0.37^{c}	1.5 ± 0.46^{d}
Al-Hoceima	TSC	312.44 ± 10.37^{a}	262.44 ± 6.84^{b}	439.78 ± 2.67^{c}	525.89 ± 1.49^{d}
	TPC	3.53 ± 0.74^{a}	47.15 ± 8.65^{b}	15.56 ± 2.88^{c}	8.59 ± 0.9^{d}
	TFC	1.23 ± 0.09^{a}	6.95 ± 0.09^{b}	10.56 ± 0.38^{c}	4.15 ± 0.09^{d}
Berkane	TSC	521.56 ± 0.79^{a}	478.56 ± 10.14^{b}	570.78 ± 4.32^{c}	513.56 ± 7.54^{d}
	TPC	31.29 ± 3.54^{a}	16.82 ± 0.74^{b}	5.30 ± 2.33^{c}	3.59 ± 2.51^{d}
	TFC	3.18 ± 1.01^{a}	8.18 ± 0.37^{b}	7.66 ± 0.55^{c}	1.1 ± 0.09^{d}
Oujda	TSC	174.56 ± 6.68^{a}	299.33 ± 1.02^{b}	204.44 ± 6.44^{c}	176.56 ± 4^{d}
	TPC	3.52 ± 1.12^{a}	6.09 ± 0.65^{b}	15.37 ± 0.75^{c}	25.18 ± 0.66^{d}
	TFC	2.47 ± 0.46^{a}	5.65 ± 1.01^{b}	10.26 ± 0.19^{c}	6.37 ± 0.19^{d}

Data are presented as the mean of three individual replicates (n = 3rd ± SEM), means followed by similar superscript lowercase letters on the same row are not different ($P < 0.05$). Bitter Almond "BA," Sweet Almond "SA," Fournat "FN," and Marcona "M". TSC; total sugars, TPC: total polyphenols, TFC: total flavonoids.

complementary approach. The ABTS cation radical is stable and easily formed by oxidation of its corresponding acid in the presence of potassium persulfate. Table 3S summarizes the antioxidant activity of DPPH free radical extracts from different almond cultivars across various regions of northern Morocco, with the ABTS test chosen as a complementary assessment in this study.

The DPPH free radical activity was measurably better for the SA variety from Al Hoceima (IC_{50} = 63.47 μg/mL) than for the other almond cultivars. However, the BA variety from all the regions studied had a very high IC_{50} compared to the other cultivars, with values as high as (966.9 μg/mL) for BA Al Hoceima.

However, a high quantity of polyunsaturated fatty acids (PUFA) in oils can lead to rapid oxidation (Arab et al., 2022). The SA variety from Al-Hoceima showed a higher antioxidant activity, which can be explained in part by the levels of tocopherols (558.5 mg/kg) in the oil, and TPC (47.15 mg EAG/g extract). Similarly, the presence of polyphenols and carotenoids prevents the damaging effects of free radicals by strengthening the antioxidant defense mechanism, and thus helps to combat hypertension, type 2 diabetes, and cancer (Kulczyński & Gramza-Michałowska, 2019).

The results obtained showed that the inhibitory action by ABTS requires a high concentration of samples to exhibit its antioxidant power. In all regions, the BA variety was less effective against the ABTS radical than the other three cultivars. One of the highest values (19.48 mg TE/g extract) was obtained from the SA Al Hoceima variety. These results confirm previous conclusions on the anti-free radical activity of DPPH. In conclusion, *Beldi* SA seeds have a good antioxidant activity according to the DPPH, and ABTS test.

3.4. Statistical analysis

3.4.1. Hierarchical clustering analysis HCA

According to HCA, the different extracts were classified by the squared Euclidean and Wards method to estimate the similarity measure. HCA was used to evaluate the correlation between the oil's samples and to highlights similarities of the 16 samples from almond seeds oils based on phenolic compounds (TSC, TPC, TFC), antioxidant activity (DPPH, ABTS), carotenoid content, polyunsaturated fatty acids (Linoleic (C18:2)), phytosterol composition, and the parameters quality (Fig. 3). According to results (Fig. 3), the three extracts were clustered into three Clusters.

Cluster I contains 8 sample representing the 50% of the total samples. They are characterized by a strong mean level of Linoleic Acid (22.501%), and a high mean value of total sterol (275.269 mg/100 g), FFA (0,480% of oleic acid), peroxide value (2.563 meq O_2/kg), TST (527.75 mg D-GluE/g), K270 (0.052), and iodine value (102.158 g I_2/100 g of oil). Moreover, they had a medium mean value of K232 (0.61), Chlorophyll (0.544 mg/kg). Furthermore, even they showed a low mean values of Carotenoid (0.194 mg/kg), TPC (12.355 mg EGA/g extract), and TFC (4.516 mg EQE/g extract), Therefore, they are characterized by low antioxidant potential (DPPH assay) comparable to other clusters.

