



# Influence of geographical origin on the sensory and volatile profiles of Portuguese monovarietal olive oils

Pedrina Rocha<sup>a,b</sup>, Daniela Ruano<sup>a</sup>, Nuno Ferreiro<sup>a</sup>, Luísa L. Martins<sup>b</sup>, Nuno Rodrigues<sup>a,\*</sup>

<sup>a</sup> CIMO, LA SusTEC, Instituto Politécnico de Bragança, Campus de Santa Apolónia, Bragança 5300-253, Portugal

<sup>b</sup> Linking Landscape, Environment, Agriculture and Food (LEAF), Instituto Superior de Agronomia, Universidade de Lisboa, 1349-017 Lisboa, Portugal

## ARTICLE INFO

### Keywords:

Extra virgin olive oil  
Aroma markers  
Volatile fingerprint  
Sensory typicity  
Cobrançosa and Galega cultivars

## ABSTRACT

The sensory and volatile profiles of monovarietal olive oils from the Portuguese cultivars Cobrançosa and Galega, produced in three geographical regions (Alentejo, Beira Interior, and Trás-os-Montes), were investigated to evaluate the effects of cultivar and geographical origin. All samples were classified as extra virgin olive oil. Sensory analysis revealed significant differences ( $p < 0.05$ ) between cultivars and among regions. Cobrançosa olive oils exhibited an intense green sensory profile, characterized by high green fruitiness, and tomato, apple, and herbaceous notes, particularly in oils from Trás-os-Montes and Alentejo. In contrast, Galega olive oils showed a more balanced and moderated sensory profile, with lower intensities of bitterness and pungency and variability among regions. Volatile characterization by HS-SPME-GC-MS led to the identification of 26 compounds in Cobrançosa and 29 in Galega olive oils, grouped into seven chemical families. Olive oils from Beira Interior and Trás-os-Montes showed higher concentrations of lipoxygenase-derived C5 and C6 compounds, such as (E)-2-hexenal, associated with green and fruity sensory sensations, whereas Alentejo oils exhibited lower volatile diversity but higher relative abundance of certain sesquiterpenes. Pearson correlation analysis revealed a strong association between sensory descriptors and key volatile compounds, highlighting region specific sensory-chemical patterns. Linear discriminant analysis (LDA) based on sensory and volatile data achieved excellent classification performance, with accuracies up to 100% for both cultivars. Overall, the results demonstrate an interaction between cultivar and geographical origin, supporting the use of sensory and volatile profiling as tools for the differentiation and authentication of Portuguese monovarietal olive oils.

## 1. Introduction

Olive oil represents the main source of dietary fat and constitutes a staple component of the traditional Mediterranean diet (Díaz-Montaña et al., 2023). In the last decades, the consumption of extra virgin olive oil has increased globally, driven not only by its nutritional and health benefits but also by its distinctive sensory attributes (Aparicio-Ruiz et al., 2022; Cecchi et al., 2021; Lobo-Prieto et al., 2020). Among food products, extra virgin olive oil is unique in being subject to a standardized commercial classification protocol that includes mandatory sensory evaluation, regulated by European legislation in accordance with the limits established by the Commission Implementing Regulation (EU), 2022/2105 of 29 July 2022.

The sensory profile of extra virgin olive oil results from complex interactions between volatile compounds and the human sensory receptors involved in taste, smell, vision, as well as trigeminal and tactile

perceptions (Campestre et al., 2017). Such interactions may generate synergistic or antagonistic effects, leading to new sensory perceptions resulting from the combination of taste and olfactory stimuli. Despite this complexity, several studies have demonstrated a strong correlation between the sensory attributes and the concentration of particular volatile compounds in olive oil (Campestre et al., 2017; García-Vico et al., 2017; Üçüncüoğlu & Sivri-Özay, 2020).

The volatile fraction of extra virgin olive oil is characterized by diverse chemical compounds present at low concentrations, belonging to different chemical classes, such as aldehydes, alcohols, esters, hydrocarbons, terpenes and furans (Cecchi et al., 2021; Stilo et al., 2021). These compounds are mainly formed during the extraction process through - enzymatic reactions mediated by lipoxygenase (LOX) pathway (Aparicio-Ruiz et al., 2020; Aprea et al., 2018; Lobo-Prieto et al., 2020, 2022). It is well established that endogenous plant enzymes involved in this pathway are responsible for the desirable green and fruity aromatic

\* Correspondence author.

E-mail address: [nunorodrigues@ipb.pt](mailto:nunorodrigues@ipb.pt) (N. Rodrigues).

attributes of extra virgin olive oil, whereas chemical oxidation and exogenous enzymes activity, commonly linked to microbial contamination, are associated with the development of sensory defects (Aparicio-Ruiz et al., 2022; Cecchi et al., 2021).

The composition and concentration of volatiles are influenced by multiple factors, including olive cultivar, pedoclimatic conditions, ripening stage at harvest, processing technology, filtering, storage conditions, and geographical origin (Cecchi et al., 2020; Lukić et al., 2018; Vidal et al., 2018). Among these, geographical origin has been shown to exert a significant effect on the volatile profile of olive oils (Cecchi et al., 2021; Lukić et al., 2018; Zago et al., 2019). Factors such as climate conditions influence the formation of volatile compounds originating from LOX pathway, namely hexanal, (E)-2-hexenal, (E)-2-hexen-1-ol and pentanal, although this influence is also modulated by other factors, such as the cultivar (Cecchi et al., 2021; Romero et al., 2016; Žanetić et al., 2021). The altitude of olive-growing, closely related to local thermal conditions, also plays a significant role in shaping the sensory characteristics of olive oil (Deiana et al., 2023; Romero et al., 2016). In general, olive oils obtained from fruits grown in high-altitude regions, exposed to lower temperatures, tend to exhibit higher intensities of bitterness, pungency and fruitiness, compared to oils from low-altitude regions with milder climates (Jukić Špika et al., 2021; Romero et al., 2016). In addition, the type of soil and its composition has been shown to influence the concentration of compounds responsible for olive oil sensory attributes (Romero et al., 2016). In general, the effects of geographical origin on extra virgin olive oil quality result from the interaction of multiple environmental and varietal factors. Several studies have shown that these combined effects can be used to support the characterization, differentiation, and traceability of olive oils according to geographical origin (Cajka et al., 2010), as well as exploring

its impact on aroma (Youssef et al., 2011). In Portugal, the Cobrançosa and Galega are two of the most representative and widespread olive cultivars, playing a central role in national olive oil production. These cultivars are well adapted to Portuguese soil and climate conditions and are recognized for producing olive oils with high sensory quality. These cultivars are part of the national olive-growing heritage and integrates different protected designation of origin (PDO) along the territory.

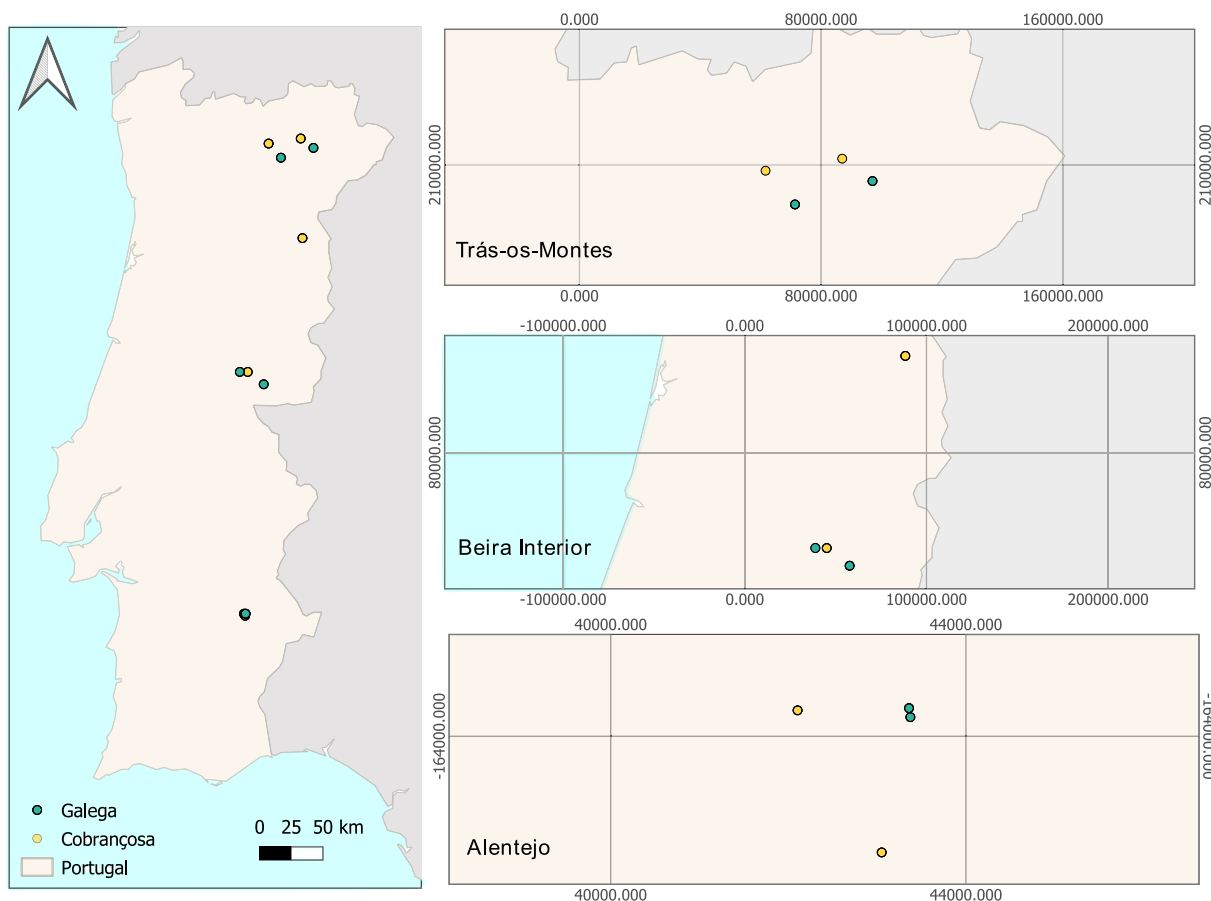
In this context, the aim of this study is to evaluate the effect of geographical origin on the sensory and volatile profile of monovarietal olive oils obtained from the Cobrançosa and Galega cultivars grown in the Portuguese main producing regions (Alentejo, Beira Interior and Trás-os-Montes). A detailed characterization of the sensory attributes and volatile profiles is expected to identify significant regional differences associated with edaphoclimatic conditions, region-specific agronomic practices, and technological processing factors.

