

Extraction methods and geographical variability influence on phenolic content, fatty acid composition and physicochemical quality, of Moroccan Picholine olive oils in the Fes-Meknes region[☆]

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Abstract – The study aims was to analyze the influence of extraction method and geographical origin on the quality of olive oils. Thirty samples of the "Moroccan Picholine" variety were collected from three types of crushers (hydraulic press, two-phase and three-phase) in four cities of the main Moroccan olive-growing region, Fes-Meknes, during the 2021 and 2022 harvest seasons. Oils from this region are generally of virgin and extra virgin olive oils quality, according to the International Olive Council, with high levels of oleic acid reaching up to $80.12 \pm 1.94\%$ for oils produced in Meknes, two-phase triturations. Two-phase extracted oils from Fez and Meknes show the highest MUFA/PUFA (monounsaturated fatty acids/ polyunsaturated fatty acids) ratios and lower quality parameters, indicating richness in monounsaturated fatty acids and improved oxidative stability. Polyphenol levels varied significantly between the cities of Fez, Meknes, Taounate and Taza, reaching 307.31 ± 17.44 mg/kg GAE for Fez, with notable differences ($p < 0.05$). In addition, chlorophyll and carotenoid levels differed significantly according to the type of extraction and the city of origin ($p = 0.004$ and $p = 0.042$, respectively). Principal component analysis identified three distinct groups based on extraction method and geographical location, highlighting the importance of these factors in obtaining olive oils with the specific characteristics sought.

Keywords: Virgin olive oil / qualitative composition / region / pigments / phenolic compounds / PCA

Résumé – Influence des méthodes d'extraction et de la variabilité géographique sur la teneur en phénols, la composition en acides gras et la qualité physicochimique des huiles d'olive picholine marocaines de la région de Fès-Meknès : L'objectif de cette étude était d'analyser l'influence de la méthode d'extraction et de l'origine géographique sur la qualité de l'huile d'olive. Trente échantillons de la variété "Picholine marocaine" ont été prélevés dans trois types de broyeurs (presse hydraulique, deux phases et trois phases) dans quatre villes de la principale région oléicole marocaine, Fès-Meknès, au cours des saisons de récolte 2021 et 2022. Les huiles de cette région sont généralement de qualité vierge et extra vierge, selon les paramètres physicochimiques du Conseil Oléicole International, avec des niveaux élevés d'acide oléique atteignant jusqu'à $80.12 \pm 1.94\%$ pour les huiles produites à Meknès, extraites en deux phases. Les huiles extraites en deux phases de Fès et de Meknès présentent les rapports AGMI/AGPI (acides gras monoinsaturés /acides gras polyinsaturés) les plus élevés et des paramètres de qualité basses, indiquant une richesse en acides gras monoinsaturés et une meilleure stabilité à l'oxydation. Les teneurs en polyphénols varient significativement entre les villes de Fès, Meknès, Taounate et Taza, atteignant 307.31 ± 17.44 mg/kg EAG pour Fès, avec des différences notables ($p < 0.05$). Par ailleurs, les teneurs en chlorophylle et en caroténoïdes diffèrent significativement selon le type d'extraction et la ville d'origine

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($p=0.004$ et $p=0.042$, respectivement). L'analyse en composantes principales a identifié trois groupes distincts en fonction de la méthode d'extraction et de la localisation géographique, soulignant l'importance de ces facteurs dans l'obtention d'huiles d'olive présentant les caractéristiques spécifiques recherchées.

Mots-clés : Huile d'olive vierge / composition qualitative / région / pigments / composés phénoliques / ACP

Highlights

- Geographical location and methods of olive oil extraction's impact on the quality of Moroccan olive oils from the Fez-Meknes region.
- Higher quality observed in olive oils extracted by two-phase compared to three-phase and hydraulic press methods.
- Oils from the cities of Fez and Meknes are identified as high-quality virgin and extra virgin oils.
- PCA analysis highlighted significant effects of extraction method and geographical origin.

1 Introduction

The olive tree is one of the most ancient cultivated woody plants and is particularly prevalent throughout the Mediterranean region (98% of global production) and contributes significantly to the rural economy, local heritage, and environmental protection [Elbir *et al.*, 2014](#)). In fact, since prehistoric times, the olive tree is considered a hardy, persistent tree, whose fruit is edible and with an extraordinary liquid extract used in food preparation, wound relief, strengthening of the human system and lighting at night. Olive oils is a richly traditional food product in an increasingly competitive international market, which requires ongoing research activity to meet the competitive needs of the global market.

In Morocco, the olive tree takes center stage as the primary fruit species, demonstrating rapid expansion with the olive production of 1.4 million tons in 2023 . With a coverage of 65% of the tree area, 33% of which is situated in the Fes-Meknes region, which is considered the main Moroccan olive oils producing area, with a production of 628 Kilotons (MAPM, 2024). The Fes-Meknes region is known for its exceptional production of high quality olive products, a testament to its natural resources and local know-how. Several of the region's products have been awarded the "Protected Geographical Indication label". The Zerhoun olive oils, with its dark green color and intense, medium-balanced fruity flavor, is grown on 9,100 hectares with an annual capacity of 400 tons, accompanied by the Lemta olive oil, characterized by its transparent golden yellow color and intense fruity, bitter, and spicy flavor, grown on 1,940 hectares with an annual capacity of over 6,200 tons. In addition, Outat El Haj's dense, transparent olive oil, characterized by a golden color with light green reflections and a fruity, bitter, and pungent taste, with a capacity of 6,300 tons per year on 810 hectares through two processing units, enriches this range of excellence in olive growing, in addition to Aazaba table olives ([Fes-Meknes Region, n.d.](#)).

Today, the techniques for mechanical extraction of virgin olive oils are mainly classified into two categories ([Clodoveo, 2013](#)): batch systems, generally equipped with a stone mill combined with hydraulic presses, and the continuous systems. The latter are distinguished by their ability to process olives in two or three phases. In two-phase systems, the olive oil is separated from a mixture of solid residues known as "pomace" and water. In three-phase systems, on the other hand, the olive oil is extracted using a three-phase centrifuge (horizontal axis), which separates the oil, water and pomace from the olive paste. Continuous systems, so called because of the continuous operation of two of their three components (the crusher and the decanter), generally consist of a mechanical crusher, a mixer and a horizontal centrifugal separator.