Cluster II contained 5 sample oil, representing the 31.25% of the total samples. They are characterized by a strong mean level of K232 (0.75), K270 (0,067), Carotenoid (0.194 mg/kg), Chlorophyll (0.574 mg/kg), Moreover, they display a medium mean value of Linoleic Acid (21.734%), FFA (0.452% of oleic acid), peroxide value (2.4 meq O_2/kg), iodine value (101.076 g I_2/100 g of oil), and Carotenoid (0.262 mg/kg). Also, this cluster is characterized by a medium mean value of TPC (13.72 mg EGA/g extract), and antioxidant activities by DPPH and to other clusters. Furthermore, they showed a low mean value of total sterol (210.47 mg/100 g), and TFC (4.22 mg EQE/g extract), and TST (173.75 mg D-GluE/g).

Cluster III contains 8 sample representing the 18.75 % of the total samples. It is characterized by a high mean value of carotenoid (0.277 mg/kg), TPC (18.923 mg EGA/g extract), TFC (4.610 mg EQE/g extract), and also by high antioxidant activities by DPPH and ABTS assays compared to other clusters. Moreover, they display a medium mean value of total sterol (269.67 mg/100 g), and TST (291.40 mg D-GluE/g). Furthermore, they are characterized by a low mean value of Linoleic Acid (20.09%), FFA (0.303% of oleic acid), peroxide value (1.83 meq O_2/kg), iodine value (100.63 g I_2/100 g of oil), K232 (0.511), K270 (0,051), and Chlorophyll (0.273 mg/kg). These results agree with the data of the PCA, in which the distribution of all extracts on the score plot indicates a similar trend. Furthermore, the PCA results were consistent with those of HCA.

3.4.2. Principal component analysis (PCA)

Fig. 2 represents that the 16 individuals are spread (of almond seeds oils) into 3 groups. Group I is made up of 11 individual (M(OJ), BA (BK), SA (BK), FN(AH), M(AH), M(AH), FN(OJ), M(BK), SA (OJ), BA (AKN), SA (AKN), FN(BK)), belongs from the 4 regions studied, they are characterized by the high content of the total phytosterol, chlorophyll and sugars contents, also the strong value of the iodine value (IV), which is characterized by the higher values of polyunsaturated fatty acids, Linoleic (C18:2)). Moreover, they have a high value of free fatty acid content (FFA).

Group II is formed by 2 samples SA and BA native from the Al-Hoceima. It is characterized by the high content of phenolic compounds (TPC), carotenoids content and the highest antioxidant activity by DPPH assay. Moreover, they display a medium antioxidant activity by ABTS assay.

Group III consists of 3 samples (FN, B, and M) originating from **Aknoul** and **Oujda.** The peroxide value (PV) of the 3 samples is significantly higher than other samples, but the levels of polyunsaturated fatty acids ((LinolenicC18:3) is lower than other samples of almond seeds oils of groups I and II, which shows low iodine value (IV). Moreover, they have a high value of extinction coefficient (K232 and K270) and strong antioxidant activity by ABTS assay.

3.4.3. Correlation matrix

Table 4S presents the Pearson correlation that made it possible to analyse the relationships between the different variables tested in this study. Moreover, Table 5S represents the p-values of the correlation matrix coefficient between all variables. Accordingly, we observed a positive significant correlation (p-value <0.05) between total sterol and sugar contents (TST) (r^2 = **0.604**), as well as between Linoleic Acid and FFA (r^2 = **0.528**). There was also a significant moderately negative correlation (p-value <0.05) between total sterol and K232 (r^2 = **-0.507**), and K270 (r^2 = **-0.748**). Moreover, the correlations data of TPC with DPPH free radical scavenging effect (r^2 = **0.627**) indicates that the polyphenol content of almond seeds oils contributes to its hydrogen electron donating abilities and that the antioxidant capacity of almond seeds oils can be attributed to the presence of polyphenol. The linear positive correlation between polyphenol and antioxidant capacity was also reported by several authors: Amri et al. (2015) and Guettaf et al. (2016).

Furthermore, a high significant positive correlation (p-value < **0.0001**) between iodine value (IV) and polyunsaturated fatty acids Linoleic (C18:2) (r^2 = **0.956**) has been found. The results are consistent with those obtained by Samuel et al. (2017), who indicated that the high iodine value of fluted pumpkin seed oil was correlated with the content of polyunsaturated fatty acids, which enhances the nutritional value of food products.

