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Analytical and sensory characterisation of Palo Cortado in comparison with Amontillado and Oloroso Sherry wines

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ABSTRACT

This research focuses on the analytical and sensory characterisation of Palo Cortado Sherry wines, using Amontillado and Oloroso as reference styles across the spectrum of biological to oxidative ageing in the Jerez region. Sensory evaluation and physicochemical analyses were carried out on samples from six wineries, including GC-FID, FTIR, and colour measurements (absorbances and CIELAB). Results revealed both common patterns among wines within styles and distinguishing factors among them. Significant differences were mainly observed in sensory attributes, colour parameters, and specific volatile compounds. Despite intra-style variability, certain grouping patterns emerged, allowing partial differentiation of the styles and revealing greater proximity between Palo Cortado and Oloroso. Acetaldehyde concentrations were 50 % higher in Amontillado than in Oloroso, and 37 % higher than in Palo Cortado. In contrast, ethyl acetate concentrations were approximately 30 % higher in Oloroso and Palo Cortado than in Amontillado, with similar values between the former two. These results emphasise the influence of the ageing processes on the concentration of these characteristic volatile compounds.

KEYWORDS: oxidative ageing, biological ageing, chemical characterisation, sensory analysis, Amontillado, Palo Cortado, Oloroso

INTRODUCTION

The history of Sherry wines dates back more than 3000 years (Consejo Regulador de las Denominaciones de Origen "Jerez-Xérès-Sherry" – "Manzanilla-Sanlúcar de Barrameda" – "Vinagre de Jerez", 2025). The style characterised by ageing under a yeast pellicle (*flor*) has been documented since the 7th century BC (Harutyunyan & Malfeito-Ferreira, 2022). Sherry wines are fortified wines obtained by the addition of grape spirit (Abreu *et al*., 2021) to the base wine. This fortification determines their ethanol content and influences their subsequent ageing process, typically resulting in ethanol levels of at least 15 % *v/v* (Avdanina & Zghun, 2022). Beyond their historical significance and global dissemination, Sherry wines are distinguished by their unique winemaking processes, although they remain relatively little studied and unknown to the wider public.

Wines bearing the *Vinos de Jerez* appellation are subject to the *Jerez-Xérès-Sherry* Protected Denomination of Origin (PDO), established in 1933. Four main styles of Sherry wines (Fino, Amontillado, Palo Cortado, Oloroso) are produced in the authorised regions: Jerez de la Frontera, El Puerto de Santa María, and Sanlúcar de Barrameda. Their distinctive characteristics arise mainly from the traditional dynamic ageing system known as *Criaderas y Soleras* (Consejo Regulador de las Denominaciones de Origen "Jerez-Xérès-Sherry" – "Manzanilla-Sanlúcar de Barrameda" – "Vinagre de Jerez", n.d.).

The distinction between styles lies primarily in their ageing conditions. During ageing, these wines can undergo either biological (under *flor*) or oxidative ageing (in the absence of *flor*), or the combination of both. Fino wines undergo purely biological ageing, with *flor* throughout the ageing process. Oloroso wines, in contrast, undergo exclusively oxidative ageing in the absence of *flor*, as development is inhibited by higher fortification levels (17 % (*v/v*) ethanol). Amontillado wines represent an intermediate style, combining an initial biological phase with a subsequent transition to oxidative ageing after fortification. Palo Cortado is also a style combining both ageing processes, but it remains less clearly defined. It undergoes both types of ageing. Initially intended as a Fino, it begins with biological ageing but then deviates and is redirected to oxidative ageing, with a much shorter biological phase than the oxidative phase (Figure 1).

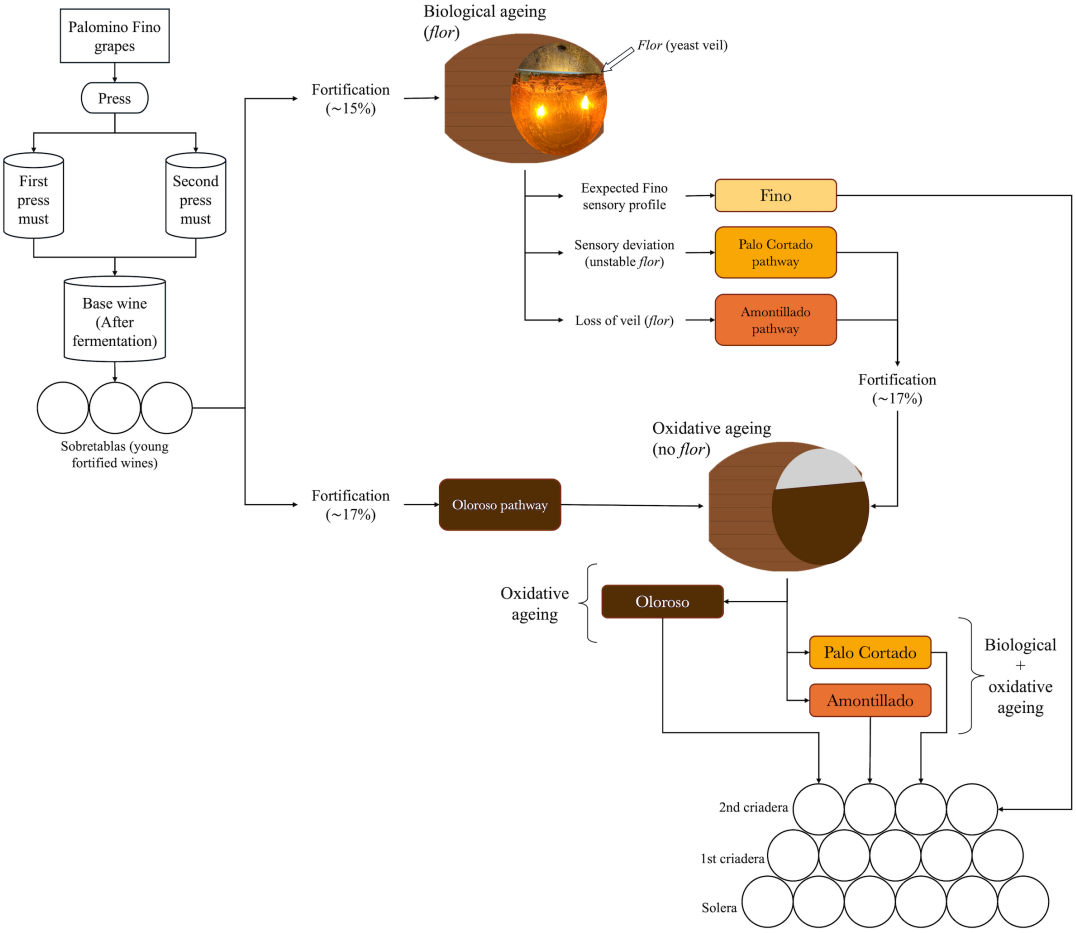


FIGURE 1. Amontillado, Palo Cortado, and Oloroso winemaking processes (created by the authors based on general descriptions reported in literature).