The expected results aim to contribute to a deeper understanding of how territorial factors influence the sensory and volatile differentiation of extra virgin olive oils, supporting the characterization of regional typicity and providing scientific support for origin verification, product genuineness, facilitating differentiation and valorization of high-quality olive oils in premium markets.

## 2. Material and methods

### 2.1. Grove selection, fruit harvesting and oil extraction

This study was carried out in the three major olive-producing regions of Portugal (Alentejo, Beira Interior, and Trás-os-Montes regions) and focused on the two most spread and cultivated olive cultivars, Cobrançosa and Galega. In each region, two olive groves per cultivar were



**Fig. 1.** Map of Portugal showing the geographic distribution of the sampling groves of the Galega and Cobrançosa olive cultivars across the regions of Trás-os-Montes, Beira Interior, and Alentejo. The map is projected in the ETRS89 / PT-TM06 coordinate reference system.

selected based on the similarity of agricultural practices (Fig. 1). In each olive grove, five plants of each cultivar were selected for analysis, resulting in a total of 10 plants per region per cultivar. Selection criteria ensured comparable conditions regarding soil management, fertilization regime, water availability, and phytosanitary treatments, thereby minimizing agronomic variability among sites. Climatic conditions during the olive maturation period, particularly in September and October, varied markedly among the regions, reflecting their distinct geographical and meteorological characteristics. Alentejo is characterized by a hot and dry Mediterranean climate. In 2023, the mean air temperature in August was 23.3 °C (minimum 15.9 °C and maximum 32.3 °C), decreasing progressively to an average of 17.8 °C in October (minimum of 12.3 °C and maximum of 23.2 °C) (IPMA, 2025). Beira Interior, located in central Portugal, exhibits a predominantly continental climate, with hot summers and cold winters. In August 2023, the mean temperature reached 24.4 °C (minimum 17.2 °C, maximum 31.6 °C), declining to 16.3 °C in October (minimum 11.6 °C, maximum 21.0 °C). Trás-os-Montes, situated in northeastern Portugal, is characterized by hot and dry summers and cold winters; during 2023, the average temperature decreased from 21.1 °C in August (minimum 13.7 °C, maximum 28.5 °C) to 12.8 °C in October (minimum 7.5 °C, maximum 18.1 °C) (IPMA, 2025). During the 2023 harvest season, in each olive grove, five trees were selected. From each tree, 5 kg of fruits were manually harvested, ensuring homogeneity of fruit ripeness. All samples presented a maturity index (MI) between 3.5 and 4.5, following the methodology established by the International Olive Council (IOC, 2011). Harvested olives were immediately transported to the laboratory of the School of Agriculture of the Bragança Polytechnic University (IPB), where oil extraction was performed. The extraction process occurred within 24 h of harvesting using a pilot-scale unit Abencor system (Comercial Abengoa SA, Seville, Spain). The process began with the olives crushing in an MC2 MM100 hammer mill (Seville, Spain), equipped with a 5.5 mm diameter sieve and a 1.5 kW single-phase motor. The resulting paste was subjected to a temperature-controlled malaxation process in an MC2 Thermo-Mixer TB-100 thermal mixer (Seville, Spain), comprising eight independent workstations, each with individual mixing containers, thermal control system, and specific blades to ensure efficient homogenization. Subsequently, phase separation was performed by centrifugation using an MC2 CF-100 centrifuge (Seville, Spain), equipped with a stainless-steel drum, operating at a speed of 3500 rpm, driven by a 1.5 kW three-phase motor with an automatic timer. The extracted oils were filtered through Whatman No. 4 filter paper over anhydrous sodium sulphate to remove solid particles and traces of residual moisture. Finally, the olive oils were bottled in 125 mL amber glass bottles and stored in the dark at room temperature (18–23 °C) until subsequent laboratory analyses.

## 2.2. Descriptive sensory profile

The sensory profile of the samples was established by a panel of eight trained tasters (five men and three women, aged from 22 to 55 years old, with an average age of 35 years) from the School of Agriculture (IPB). The panel, active since 2014, comprises assessors with experience in olive oil sensory evaluation who undergo continuous training following IOC guidelines, particularly in the identification of positive sensory attributes. Although not formally certified or accredited, as the analyses were conducted for research purposes, internal validation procedures are applied to ensure data reliability, with result variability monitored and maintained below 20%; when this threshold is exceeded, the evaluation is repeated. The sensory analysis was carried out following the methodology described by Rodrigues et al. (2020), using an adapted evaluation form based on the model proposed by the International Olive Oil Council (IOC, 2005), organized into three distinct sections: olfactory, gustatory and olfactory-gustatory sensations. The intensity of the different sensory attributes was quantified using an unstructured scale from 0 to 10 cm, where zero corresponded to the total absence of the

sensation and ten indicated the maximum intensity perceived. In terms of olfactory sensations, the intensity of the fruitiness (green or ripe) was assessed, as well as the fruit and herbaceous notes, and the harmony of the whole. With regard to taste sensations, in addition to the parameters already mentioned for the olfactory evaluation, the intensity of sweetness, bitterness and pungency were also taken into account. In the area of olfactory-gustatory and taste sensations we analyzed the attributes of complexity and persistence. Complexity refers to the diversity and combination of positive sensations present in the oil, and high values in this parameter indicate samples rich in different sensory perceptions. On the other hand, persistence is related to the duration of the sensations perceived after tasting, with greater intensity being attributed to samples whose attributes remain in the oral cavity for longer. In order to allow for a more comprehensive sensory characterization and avoid conditioning the tasters, blank lines were included on the tasting sheet to record additional perceptions that were not included in the original list of attributes. The tasting sessions were held in an appropriate room, with natural lighting, room temperature and free of interfering odors. To ensure visual neutrality and avoid the influence of the color of the oil on the evaluation, official tasting glasses were used, with blue or red coloring, as established by the International Olive Council. The temperature of the samples was kept at around 28 °C at the time of evaluation, in order to favor the release of aromatic compounds and ensure a more accurate and representative analysis.

## 2.3. Volatile compounds

The volatile profile of the olive oils was characterized using gas chromatography coupled to mass spectrometry (GC–MS) and the headspace solid-phase microextraction (HS-SPME) according to Peres et al. (2013), with minor modifications as described below. For this purpose, a Shimadzu (Japan) GC-2010 Plus gas chromatograph coupled to a GC/MS-QP 2010 SE mass detector (Shimadzu, Japan) was used. The compounds were separated on a TRB-5MS capillary column (30 m × 0.25 mm × 0.25 µm; Teknokroma, Spain). For the extraction, 3.00 g of each sample was placed in a 50 mL glass vial, sealed with a screw cap fitted with a silicone septum coated with polytetrafluoroethylene (PTFE). The vials were kept in a water bath at 40 °C for 5 min, with constant stirring at 350 rpm, to promote the release of the volatile compounds from the oily matrix. A volume of 5 µL of internal standard (4-methyl-2-pentanol, 98%, Sigma Aldrich) dissolved in methanol was then added at a concentration of 0.127 mg/mL. This compound was selected due to its absence in olive oil samples and its suitable behavior under HS-SPME-GC–MS conditions. Volatile compounds were semi-quantified and expressed as mass equivalents of the internal standard, without applying individual response factors, which is a widely accepted approach for comparative analysis of complex volatile profiles. Five minutes after adding the standard, the SPME fiber (DVB/CAR/PDMS, 50/30 µm; Supelco, USA) was inserted into the head of the flask, exposing it to the gas phase for 30 min to adsorb the volatile compounds. Once the extraction phase was complete, the fiber was introduced into the GC injector in splitless mode, where the compounds were thermally desorbed at 220 °C for 1 min. To ensure the fiber was cleaned and reconditioned before analyzing new samples, it remained in the injector for another 10 min. The carrier gas used was helium (Alphagaz, Air Liquide, Portugal), with a linear flow of 30 cm/s and a total flow of 24.4 mL/min. The oven temperature program started at 40 °C (1 min), followed by a heating ramp of 2 °C/min until it reached 158 °C, a temperature that was maintained for 5 min. The ionization source was kept at 250 °C, with an energy of 70 eV and an ionization current of 0.1 kV. The mass spectra were acquired by electron ionization in the scanning range between 35 and 500 *m/z*. The volatile compounds were identified by comparing the spectra obtained with those in the NIST 11 library (National Institute of Standards and Technology, Gaithersburg, MD, USA), considering only matches with a similarity index equal to or greater than 85%. To reinforce identification, the Kováts indexes were also checked against the

NIST 69, PubChem and ChemSpider databases. Relative quantification was carried out based on the area of the peaks obtained in the total ion chromatogram (TIC), with the results expressed in mass equivalent to that of the internal standard. The limit of detection (LOD) was estimated based on the signal-to-noise ratio (S/N) of the total ion chromatogram (TIC), considering a minimum S/N of 3, with noise evaluated in regions

close to the retention time of each compound. Compounds with signals below this threshold were classified as not detected (ND). All analyses were conducted in duplicate.