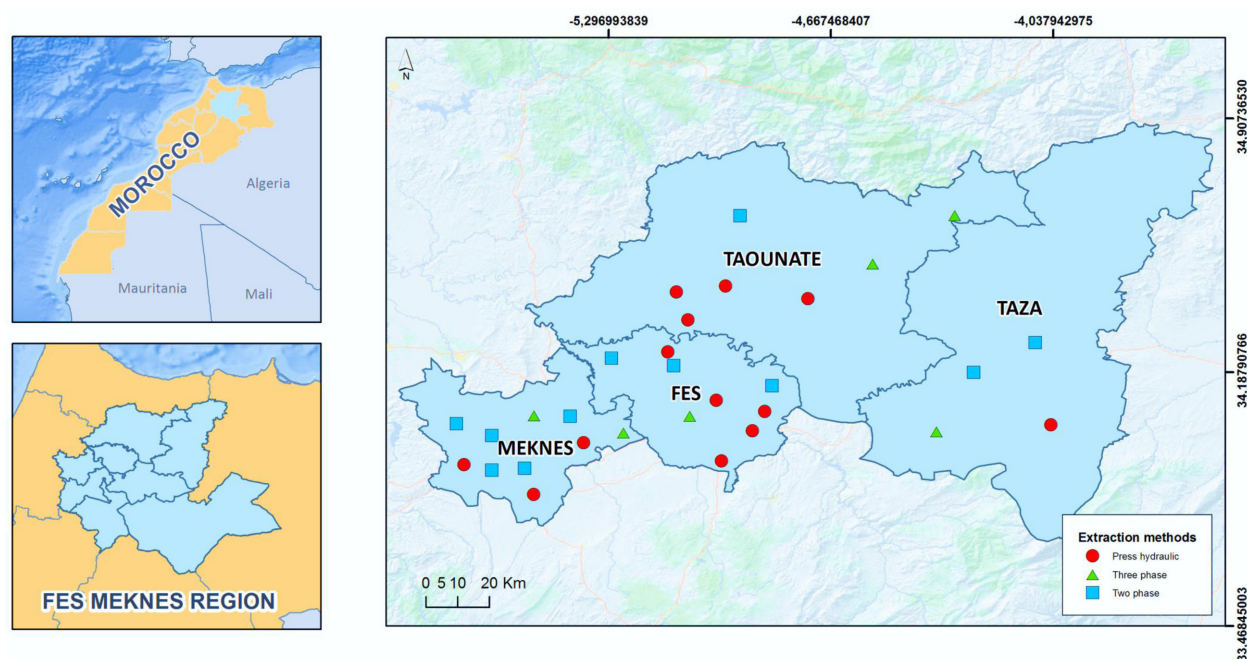
The quality of olive oils is evaluated based on multiple criteria, including physicochemical parameters, fatty acid composition, and organoleptic tests, as per the International Olive Council ([IOC, 2022](#)), Ensuring nutritional value, purity, and authenticity of olive oils accessible in markets requires effective and continuous monitoring. A thorough grasp of the composition of the fatty acids, and non-volatile minor components quantity, such as phenolic substances and pigments, enables the elaboration of high quality virgin olive oils from the local varietie of "Picholine marocaine". These varieties cover extensive arable land in Morocco, approximately 1.2 million hectares, and respond to the increasing demand for nutritionally rich products with superior oxidation stability ([Gagour *et al.*, 2022](#)).

Furthermore, Several factors intricately determine the quality of olive oils, including environmental conditions, consumption conditions ([Klisović *et al.*, 2022](#)), maturation stage ([Dag *et al.*, 2011](#); [Hachicha Hbaieb *et al.*, 2017](#)), geographical location ([Li *et al.*, 2022](#)) and methods used for pressing ([Rotondi *et al.*, 2011](#)). The constitution of olive oils plays a pivotal role in preventing auto-oxidation and photo-oxidation during storage, affected by factors such as the presence of naturally occurring pro-oxidant pigments like chlorophyll in presence of light, the degree of fatty acid unsaturation, and the antioxidants abundance like carotenes and phenolic compounds ([Servili *et al.*, 2009](#); [Escudero *et al.*, 2016](#); [Tang *et al.*, 2022](#)). Additionally, it is the ability to withstand biological and abiotic stress that affects the olive oil's quality ([Wang *et al.*, 2018a](#)). Numerous studies were undertaken to assess the quality of Moroccan olive oils, examining their composition and physicochemical properties, oxidative stability, and the impact of environmental conditions ([Gharby *et al.*, 2013](#); [Mansouri and Elamrani, 2015](#); [Mansouri *et al.*, 2019](#); [Kiai *et al.*, 2020](#)).

The aims of this study are to conduct the physicochemical characterization and phenolic fraction analysis of oil samples produced in the Fes-Meknes region during the 2021 and 2022 agricultural campaigns. This will be accomplished using spectrophotometric UV and GC-MS methods. Additionally,

Table 1. Geographical and climatic characteristics of the agroclimatic site and soil types sampled.

Sampling areas	Geographical coordinates	Altitude	Minimum Temperature °C	Maximum Temperature °C	Soil type
Fes	34°02'36"N, 05°00'12"O	432	5.2	43.8	Isohumic Vertisols
Meknes	33° 53' 42" N, 5° 33' 17" O	552	4.2	34.2	Vertisols Isohumic
Taounate	34° 32' 11" N, 4° 38' 24" O	600	10	37	Calcimagnesian
Taza	30° 28' 13" N, 8° 52' 37" O	550	3	43	Little developed Vertisols

**Fig. 1.** Geographical location and sampling stations of olive oil samples.

We intend to assess how both geographical origin and extraction method influence the quality and compositional properties of the extracts. Finally, we will evaluate the feasibility of creating models for geographical classification of the oils using physicochemical characteristics, phenolic data, and fatty acid composition, employing principal component analysis.

2 Materials and methods

2.1 Samples and site description

Our investigation is centered on thirty samples of non-irrigated monovarietal «picholine marocaine» olive oils obtained from four cities in Fes-Meknes region: Meknes (10 samples); Fes (9 samples); Taounate (7 samples) and Taza (4 samples), have been collected during the 2021 and 2022 olive growing seasons. This production area located in the center of Morocco, is characterized by typically mediterranean climate (Sakar *et al.*, 2024) and soil type (Fes Meknes Region, 2019; Tab. 1). In each city, at least three local olive mills were chosen for analysis. These olive mills were outfitted with high-pressure, two-phase, and three-phase extraction systems.

According to the "Strategic Territorial Diagnosis Report" by Fes Meknes Region (2019), the region's climate ranges from Mediterranean to continental, with warm winters and summers. Geographical disparities within the region introduce important distinctions in terms of rainfall: the two cities of Fes and Meknes are located in dry to moderately watered areas, with average annual precipitation varying between 400 and 600 mm. The cities of Taounate and Taza, however, are characterized by higher average annual precipitation of over 800 mm.

After the manual olive harvesting carried out by the producers, the olive oils were extracted within 24 to 48 h post-harvest by the suppliers using three distinct methods (Azbar *et al.*, 2004) : The traditional extraction method, is a discontinuous Process (hydraulic Press): This method extracts oil from olives by a sequence of mechanical movements. Initially, the olives are cleaned to eliminate debris and contaminants. Then they're crushed or ground into a paste with a mill or grinder. This paste is then transferred to a press, where it is pressurized to extract the virgin olive oils. The press may be hydraulic, screw, or pneumatic, exerting force to separate the oil from the solids. Continuous Process (Three-phase System): In this process, olives are introduced into a grinder where they are transformed into a paste. Then, this paste is sent

to a centrifugal decanter where it is separated into three phases: olive oil, wastewater, and solid waste called olive pomace. Additional water is added to facilitate separation. Continuous Process (Two-phase System): In this method, olives are crushed into a paste using a grinder, similar to the three-phase system. However, instead of using a centrifugal decanter, a two-phase separation system is employed. This system divides the olive paste into two main phases: the oil Phase and the wet Pomace Phase. Following extraction, the virgin olive oils were promptly packaged in 250 mL opaque glass containers and were transported in a cooler maintained at 4 °C to our analysis laboratory. Throughout the analysis period, both the virgin olive oils and phenolic extracts were rigorously preserved at a consistent temperature of 4 °C. [Figure 1](#) shows the geographical locations of the four study areas.

2.2 Maturity index of olives

The olives are harvested during the similar period of the two olive-growing seasons (early December) and the ripeness index is calculated within 24 h of sampling, based on the sensory analysis of 100 randomly chosen olives from a one-kilogram sample. The olives are then divided into eight groups, ranging from vivid green or dark green to black and entirely dark pulped olive ([Cherfaoui et al., 2018](#)).

Class 0: Olives with a deep green or emerald skin tone

Class 1: Olives having a bright yellow or greenish-yellow skin

Class 2: Olives with crimson markings and a yellowish epidermis

Class 3: Olives having light purple or reddish skin

Class 4: Olives having a totally green mesocarp and a black epidermis

Class 5: Olives with a purple mesocarp that is up to half as thick as its black epidermis

Class 6: Olives with a purple mesocarp extending to the pit and a black epidermis

Class 7: Olives having a wholly dark mesocarp and a black epidermis.

With n representing the frequency per hundred olives and $n_0, n_1, \dots, n_7$ representing the number of olives in each category.

The maturity index is computed as follows: $IM = [(0n_0) + (1n_1) + (2n_2) + (3n_3) + (4n_4) + (5n_5) + (6n_6) + (7n_7)] / 100$.