Figure 1 illustrates the winemaking process of each style, from must extraction and alcoholic fermentation to obtain the base wine, followed by fortification and subsequent ageing. Amontillado and Palo Cortado undergo initial biological ageing under *flor*, followed by oxidative ageing, whereas Oloroso undergoes oxidative ageing immediately after fortification. The subsequent ageing in the Criaderas and Soleras system for the three styles is also illustrated in Figure 1.

Fino wines usually exhibit aromas derived from the yeast metabolism, characterised by sharp notes, associated with acetaldehyde, such as overripe and ripe apples, citrus and balsamic notes (Durán-Guerrero *et al*., 2021). Amontillado wines present a more complex profile, combining biological ageing notes such as yeast, bakery, and acetaldehyde-derived aromas with fruity and ethanol-like notes, as well as green or cooked apple, honey, floral, and dried fruit nuances (Marcq & Schieberle, 2015; Palacios *et al*., 2018).

Palo Cortado wines share characteristics with both Amontillado and Oloroso, combining biological and oxidative attributes. They may also exhibit additional sensory nuances, such as lactic and citrus notes, and have been described as presenting caramel, milk, and wood aromas, together with a fuller mouthfeel, buttery sensations, and slight bitterness (Palacios *et al*., 2018; Valcárcel-Muñoz *et al*., 2022). On the other hand, Oloroso wines are characterised by more intense and structured sensory profiles dominated by oxidative notes such as nuts (*e.g.*, walnut), toast, wood, balsamic, and vegetable nuances (Valcárcel-Muñoz *et al*., 2022).

Acetaldehyde and ethyl acetate are considered indicators of the ageing style. Acetaldehyde is associated with yeast metabolism during the ageing under *flor*, while ethyl acetate is associated with oxidative ageing, arising from the esterification of compounds (Zea *et al*., 2001). Under the *flor,* volatile acidity is reduced and acetaldehyde increases. In the literature, for a given Oloroso solera system with age ranging from approximately 6 years (youngest *criadera)* to over 40 years (oldest *criadera*), and around 50 years (*solera* stage), increases in alcohol and glycerol concentrations have been reported, as well as acetaldehyde, ethyl acetate, acetic acid, etc., mainly due to concentration effects associated with *merma*. Alcohol content increased from 17.63 % *v/v* (base wine) to an average of 18.47 % v/v (7th *criadera*) and up to 23.73 % *v/v*. Glycerol increased from 6.15 g/L (fortified base wine) to 6.48 g/L (7th *criadera*) and up to 16.22 g/L (*solera*). Acetaldehyde concentration increased from 63.7 mg/L (fortified wine) to 159.7 mg/L (7th *criadera)* and 165.7 mg/L (1st *criadera)*. Volatile and total acidity showed a similar behaviour. A comparable trend was observed for Palo Cortado, although it was associated with different ageing durations (Valcárcel-Muñoz *et al*., 2022). *Flor* yeasts belong to a group of *S. cerevisiae* strains, whose distinctive behaviour has been associated with genetic and allelic variations (Legras *et al*., 2016).

The volatile composition of Amontillado and Oloroso has been broadly characterised. Biologically aged wines typically show higher concentrations of C6 alcohols (E- and Z-3-hexenol), organic acids, lactones, terpenoid alcohols, and aldehydes (Durán-Guerrero *et al*., 2021). In oxidatively aged wines, esters such as ethyl laurate and diethyl succinate, as well as certain higher alcohols, show an increase, favoured by oxidative chemical pathways. In contrast, other organic acids and lactones have been found at lower concentrations in wines with oxidative ageing, contributing to the differentiation among styles. Regarding aromas, 1-decanol, propyl butanoate, and methyl butanoate have been correlated with style differentiation (Zea *et al*., 2001).

While Fino, Amontillado and Oloroso are widely recognised, Palo Cortado remains ambiguous. It has been described as a Fino that undergoes an unexpected sensory deviation during ageing, leading to fortification and redirection towards oxidative ageing. From a sensory and technical perspective, it has been more closely associated with Amontillado and Oloroso than with Fino. It has been described as an Oloroso in mouthfeel, and as an Amontillado aromatically. However, its classification has relied on sensory descriptions (Luyten, 2015), rather than physicochemical or technical attributes, and previous studies have not established analytical criteria for its definition (Palacios *et al*., 2018). For a full understanding, it is essential to analyse its chemical composition, particularly the polyphenolic, colouring, and volatile compounds, and to associate this data with a specific tasting methodology that allows assessment of their qualities. From a commercial perspective, Sherry wines are challenging to promote due to their unique profile, broad diversity, and lack of comparable products. This makes it difficult to provide consumers with appropriate references to set their expectations for these wines. This is especially true for Palo Cortado, which is particularly hard to market due to its ambiguous definition, leaving the average consumer unclear (Saldaña, 2022). However, in recent years, Palo Cortado has gained interest due to its distinctive profile and complex production process.

The main goal of this work was to characterise Palo Cortado Sherry wines using sensory and analytical parameters, compare them with Amontillado and Oloroso, and determine whether significant physicochemical differences could support their differentiation and assess their resemblance to either style.

MATERIALS AND METHODS

1. Wine samples

Wineries from the Sherry PDO supplied 18 wines with winery-defined styles (Amontillado, Palo Cortado, and Oloroso) (Table 1). Only one bottle was available for each wine sample; therefore, no analytical or sensory repetitions were performed. All measurements, both chemical and sensory, were performed as single determinations for each sample. For clarity, samples were identified according to wine style and winery (*e.g.*, AM – W1 to AM – W6 for Amontillado, PC – W1 to PC – W6 for Palo Cortado, and OL – W1 to OL – W6 for Oloroso). The samples were stored in amber 100 mL bottles under refrigeration and sealed with screw caps.

2. Chemical analysis

2.1 Oenological parameters

pH was measured using a Basic20 pH meter (Crison Instruments, Barcelona, Spain). Before conducting the measurements, the device was calibrated according to the manufacturer's instructions using the standard buffer solutions 4.01 and 7.00. All measurements were performed at room temperature, with the samples maintained at an average temperature of 20 ºC.

TABLE 1. Winery, region, grape variety, and sample identification of the Sherry wines analysed.