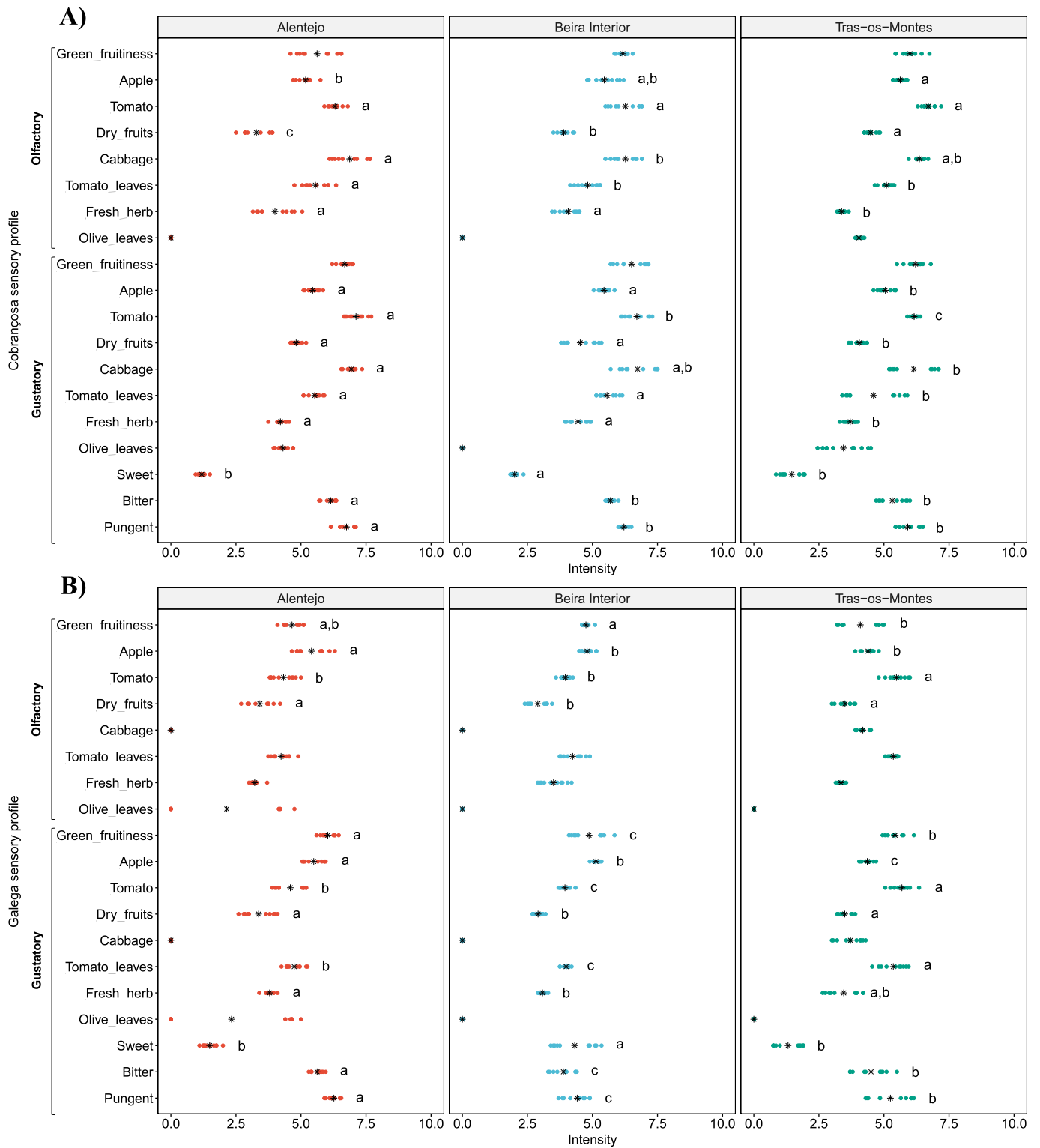


Fig. 2. Dot plot with mean values analysis of the olfactory and gustatory profile (fruity and herbaceous sensations) found in olive oils extracted from the A) Cobrançosa; B) Galega cvs; in the Alentejo, Beira Interior and Trás-os-Montes regions. Different lowercase letters mean statistically significant differences at a 5% significance level (one-way ANOVA followed by Tukey's multiple comparison test).

## 2.4. Statistical analysis

To evaluate the potential impacts of geographical origin (Alentejo, Beira Interior, and Trás-os-Montes regions) on the sensory and volatile profiles of Galega and Cobrançosa olive oils, one-way analysis of variance (one-way ANOVA) was applied. When statistically significant differences were found ( $P$  value  $< 0.050$ ), Tukey's post-hoc test was applied for multiple comparisons. For volatile compound detected in only two samples, comparisons were performed using Student's  $t$ -test. For sensory profile data analysis, a dot plot graph with superimposed means were used, allowing comparative visualization of perceived olfactory and gustatory intensity among regions for the various sensory descriptors. Pearson's linear correlation coefficients (R-Pearson) were used to determine the existence of bivariate correlations between the parameters analyzed in the olive oils (sensory attributes and volatile compounds) and the geographical origin. The results were represented in the form of a heatmap, allowing the direction and intensity of the correlations to be visualized graphically. The color scale ranges from green (negative correlation) to red (positive correlation), with correlation coefficients  $r$  close to  $+1$  indicating strong positive correlation, while values close to  $-1$  indicate strong negative correlation. In addition, Linear Discriminant Analysis (LDA) was applied as a supervised pattern recognition tool to classify and discriminate olive oils according to their region of origin using olive oil sensory and volatile profile data from Cobrançosa and Galega cultivars. Optimal parameter subsets of variables were identified using a simulated annealing (SA) variable selection algorithm. The classification performance of each model was evaluated using sensitivity metrics for the training dataset, leave-one-out cross-validation (leave-one-out-CV), and repeated K-fold CV (4 folds with 10 random repetitions).

All analyses were performed using RStudio statistical software, version 4.4.1, using open source packages. The level of statistical significance was set at 5%.

## 3. Results and discussion

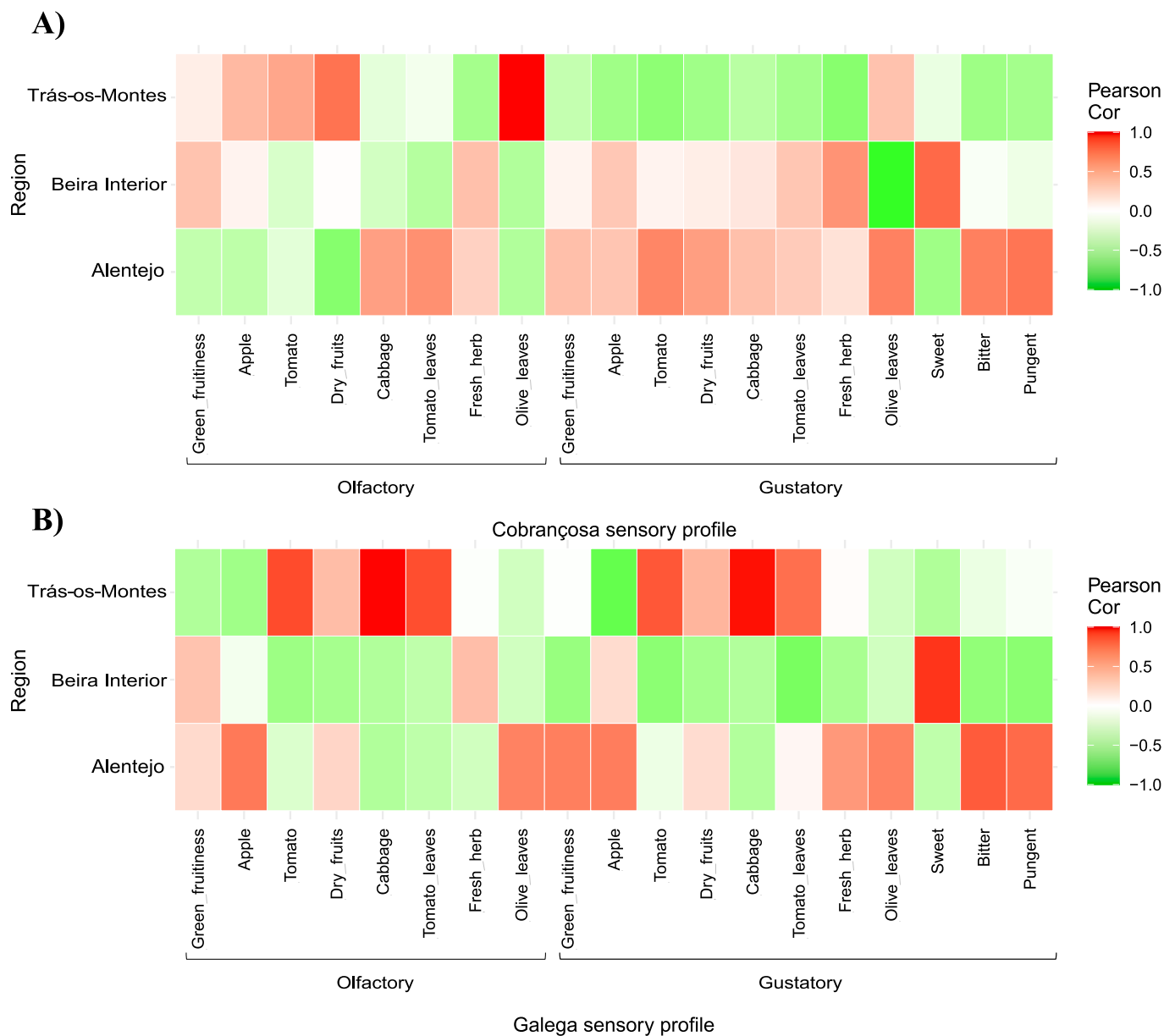
### 3.1. Sensory profile

The descriptive sensory profile was evaluated for all collected samples. Prior to sensory analysis, the olive oils were assessed for quality classification and all samples were classified as extra virgin olive oil (data not shown). Fig. 2 shows the olfactory and gustatory sensations identified by the trained panel in Cobrançosa and Galega olive oils produced in the Alentejo, Beira Interior, and Trás-os-Montes regions. Statistically significant differences ( $p < 0.05$ ) were observed among regions and between cultivars for several sensory descriptors (Fig. 2A and B). For the Cobrançosa cultivar (Fig. 2A), the olfactory profile was characterized by a pronounced green fruity sensation in olive oils, with mean intensity values around 6.0, and no significant differences were observed from the three geographical proveniences. This intensity range is consistent with previous studies describing Cobrançosa olive oils as having a marked green sensory profile (Peres et al., 2016). Fruity notes such as apple, tomato, and dry fruits were perceived, with significant differences among regions. Apple intensity ranged from 5.1 to 5.6, tomato from 6.2 to 6.7, and dry fruits from 3.2 to 4.5, with oils from Trás-os-Montes exhibiting the highest intensities. Similar fruity attributes and intensity ranges have been reported for this cultivar, particularly those from northern Portuguese regions (Marx et al., 2021). Concerning herbaceous sensations, cabbage notes ranged from 6.3 to 6.9, tomato leaves from 4.8 to 5.6, and fresh herbs from 3.4 to 4.0. Olive oils from the Alentejo region exhibited the highest intensities for most herbaceous descriptors, which is in line with previous findings indicating that warmer and drier climatic conditions favor the expression of intense herbaceous notes. Olive leaf sensation (mean intensity of 4.0) was detected exclusively in oils from the Trás-os-Montes, a feature commonly associated with olive oils produced in cooler and higher-