2.3 Physicochemical quality standards

The International Oil Council's analytical procedures were used to evaluate the physicochemical quality criteria of oil, including free fatty acids (FFA), specific extinction values at 232 and 270 nm, and peroxide value (PV) ([IOC, 2019; 2017a; 2017b](#)).

2.4 Fatty acid composition

The methyl esters of fatty acids in olive oil samples are prepared according to the standard method recommended by ([IOC, 2017c](#)). Subsequently, they are analyzed on a capillary

column (TG-5: 30 m * 0.25 mm * ID 0.25 μ m) using gas chromatography coupled with mass spectrometry (GC-MS) Thermo Trace 1300/TSQ 8000 EVO THERMO/Quadrupole triple instrument, housed at the Technical Support Units for Scientific Research of the National Center for Scientific Research. 0.01 g of olive oils is added to 2 ml of heptane and 0.2 ml of 2N methanolic KOH. After stirring for 30 s, the mixture is left to rest until the upper phase of the solution becomes clear. The upper heptane phase of methyl esters of fatty acids thus obtained is analyzed by GC. The column was programmed with an initial temperature of 70 °C, ramped up to 250 °C at a rate of 5 °C/min over a duration of 30 min, while the helium carrier gas flow rate was maintained at 0.5 mL/min. Methyl esters (0.5 μ L) were injected in split mode with a 50:1 split ratio and a split flow rate of 25 mL/min at an injector temperature of 270 °C. The results were quantified as (%) of specific fatty acids using mass spectra compared to reference standards, the analysis duration spans 30 min. In summary, the preparation of methyl esters follows the IOC33-2017 method, while the subsequent analysis follows the prescriptions of GC-MS.

2.5 Determination of polyphenols

2.5.1 Extraction of polyphenols

The extraction of phenolic compounds is effectuated in compliance with Bajoub's protocol ([Bajoub et al., 2016](#)). two grams of olive oil are dissolved in 1 mL of hexane, this solution is introduced into a separatory funnel and 30 mL of methanol/water (80/20) mixture is added, the mixture is vigorously agitated for 5 min then left to separate, the polar phase (methanolic phase) containing the phenolic compounds is recovered, while the apolar phase undergoes a second and third extraction to recover the remaining phenolic fraction. The polar fractions containing phenolic compounds was recovered and washed three times in hexane. The solution was centrifuged at 3500 rpm for 6 min, then evaporated at 30 degrees under reduced vacuum (rotary evaporator, PHOENIX Instrument RE-100D). The recovered residue was reconstituted with methanol and was examined using a spectrophotometer (JASCO V-730).

2.5.2 Total phenols determination

The determination of total phenolic compounds is performed using the Folin-Ciocalteu reagent and is carried out according to the method of ([Merouane et al., 2015](#)). To perform the assay, 50 μ L of extract is added to 500 μ L of Folin-Ciocalteu (10%), after 5 min, 400 μ L of Na₂CO₃ (7.5%) is added. The reaction mixtures, corresponding to each standard and sample, are shaken and then incubated for 40 min in the obscurity. The absorbance reading at 725 nm is done using a UV-visible spectrophotometer. The total phenolic content is given in mg of gallic acid equivalent (GAE) per kg of olive oil.

2.5.3 Flavonoid determination

The content of flavonoid of the different olive oil samples was determined using the aluminum trichloride (AlCl₃) colorimetric method. A volume of 1 ml of each extract was

Table 2. Physicochemical characterization of olive oils at Fes-Meknes region.

City	Crushing	Olive maturity index	K 270 nm	K 232 nm	Acidity (oleic acid%)	PV (meq active O ₂ /kg)
Fez	Hydraulic press	3.31 ± 1.10 ^a	0.23 ± 0.03 ^a	2.20 ± 0.38 ^a	0.81 ± 0.13 ^a	8.1 ± 1.8 ^a
	Three phase	2.86 ± 1.02 ^a	0.12 ± 0.03 ^a	1.21 ± 0.06 ^a	0.84 ± 0.06 ^a	8.0 ± 0.7 ^a
	Two phase	3.38 ± 0.59 ^a	0.14 ± 0.04 ^a	1.54 ± 0.18 ^a	0.75 ± 0.00 ^a	7.3 ± 1.1 ^a
Meknes	Hydraulic press	2.82 ± 0.60 ^a	0.24 ± 0.03 ^a	2.20 ± 0.15 ^a	1.06 ± 0.19 ^{ab}	10.0 ± 0.5 ^{ab}
	Three phase	3.20 ± 0.29 ^a	0.15 ± 0.04 ^a	1.53 ± 0.02 ^b	0.75 ± 0.00 ^a	7.2 ± 1.7 ^a
	Two phase	3.71 ± 0.85 ^a	0.15 ± 0.03 ^a	1.63 ± 0.21 ^a	0.65 ± 0.17 ^a	7.8 ± 1.0 ^a
Taounate	Hydraulic press	2.72 ± 0.76 ^a	0.27 ± 0.01 ^a	2.53 ± 0.17 ^a	1.59 ± 0.33 ^b	12.8 ± 0.8 ^b
	Three phase	2.54 ± 0.77 ^a	0.19 ± 0.01 ^a	1.78 ± 0.08 ^c	0.79 ± 0.06 ^a	9.0 ± 0.0 ^a
	Two phase	3.00 ± 0.19 ^a	0.21 ± 0.04 ^a	1.63 ± 0.01 ^a	0.84 ± 0.00 ^a	8.5 ± 1.4 ^a
Taza	Hydraulic press	3.68 ± 1.37 ^a	0.25 ± 0.03 ^a	2.20 ± 0.18 ^a	1.03 ± 0.07 ^a	11.0 ± 2.1 ^{ab}
	Three phase	2.81 ± 0.11 ^a	0.12 ± 0.00 ^a	1.53 ± 0.08 ^b	0.84 ± 0.00 ^a	9.0 ± 0.2 ^a
	Two phase	3.65 ± 0.70 ^a	0.15 ± 0.01 ^a	1.56 ± 0.05 ^a	0.56 ± 0.13 ^a	7.5 ± 0.7 ^a
Extraction Methods comparison		<i>p</i> -value	0.098	0.000	0.003	0.005

^{a-c} The Tukey test indicates significant differences ($p < 0.05$) between cities for each extraction method in columns where different letters indicate significantly different means. A *p*-value of less than 0.05 indicates statistically significant differences. Acidity: free fatty acids; PV: peroxide value; K237/K270: specific extinctions at 232 and 270 nm.

mixed with 1 ml of an ALCL3 solution (2% in methanol). The mixture was shaken with a vortex and incubated for 10 min in the dark. The optical density was measured at 430 nm. The results obtained are expressed in mg of quercetin equivalent (QE)/kg of olive oil (Djeridane *et al.*, 2006).

2.5.4 Determination of ortho-diphenols

Four ml of a solution that was prepared by combining 0.5 ml of methanolic extract with 5 ml of a mixture of methanol and water (1 :1 v/v) was incorporated into 1 ml of a 5% of dehydrated sodium molybdate in a mixture of ethanol and water (1 :1 v/v). after mixing for 1 min, the solution was to incubate for 10 min at ambient temperature, the resulting solution was centrifuged for 5 min at 3000 rpm, and The concentration of o-diphenols was subsequently measured at 370 nm. The quantification obtained are reported as mg of caffeic acid equivalent (CAE) per kg of olive oil (Cerretani *et al.*, 2005).

2.6 Determination of chlorophyll and carotenoid contents

Total quantity of carotenoids and chlorophyll derivatives is determined using the (Borello and Domenici, 2019) technique, which comprises the computation of two indices, K670 and K470, connected to the absorbance values of olive oil in cyclohexane at wavelengths 670 nm and 470 nm, respectively. The K670 index quantitatively measures chlorophyll concentration, as olive oil's absorbance at 670 nm is solely attributable to the existence of this pigment fraction. Phytytin A is the primary component of this fraction in normal olive oils. The UV extinction coefficient at 670 nm in an ethanol solution is $\varepsilon = 613$. The K470 index assesses overall carotenoid content, as carotenoids impact the absorbance of olive oils at 470 nm. The level of carotenoid is represented in

terms of lutein, which is the primary carotenoid pigment found in olive oils. According to the literature, the extinction coefficient in UV at 470 nm in an ethanol solution is $\varepsilon = 2000$. To ensure the linearity of the Beer-Lambert law, the olive oil sample is diluted using the following method: Dissolve 7.5 g of precisely weighed olive oil in cyclohexane to make a final volume of 25 mL. The total carotenoids and total chlorophylls are computed using the absorbance values at 470 nm (A470) and 670 nm (A670), respectively.