Winery	Region	Grape variety	Amontillado	Palo Cortado	Oloroso
W1 – Lustau	Jerez de la Frontera	Palomino Fino	AM – W1	PC – W1	OL – W1
W2 – González Byass	Jerez de la Frontera	Palomino Fino	AM – W2	PC – W2	OL – W2
W3 – José Estevez	Jerez de la Frontera	Palomino Fino	AM – W3	PC – W3	OL – W3
W4 – Williams Humbert	Jerez de la Frontera	Palomino Fino	AM – W4	PC – W4	OL – W4
W5 – Bodegas Díez-Mérito	Jerez de la Frontera	Palomino Fino	AM – W5	PC – W5	OL – W5
W6 – Fundador	Jerez de la Frontera	Palomino Fino	AM – W6	PC – W6	OL – W6

The Total Polyphenol Index (TPI) was estimated by measuring the absorbance of the wine samples at 280 nm (I280), following spectrophotometric methods reported in the literature (Mataix & Luque De Castro, 2001). Before analysis, the samples were diluted (1:50) with distilled water. Measurements were performed using a UV 2005 4120020 spectrophotometer (J.P. Selecta, Barcelona, Spain) with a 1-cm quartz cuvette.

General oenological parameters were determined using a Fourier Transform Infrared Spectroscopy (FTIR) analyser, OenoFoss™ (FOSS, Barcelona, Spain), based on FTIR approaches reported in the literature for wine analysis (Bauer *et al*., 2008). Measurements were performed using the calibration range "finished wine", following the manufacturer's standard procedure. The parameters obtained were total acidity, volatile acidity, density, reducing sugars, malic acid, lactic acid, glucose, and fructose.

2.2 Chemical colour evaluation

CIELAB coordinates were obtained using a Smart Analysis spectrophotometer, coupled with the SmartAnalysis mobile application (DNA Phone SRL, Parma, Italy). This device provided the values for several colour parameters: intensity, tonality (shade), L*, a*, b*, chroma, and hue. Absorbance values at 420, 520, and 620 nm were also generated by the device, although no direct absorbance measurements were performed. Colour intensity was calculated as the sum of absorbance at 420, 520 and 620 nm, and hue was calculated as the ratio between absorbance at 420 and 520 nm. Based on the values, the percentages of yellow, red, and blue pigments were calculated following the procedure originally described by Glories (1984) and applied by Jagatić Korenika *et al.* (2020).

2.3 Volatile compounds

Volatile compounds were quantified using an Agilent 6850 Network GC System equipped with an autosampler and a flame ionisation detector (GC-FID) (Agilent Technologies, USA), following previously reported methods for the analysis of volatile compounds in wine (Paolini *et al*., 2022). Wine samples were filtered (0.45 µm MCE syringe filters), and 100 µL of internal standard (4-methyl-2-pentanol) was added to each sample. Separation was performed on a DB-624 capillary column (J&W 122-1364 E DB-624, 60 m × 250 µm, 1.40 µm film thickness; Agilent Technologies, USA). Hydrogen was used as carrier gas (1.372 bar; 2.2 mL/min). The oven program started at 40 °C (5 min), increased at 10 °C/min to 250 °C (5 min hold), for a total of 36 minutes. Injection was performed in split mode (3:1) at 250 °C, with a 1.0 µL injection volume. Detection was carried out with FID at 300 °C. Compounds were identified by comparing their retention times with standards and quantified using peak areas relative to the internal standard. When necessary, retention time windows were adjusted to ensure proper integration and quantification of these compounds.

3. Sensory analysis

A panel of eight tasters, with a strong background in oenology and prior experience in wine tasting, performed the sensory evaluation. No formal panel selection or training was applied. All wines were evaluated in a single session and presented in sets of six wines, using a sequential monadic design. Each set comprised wines from two wineries, with one wine of each style per winery, presented in a fixed order: Winery 1 (Amontillado, Palo Cortado, Oloroso), followed by Winery 2 (Amontillado, Palo Cortado, Oloroso), and so forth. Samples were labelled using numerical codes for identification purposes. No information regarding the identity of the wines was provided to the panellists. Wines were served at 12–14 °C in standard tasting glasses (International Organization for Standardization (ISO), 1977). The sensory evaluation session was conducted in the tasting room of the Chemistry and Food Technology laboratories at ETSIAAB, Universidad Politécnica de Madrid (UPM), Madrid, Spain. The session took place under both natural and artificial lighting at ambient temperature. No coloured or masking lighting was used. Water was provided for palate cleansing, which panellists used freely between samples.

A tasting sheet was designed with particular focus on the perception of ageing notes, aiming to assess whether each wine sample was perceived as more biological or oxidative. For most attributes, a structured 5-point scale (1–5) was used, where the extreme values represented the opposite ends of each sensory attribute, providing a general framework

to describe the sensory characteristics of the wines. Given the nature of the panel, a reduced scale was selected to promote consistent scoring and minimise variability among panellists. The aim was to identify general trends across wine styles rather than to perform a detailed descriptive analysis. Specifically, for ageing-related attributes (aromas on the nose and notes on the palate), a separate structured bipolar scale ranging from − 3 to 3 was used, where – 3 represented exclusively biological notes, 3 exclusively oxidative notes, and 0 a balance between both, allowing the assessment of the direction of perception. Two ageing-related attributes were evaluated: the biological versus oxidative character, and the positioning of the wine between Amontillado-like and Oloroso-like profiles.

4. Statistical analysis

Statistical analysis was conducted using SPSS Statistics, Version 31.0 (IBM, 2025), and R, Version 4.5.0 (R Core Team, 2025). One-way ANOVA was performed after confirming normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test). Post-hoc comparisons were conducted using Tukey's HSD when homoscedasticity was met. Otherwise, Games-Howell was used. For non-normally distributed data, the Kruskal-Wallis test followed by Dunn's test was applied. Holm correction was applied to adjust for multiple comparisons.

MANOVA was performed for selected sensory and colour parameters, with wine style as the fixed factor. Prior to analysis, assumptions were evaluated (multivariate normality, homogeneity of covariance matrices (Box's M test), and detection of multivariate outliers using Mahalanobis distance). Only datasets where the number of observations exceeded the number of dependent variables were considered. Multivariate effects were interpreted using Wilks' λ, followed by univariate ANOVAs and Bonferroni-adjusted pairwise comparisons where suitable.

Principal Component Analysis (PCA) was conducted to explore grouping patterns of the samples. Data suitability was assessed using Bartlett's test of sphericity and the Kaiser-Meyer-Olkin Measure (KMO). Variables with inadequate sampling adequacy were excluded based on MSA, communalities, and factor loadings. Separate PCAs were performed for sensory, colour, oenological, and volatile compound datasets.

Pearson or Spearman correlation analyses were performed depending on assumption compliance. Hierarchical cluster analysis was conducted on standardised data using Euclidean distances as the dissimilarity measure and average linkage as the clustering method. Linear regression analyses were applied to assess the extent to which physicochemical parameters explained sensory perception. Models were fitted using least squares. Coefficients of determination (R^2) and significance levels (*p*-values) were reported.

Multiple Factor Analysis was performed using XLSTAT software (Lumivero, 2025).

RESULTS

1. Oenological parameters

Oloroso showed the highest pH values (Table 2), Amontillado the lowest, and Palo Cortado presented intermediate values, showing lower variability. Palo Cortado appeared between the other two styles, tending closer to Oloroso. Significant differences were observed, with Oloroso differing from Amontillado wines.