altitude environments. These sensory perceptions are characteristic of the cultivar and are consistent with profiles previously described by Marx et al. (2021). From the gustatory perspective (Fig. 2A), green fruitiness presented a mean intensity of approximately 6.5, with no significant differences among regions. Fruity sensations of apple ranged from 5.0 to 5.4, tomato from 6.1 to 7.1, and dry fruits from 4.0 to 4.8, with the highest intensities generally observed in oils from Alentejo. Herbaceous gustatory sensations included cabbage (6.1–6.9), tomato leaves (4.6–5.6), fresh herbs (3.7–4.4), and olive leaves (3.4–4.3). The higher gustatory intensities observed in Alentejo oils are consistent with reports indicating that olive oils produced under warmer Mediterranean conditions tend to exhibit stronger taste attributes, including bitterness and pungency, resulting in a more intense sensory perception (Deiana et al., 2023; Peres et al., 2021).

For the Galega cultivar (Fig. 2B), the olfactory profile was characterized by a moderate green fruitiness, with median intensity values around 4.5, with significant differences among regions. This behavior is consistent with previous studies reporting that Galega olive oils generally exhibit a milder green sensory profile compared with stronger aroma cultivars, which has been associated with their volatile composition and lower phenolic content (Peres et al., 2013; Peres et al., 2016). Fruity sensations of apple, tomato, and dry fruit were identified, with intensity values ranging from 4.4 to 5.4 for apple, 4.0 to 5.5 for tomato, and 2.9 to 3.5 for dry fruits. Although these descriptors are typical of Galega olive oils, no clear region effect was observed, suggesting a higher sensitivity of this cultivar to environmental and agronomic factors rather than a fixed regional sensory pattern. In Galega olive oils, herbaceous sensations included tomato leaves (4.2–5.4) and fresh herbs, with variations between 3.2 and 3.5. Cabbage notes were detected exclusively in olive oils from the Trás-os-Montes region, whereas olive leaves sensations were only perceived in oils from the Alentejo region. From a gustatory perspective (Fig. 2B), green fruitiness was perceived in olive oils from all regions, with a mean intensity of 5.4, with Alentejo oils exhibiting significantly higher intensities. Fruity and herbaceous sensations followed similar trends to those observed in the olfactory profile. Overall, the lower expression of bitterness and pungency typically associated with Galega olive oils is consistent with their lower phenolic contents and contribute to a smoother and more harmonious sensory profile (Peres et al., 2016).

Based on the obtained results, Cobrançosa olive oils were characterized by a more intense and predominantly green sensory profile, with greater expression of green fruitiness, fruity and herbaceous descriptors, bitterness and pungency, whereas Galega olive oils presented a smoother and more balanced sensory profile. Regional effects were more pronounced for Cobrançosa, with olive oils from Trás-os-Montes showing higher olfactory intensity and those from Alentejo exhibiting strong gustatory sensations. In contrast, the Galega olive oils showed greater sensory variability inside the region, without a consistent regional pattern, highlighting the greater sensitivity of this cultivar to environmental and agronomic factors. To better understand the relationships between sensory descriptors, cultivar and geographical origin, Pearson correlation analysis was performed and graphically represented as heat maps. Fig. 3 shows the Pearson correlation matrices for Cobrançosa (Fig. 3A) and Galega (Fig. 3B) olive oils produced in three Portuguese regions. The color scale indicates positive (red) and negative (green) correlations, allowing direct visualization of the strength and direction of associations. Regarding Cobrançosa (Fig. 3A), olfactory correlations indicated positive associations between green fruitiness and oils from Beira Interior and Trás-os-Montes, while Alentejo oils showed a negative relationship with this descriptor. Oils from Trás-os-Montes correlated positively with olive leaves (1.0), dry fruits (0.7), tomato (0.5), and apple (0.4) and negatively with fresh herbs ( $-0.6$ ), whereas Beira Interior oils were positively associated with fresh herbs (0.6) and apple. Alentejo oils showed positive correlations with tomato leaves (0.6), cabbage (0.5), and fresh herbs, and a negative correlation with dry fruits ( $-0.7$ ).



**Fig. 3.** Heat maps of Pearson correlations between the average sensory profiles of three Portuguese olive oil producing regions (Alentejo, Beira Interior, and Trás-os-Montes) and the sensory profiles of the **Cobrançosa A** and **Galega B** cultivars. The intensity of the color represents the degree and direction of the correlation: shades of red indicate a positive correlation (greater similarity between sensory profiles) and shades of green indicate a negative correlation (less similarity). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the gustatory profile (Fig. 3A), an inverse trend was observed. Alentejo olive oils correlated positively with green fruitiness tomato (0.6), olive leaves (0.6), dry fruits (0.5), bitter (0.6), and pungent (0.7), whereas olive oils from Trás-os-Montes showed mainly negative correlation with exception of olive leaves (1.0). Beira Interior showed positive correlations with fresh herbs (0.6), apple, tomato leaves, and sweet (0.7). These results are in line with the trends previously observed in the description of the sensory profile of the Cobrançosa oils from Trás-os-Montes exhibit a more intense olfactory profile, while those from Beira Interior and Alentejo display stronger gustatory sensations. For Galega oils (Fig. 3B), similar correlation patterns were observed for olfactory and gustatory profiles. Olive oils from Alentejo correlated positively with green fruit, apple, dry fruits, olive leaves, bitter, and pungency. Trás-os-Montes oils showed positive correlations with tomato, dry fruits, cabbage, and tomato leaves, while those from Beira Interior correlated positively with fresh herbs, apple, and sweetness. These results

demonstrate that the sensory profile of monovarietal olive oils is strongly influenced by geographical origin and cultivar.

### 3.2. Volatile characterization

The characterization of the volatile profile of olive oils is fundamental to understanding their sensory attributes, to establish product profiling and to determining the influence of geographical origin. In this study, the volatile composition of monovarietal olive oils from the Cobrançosa and Galega cultivars, originating from three Portuguese regions (Alentejo, Beira Interior, and Trás-os-Montes), was evaluated. The volatile compounds identified in the olive oils studied were grouped into seven chemical families (Table 1). In the Cobrançosa olive oils, 26 volatile compounds were identified and quantified, comprising six ketones, six aldehydes, three alcohols, four hydrocarbons, two esters, six terpenes, and one ether. While in Galega oils, 29 compounds were

**Table 1**Concentration (mean  $\pm$  standard deviation,  $\mu\text{g}$  of internal standard equivalents/g of olive oil) of the volatile compounds identified in olive oils from Alentejo, Beira Interior and Trás-os-Montes regions.\*, \*\*