The content is expressed in mg of pigment per kg of olive oil using the following equations:

$$\text{Total Chlorophylls in mg/kg} = \frac{A_{670} \cdot 10^6}{613 \cdot 100 \cdot d}$$

$$\text{Total carotenoids in mg/kg} = \frac{A_{470} \cdot 10^6}{2000 \cdot 100 \cdot d},$$

where *d* represents the length of the cuvette's optical path (1 cm).

2.7 Statical analysis

The findings depict the mean ± standard deviation of each extraction mode for every city. Each sample's parameters were examined in triplicate. To begin this analysis, the impact of geographical location and extraction process on the qualitative indices and physicochemical properties of the Fes-Meknes olive oils, was assessed using a test for the homogeneity of the variances was conducted, specifically the Levene. The one-way analysis of variance (ANOVA) test was used to compare means between each qualitative variable, while the two-way analysis of variance (ANOVA) was employed for the two qualitative variables. Significant variances in average values between cities and extraction methods ($p < 0.05$) were identified by Tukey test to identify particular variances between means. A principal component analysis was adopted

using R software for a better visual distribution of the data based on their geographical provenance and the method of extraction applied (30 samples, 15 quantitative variables).

3 Results

3.1 Qualitative characterization

Thirty samples of virgin olive oils were processed using three methods: hydraulic press, two-phase, and three-phase, in four cities: Fes, Meknes, Taza, and Taounate. The physico-chemical characterization results, and maturity index are presented in Table 2. The mean values of the maturity index ranged from 2.54 ± 0.77 for Taounate concerning olives destined for extraction by three-phase method to 3.71 ± 0.85 for Meknes olives extracted using two-phase processing. the ANOVA test indicated that there were no statistically significant differences found between the various cities or extraction methods. This eliminates the impact of ripeness on the characteristics and composition of the oils being examined. As a result, the only factors that were taken into consideration as contributors to variance were the method of extraction and the location of the processed olives. The majority of the olive oils obtained by the two-phase and three-phase extraction methods belong to the category of "extra virgin olive oil" in terms of physico-chemical quality standards, with acidity levels ranging from 0.56% to 0.84%. The lowest free acidities are recorded for oils obtained by two-phase processes (0.56 ± 0.13 for the city of Taza). On the other hand, olive oils extracted by hydraulic press instead of hydraulic pressure, particularly in Meknes, Taza and Taounate, have acidity levels higher than 0.8% (1.06%, 1.03% and 1.59% respectively), placing them in the category of virgin olive oils.

As the results shown, the peroxide value ranged from 7.2 meq active O_2 /kg oil to 12.8 meq active O_2 /kg oil. Within the 20 meq active O_2 /kg oil limit set for the extra-virgin oil category. However, olive oils extracted by hydraulic press showed the most advanced values (12.8 meq active O_2 /kg oil for taonate). Significant difference are recorded between the three types of extraction ($p=0.005$). The ultraviolet absorbance values (K232 and K270) of the different samples showed significant differences between the four cities and the three extraction methods ($p=0.000$, $p=0.000$ respectively) (Tab. 2). They were below the limits set for extra virgin olive oils ($K232 \leq 2.50$ and $K270 \leq 0.22$) for olive oils extracted by continuous methods (two-phase and three-phase) and ranged from 0.12 to 0.21 (K270) and from 1.21 to 2.20 (K232), but exceeded these limits for oils extracted by hydraulic press in all four cities (0.27 (K270) and 2.53 (K232)).

3.2 Chemical characterization

3.2.1 Fatty acid composition

To gain a comprehensive understanding of these findings, we delved into the data city by city and evaluate the three extraction techniques: hydraulic press, two-phase and three phase extraction. The fatty acid composition of the samples studied is summarized in Table 3 (percentage of methyl esters), along with the monounsaturated fatty acids/ polyunsaturated fatty acids ratio (MUFA /PUFA), polyunsaturated fatty acids

/saturated fatty acids ratio (MUFA/SFA), and the linoleic acid/ alpha linolenic acid (n6/n3) ratio. all Fatty acids are below the restrictions set by the IOC for virgin olive oils. Unsaturated fatty acids predominate over saturated fatty acids, the oleic acid is the majority acid, with percentages ranging from 67.24% to 80.12%, followed by linoleic acid: 10.67% and 17.01%. Among the three types of extraction, olive oils extracted by two-phase and by three-phase extractions presented the highest contents of oleic acid, however hydraulic press extraction presented the highest contents in terms of palmitic acid, stearic acid, linoleic acid, eicosenoic acid and linolenic acid at the different cities studied, with a significant variations ($p < 0.05$) for the three types of extraction concerning both palmitic acid, oleic acid, linoleic and), specially between hydraulic press and two-phase extraction.

Concerning the location of the samples studied. We noted significant differences ($p < 0.05$) on the majority of fatty acids identified (palmitoleic acid, stearic acid, oleic acid, linolenic acid, eicosenoic acid and MUFA/PUFA ratio). Olive oils from the two cities of Fes and Meknes had the highest percentages of palmitoleic acid, oleic acid and n6/n3 ratio, and the lowest levels of stearic acid, linoleic acid, linolenic acid, arachidic acid and eicosenoic acid. However, the town of Taouante followed by the town of Taza recorded the lowest levels of oleic acid and both PUFA/MUFA and n6/n3 ratios.

3.2.2 Content of phenolic compounds and pigments

The results of the determination of phenolic compounds indicate that the olive oils studied are particularly rich in total polyphenols (Tab. 4). The analysis of the different extraction methods used showed that olive oils extracted by two phases and by hydraulic press had the highest levels of total phenolics, reaching 328.65 mg/kg GAE and 307.31 mg/kg GAE, respectively. In contrast, olive oils extracted by three-phase extraction showed the lowest concentrations of total phenolics, ranging from 261.34 mg/kg GAE to 272.83 mg/kg GAE. These differences in content between extraction methods were statistically significant ($p=0.008$), with a notable difference between two-phase and three-phase extraction ($p=0.004$). The city of Taounate had the lowest levels for all three extraction methods, with a significant difference from the city of Fes ($p=0.003$).

The analyses of the O-diphenol content showed minimal variations both between the different extraction methods and between the different towns studied. In general, olive oils extracted in two phases showed the highest concentrations of flavonoids, especially in Taounate, where the highest values were recorded for all three extraction methods. With regard to O-diphenols, no significant differences were observed between the extraction methods or between the cities. However, the highest level was recorded for olive oils extracted in three phases in Taounate, with an average of 131.44 mg/kg CAE.

The results of chlorophyll and carotenoid analyses in olive oils extracted by different methods and in different cities show significant and interesting variations. In general, olive oils extracted by hydraulic pressure showed higher levels of chlorophylls and carotenoids compared to three-phase and two-phase extractions. In Fes, hydraulic pressure extraction produced oils with chlorophyll concentrations of 6.65 mg/kg and carotenoids of 3.25 mg/kg, significantly higher than those

Table 3. Fatty acid composition.