Total Polyphenol Index (TPI) varied by winery. On average, Palo Cortado showed higher values, closer to Oloroso than to Amontillado, whereas Amontillado samples showed lower values, suggesting differences in TPI content among these styles. This is consistent with previous observations, although these differences may depend on analytical conditions and sample variability (Villaño *et al*., 2004). No significant differences among styles were found.

TABLE 2. Oenological parameters determined in the analysed samples (mean ± SD).

Wine style/Parameter	Amontillado	Palo Cortado	Oloroso
pH	2.98 ± 0.14b	3.08 ± 0.07ab	3.16 ± 0.10a
Total Polyphenol Index (TPI)	23.23 ± 5.56a	27.17 ± 4.16a	27.09 ± 3.26a
FTIR parameters			
Total acidity [g/L]	6.44 ± 1.14a	6.45 ± 0.44a	5.85 ± 0.66a
Volatile acidity [g/L]	0.10 ± 0.06a	0.13 ± 0.09a	0.12 ± 0.06a
Density [g/mL]	0.99 ± 0.00a	0.99 ± 0.00a	0.99 ± 0.00a
Reducing sugars [g/L]	0.52 ± 0.48b	1.85 ± 0.82a	2.03 ± 0.27a
Malic acid [g/L]	0.45 ± 0.30a	0.45 ± 0.14a	0.43 ± 0.08a
Lactic acid [g/L]	0.85 ± 0.27a	1.00 ± 0.06a	0.78 ± 0.17a
Glucose [g/L]	4.33 ± 0.76a	4.60 ± 0.75a	4.05 ± 0.42a
Fructose [g/L]	1.02 ± 0.19b	1.95 ± 0.69a	1.80 ± 0.09a

Values are expressed as mean ± standard deviation. Different superscript letters within a row indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

According to Fourier Transform Infrared Spectroscopy (FTIR) data (Table 2), total acidity was similar across styles, with slightly higher values for Palo Cortado and Amontillado, compared to Oloroso. Amontillado samples showed greater variability. In terms of volatile acidity, Palo Cortado showed slightly higher values, followed by Oloroso and Amontillado, although no significant difference was observed. Density remained similar across the three wine styles. Reducing sugars were lower in Amontillado and higher in Oloroso, with Palo Cortado presenting intermediate values. Malic acid values were similar across styles, with only a slight decrease in Oloroso. In contrast, lactic acid values were slightly higher in Palo Cortado. This is consistent with the PDO specifications, which describe its organoleptic characteristics as "dried fruits and noble wood, with possible presence of citric and/or lactic notes" (Junta de Andalucía, 2023), being the only style in which these latter notes are specifically stated.

Glucose values showed slight variation among wine styles, with Oloroso presenting lower values and Palo Cortado higher values, although no significant differences were observed. In contrast, fructose showed significant differences between Amontillado and the other two styles, with Amontillado presenting lower values and Palo Cortado higher, while Oloroso remained intermediate. Reducing sugars also showed significant differences among Amontillado, Oloroso, and Palo Cortado, with Oloroso showing higher values, Amontillado showing lower, and Palo Cortado intermediate.

To further explore the relationship between chemical composition and sensory perception, a correlation analysis was performed between a combined acidity parameter (sum of total, volatile, malic, and lactic acids) (from FTIR measurements) and perceived acidity ($r = 0.549$, $p = 0.018$). A positive significant association was observed, indicating that variations in acid composition were reflected in the sensory perception of acidity. Oloroso samples were associated with lower acid concentrations and lower perceived acidity, while Amontillado displayed greater dispersion in both measured and perceived acidity. Palo Cortado samples were generally positioned between the two styles. Other variables did not show clear relationships. However, to further explore the relationship between chemical composition and sensory perception, linear regression analysis was performed. Total acidity measured by FTIR significantly explained perceived acidity ($R^2 = 0.478$, $p = 0.0015$).

2. Chemical colour evaluation

At 420 nm, Palo Cortado showed higher absorbance values, with comparable values for Oloroso, followed by Amontillado (Table 3). These values are typically associated with brown tonalities typically observed in wines undergoing oxidative ageing (Li *et al*., 2008). Amontillado showed values comparable to those of Oloroso.

For the calculated yellow component, Amontillado showed higher values, while Oloroso presented the lowest. Red and blue components were also calculated. Red percentages were higher in Oloroso, whereas blue values were minimal (2.8–3.6 %) across all styles, indicating a negligible contribution to the overall chromatic profile. Similar colour patterns have been reported in wines undergoing oxidative ageing (Ortega *et al*., 2008).

TABLE 3. Colour parameters determined in the analysed Sherry wine samples (mean ± SD).

Parameter	Wine style		
	Amontillado	Palo Cortado	Oloroso
	Absorbance		
A420	0.32 ± 0.07a	0.36 ± 0.06a	0.36 ± 0.04a
A520	0.10 ± 0.04a	0.11 ± 0.04a	0.13 ± 0.03a
A620	0.02 ± 0.02a	0.02 ± 0.02a	0.02 ± 0.01a
Yellow [%]	76.11 ± 9.48a	74.58 ± 6.45a	70.99 ± 4.33a
Red [%]	21.09 ± 4.82a	22.17 ± 2.94a	25.45 ± 2.27a
Blue [%]	2.80 ± 4.81a	3.25 ± 3.98a	3.57 ± 2.31a
Colour intensity	0.44 ± 0.13a	0.49 ± 0.11a	0.51 ± 0.08a
Tonality (hue)	3.90 ± 1.55a	3.43 ± 0.65a	2.82 ± 0.46a
L*	93.90 ± 2.95a	92.75 ± 2.92a	92.17 ± 1.83a
a*	1.00 ± 1.67b	2.07 ± 1.38ab	3.39 ± 1.06a
b*	21.77 ± 3.50a	24.41 ± 2.41a	24.63 ± 2.20a
Chroma (C*)	21.84 ± 3.54a	24.53 ± 2.46a	24.88 ± 2.19a
Hue (h*)	87.91 ± 4.39a	85.26 ± 3.03ab	82.13 ± 2.42b

Values are expressed as mean ± standard deviation. Different letters within a row indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

Regarding colour intensity, Oloroso showed higher values. Although distribution trends suggested slightly higher median values in some Palo Cortado and Oloroso samples, no clear separation among styles was observed. As for tonality, Amontillado showed higher values, while Oloroso showed lower values. Similar colour characteristics have been described for wines undergoing biological ageing under *flor* (Fabios *et al*., 2000).