Volatile compound	RT min	Region of Portugal			P-value
		Alentejo	Beira Interior	Trás-os-Montes	
<b>Alcohols</b>					
(Z)-2-Penten-1-ol	6.8	0.34 $\pm$ 0.05c	0.92 $\pm$ 0.08a	0.72 $\pm$ 0.11b	<0.0001
(Z)-3-Hexen-1-ol	10.4	0.35 $\pm$ 0.08	ND	ND	–
1-Hexanol	11.1	0.04 $\pm$ 0.01b	0.04 $\pm$ 0.01b	0.14 $\pm$ 0.13a	0.010
<b>Aldehydes</b>					
(E)-2-Pentenal	5.9	0.01 $\pm$ 0.00b	0.02 $\pm$ 0.01a	0.02 $\pm$ 0.01a	<0.0001
(Z)-3-Hexenal	7.8	0.98 $\pm$ 0.32c	4.43 $\pm$ 1.66a	2.91 $\pm$ 0.99b	<0.0001
(E)-2-Hexenal	10.2	0.24 $\pm$ 0.13b	4.60 $\pm$ 0.82a	5.65 $\pm$ 2.85a	<0.0001
(E,E)-2,4-Hexadienal	13.5	0.02 $\pm$ 0.01b	0.15 $\pm$ 0.03a	0.13 $\pm$ 0.04a	<0.0001
(E)-4-Oxohept-2-enal	16.4	0.09 $\pm$ 0.03c	1.31 $\pm$ 0.29a	0.64 $\pm$ 0.19b	<0.0001
Decanal	33.8	0.21 $\pm$ 0.27a	ND	0.02 $\pm$ 0.03b	0.010
<b>Esters</b>					
Hexyl acetate	20.2	ND	0.01 $\pm$ 0.00a,b	0.01 $\pm$ 0.00a	0.003
Methyl salicylate	32.8	ND	0.01 $\pm$ 0.00a	0.01 $\pm$ 0.00a	<0.0001
<b>Ethers</b>					
(Z)-1-methoxy-3-hexene	9.3	0.09 $\pm$ 0.10	ND	ND	–
<b>cv. Cobrançosa</b>					
<b>Hydrocarbons</b>					
3-Ethyl-1,5-octadiene (isomer I)	12.6	0.04 $\pm$ 0.01c	0.21 $\pm$ 0.02a	0.17 $\pm$ 0.03b	<0.0001
3-Ethyl-1,5-octadiene (isomer II)	15.2	0.25 $\pm$ 0.07c	1.80 $\pm$ 0.18a	1.34 $\pm$ 0.29b	<0.0001
3-Ethyl-1,5-octadiene (isomer III)	15.6	0.22 $\pm$ 0.05c	2.21 $\pm$ 0.21a	1.82 $\pm$ 0.46b	<0.0001
4,8-Dimethyl-1,7-nonadiene	19.1	0.35 $\pm$ 0.11b	4.44 $\pm$ 0.48a	3.36 $\pm$ 1.66a	<0.0001
<b>Ketones</b>					
1-Penten-3-one	4.5	1.69 $\pm$ 0.18b	3.59 $\pm$ 0.47a	3.95 $\pm$ 0.70a	<0.0001
6-Methyl-5-heptene-2-one	18.3	0.01 $\pm$ 0.00	0.01 $\pm$ 0.00	0.01 $\pm$ 0.01	0.691
3,3,6-Trimethyl-1,5-heptadien-4-one	21.5	0.01 $\pm$ 0.00b	0.10 $\pm$ 0.03a	0.08 $\pm$ 0.02a	<0.0001
2-methyl-6-methylene-1,7-octadien-3-one	25.9	0.05 $\pm$ 0.02a	0.02 $\pm$ 0.00b	0.01 $\pm$ 0.00b	<0.0001
<b>Terpene</b>					
D-Limonene	21.2	0.01 $\pm$ 0.00b	0.01 $\pm$ 0.00a	0.01 $\pm$ 0.00a	0.002
.beta.-Ocimene	22.5	ND	0.04 $\pm$ 0.01a,b	0.09 $\pm$ 0.08a	0.002
Linalool	26.2	ND	0.01 $\pm$ 0.00a	0.01 $\pm$ 0.00b	<0.0001
Geranyl nitrile	27.4	2.99 $\pm$ 1.38a	1.00 $\pm$ 0.16b	0.47 $\pm$ 0.27b	<0.0001
.alfa.-Copaene	45.2	ND	0.01 $\pm$ 0.00	ND	–
.alpha.-Farnesene	53.5	ND	ND	0.01 $\pm$ 0.01	–
<b>Alcohols</b>					
(Z)-2-Penten-1-ol	6.8	0.27 $\pm$ 0.07b	0.65 $\pm$ 0.11a	0.33 $\pm$ 0.11b	<0.0001
(E)-2-Hexen-1-ol	10.9	ND	0.04 $\pm$ 0.03a	0.02 $\pm$ 0.03a,b	0.005
1-Hexanol	11.1	0.03 $\pm$ 0.01b	0.05 $\pm$ 0.01a	0.07 $\pm$ 0.02a	<0.0001
<b>Aldehydes</b>					
(E)-2-Pentenal	5.9	ND	0.02 $\pm$ 0.00	0.02 $\pm$ 0.01	0.306
(Z)-3-Hexenal	7.8	0.68 $\pm$ 0.39b	1.83 $\pm$ 0.51a	1.94 $\pm$ 1.18a	0.002
(E)-2-Hexenal	10.2	0.65 $\pm$ 0.24c	6.09 $\pm$ 1.73b	10.12 $\pm$ 1.81a	<0.0001
(E,E)-2,4-Hexadienal	13.5	0.03 $\pm$ 0.01b	0.07 $\pm$ 0.02a	0.07 $\pm$ 0.03a	<0.0001
(E)-4-Oxohept-2-enal	16.4	0.07 $\pm$ 0.04b	0.17 $\pm$ 0.04b	0.40 $\pm$ 0.35a	0.005
Decanal	33.8	0.02 $\pm$ 0.01	0.03 $\pm$ 0.03	0.02 $\pm$ 0.01	0.403
<b>Esters</b>					
(Z)-3-Hexenyl acetate	19.7	0.01 $\pm$ 0.00	ND	0.04 $\pm$ 0.06	0.061
Hexyl acetate	20.2	ND	ND	0.01 $\pm$ 0.01	–
Methyl salicylate	32.8	ND	ND	0.02 $\pm$ 0.01	–
<b>Hydrocarbons</b>					
3-Ethyl-1,5-octadiene (isomer I)	12.6	0.06 $\pm$ 0.02b	0.12 $\pm$ 0.02a	0.13 $\pm$ 0.02a	<0.0001
3-Ethyl-1,5-octadiene (isomer II)	15.2	0.40 $\pm$ 0.12b	0.95 $\pm$ 0.15a	1.09 $\pm$ 0.26a	<0.0001
3-Ethyl-1,5-octadiene (isomer III)	15.6	0.35 $\pm$ 0.14b	1.08 $\pm$ 0.14a	1.29 $\pm$ 0.26a	<0.0001
4,8-Dimethyl-1,7-nonadiene	19.1	0.41 $\pm$ 0.12b	1.94 $\pm$ 0.30a	2.44 $\pm$ 0.86a	<0.0001
2,6-Dimethyl-2,4,6-octatriene	29.2	ND	0.01 $\pm$ 0.00	ND	–
<b>Ketones</b>					
1-Penten-3-one	4.5	1.51 $\pm$ 0.35b	3.10 $\pm$ 0.64a	1.75 $\pm$ 0.47b	<0.0001
3-Pentanone	4.7	0.09 $\pm$ 0.11	ND	ND	–
6-Methyl-5-heptene-2-one	18.3	0.01 $\pm$ 0.01	0.01 $\pm$ 0.00	0.01 $\pm$ 0.01	0.348
3,3,6-Trimethyl-1,5-heptadien-4-one	21.5	0.01 $\pm$ 0.01b	0.03 $\pm$ 0.01a,b	0.04 $\pm$ 0.04a	0.025
2-methyl-6-methylene-1,7-octadien-3-one	25.9	0.01 $\pm$ 0.00	0.02 $\pm$ 0.01	0.01 $\pm$ 0.00	0.118
<b>Terpene</b>					
D-Limonene	21.2	0.01 $\pm$ 0.00b	0.01 $\pm$ 0.00a,b	0.01 $\pm$ 0.00a	<0.0001
.beta.-Ocimene	22.5	0.01 $\pm$ 0.00b	0.12 $\pm$ 0.06b	0.08 $\pm$ 0.03a	<0.0001
Linalool	26.2	0.01 $\pm$ 0.00	0.01 $\pm$ 0.00	0.01 $\pm$ 0.00	0.381
Geranyl nitrile	27.4	0.64 $\pm$ 0.15	0.83 $\pm$ 0.35	0.57 $\pm$ 0.19	0.059
(+)-Cyclosativene	44.5	0.01 $\pm$ 0.00	ND	ND	–
.alfa.-Copaene	45.2	0.07 $\pm$ 0.01a	0.04 $\pm$ 0.01b	0.03 $\pm$ 0.03b	0.002
.alpha.-Muuroleone	53.1	0.01 $\pm$ 0.00a	0.01 $\pm$ 0.00a,b	0.01 $\pm$ 0.01b	0.026

\* Different letters between regions mean that they differ statistically (p-value <0.05) for the concentration of the volatile compound in question. N/A means not detected. The test applied when the volatile compound was present in all three samples was a one-way ANOVA followed by the Tukey test. When the volatile compound was only present in two samples, the t-Student test was applied.

\*\* NA (not detected) indicates that the compound was not detected in the analyzed olive oil samples, meaning its concentration was below the detection limit of the analytical method employed. This outcome may reflect a true absence of the compound.

identified distributed among five ketones, six aldehydes, three alcohols, five hydrocarbons, three esters, and seven terpenes (Table 1). The results revealed marked differences in the volatile profile highlighting the influence of cultivar and geographical origin.

For Cobrançosa, alcohols showed significant regional variations. The compound (Z)-2-Penten-1-ol showed significantly higher concentrations in olive oils from Beira Interior ( $0.92 \pm 0.08 \mu\text{g/g}$  of olive oil) and olive oils from Trás-os-Montes ( $0.72 \pm 0.11 \mu\text{g/g}$  of olive oil). 1-Hexanol was most abundant in Trás-os-Montes ( $0.14 \pm 0.13 \mu\text{g/g}$  of olive oil), while (Z)-3-Hexen-1-ol was detected exclusively in Alentejo olive oils ( $0.35 \pm 0.08 \mu\text{g/g}$  of olive oil). These alcohols are associated with fresh, green, and fruity sensory attributes in olive oil (Caratti et al., 2025). According to Kopsahelis et al. (2024) (Z)-3-Hexen-1-ol, together with other alcohols, has been linked to bitterness and pungency, which is consistent with the sensory profile described for Cobrançosa olive oils from Alentejo. Among the aldehydes, (Z)-3-Hexenal and (E)-2-Hexenal, related to green and fruity notes, were present in significantly higher concentration in olive oils from Beira Interior and Trás-os-Montes. With special emphasis on (E)-2-Hexenal that reached  $5.65 \pm 2.85 \mu\text{g/g}$  of olive oil in Trás-os-Montes, compared to only  $0.24 \pm 0.13 \mu\text{g/g}$  of olive oil in Alentejo.

As the predominant C6 aldehydes formed via lipoxygenase pathway, (E)-2-Hexenal is strongly associated with green, fruity, and floral sensations of olive oil (Ríos-Reina et al., 2023) suggesting high lipoxygenase pathway activity in olive oils from Trás-os-Montes and Beira Interior. Also, Žanetić et al. (2021) report that geographical origin, probably due to climatic conditions, has a significant effect on the concentration of the LOX-derived volatiles (Z)-3-Hexenal, (Z)-3-Hexenol, Hexanal, Hexanol, (E)-2-Hexenal, (E)-3-Hexenol, and (E)-2-Hexenol. Hydrocarbons followed a similar trend, with higher concentrations of the three isomers 3-Ethyl-1,5-octadiene in Beira Interior olive oils, followed by Trás-os-Montes and lower levels in Alentejo. The similar pattern was observed for 4,8-Dimethyl-1,7-nonadiene which has been associated with sweet and apple-like sensory notes Olmo-Cunillera et al. (2022). For terpenes, Geranyl nitrile was more abundant in Alentejo olive oils ( $2.99 \pm 1.38 \mu\text{g/g}$  of olive oil), while Linalool and .beta.-Ocimene, were predominantly detected in olive oils from Trás-os-Montes and Beira Interior regions, respectively. Geranyl nitrile has been previously associated with a severe water deficit in olive oils from Leccino when different irrigation strategies were studied (Servili et al., 2007). Linalool and .beta.-Ocimene are described as contributing for citrus and floral aroma (Stilo et al., 2021). These differences highlight distinct volatile profiles between regions.