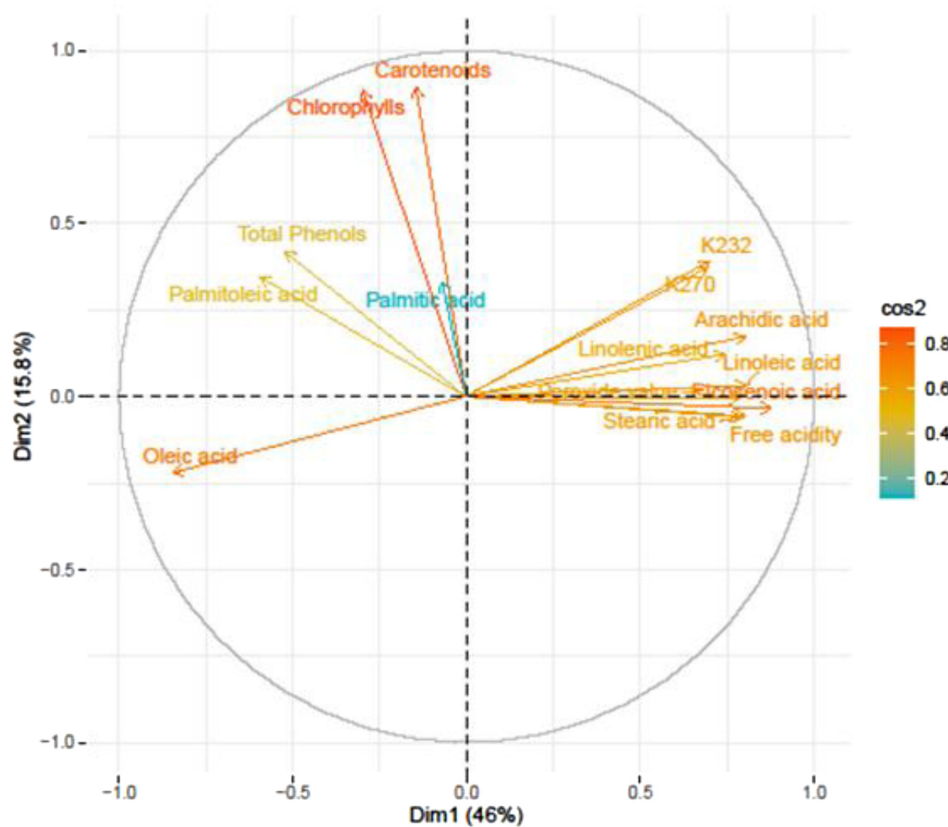
City	Extraction methods	Palmitic acid	Palmitoleic acid	Stearic acid	Oleic acid	Linoleic acid	Linolenic acid	Arachidic acid	Eicosenoic acid	MUFA/PUFA	PUFA/SFA	n6 /n3
Fez	Hydraulic press	7.31 ± 0.51 ^{ab}	0.23 ± 0.04 ^{ab}	2.23 ± 0.87 ^a	77.13 ± 3.39 ^b	12.10 ± 2.12 ^a	0.76 ± 0.46 ^a	0.10 ± 0.03 ^a	0.08 ± 0.03 ^a	6.22 ± 1.26 ^a	1.33 ± 0.15 ^a	20.34 ± 9.87 ^a
	Three phase	6.11 ± 0.89 ^a	0.13 ± 0.01 ^a	2.51 ± 0.78 ^a	78.91 ± 1.25 ^c	11.72 ± 2.95 ^a	0.46 ± 0.05 ^a	0.06 ± 0.01 ^a	0.07 ± 0.01 ^a	6.50 ± 0.95 ^a	1.40 ± 0.12 ^a	25.48 ± 6.85 ^b
Meknes	Two phase	5.70 ± 1.70 ^a	0.27 ± 0.06 ^a	2.03 ± 0.86 ^a	79.89 ± 0.26 ^b	11.15 ± 1.25 ^a	0.72 ± 0.39 ^a	0.08 ± 0.02 ^a	0.07 ± 0.02 ^a	6.81 ± 0.73 ^a	1.58 ± 0.46 ^a	18.38 ± 7.98 ^a
	Hydraulic press	8.13 ± 1.33 ^b	0.28 ± 0.12 ^b	4.10 ± 1.99 ^{ab}	71.62 ± 4.95 ^{ab}	14.64 ± 4.76 ^a	0.92 ± 0.39 ^a	0.10 ± 0.03 ^a	0.09 ± 0.03 ^a	4.98 ± 1.64 ^a	1.27 ± 0.42 ^a	17.16 ± 6.01 ^a
Taounate	Three phase	7.40 ± 0.35 ^a	0.19 ± 0.01 ^a	2.36 ± 0.11 ^a	77.77 ± 1.10 ^c	11.58 ± 1.58 ^a	0.54 ± 0.04 ^a	0.07 ± 0.01 ^a	0.07 ± 0.01 ^a	6.50 ± 0.92 ^a	1.24 ± 0.21 ^a	21.79 ± 4.40 ^{ab}
	Two phase	5.79 ± 0.90 ^a	0.24 ± 0.05 ^a	2.35 ± 1.89 ^a	80.12 ± 1.94 ^b	10.67 ± 1.06 ^a	0.59 ± 0.26 ^a	0.08 ± 0.04 ^a	0.07 ± 0.03 ^a	7.18 ± 0.53 ^a	1.48 ± 0.47 ^a	20.28 ± 6.48 ^a
Taza	Hydraulic press	5.82 ± 0.67 ^a	0.12 ± 0.02 ^a	5.47 ± 1.45 ^b	70.07 ± 2.99 ^{ab}	17.01 ± 1.54 ^a	1.17 ± 0.34 ^a	0.14 ± 0.02 ^a	0.15 ± 0.01 ^b	3.91 ± 0.52 ^a	1.61 ± 0.23 ^a	15.50 ± 4.43 ^a
	Three phase	6.89 ± 0.68 ^a	0.17 ± 0.04 ^a	6.42 ± 1.39 ^{ab}	71.61 ± 0.44 ^a	13.58 ± 2.08 ^a	1.01 ± 0.41 ^a	0.13 ± 0.06 ^a	0.10 ± 0.06 ^a	5.00 ± 0.88 ^a	1.11 ± 0.35 ^a	14.2 ± 3.71 ^{ab}
Extraction Methods comparison	Two phase	6.56 ± 0.65 ^a	0.19 ± 0.03 ^a	4.62 ± 1.45 ^a	74.82 ± 0.32 ^a	12.36 ± 1.45 ^a	1.16 ± 0.11 ^a	0.10 ± 0.02 ^a	0.11 ± 0.01 ^a	5.56 ± 0.01 ^a	1.20 ± 0.32 ^a	10.66 ± 5.24 ^a
	Hydraulic press	7.40 ± 0.52 ^{ab}	0.22 ± 0.01 ^{ab}	2.70 ± 0.89 ^{ab}	67.24 ± 5.02 ^a	10.91 ± 1.08 ^a	0.48 ± 0.01 ^a	0.09 ± 0.02 ^a	0.07 ± 0.02 ^a	5.92 ± 1.02 ^a	1.11 ± 0.15 ^a	22.72 ± 7.32 ^a
COI Standard	Three phase	6.56 ± 0.62 ^a	0.19 ± 0.06 ^a	4.62 ± 0.01 ^a	74.82 ± 1.54 ^b	12.36 ± 2.36 ^a	1.16 ± 0.23 ^a	0.10 ± 0.01 ^a	0.11 ± 0.03 ^a	5.56 ± 0.97 ^a	1.20 ± 0.21 ^a	10.66 ± 5.24 ^a
	Two phase	6.84 ± 0.62 ^a	0.21 ± 0.01 ^a	3.00 ± 0.70 ^a	77.00 ± 1.53 ^{ab}	11.72 ± 1.97 ^a	0.98 ± 0.37 ^a	0.10 ± 0.01 ^a	0.08 ± 0.03 ^a	6.14 ± 0.89 ^a	1.28 ± 0.17 ^a	13.40 ± 7.17 ^a
Methods comparison	<i>p-value</i>	0.063	0.180	0.184	0.002	0.022	0.599	0.183	0.142	0.011	0.373	0.972
COI Standard	7.50 – 20.00	0.30 – 3.50	0.50 – 5.00	55.00 – 85.00	2.50 – 21.00	≤1.00	≤0.60	≤0.50				

^{a-c} The Tukey test indicates significant differences ($p < 0.05$) between cities for each extraction method in columns where different letters indicate significantly different means. A *p*-value of less than 0.05 indicates statistically significant differences. MUFA: Monounsaturated fatty acids; PUFA: Polyunsaturated fatty acids; SFA: Saturated fatty acids; n6/n3 ratio polyunsaturated fatty acids.