The greatest colour difference (ΔE) was observed between Amontillado and Oloroso. For the CIELAB parameters, Amontillado showed the highest L* (luminosity) values, followed by Palo Cortado and Oloroso, which showed similar values. For a*, Oloroso exhibited higher values, while Amontillado showed lower values. For b*, Palo Cortado and Oloroso showed higher median values than Amontillado. For chroma (C*), Amontillado showed the lowest values, Oloroso the highest, and Palo Cortado intermediate values, closer to Oloroso than to Amontillado. Regarding colour parameters, Amontillado showed the greatest variability. Amontillado showed higher hue values (≈ 87 °), indicating predominantly yellow tonalities followed by Palo Cortado (> 85 °), while Oloroso presented lower values (> 80 °). Changes in CIELAB parameters during ageing, including decreases in lightness and hue shifts towards red tonalities, have been previously reported in Sherry wines (Serratosa *et al*., 2016). Statistical analysis revealed significant differences for hue and a*, particularly between Amontillado and Oloroso.

For visual hue, correlation analysis (Table S1) revealed strong and significant relationships with hue ($r = -0.893$, $p < 0.001$), a* ($r = 0.871$, $p < 0.001$), tonality ($r = -0.846$, $p < 0.001$), red percentage ($r = 0.784$, $p < 0.001$), absorbance at 520 nm ($r = 0.777$, $p < 0.001$), and yellow percentage ($r = -0.766$, $p < 0.001$). Moderate but significant correlations were observed with absorbance at 420 nm ($r = 0.613$, $p = 0.007$) and b* ($r = 0.591$, $p = 0.01$). These results indicate a strong association between sensory perception of hue and instrumental colour measurements. To further explore the relationship between chemical composition and sensory perception, linear regression analysis was performed. Visual hue showed significant relationships with CIELAB-derived hue ($R^2 = 0.45$, $p = 0.0023$), as well as with absorbance-based tonality ($R^2 = 0.352$, $p = 0.0094$), absorbance at 420 nm ($R^2 = 0.288$, $p = 0.0217$) and red component ($R^2 = 0.293$, $p = 0.0203$), indicating that the sensory perception of hue was associated with variations in the yellow and red components of the wines.

3. Volatile compounds analysis

As shown in Table 4, several volatile compounds followed characteristic trends among the three Sherry wine styles.

Acetaldehyde concentrations were highest in Amontillado samples, decreased in Palo Cortado, and were the lowest in Oloroso (Figure 2a). In contrast, ethyl acetate showed comparable values for Palo Cortado and Oloroso, with lower concentrations in Amontillado (Figure 2b).

Acetoin showed similar concentrations in Amontillado and Oloroso, while Palo Cortado showed higher values. Similarly, 2,3-butanediol showed higher mean concentrations for Palo Cortado, followed by Oloroso and Amontillado. Isobutanol showed higher values in Amontillado, followed by Palo Cortado and Oloroso. 2-Phenylethanol showed higher concentrations in Palo Cortado, followed by Oloroso and Amontillado. 2-Phenylethyl acetate showed comparable values in Amontillado and Palo Cortado, with slightly lower values in Oloroso. Isobutyl acetate was present at low concentrations across all samples, with the lowest values found in Oloroso. Ethyl butyrate showed lower values in Palo Cortado than to Amontillado and Oloroso, while ethyl lactate showed similar concentrations in Amontillado and Palo Cortado, with slightly higher values in Oloroso. Hexanol levels showed slightly higher values for Amontillado, with the values decreasing for Palo Cortado and then for Oloroso. The distribution of volatile compounds observed is consistent with previous studies on Sherry wines (García-García *et al*., 2025).

For the non-normal variables, only 2-phenylethanol showed a significant difference between Amontillado and Palo Cortado. Ethyl acetate showed significant differences among wine styles; however, post-hoc pairwise comparisons did not reveal significant differences between specific groups. However, several compounds exhibited high variability across samples, as reflected in large standard deviations.

These observations were further explored through correlation analysis between volatile compound quantification and perceived ageing notes. A weak negative relationship was observed between acetaldehyde concentration and biological *vs* oxidative perception on the nose ($r = -0.310$); however, this relationship was not statistically significant ($p = 0.210$). In contrast, oxidative-related compounds, particularly ethyl acetate, showed clearer associations. A strong and significant correlation was observed with the palate ageing profile ($r = 0.776$, $p < 0.001$). Moderate to strong significant correlations were also found for the biological versus oxidative perception on the nose ($r = 0.603$, $p = 0.008$) and for the combined ageing perception integrating nose and palate attributes ($r = 0.637$, $p = 0.004$). Additionally, a moderate and significant correlation was observed between the stylistic attributes of Amontillado and Oloroso ($r = 0.529$, $p = 0.024$).

No correlation analysis was performed between lactic acid and ethyl lactate concentrations, as the data did not meet the required assumptions. Descriptively, ethyl lactate concentrations were highest in Oloroso, intermediate in Palo Cortado, and lowest in Amontillado. In contrast, lactic acid concentrations were highest in Palo Cortado, suggesting a more balanced profile with comparable levels of both compounds, while Amontillado showed intermediate values and Oloroso the lowest.

4. Sensory evaluation

The results of sensory evaluation are listed in Table 5. Differences in chromatic characteristics among wine styles were consistent with instrumental colour measurements.

Amontillado samples were described as brighter, with yellow-amber hues; Oloroso as darker, with brownish tones; and Palo Cortado as showing intermediate shades.

Variability in colour perception was observed within and across wine styles. According to the panellists' observations, Oloroso samples were generally perceived as darker than Amontillado, while Palo Cortado presented intermediate values. A similar trend was observed for colour intensity, whereas clarity scores were highest for Palo Cortado and lowest for Amontillado.

Regarding olfactory attributes, Amontillado showed the highest aroma intensity. For the attributes aimed at evaluating the perception of the ageing profile (biological *vs* oxidative), Amontillado showed lower values, while Palo Cortado and Oloroso showed higher values, indicating a stronger oxidative perception in the latter two styles. For the stylistic scale (Amontillado *vs* Oloroso), Palo Cortado showed higher values than Oloroso, while Amontillado showed lower values. Based on both attributes, Palo Cortado appeared closer to Oloroso, as shown in Figure 3. Similar observations have been reported in previous studies on Sherry wines (Zea *et al*., 2015).

On the palate, Oloroso samples showed higher values for body, complexity and density, indicating a fuller mouthfeel. Palo Cortado showed the highest perceived alcohol intensity. In terms of ageing profile on the palate, Oloroso again showed higher values, while Amontillado presented lower values, with Palo Cortado remaining closer to Oloroso, when focusing on biological *vs* oxidative perception.

ANOVA revealed significant differences among wine styles for several sensory attributes. Visual hue, ageing aromas (biological *vs* oxidative), body perception, and ageing notes in palate (biological *vs* oxidative), between Amontillado and Oloroso, while alcohol perception showed a significant difference between Palo Cortado and the other two styles.

5. Univariate statistical analysis

A summary of the univariate statistical analysis, including parameters showing significant differences among wine styles, is presented in Table 6 below.