In Galega oils, partially similar trends were observed. (Z)-2-Penten-1-ol reached its highest concentration in Beira Interior olive oils ( $0.65 \pm 0.11 \mu\text{g/g}$  of olive oil), while 1-Hexanol was more abundant in Trás-os-Montes olive oils ( $0.07 \pm 0.02 \mu\text{g/g}$  of olive oil). Aldehydes showed pronounced regional variation, with (E)-2-Hexenal particularly higher concentration in Trás-os-Montes ( $10.12 \pm 1.81 \mu\text{g/g}$  of olive oil), followed by Beira Interior ( $6.09 \pm 1.73 \mu\text{g/g}$  of olive oil), compared to Alentejo ( $0.65 \pm 0.24 \mu\text{g/g}$  of olive oil). These values are in line with those reported by Peres et al. (2013) for Galega olive oils produced in Beira Baixa. Hydrocarbons tended to be more concentrated in the Beira Interior and Trás-os-Montes olive oils. Terpenes such as .beta.-Ocimene were more abundant in Beira Interior, and compounds such as (+)-Cyclosativene and .alpha.-Copaene were more concentrated in Alentejo olive oils, reflecting marked differences in the terpene composition between regions. Sesquiterpenes .alpha.-Copaene, .alpha.-Muuroleone, and .alpha.-Farnesene have previously demonstrated capacity for discriminate cultivar and geographical origin in Hojiblanca and Picual olive oils (Caratti et al., 2025). Benelli et al. (2015) also observed that water deficit in the olive grove affects the presence of cyclosativene and alpha-muuroleone in Frantoio olive oils.

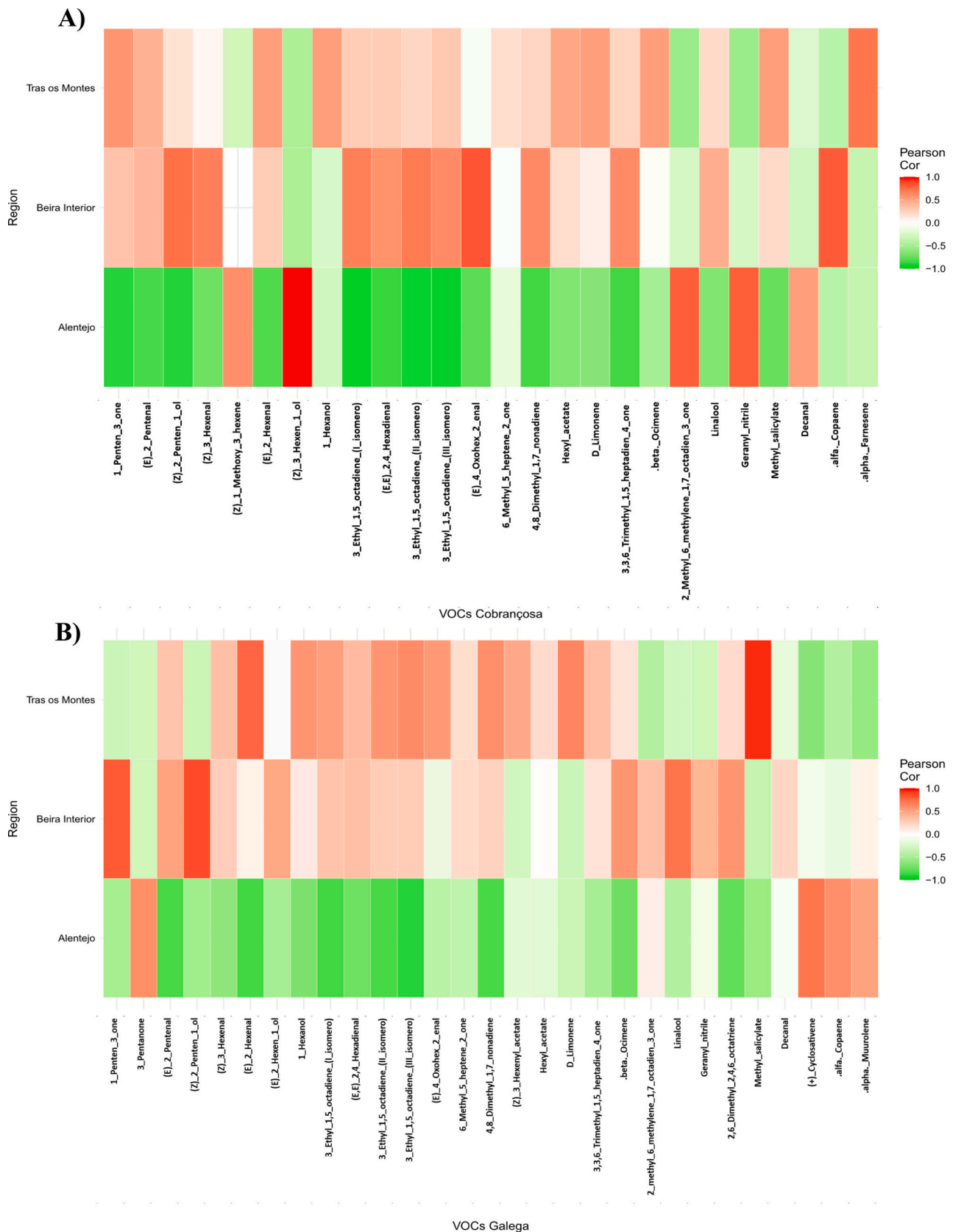
Overall, olive oils from Beira Interior and Trás-os-Montes were characterized by higher levels of volatile compounds associated with positive sensory attributes, including freshness, green fruit, and aromatic complexity. In contrast, olive oils from Alentejo exhibited less volatile diversity and concentration but showed a significant presence of certain sesquiterpenes. The interaction between genetic factors (cultivar) and environmental factors (production region) constitutes a fundamental tool for understanding the volatile profile of olive oils. To better explore these relationships, Pearson correlation analysis was performed between volatile compounds and production regions for both cultivars. Heat map visualization (Fig. 4) enabled intuitive assessment of association between the chemical variables (volatile compounds) and geographical origin. In Cobrançosa (Fig. 4A), olive oils from Trás-os-Montes evidenced significant positive correlations with 1-Penten-3-one, (E)-2-Hexenal and .alpha.-Farnesene, molecules associated with green, fruity and floral notes (Caratti et al., 2025; Cecchi et al., 2021). Beira Interior olive oils correlated positively with (Z)-2-Penten-1-ol, (E)-4-Oxohex-2-enal and .alpha.-Copaene that confer notes of green, fruity, sweet and floral (Cecchi et al., 2021; Üçüncüoğlu & Sivri-Özay, 2020). Whereas Alentejo olive oils showed marked negative correlations with several aldehydes (E)-2-Pentenal, (Z)-3-Hexenal and (E)-2-Hexenal, but a positive correlation with (Z)-3-Hexen-1-ol, evidencing a green and fresh sensations as cut grass (Ríos-Reina et al., 2023). In Galega (Fig. 4B), Trás-os-Montes olive oils were positively correlated with (E)-2-Hexenal, D-Limonene and Methyl salicylate, associated with green, fruity, citrus and sweet notes (Mariotti et al., 2022). Whereas Beira Interior samples showed positive associations with 1-Penten-3-one; (Z)-2-Penten-1-ol and Linalool, associated to green, fruity, sweet and lavender sensations (Üçüncüoğlu & Sivri-Özay, 2020). Olive oils from Alentejo correlated positively only with 3-Pentanone and (+)-Cyclosativene, .alpha.-Copaene and .alpha.-Muuroleone. These patterns support the role of volatile compounds as chemical markers of varietal identity and geographical origin.

### 3.3. Region discrimination based on sensory and volatile profiles

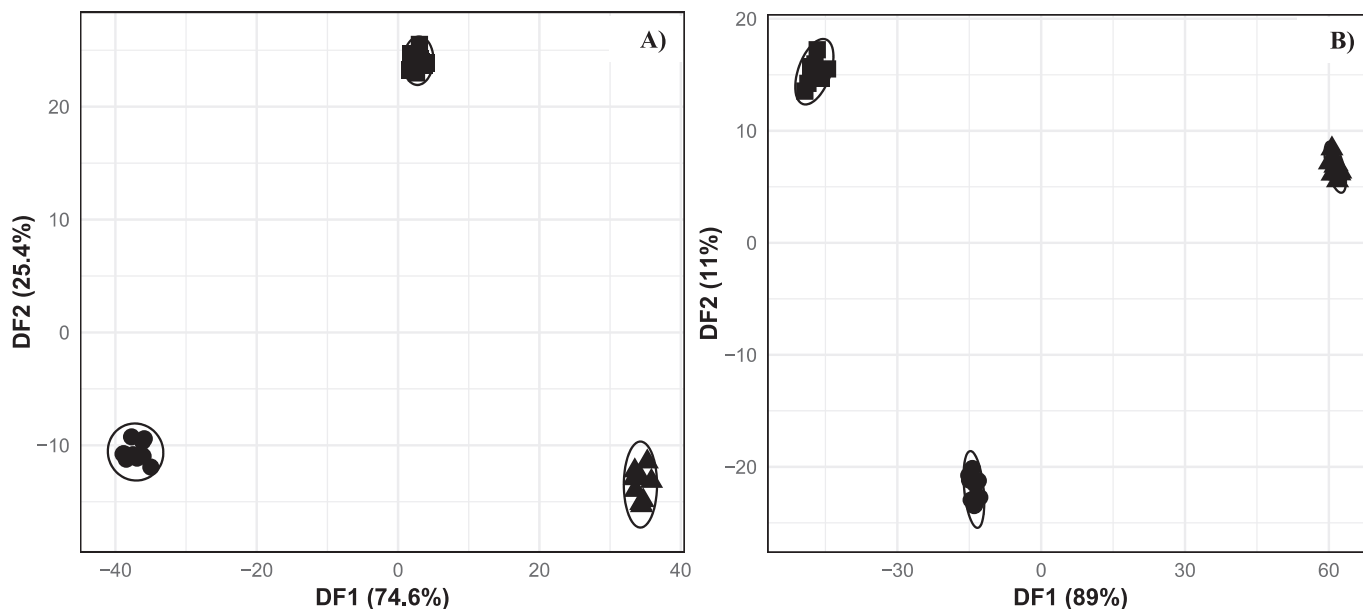
Independent Linear Discrimination Analysis (LDA) models were developed to assess the ability of sensory attributes and volatile compounds to discriminate olive oils from the Cobrançosa and Galega cultivars according to geographical origin (Alentejo, Beira Interior, and Trás-os-Montes) (Fig. 5). For Cobrançosa oils (Fig. 5A) the discrimination was based on 23 selected variables from sensory attributes and volatile compounds (variables O.Green\_fruitiness, O.Dry\_fruits, O.Cabbage, O.Tomato\_leaves, O.Fresh\_herb, O.Olive\_leaves, Sweet, Pungent, G.Apple, G.Dry\_fruits, G.Fresh\_herb, (E).2.Pentenal, (Z).3.Hexenal, (E).E).2,4.Hexadienal, (E).4.Oxohex\_2\_enal, 4,8.Dimethyl\_1,7\_nonadiene, (Z).3.Hexenyl\_acetate, D.Limonene, .beta.Ocimene, 2.Methyl\_6\_methylene\_1,7\_octadien\_3\_one, Terpinolene, 2,6.Dimethyl\_2,4,6\_octatriene and Decanal). The model showed a high discriminatory capacity, allowing a clear separation of olive oils according to their region of origin. The accuracy of the original model was 100%, remaining unchanged after Leave-One-Out (LOO-CV) cross-validation. A slight decrease was observed in the Repeated K-Fold cross-validation, although remained very high, with a value of 97.33%, supporting the consistency of the model within the studied dataset.