Table 4. Phenolic compounds and pigments of olive oils.

City	Crushing	Total Phenols “mg GAE/ kg”	Flavonoids “mg QE /kg”	O-diphenols “mg CAE /kg”	Chlorophylls “mg/kg”	Carotenoids “mg/kg”
Fez	Hydraulic press	307.31 ± 17.44 ^a	11.93 ± 3.46 ^{bc}	94.6 ± 12.83 ^a	6.65 ± 2.75 ^b	3.25 ± 0.88 ^a
	Three phase	261.34 ± 14.94 ^a	14.95 ± 0.45 ^a	99.84 ± 11.25 ^a	2.20 ± 1.25 ^a	1.41 ± 0.16 ^a
	Two phase	328.65 ± 9.01 ^a	11.52 ± 1.71 ^a	85.55 ± 4.99 ^a	3.71 ± 0.56 ^a	2.03 ± 0.58 ^a
Meknes	Hydraulic press	289.13 ± 41.59 ^a	8.02 ± 0.33 ^{ab}	90.85 ± 27.44 ^a	5.70 ± 2.98 ^b	2.72 ± 0.63 ^a
	Three phase	269.71 ± 1.06 ^a	7.64 ± 2.19 ^a	91.84 ± 13.38 ^a	1.27 ± 0.73 ^a	0.75 ± 0.31 ^a
	Two phase	304.41 ± 27.61 ^a	11.01 ± 4.55 ^a	89.06 ± 13.61 ^a	4.8 ± 2.09 ^a	2.53 ± 1.01 ^a
Taounate	Hydraulic press	259.98 ± 7.71 ^a	14.09 ± 1.59 ^c	88.61 ± 7.74 ^a	1.53 ± 0.78 ^a	0.61 ± 0.35 ^a
	Three phase	264.91 ± 21.04 ^a	13.03 ± 4.59 ^a	131.44 ± 11.69 ^a	1.72 ± 0.44 ^a	1.07 ± 0.61 ^a
	Two phase	277.07 ± 10.52 ^a	15.32 ± 3.75 ^a	98.20 ± 9.76 ^a	2.74 ± 0.32 ^a	0.99 ± 0.13 ^a
Taza	Hydraulic press	301.56 ± 12.85 ^a	5.64 ± 0.56 ^a	100.95 ± 13.42 ^a	6.29 ± 1.52 ^b	4.22 ± 0.51 ^a
	Three phase	272.83 ± 10.45 ^a	12.53 ± 1.63 ^a	83.58 ± 7.63 ^a	1.70 ± 0.11 ^a	1.30 ± 0.11 ^a
	Two phase	306.41 ± 14.26 ^a	14.27 ± 0.20 ^a	87.10 ± 12.55 ^a	3.77 ± 2.97 ^a	1.98 ± 1.15 ^a
Extraction Methods comparison		<i>p-value</i>	<i>0.008</i>	<i>0.813</i>	<i>0.245</i>	<i>0.004</i>

^{a-c} The Tukey test indicates significant differences ($p < 0.05$) between cities for each extraction method in columns where different letters indicate significantly different means. A *p*-value of less than 0.05 indicates statistically significant differences. GAE: Gallic acid equivalent; QE: quercetin equivalent; CAE: caffeic acid equivalent.

**Fig. 2.** Projection of the variables on the factor-plane (Dim1 × Dim2) considering the 15 variables.

obtained by three-phase and two-phase extraction. Although the differences were not as pronounced for the city of Taounate, oils extracted by hydraulic pressure showed higher concentrations of chlorophylls (1.53 mg/kg) and carotenoids (0.61 mg/kg) compared to the other extraction methods. An overall comparison of the extraction methods showed significant differences ($p=0.004$ and $p=0.042$) for chlorophyll and carotenoid contents.

3.2.3 Principal Component Analysis (PCA)

To adopt a principal component analysis, we selected the 15 quantitative variables: Free acidity, peroxide value, K232, K270, palmitoleic acid, palmitic acid, stearic acid, linoleic acid, oleic acid, linolenic acid, eicosenoic acid, arachidic acid, chlorophylls, carotenoids, total phenols (Fig. 2).

This analysis concerns 30 individuals, the first two axes of the PCA account for 61.84% of the total inertia of the variability, indicating that 61.84% of the variance among all individuals or variables is delineated in this two-dimensional plane. This result is significantly more than the reference value of 33.31%, hence the variability explained by this plane is quite substantial. The two variables are expressed according to the two equations below:

Dim1=0.69 K270 + 0.70 K232 + 0.80 Acidity + 0.79 Peroxide value - 0.52 Total Phenols - 0.15 Carotenoids - 0.30 Chlorophylls - 0.07 Palmitoleic acid - 0.59 Palmitic acid - 0.84 Oleic acid + 0.79 Stearic acid + 0.80 Linoleic acid + 0.74 Linolenic acid + 0.80 Arachidic acid + 0.87 Eicosenoic acid

Dim2= 0.37 K270 + 0.38 K232 - 0.05 Acidity - 0.004 Peroxide value + 0.41 Total Phenols + 0.89 Carotenoids + 0.88 Chlorophylls + 0.33 Palmitic acid + 0.34 Palmitoleic acid - 0.22 Oleic acid - 0.06 Stearic acid + 0.03 Linoleic acid + 0.17 Arachidic acid - 0.03 Eicosenoic acid + 0.12 Linolenic acid

4 Discussion

4.1 Qualitative characterization

The physicochemical quality of olive oil and its attributes are the result of a multifactorial approach and are very important for the evaluation of olive oil freshness and triacylglyceride hydrolysis as well as for its classification (Korkmaz, 2023). According to the results obtained in the results section, significant variations were registered concerning the two qualitative variables extraction method and cultivation area (cities). The t-tuckey test showed significant differences (Tab. 2) between the three extraction methods and the four cities regarding acidity ($p < 0.05$). Olive oils from hydraulic presses had maximum acidity values higher than the standard established for extra virgin olive oils ($>0.8\%$). This is because the prolonged contact of the olives with the additional water during pressing promotes the hydrolysis of triglycerides, leading to increased formation of free fatty acids (Boskou and Clodoveo 2020). In contrast to two-phase or three-phase methods, which closely control temperature and minimize contact with water, hydraulic pressing further exposes the olives to conditions conducive to the release of free fatty acids,

negatively affecting the acidity and sensory quality of the olive oils produced (Nardella *et al.*, 2023).

Oils extracted using continuous methods had peroxide values between 7.2 and 9.0 meq active O_2 /kg, whereas oils extracted traditionally had values between 8.1 and 12.8 meq active O_2 /kg. The differences observed in peroxide values between oils extracted by continuous methods and those extracted by hydraulic press can be explained mainly by technological improvements in continuous methods. These two and three phase systems offer precise control of extraction conditions, including rigorous temperature management and reduced exposure to oxygen, which limits the formation of peroxides in the extracted oil. The peroxide index and acidity were shown to positively correlate ($R=0.845$), as free fatty acids readily oxidize quickly (Guillén and Cabo 1997). Ultraviolet absorption is linked to the presence of conjugated double bonds. Absorbance at 232 nm is induced by hydroperoxides (primary oxidation stage) and conjugated dienes (intermediate oxidation stage). Absorbance at 270 nm is due to carbonyl compounds and conjugated trienes (Houshia *et al.*, 2019). With regard to UV absorption: K232 and K270, all the olive oil samples extracted by the two-phase and three-phase methods showed values within the limits set for extra virgin olive oils. This compliance is significantly different for olive oils extracted by hydraulic press in Taounate, where K232 and K270 values exceed the acceptable thresholds for extra virgin olive oils, thus classifying them as virgin olive oils. These results correlate positively ($R=0.675$) with those of the peroxide value, since both PV and K232 are markers of primary oxidation following different pathways. This phenomenon can be explained by the fact that the paste remains in the stone mold for a long time (Gómez-Rico *et al.*, 2009), in contact with air and light, which favors oxidation.