TABLE 4. Volatile compounds determined by gas chromatography in the analysed wines (mean ± standard deviation).

	Wine style			
Compound [mg/L]	Amontillado	Palo Cortado	Oloroso	Statistical test
Acetaldehyde	149.07 ± 104.78a	93.58 ± 30.56a	73.74 ± 6.28a	Kruskal-Wallis
Methanol	63.82 ± 33.55a	54.33 ± 13.60a	48.45 ± 19.29a	ANOVA
1-propanol	54.21 ± 5.22a	50.60 ± 11.63a	42.80 ± 8.85a	ANOVA
Diacetyl	6.20 ± 3.72a	3.72 ± 2.11a	2.64 ± 0.92a	ANOVA
Ethyl acetate	159.73 ± 39.19a	204.53 ± 36.69a	206.60 ± 16.37a	ANOVA
2-butanol	2.29 ± 1.15a	2.82 ± 1.96a	2.29 ± 1.13a	Kruskal-Wallis
Isobutanol	64.76 ± 10.35a	55.53 ± 14.63a	51.00 ± 3.56a	ANOVA
Acetic acid	114.90 ± 28.51a	188.98 ± 74.03a	160.89 ± 59.63a	ANOVA
1-butanol	8.29 ± 3.06a	16.60 ± 20.75a	5.66 ± 2.60a	Kruskal-Wallis
Acetoin	11.62 ± 2.25a	18.02 ± 8.24a	11.49 ± 4.89a	Kruskal-Wallis
3-methyl-1-butanol	170.41 ± 17.54a	158.63 ± 31.03a	155.69 ± 15.37a	ANOVA
2-methyl-1-butanol	71.10 ± 5.13a	72.65 ± 9.51a	67.58 ± 4.32a	ANOVA
Isobutyl acetate	1.66 ± 2.58a	1.95 ± 3.43a	0.54 ± 1.32a	Kruskal-Wallis
Ethyl butyrate	2.71 ± 1.60a	1.80 ± 0.73a	2.19 ± 1.32a	Kruskal-Wallis
Ethyl lactate	84.94 ± 63.38a	87.24 ± 60.81a	94.19 ± 80.71a	ANOVA
2,3-butanediol	255.58 ± 247.82a	399.49 ± 328.32a	335.00 ± 263.72a	Kruskal-Wallis
Isoamyl acetate	0.29 ± 0.71a	0.46 ± 1.13a	0.29 ± 0.72a	Kruskal-Wallis
Hexanol	4.58 ± 2.39a	4.07 ± 1.12a	3.85 ± 0.25a	Kruskal-Wallis
2-phenylethanol	10.07 ± 0.94a	15.16 ± 7.75b	11.89 ± 1.57a	Kruskal-Wallis
2-phenylethyl acetate	11.20 ± 6.98a	10.81 ± 4.53b	8.75 ± 0.96a	Kruskal-Wallis

Values are expressed as mean ± standard deviation. Different superscript letters within the same row indicate significant differences among wine styles ($p < 0.05$). Statistical differences were assessed using ANOVA followed by Tukey's HSD test or, when normality assumptions were not met, using the Kruskal-Wallis test followed by Dunn's post-hoc test.

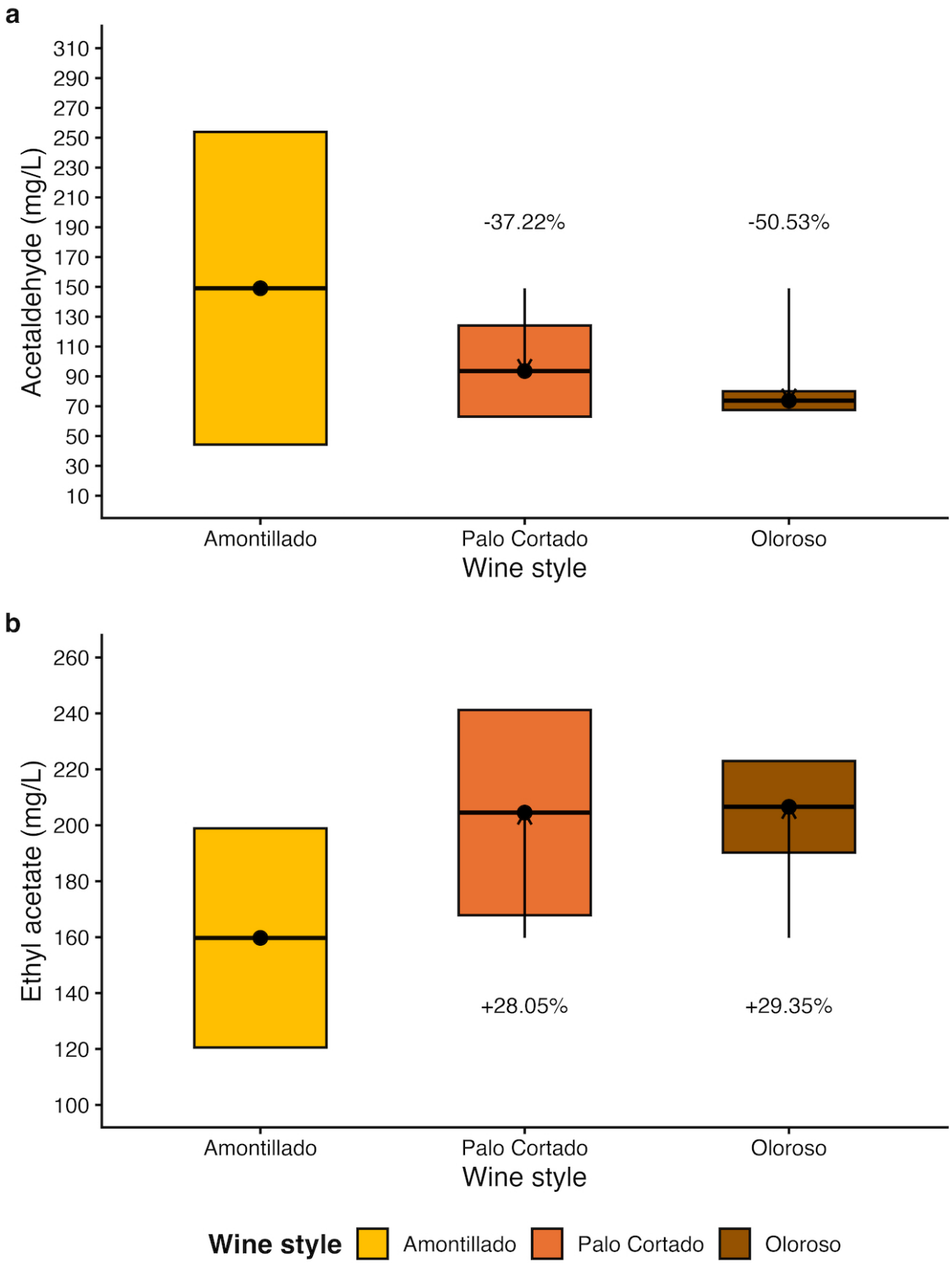


FIGURE 2. Volatile compound concentrations (mg/L) in wine samples determined by GC-FID according to wine style.