Aremu et al. (2006) showed that the lower the iodine value the lesser the number of unsaturated bonds. In addition, Eze, 2012 indicated that high iodine value is a pointer to the presence of high percentage of unsaturated fatty acids in the seed oil; as such, amount of iodine that will be absorbed by the unsaturated acids would be higher.

4. Conclusion

The Mediterranean climate and geomorphological characteristics of

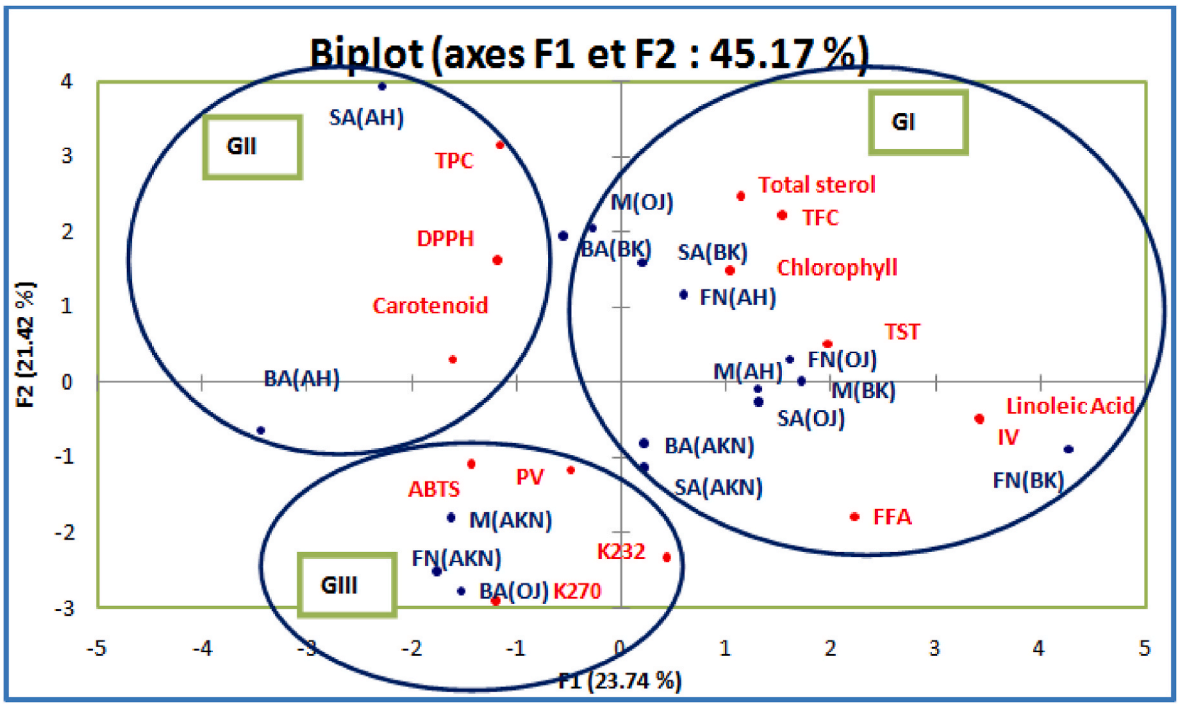

Fig. 2. Projection of individuals on the factorial plan (F1 × F2). GI: Group I; GII: Group II
SA (AH): Sweet Almond from Al Hoceima. BA (AH): Bitter Almond from Al Hoceima. M(AH): Marcona from Al Hoceima. FN(AH): Fournat from Al Hoceima. SA (AKN): Sweet Almond from Aknoul. BA (AKN): Bitter Almond from Aknoul. M(AKN): Marcona from Aknoul. FN(Akn): Fournat from Aknoul. SA (OJ): Sweet Almond from Oujda. BA (OJ): Bitter Almond from Oujda. M(OJ: Marcona from Oujda. FN(OJ): Fournat from Oujda. SA (BK): Sweet Almond from Berkane. BA (BK): Bitter Almond from Berkane. M(BK): Marcona from Berkane. FN(BK): Fournat from Berkane.