The significant differences observed between the different cities studied can be attributed to the specific characteristics of their agricultural environment (Fuentes de Mendoza *et al.*, 2013). For example, the city of Taounate, characterized by poorly evolved calcimagnesian soils and annual rainfall in excess of 800 mm, produced olive oils with more advanced quality indices than other cities such as Fez, Meknes and Taza. The latter are characterized by isohumic soils and vertisols, offering better farming conditions and favorable cultivation suitability. The variation observed could also be attributed to the climate (Keceli and Celik 2024) and the characteristics of the soil (García-Ruiz *et al.*, 2009), which is drier in Fes and Meknes than in the other two cities.

In all samples, free acidity, peroxide value and specific extinction did not exceed the limit set by the IOC for superior quality olive oil, designated as virgin (oil extracted by hydraulic press) and extra-virgin (olive oils extracted by two and three phases). These results can be attributed to the speed with which studied samples were crushed and also to the good storage conditions under which they remained during the analysis period (in dark bottles at temperature 4°C). Regarding the qualitative criteria, our findings confirm those of the olive oils of northern Morocco, which classified olive oils into two categories: Extra Virgin and Virgin (Bajoub *et al.*, 2015).

In conclusion, our results highlight the significant impact of water pressure, two-phase and three-phase extraction methods, as well as agroclimatic zone, on the physicochemical

composition of olive oils. Hence the importance of taking into account a variety of factors, including extraction method and regional specificities, when choosing olive tree locations and olive extraction methods.

4.2 Fatty acid composition

The consumption of unsaturated fatty acids plays a pivotal role in advancing cerebral and ocular wellness, preventing cardiovascular, cerebrovascular, and vascular diseases, regulating weight, and reducing blood lipids (Wang *et al.*, 2018b; Zhao *et al.*, 2021).

The results of our study highlight significant differences in the fatty acid profiles of oils extracted by two-phase, three-phase and hydraulic presses, as well as between the different geographical locations studied. A remarkable predominance of oleic acid was observed, representing between 67.24% and 80.12% of the total fatty acids, followed by linoleic acid and palmitic acid. Significant differences ($p < 0.05$) were observed between the three extraction methods for palmitic, oleic, linoleic, arachidic and eicosenoic acids. Two-phase extracted oils generally have higher concentrations of unsaturated fatty acids, especially oleic acid, and are less rich in saturated fatty acids such as stearic and palmitic acid, which are beneficial to cardiovascular health by reducing LDL and increasing HDL levels, as shown in several studies (Torres and Maestri, 2006). The high content of unsaturated fatty acids, mainly oleic acid, as well as the presence of antioxidants in olive oils have been documented to have positive effects on human health, particularly on lipid profile and serum cholesterol levels (Clodoveo 2013). Two- and three-phase extracted oils also have the highest MUFA/PUFA ratios, which contributes to their relative stability. In contrast, hydraulic pressed oils have higher levels of saturated fatty acids, particularly palmitic, stearic, and arachidic acids.

These results are in line with Sakar's findings on the superior quality of olive oils produced by two-phase decanters, which have a better resistance to oxidation during storage (Sakar *et al.*, 2024). Several authors (Khdaif, Ayoub, and Abu-Rumman 2015), (Arslan and Ok 2020), and (Ben Hassine *et al.*, 2022), also highlighted the significant impact of extraction techniques on the fatty acid profile of olive oils, a finding supported by (Nardella *et al.*, 2023) in his study on the impact of traditional and innovative techniques on the nutritional composition and sensory quality of olive oil. With regard to the effect of geographic area, we observed significant differences among the four cities studied in the levels of several fatty acids (palmitic acid, stearic acid, oleic acid, arachidic acid, and eicosenoic acid), as well as in the MUFA/PUFA ratio. These significant differences are generally due to the climatic conditions and different geographical characteristics of each city. For example, the cities of Fez and Meknes, characterized by an arid, dry climate with isohumic Vertisol soils, showed higher oleic acid concentrations. Contrarily, Taounate showed higher levels of linoleic and linolenic acids, along with lower MUFA/PUFA ratios. The oleic acid content in Taounate and Taza reached 74.82% and 77.00%, respectively. These results align with those of "Picholine marocaine," a single-variety olive oil from Taounate and Taza, which reported levels of 76.94% and 75.89%, respectively

(Bouymajane *et al.*, 2020). These observations confirm the significant importance of environmental conditions on the final composition of olive oils (Bedbabis *et al.*, 2016).

This influence is confirmed by several authors (Harrak *et al.*, 2024), (Gagour *et al.*, 2024), (El Qarnifa, El Antari, and Hafidi 2019) who have reported the interesting influence of environmental conditions on the lipid profile and composition of virgin olive oil.

4.3 Content of phenolic compounds and pigments

With a diverse array of structures isolated from edible plants, polyphenols encompass the largest variety of compounds in the botanic realm (Manach *et al.*, 2004). Polyphenols can influence the amounts of antioxidants, pro-inflammatory proteins, indicators of endothelial dysfunction, and DNA damage (Gorzynik-Debicka *et al.*, 2018; Jiménez-Sánchez *et al.*, 2022).

The total phenol content of the analyzed olive oils ranges from 259.98 ± 7.71 mg/kg GAE to 307.31 ± 17.44 mg/kg GAE, indicating a significant diversity. The techniques used for extraction are important: the highest concentrations are found in materials obtained through two-phase extraction followed by hydraulic pressing, while the lowest levels are found in materials obtained through three-phase extraction. This difference is statistically significant ($p = 0.008$), suggesting that the introduction of water prior to oil separation could influence the transfer of phenols to the various extraction products (margine, pomace and olive oil) (Jerman Klen and Mozetič Vodopivec 2012). Concerning the four cities studied, Taounate stands out for lower concentrations of total phenols compared to the other regions. This decrease could be attributed to specific pedoclimatic characteristics such as soil type, precipitation regime and altitude. These geographical factors play a key role in the production and accumulation of phenolic compounds in olives, thus influencing the quality and quantity of phenols present in the extracted virgin olive oils (Youssef *et al.*, 2012; Dabbou *et al.*, 2010; Vinha *et al.*, 2005). Agronomic and technological parameters such as maturity stage, harvest season, and production technique all have a significant impact on the concentration of phenolic chemicals. (Cerretani *et al.*, 2005; Baccouri *et al.*, 2008).

Significant variations ($p < 0.05$) in the composition of chlorophyll and carotenoid compounds were also found by analysis of variance based on the regions and techniques used to extract olive oil. This finding underlines the simultaneous impact of extraction methods on the concentration of these pigments, and of local pedoclimatic characteristics on their presence in oils. Several previous studies confirm the influence of growing areas and extraction methods on the levels of these pigments in olive oils (Issaoui *et al.*, 2009; Tura *et al.*, 2007). The cities of Fez, Meknes and Taza showed the highest concentrations of the two pigments important for the stability of their olive oils. Indeed, high levels of chlorophyll can confer antioxidant, chemopreventive and antimutagenic properties to these oils (Quiles *et al.*, 2022).