(a) Acetaldehyde; (b) ethyl acetate. Boxplots represent the distribution of values in Amontillado, Palo Cortado, and Oloroso wines. The central line indicates the median, the box represents the interquartile range (IQR), and the arrows indicate the percentage difference between medians among styles.

TABLE 5. Sensory characteristics evaluated in the samples (mean ± standard deviation).

Attribute	Amontillado	Palo Cortado	Oloroso
Visual intensity	3.08 ± 0.29a	3.48 ± 0.46b	3.7 ± 0.43b
Visual clarity	1.40 ± 0.15a	1.46 ± 0.1a	1.43 ± 0.06a
Visual hue	2.35 ± 0.84a	3.15 ± 0.51b	3.58 ± 0.57b
Nose intensity	3.62 ± 0.22a	3.42 ± 0.30a	3.29 ± 0.15a
Nose complexity	3.54 ± 0.22a	3.73 ± 0.22a	3.35 ± 0.33a
Aging aromas (biological *vs* oxidative)	– 0.10 ± 0.38a	0.54 ± 0.52b	0.62 ± 0.52b
Aging aromas: Amontillado *vs* Oloroso	– 0.17 ± 0.42a	0.40 ± 0.38a	0.35 ± 0.43a
Palate intensity	3.27 ± 0.37a	3.62 ± 0.16a	3.58 ± 0.31a
Palate complexity	3.25 ± 0.16a	3.38 ± 0.11a	3.44 ± 0.13a
Palate acidity	2.94 ± 0.38a	2.98 ± 0.09a	2.79 ± 0.19a
Palate alcohol	2.83 ± 0.33a	3.21 ± 0.20b	2.83 ± 0.13a
Palate tannins	2.19 ± 0.27a	2.44 ± 0.26a	2.47 ± 0.30a
Palate body	2.42 ± 0.23a	2.65 ± 0.15b	2.81 ± 0.17b
Palate density	2.69 ± 0.23a	2.65 ± 0.17a	2.98 ± 0.34a
Palate aging notes (biological *vs* oxidative)	– 0.17 ± 0.35a	0.27 ± 0.33b	0.67 ± 0.37b
General evaluation	3.31 ± 0.39a	3.19 ± 0.17a	3.40 ± 0.31a

Values are expressed as mean ± standard deviation. Different superscript letters within the same row indicate significant differences among wine styles ($p < 0.05$). Statistical differences were assessed using ANOVA followed by Tukey's HSD test or, when normality assumptions were not met, using the Kruskal-Wallis test followed by Dunn's post-hoc test.

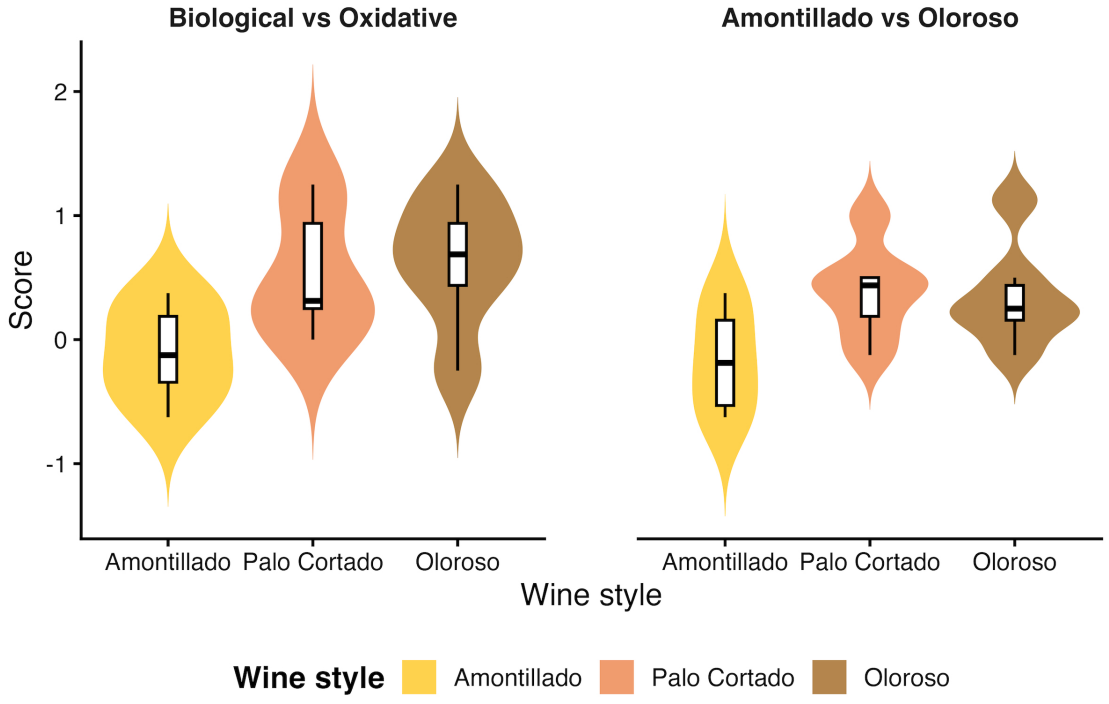


FIGURE 3. Perceived ageing profile according to wine style.

Sensory evaluation of ageing-related attributes according to wine style. Left panel: perception of biological versus oxidative ageing (negative values indicate biological perception, positive values indicate oxidative perception). Right panel: stylistic perception along the Amontillado–Oloroso scale (negative values indicate similarity to Amontillado, positive values indicate similarity to Oloroso). Violin plots represent the distribution of scores, with embedded boxplots showing the median and interquartile range.

TABLE 6. Summary of significant univariate differences among wine styles (sensory, colour, oenological, and volatile parameters).