The graphical analysis showed a clear separation between the groups according to region, indicating that the sensory and volatile profiles are characteristic of each geographical origin. This differentiation reflects the influence of edaphoclimatic conditions and local agronomic practices on olive oil composition. However, these results should be interpreted with caution due to the size of the dataset and the absence of external validation.

A similar treatment was applied to Galega oils (Fig. 5B). for this



**Fig. 4.** Pearson correlation heatmaps between the volatile profiles of monovarietal olive oils (A) cv. Cobrançosa and (B) cv. Galega and the average volatile profiles of oils from three Portuguese regions: Alentejo, Beira Interior, and Trás-os-Montes. Volatile compounds are represented on the x-axis and regional profiles on the y-axis. The color scale indicates the direction and strength of the correlation: red tones represent positive correlations and green tones represent negative correlations. The analysis reveals distinct patterns of similarity between cultivar-specific volatile profiles and regional oils. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 5.** LDA-SA classification performance (training) according to the geographical origin (■ Alentejo, ● Beira Interior, and ▲ Trás-os-Montes) based on the sensory and volatile profiles of olive oils obtained from cvs. Cobrançosa A) and Galega B). The separation of regional clusters highlights the discriminative power of sensory and volatile attributes in distinguishing olive oils according to their cultivar and region of origin.

cultivar, the LDA model was constructed based on 35 selected variables, encompassing sensory attributes and volatile compounds (variables O\_Green\_fruitiness, O\_Tomato, O\_Olive\_leaves, G\_Green\_fruitiness, Sweet, Bitter, Pungent, G\_Apple, G\_Tomato, G\_Dry\_fruits, G\_Cabbage, G\_Fresh\_herb, 1\_Penten\_3\_one, (E)\_2\_Pentenal, (Z)\_2\_Penten\_1\_ol, (Z)\_3\_Hexenal, (E)\_2\_Hexenal, (E)\_2\_Hexen\_1\_ol, 1\_Hexanol, 3\_Ethyl\_1,5-octadiene (I\_isomer), (E,E)\_2,4\_Hexadienal, 3\_Ethyl\_1,5-octadiene (II\_isomer), 3\_Ethyl\_1,5-octadiene (III\_isomer), (E)\_4\_Oxohex\_2\_enal, (Z)\_3\_Hexenyl\_acetate, Hexyl\_acetate, D\_Limonene, 3,3,6-Trimethyl\_1,5\_heptadien\_4\_one, Linalool, Terpinolene, 2,6-Dimethyl\_1,2,4,6\_octatriene, Dodecane, Decanal, and (+)\_Cyclosativene). The selected variable represents the most relevant sensory sensations as well as the volatile compounds contributing to the characterization of Galega olive oils. The LDA model achieved high classification performance, with 100% classification accuracy in both the original classification, the Leave-One-Out (LOO-CV) and Repeated K-Fold cross-validations. A clear separation between geographical groups was observed, indicating distinct sensory and volatile profiles among regions. Overall, the results indicate that sensory perceptions and volatile compounds are informative variables for geographical discrimination. Nevertheless, the classification performance should be interpreted within the context of the studied dataset, and further studies including larger sample sets and external validation would be valuable to confirm the generalization of these findings.

#### 4. Conclusion

This study demonstrates that both cultivar and geographical origin exert a decisive influence on the sensory and volatile profiles of Portuguese monovarietal olive oils. Clearly differences in sensory expression were observed between the two cultivars evaluated, with Cobrançosa olive oils exhibited a more intense and predominantly green sensory profile, characterized by higher green fruitiness, herbaceous notes, bitterness, and pungency, whereas Galega oils showed a milder, more balanced and harmonious sensory profile.

Geographical origin further modulated the sensory and chemical composition of both cultivars. Olive oils from Trás-os-Montes and Beira Interior were generally associated with higher concentrations of lipoxygenase-derived volatile compounds, particularly C5 and C6

aldehydes and alcohols, which were strongly correlated with positive green and fruity sensory attributes. In contrast, olive oils from the Alentejo region exhibited lower overall volatile diversity but higher relative contributions of specific sesquiterpenes, reflecting the influence of warmer and drier climatic conditions on aroma development.

The integration of sensory evaluation, volatile profiling by HS-SPME-GC-MS, and multivariate statistical approaches proved to be highly effective in discriminating olive oils according to both, cultivar and geographical origin. Pearson correlation analysis revealed clear sensory-chemical relationships, while linear discriminant analysis achieved excellent classification performance, with accuracies reaching 100% for both cultivars, underscoring the robustness and predictive power of the developed models. Overall, these findings emphasize the strong interaction between genetic factors and environmental conditions in shaping olive oil quality and typicity. The combined sensory-chemical approach applied in this study constitutes a reliable and powerful tool for the authentication of geographical origin, supports the valorization of Portuguese monovarietal olive oils, and contributes to the protection of their identity in quality-driven and designation-of-origin markets.

#### Authors contribution

Conceptualization, N.R. and L.L.M.; methodology, P.R., D.R., N.F. and N.R.; software, N.R.; formal analysis, P.R., D.R., N.F. and N.R.; investigation, P.R., D.R., N.F., L.L.M. and N.R.; resources, N.R.; writing-original draft preparation, P.R.; writing-review and editing, N.R., D.R., N.F. and L.L.M.; supervision, N.R. and L.L.M.; project administration, N. R.; funding acquisition, N.R. All authors have read and agreed to the published version of the manuscript.

#### CRediT authorship contribution statement

**Pedrina Rocha:** Writing – original draft, Methodology, Investigation, Formal analysis. **Daniela Ruano:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Nuno Ferreira:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Luísa L. Martins:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Nuno Rodrigues:** Writing – review & editing,

Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

## 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.

## Acknowledgements

This work was supported by national funds through FCT/MCTES (PIDDAC): CIMO UID/00690/2025 (10.54499/UID/00690/2025) and UID/PRR/00690/2025 (10.54499/UID/PRR/00690/2025); SusTEC, LA/P/0007/2020 (DOI: 10.54499/LA/P/0007/2020). National funding by FCT- Foundation for Science and Technology, through the institutional scientific employment program-contract with Nuno Rodrigues and by the PhD the grant scholarship (PRT/BD/154026/2022) to Pedrina Rocha.

## Data availability

Data will be made available on request.