In summary, this study reveals significant variability in bioactive compounds, including polyphenols, flavonoids, and ortho-diphenols, in virgin olive oils from different cities. Agronomic and technological aspects play a pivotal part in the

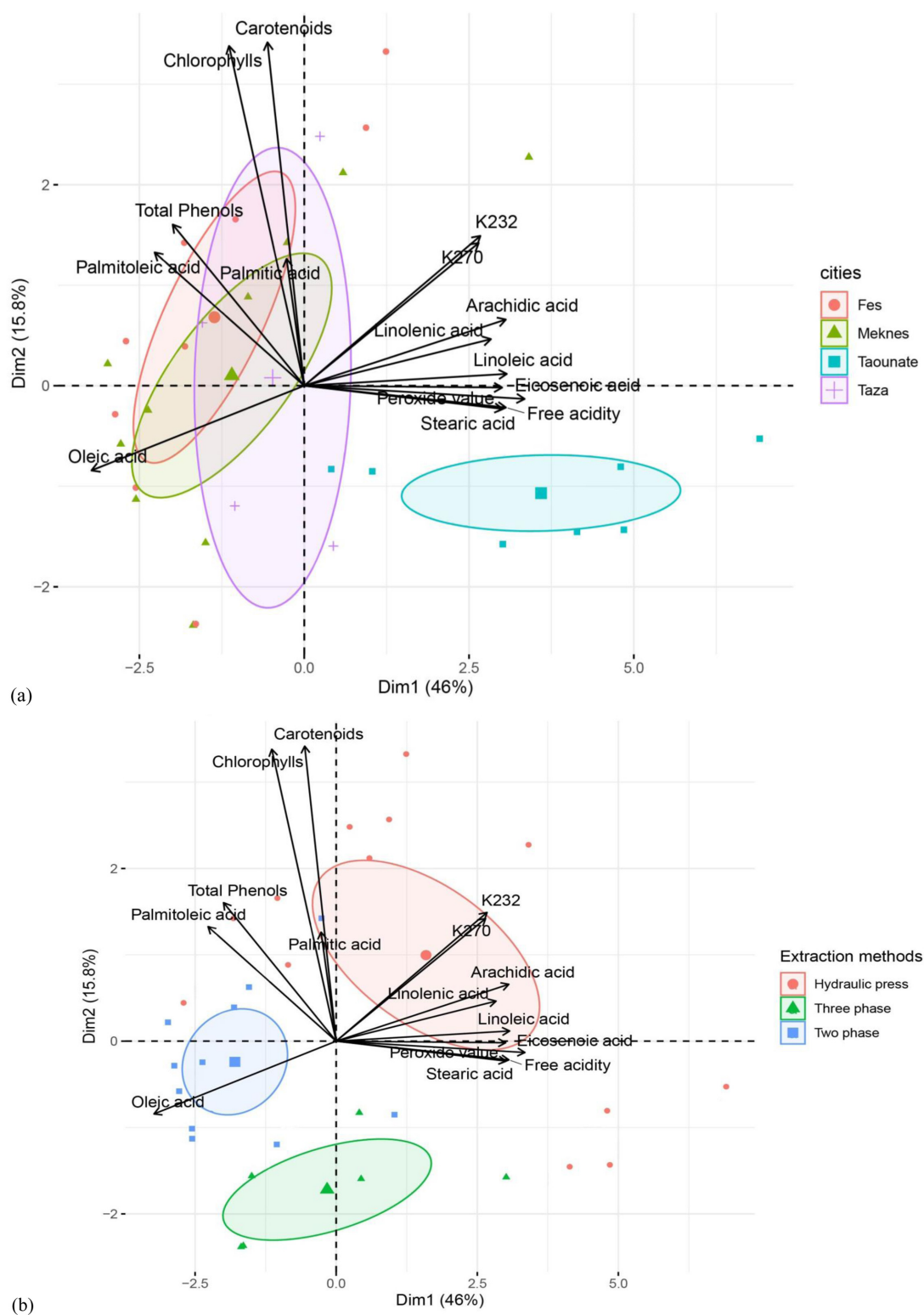


Fig. 3. Visual distribution of the studied samples according to the cities (a) and to extraction method (b).

composition of phytochemical compounds, with pronounced differences between the cities of Taounate and Fes. Furthermore, the levels of chlorophyll and carotenoids also vary based on geography and extraction type. These findings underscore the importance of considering these factors in assessing the nutritional quality and health benefits of olive oils, highlighting their potential as antioxidants and chemopreventive agents.

4.4 PCA discussion

The analysis of the relations between the diverse variables studied revealed average to highly positive relations between the physicochemical parameters (specific extinction, acidity, and peroxide value), as well as chlorophylls, carotenoids, and total phenol contents. The principal component analysis indicated an influence from both type of extraction method used and the geographical origin of the olive trees on the olive oil's physical, chemical and nutritional quality, hence the choice of the two qualitative variables "type of extraction and geographical origin" as essential elements for the visual distribution of the virgin olive oil samples (Fig. 2).

The PCA analysis indicates a significant difference between the two groups (Fig. 3a). The olive oils from the three cities of Fes, Meknes, and Taza are identified by low levels of other acids and physicochemical parameters and high levels of total phenolics, chlorophylls, carotenoids, oleic acid, and palmitoleic acid. The second group, to which the individuals of the city of Taounate belong and which is mainly crushed by hydraulic press, presents high values for the variables: peroxide value, acidity, K270, K232, linoleic acid, stearic acid, arachidic acid, and eicosenoic acid. This dichotomy could be attributed to geographical-climatic parameters, specifically the higher altitude coupled with a colder climate and increased precipitation present for Taounate compared to its counterparts. It is plausible, then, that these factors may have played an influential role in both the olive tree growing conditions and the resulting oil characteristics (Rodrigues *et al.*, 2018).

It was possible to distinguish three main groups (Fig. 3b). The first group, composed of oils extracted by hydraulic press, includes samples characterized by high values for the variables: free acidity, peroxide value, K270, K232, linolenic acid, linoleic acid, arachidic acid, stearic acid, chlorophylls and carotenoids. The second group comprises individuals of olive oils extracted by three-phase methods, with lower values of K232, K270, acidity and peroxide value, chlorophylls and carotenoids. The last group in which the olive oils extracted by two-phase methods, characterized by low physico-chemical parameters (free acidity, peroxide value and specific extinction) and high values for the total phenols, palmitoleic acid and oleic acid.

The analysis highlights the complex interplay of physico-chemical parameters, extraction methods, and geographical factors in determining virgin olive oil quality criteria. The results suggest that both environmental conditions and extraction techniques play pivotal roles in shaping the ultimate properties of the virgin olive oil, and understanding these relationships can be valuable for the olive oil industry and for consumers seeking specific characteristics in their virgin olive oil.

5 Conclusion

This study aimed to characterize virgin olive oils from the Fes-Meknes region by assessing their physicochemical quality parameters and mineral component compositions, comparing hydraulic press, two phase and three phase extraction methods. Additionally, Principal Component Analysis revealed statistically significant distinctions between the three extraction methods and also with respect to their geographic origin. This suggests that both the physical and chemical quality parameters, as well as component compositions, have the potential to distinguish virgin olive oils based on their origin and processing method. However, it is essential to emphasize the need for a comprehensive understanding of the impact of each stage in the virgin olive oils production process on its overall quality. The usefulness of our contribution can be viewed from two angles: Firstly, underlined the richness of extra virgin olive oils received in the four cities we studied, particularly in terms of oleic acids and minor compounds like polyphenols. This finding holds particular importance for consumers and producers as it can promote the marketing of these oils as healthful products. Secondly, the method we have developed may prove to be a vital tool for verifying the geographical authenticity of oils produced in this region using both extraction systems.

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Conflicts of interest

The authors affirm that there are no conflict of interest.

Data availability statement

The datasets utilized in the current study obtained from the corresponding author on reasonable request.

Author contribution statement

Siham BECHAR: Designed the model and the computational framework, analyzed the data, critically revised the article, and wrote the manuscript with input from all authors. **Chaymae NAJIMI:** Involved in the conception or design of the work, participated in data collection, provided critical revision of the article, and worked out the technical details of the manuscript. **Mohamed KHAMAR and Essediya CHERKAOU:** Contributed to the conception or design of the work, drafted the article, and participated in the critical revision of the article. **Ilhame BOURAIS and Abderrahman NOUNAH:** helped in revising the final version of the manuscript by providing constructive ideas. All authors have read and approved the final manuscript and agreed to the published version of the manuscript

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