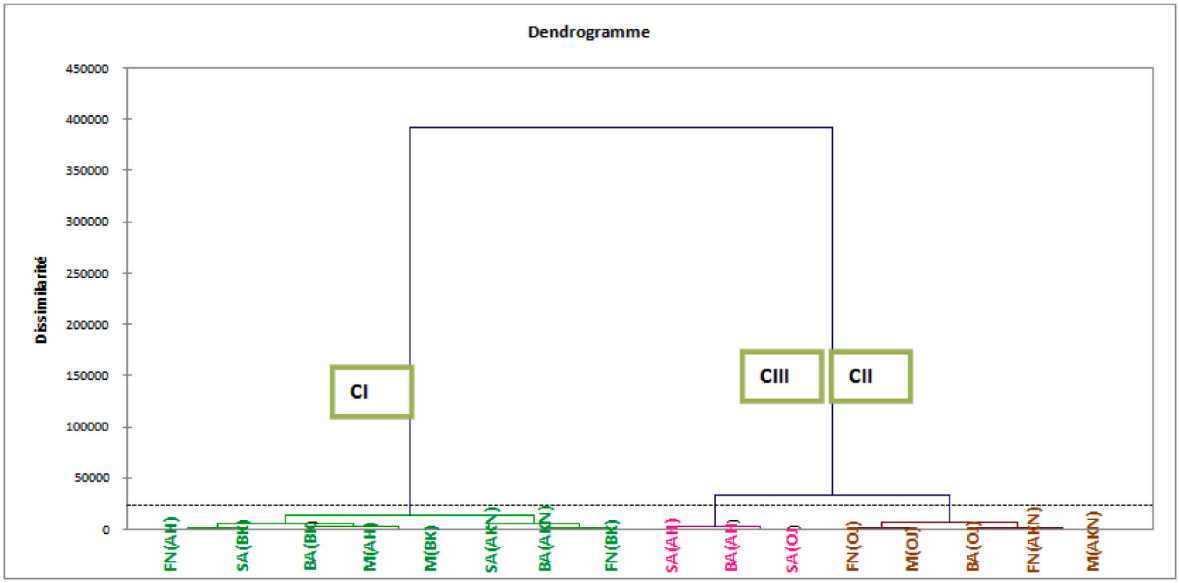

Fig. 3. Dendrogram of the sample's oils studied obtained by cluster analysis (Ward and Euclidean distance)
SA (AH): Sweet Almond from Al Hoceima. BA (AH): Bitter Almond from Al Hoceima. M(AH): Marcona from Al Hoceima. FN(AH): Fournat from Al Hoceima. SA (AKN): Sweet Almond from Aknoul. BA (AKN): Bitter Almond from Aknoul. M(AKN): Marcona from Aknoul. FN(Akn): Fournat from Aknoul. SA (OJ): Sweet Almond from Oujda. BA (OJ): Bitter Almond from Oujda. M(OJ: Marcona from Oujda. FN(OJ): Fournat from Oujda. SA (BK): Sweet Almond from Berkane. BA (BK): Bitter Almond from Berkane. M(BK): Marcona from Berkane. FN(BK): Fournat from Berkane. CI: Cluster I, CII: Cluster II, CIII: Cluster III.

Morocco provides favorable conditions for the development of a rich and varied flora-giving rise to an important potential in plants of socio-economic interest. The work has focused on the comparative study of yield, chemical composition of the vegetable oil extracted with hexane and methanolic extract of almonds (*Amygladus communis*) of the eastern region (Oujda, Berkane, Al-Hoceima, Aknoul) for the cultivars BA (*Prunus amara*) and SA (*Prunus dulcis*). The latter includes foreign one Bitter Almond *Beldi* (BA) and three SA cultivars: *Beldi* "SA", *Fournat de Breznaud* "FN", and *Marcona* "M". The studie have compared the physicochemical parameters, chemical composition, phenolic compound contents, and antioxidant activity of polar and apolar extracts.

This comprehensive analysis of almonds shows that their chemical

composition and antioxidant properties are influenced by geographical origin and cultivar. These differences in fatty acids, sterols, tocopherols, polyphenols, and flavonoids can affect the nutritional and health advantages of almond oils. The research indicates that the SA variety from Al-Hoceima stands out for its high antioxidant activity, while the BA variety was the least effective against the ABTS radical than the other three cultivars. This study highlights the critical role of the origin and variety of almond oil in determining its quality and health-related properties. Based on the findings of this study, we strongly support the cultivation and consumption of sweet almonds (*Beldi*, M and FN), as they have remarkable virtues that can significantly contribute to human well-being.

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Sara El Bernoussi: Writing – original draft, Investigation, Formal analysis. **Ihssan Boujemaa:** Methodology, Data curation. **Chakir El Guezzane:** Software, Methodology, Conceptualization. **Youssef Bouzoukni:** Visualization, Validation, Supervision. **Issmail Nounah:** Visualization, Software, Methodology. **Abdelhakim Bouyahya:** Supervision, Funding acquisition. **Riaz Ullah:** Methodology, Investigation, Funding acquisition. **Zafar Iqbal:** Methodology, Funding acquisition, Formal analysis, Data curation. **Filippo Maggi:** Supervision, Software. **Giovanni Caprioli:** Writing – review & editing. **Hicham Harhar:** Writing – review & editing, Software, Project administration. **Mohamed Tabyaoui:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2024.116587.

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