## References

- Aparicio-Ruiz, R., Barbieri, S., Gallina Toschi, T., & García-González, D. L. (2020). Formulations of rancid and winey-vinegary artificial olfactory reference materials (AORMs) for virgin olive oil sensory evaluation. *Foods*, 9(12), 1870. <https://doi.org/10.3390/foods9121870>
- Aparicio-Ruiz, R., Ortiz Romero, C., Casadei, E., García-González, D. L., Servili, M., Selvaggini, R., Lacoste, F., Escobessa, J., Vichi, E., Quintanilla-Casas, B., Golay, P., Lucci, P., Moret, E., Valli, E., Bendini, A., & Gallina Toschi, T. (2022). Collaborative peer validation of a harmonized SPME-GC-MS method for analysis of selected volatile compounds in virgin olive oils. *Food Control*, 35, Article 108756. <https://doi.org/10.1016/j.foodcont.2021.108756>
- Aprea, E., Gasperi, F., Betta, E., Sani, G., & Cantini, C. (2018). Variability in volatile compounds from lipoxigenase pathway in extra virgin olive oils from Tuscan olive germoplasm by quantitative SPME/GC-MS. *Journal of Mass Spectrometry*, 53(9), 824–832. <https://doi.org/10.1002/jms.4274>
- Benelli, G., Caruso, G., Giunti, G., Cuzzola, A., Saba, A., Raffaelli, A., & Gucci, R. (2015). Changes in olive oil volatile organic compounds induced by water status and light environment in canopies of *Olea europaea* L. trees. *Journal of the Science of Food and Agriculture*, 95(12), 2473–2481. <https://doi.org/10.1002/jsfa.6977>
- Cajka, T., Riddellova, K., Klimankova, E., Cerna, M., Pudil, F., & Hajšlova, J. (2010). Traceability of olive oil based on volatiles pattern and multivariate analysis. *Food Chemistry*, 121, 282–289. <https://doi.org/10.1016/j.foodchem.2009.12.011>
- Campestre, C., Angelini, G., Gasbarri, C., & Angerosa, F. (2017). The compounds responsible for the sensory profile in monovarietal virgin olive oils. *Molecules*, 22(11), 1833. <https://doi.org/10.3390/molecules22111833>
- Caratti, A., Fina, A., Trapani, F., Libertò, E., Jiménez-Herrera, B., Arce, L., ... Cordero, C. (2025). Beyond current quality indices: Quantitative volatiles unveiled cultivar traits, harvesting practices impact, and aroma blueprint of extra-virgin olive oils. *Journal of Food Composition and Analysis*, 137, Article 106975. <https://doi.org/10.1016/j.jfca.2024.106975>
- Cecchi, L., Migliorini, M., Giambanelli, E., Rossetti, A., Cane, A., Mulinacci, N., & Melani, F. (2020). Authentication of the geographical origin of virgin olive oils from the main worldwide producing countries: A new combination of HS-SPME-GC-MS analysis of volatile compounds and chemometrics applied to 1217 samples. *Food Control*, 112. <https://doi.org/10.1016/j.foodcont.2020.107156>
- Cecchi, L., Migliorini, M., & Mulinacci, N. (2021). Virgin olive oil volatile compounds: Composition, sensory characteristics, analytical approaches, quality control, and authentication. *Journal of Agricultural and Food Chemistry*, 69(7), 2013–2040. <https://doi.org/10.1021/acs.jafc.0c07744>
- Commission Implementing Regulation (EU) 2022/2105 of 29 of July 2022. (2022). *Laying down rules on conformity checks of marketing standards for olive oil and methods of analysis of the characteristics of olive oil*. Official Journal European Union. L248/23–48.
- Deiana, P., Motroni, A., Filigheddu, M. R., Dettori, S., Nieddu, G., Mercenaro, L., ... Santona, M. (2023). Effect of pedoclimatic variables on analytical and organoleptic characteristics in olive fruit and virgin olive oil. *European Journal of Agronomy*, 148, Article 126856. <https://doi.org/10.1016/j.eja.2023.126856>
- Díaz-Montaña, E. J., Aparicio-Ruiz, R., & Morales, M. T. (2023). Effect of flavorization on virgin olive oil oxidation and volatile profile. *Antioxidants*, 12(2). <https://doi.org/10.3390/antiox12020242>
- García-Vico, L., Belaj, A., Sánchez-Ortiz, A., Martínez-Rivas, J. M., Pérez, A. G., & Sanz, C. (2017). Volatile compound profiling by HS-SPME/GC-MS-FID of a core olive cultivar collection as a tool for aroma improvement of virgin olive oil. *Molecules*, 22(1), 141. <https://doi.org/10.3390/molecules22010141>
- IOC, International Olive Council. (2011). Guide for the determination of the characteristics of oil-olives, IOC 2011, 1–41. <http://www.internationaloliveoil.org/> (accessed 2026-01).
- IOC, International Olive Oil Council. (2005). COI/T.20/Doc. No.22; Method for the Organoleptic Assessment of Extra Virgin Olive Oil Applying to Use a Designation of Origin. <https://www.internationaloliveoil.org/what-we-do/chemistry-standardisation-unit/standards-and-methods/>.
- IPMA. (2025). Instituto Português do Mar e da Atmosfera. <https://www.ipma.pt/pt/oc/ima/monitoriza.dia/> Accessed on January 10, 2026.
- Jukić Špika, M., Perica, S., Žanetić, M., & Škevin, D. (2021). Virgin olive oil phenols, fatty acid composition and sensory profile: Can cultivar overpower environmental and ripening effect? *Antioxidants*, 10(5), 689. <https://doi.org/10.3390/antiox10050689>
- Kopsahelis, N., Karabagias, I. K., Papapostolou, H., & Eriotou, E. (2024). Cultivar authentication of olive oil from Ionian islands using volatile compounds and chemometric analyses. *Journal of Food Measurement and Characterization*, 18(6), 4402–4416. <https://doi.org/10.1007/s11694-024-02502-0>
- Lobo-Prieto, A., Tena, N., Aparicio-Ruiz, R., García-González, D. L., & Sikorska, E. (2020). Monitoring virgin olive oil shelf-life by fluorescence spectroscopy and sensory characteristics: A multidimensional study carried out under simulated market conditions. *Foods*, 9(12). <https://doi.org/10.3390/foods9121846>
- Lobo-Prieto, A., Tena, N., Aparicio-Ruiz, R., Morales, M. T., & García-González, D. L. (2022). A study of the dynamic changes of stability taking place during virgin olive oil storage period examined by mesh cell-FTIR spectroscopy. *Food Science and Technology*, 172, Article 114160. <https://doi.org/10.1016/j.lwt.2022.114160>
- Lukić, I., Horvat, I., Godena, S., Krapac, M., Lukić, M., Vrhovsek, U., & Brkić Bubola, K. (2018). Towards understanding the varietal typicity of virgin olive oil by correlating sensory and compositional analysis data: A case study. *Food Research International*, 112, 78–89. <https://doi.org/10.1016/j.foodres.2018.06.022>
- Mariotti, R., Núñez-Carmona, E., Genzardi, D., Pandolfi, S., Sberveglieri, V., & Mousavi, S. (2022). Volatile olfactory profiles of Umbrian extra virgin olive oils and their discrimination through MOX chemical sensors. *Sensors*, 22(19), Article 7164. <https://doi.org/10.3390/s22197164>
- Marx, Í. M. G., Rodrigues, N., Veloso, A. C. A., Casal, S., Pereira, J. A., & Peres, A. M. (2021). Effect of malaxation temperature on the physicochemical and sensory quality of cv. Cobrançosa olive oil and its evaluation using an electronic tongue. *LWT*, 137, Article 110426. <https://doi.org/10.1016/j.lwt.2020.110426>
- Olmo-Cunillera, A., Casadei, E., Valli, E., Lozano-Castellón, J., Miliarakis, E., Domínguez-López, L., ... Bendini, A. (2022). Aromatic, sensory, and fatty acid profiles of arbequina extra virgin olive oils produced using different malaxation conditions. *Foods*, 11(21), 3446. <https://doi.org/10.3390/foods11213446>
- Peres, F., Jelen, H. H., Majcher, M. M., Arraias, M., Martins, L. L., & Ferreira-Dias, S. (2013). Characterization of aroma compounds in Portuguese extra virgin olive oils from Galega vulgar and Cobrançosa cultivars using GC-O and GC×GC-ToFMS. *Food Research International*, 54(2), 1979–1986. <https://doi.org/10.1016/j.foodres.2013.06.015>
- Peres, F., Martins, L. L., Mourato, M., Vitorino, C., Antunes, P., & Ferreira-Dias, S. (2016). Phenolic compounds of 'Galega vulgar' and 'Cobrançosa' olive oils along early ripening stages. *Food Chemistry*, 211, 51–58. <https://doi.org/10.1016/j.foodchem.2016.05.022>
- Peres, F., Talhinhas, P., Afonso, H., Alegre, H., Oliveira, H., & Ferreira-Dias, S. (2021). Olive oils from fruits infected with different anthracnose pathogens show sensory defects earlier than chemical degradation. *Agronomy*, 11(6), 1041. <https://doi.org/10.3390/agronomy11061041>
- Ríos-Reina, R., Aparicio-Ruiz, R., Morales, M. T., & García-González, D. L. (2023). Contribution of specific volatile markers to green and ripe fruitiness attributes in extra virgin olive oils studied with three analytical methods. *Food Chemistry*, 399, Article 133942. <https://doi.org/10.1016/j.foodchem.2022.133942>
- Rodrigues, N., Casal, S., Peres, A. M., Baptista, P., & Pereira, J. A. (2020). Seeking for sensory differentiated olive oils? The urge to preserve old autochthonous olive cultivars. *Food Research International*, 128. <https://doi.org/10.1016/j.foodres.2019.108759>
- Romero, N., Saavedra, J., Tapia, F., Sepúlveda, B., & Aparicio, R. (2016). Influence of agroclimatic parameters on phenolic and volatile compounds of Chilean virgin olive oils and characterization based on geographical origin, cultivar and ripening stage. *Journal of the Science of Food and Agriculture*, 96(2), 583–592. <https://doi.org/10.1002/jsfa.7127>
- Servili, M., Esposito, S., Lodolini, E., Selvaggini, R., Taticchi, A., Urbani, S., ... Gucci, R. (2007). Irrigation effects on quality, phenolic composition, and selected volatiles of virgin olive oils cv. Leccino. *Journal of Agricultural and Food Chemistry*, 55(16), 6609–6618. <https://doi.org/10.1021/jf070599n>
- Stilo, F., Libertò, E., Reichenbach, S. E., Tao, Q., Bicchi, C., & Cordero, C. (2021). Exploring the extra-virgin olive oil Volatilome by adding extra dimensions to comprehensive two-dimensional gas chromatography and time-of-flight mass spectrometry featuring tandem ionization: Validation of ripening markers in headspace linearity conditions. *Journal of AOAC International*, 104(2), 274–287. <https://doi.org/10.1093/jaoacint/qsaa095>
- Üçüncüoğlu, D., & Sivri-Özay, D. (2020). Geographical origin impact on volatile composition and some quality parameters of virgin olive oils extracted from the "Ayvalık" variety. *Heliyon*, 6(9). <https://doi.org/10.1016/j.heliyon.2020.e04919>
- Vidal, A. M., Alcalá, S., Ocaña, M. T., De Torres, A., Espínola, F., & Moya, M. (2018). Modeling of volatile and phenolic compounds and optimization of the process conditions for obtaining balanced extra virgin olive oils. *Grasas y Aceites*, 69(2). <https://doi.org/10.3989/gya.1220172>

- Youssef, O., Guido, F., Manel, I., Youssef, N. B., Luigi, C. P., Mohamed, H., Daoud, D., & Mokhtar, Z. (2011). Volatile compounds and compositional quality of virgin olive oil from Oueslati variety: Influence of geographical origin. *Food Chemistry*, *124*, 1770–1776. <https://doi.org/10.1016/j.foodchem.2010.08.023>
- Zago, L., Squeo, G., Bertocini, E. I., Difonzo, G., & Caponio, F. (2019). Chemical and sensory characterization of Brazilian virgin olive oils. *Food Research International*, *126*, Article 108588. <https://doi.org/10.1016/j.foodres.2019.108588>
- Žanetić, M., Jukić Spika, M., Ožić, M. M., & Brkić Bubola, K. (2021). Comparative study of volatile compounds and sensory characteristics of dalmatian monovarietal virgin olive oils. *Plants*, *10*, 1995. <https://doi.org/10.3390/plants10101995>