Section	Parameter	Statistical test	*p*-value	Significant differences (pairwise comparisons)
Oenological parameters	pH	ANOVA + Tukey	0.038	Oloroso *vs* Amontillado
	Reducing sugars	ANOVA + Tukey	0.0006	Oloroso *vs* Amontillado; Palo Cortado *vs* Amontillado
	Fructose	Kruskal-Wallis + Dunn	0.0085	Amontillado *vs* Oloroso; Amontillado *vs* Palo Cortado
Colour parameters	a*	ANOVA + Tukey	0.0307	Oloroso *vs* Amontillado
	Hue	ANOVA + Tukey	0.0254	Oloroso *vs* Amontillado
Volatile compounds	Ethyl acetate	ANOVA + Tukey	0.0403	No significant pairwise differences
	2-Phenylethanol	Kruskal-Wallis + Dunn	0.0115	Amontillado *vs* Palo Cortado
Sensory analysis	Visual hue	ANOVA + Tukey	0.0172	Oloroso *vs* Amontillado
	Aging aromas (biological *vs* oxidative)	ANOVA + Tukey	0.0364	Oloroso *vs* Amontillado
	Palate alcohol	ANOVA + Tukey	0.0217	Palo Cortado *vs* Amontillado; Palo Cortado *vs* Oloroso
	Palate body	ANOVA + Tukey	0.0081	Oloroso *vs* Amontillado
	Palate aging notes biological *vs* oxidative	ANOVA + Tukey	0.0034	Oloroso *vs* Amontillado

Only parameters showing significant differences ($p < 0.05$) among styles are included. Post-hoc comparisons were performed using Tukey's HSD test after ANOVA or Dunn's test after Kruskal-Wallis, when applicable.

6. Principal component analysis (PCA)

6.1 FTIR parameters

Principal Component Analysis (PCA) was performed as an exploratory tool to evaluate potential grouping of the wines based on the oenological parameters. The first two principal components explained 56.19 % of the total variance (PC1: 31.70 %; PC2: 24.50 %). According to the component loadings (Table S2), total acidity and malic acid contributed most to PC1, whereas fructose and reducing sugars contributed most to PC2.

The PCA score plot (Figure S1) showed considerable overlapping between groups, with no clear differentiation among styles. Inclusion of the third component, associated with volatile acidity, density, and TPI, did not improve clustering patterns.

Based on Euclidean distances, Oloroso showed lower dispersion among samples, suggesting greater homogeneity, while Amontillado showed higher internal variability. Some proximity between Palo Cortado and Oloroso samples was observed. According to the dendrogram (Figure S2), mixed clustering patterns were observed; some variability within sample groupings was observed, with no consistent grouping according to wine style.

6.2 Chemical colour evaluation

Principal Component Analysis (PCA) was performed as an exploratory tool to evaluate potential grouping of the wines based on absorbance measurements. The PCA score plot (Figure S3) showed partial overlap among wine styles, with no clear differentiation between groups. PC1 was mainly associated with the absorbances at 520 and 620 nm, as shown in Table S3, with absorbance at 620 nm representing

the strongest contribution. In contrast, PC2 was associated with absorbance at 420 nm, related to yellow hues. The first two principal components explained 96.80 % of the total variance (PC1: 91.10 %; PC2: 5.70 %). However, PC2 accounted for only 6.00 % of the variance, which limits its contribution to the overall interpretation.

Hierarchical cluster analysis based on absorbance parameters (Figure S4) provided an exploratory overview of the relationships among samples. Amontillado wines showed greater dispersion, indicating higher internal variability, whereas Oloroso samples appeared more closely grouped. In terms of inter-style comparison, the largest dissimilarity was observed between Amontillado and Palo Cortado, while Palo Cortado and Oloroso showed more similar absorbance profiles. Although some clustering of samples within the same style was observed, particularly for Amontillado, this pattern was not consistent across all styles. Palo Cortado samples were distributed between clusters associated with both Amontillado and Oloroso, supporting its intermediate position. Overall, the clustering pattern was not sufficiently distinct to allow a clear classification of samples by style, reflecting the inherent variability of these wines.

For CIELAB determinations, PCA explained 83.17 % of the total variance, with the second component accounted for 12.50 %. Together, the two components explained 95.67 % of the variance. According to the component loadings, PC1 was mainly associated with a*, while L* showed a negative contribution. PC2 was primarily associated with b*, representing variation along the yellow-blue axis. No clear differentiation among styles was found with the PCA score plot (Figure S5). Dispersion within samples appeared higher for Amontillado than for Oloroso, whereas the lowest dispersion appeared in Palo Cortado. Based on inter-style distances, greater proximity appeared for the Oloroso – Palo Cortado pair, while the Amontillado – Oloroso pair showed higher separation, with Amontillado – Palo Cortado presenting intermediate values. showed mixed clustering patterns, with no consistent grouping according to wine style.

Hierarchical cluster analysis for CIELAB parameters (Figure S6) did not show clear differentiation among styles. Amontillado showed greater dispersion, suggesting higher variability, while Oloroso showed lower dispersion. Some proximity was observed between Palo Cortado and Oloroso samples, as well as between some Amontillado and Oloroso samples; however, clustering patterns were not consistent across wine styles.

6.3 Volatile compounds

Volatile compounds that consistently showed null values across samples were excluded from the PCA. The analysis was performed exclusively for exploratory purposes, to assess potential grouping patterns among samples.

Six components were extracted based on the eigenvalue criterion. The first two principal components explained 48.54 % of the total variance (PC1: 27.51 %; PC2: 21.03 %). According to the rotated component matrix (Table S4), PC1 was mainly associated with 1-propanol, 3-methyl-1-butanol, isobutanol, and 2-methyl-1-butanol, while PC2 was associated with 2-phenylethanol and 1-butanol, with a contribution from acetic acid. Given the relatively low percentage of variance explained by the first components, and the overlap present in the PCA scores plot (Figure S7), PCA results should be interpreted with caution, and no clear grouping among wine styles can be concluded. Inclusion of additional components did not improve clustering patterns.

Hierarchical cluster analysis suggested that Palo Cortado presented higher intra-style variability, followed by Amontillado, while Oloroso showed the lowest variation among samples. The corresponding dendrogram (Figure S8) showed limited clustering patterns, with no clear grouping according to wine style.

6.4 Sensory analysis

Principal Component Analysis extracted two principal components (PC) with eigenvalues greater than one, explaining 82.33 % of the total variance (PC1: 68.47 %; PC2 13.86 %). PCA was used as an exploratory tool to assess overall trends among wine styles based on sensory evaluation.

The contribution of the variables to each principal component is presented in the rotated component matrix (Table S5). Variables with high loadings on PC1 were mainly related to mouthfeel and structural attributes, such as body, biological/oxidative perception on the palate, palate complexity, and biological/oxidative perception on the nose. In contrast, variables with the highest loadings on PC2 were mainly visual parameters, such as visual intensity and hue, along with tannin perception. Palate intensity showed relevant and comparable loadings on both components.

The PCA score plot (Figure 4a) showed partial overlap among wine styles, indicating no clear differentiation between groups. Although a tendency was observed for Amontillado samples to appear towards negative PC1 values, this pattern was not consistent, and a clear separation among styles was not achieved. The PCA biplot (Figure 4b**)** allows visualisation of the contribution of variables to the principal components. PC1 was mainly associated with mouthfeel and structural attributes, whereas PC2 was primarily related to visual attributes.

The PCA biplot shows that most sensory variables were oriented in similar directions, indicating that they contribute jointly to the main source of variability represented by PC1. In general, attributes related to ageing perception (both in nose and palate) were distributed towards the positive side of PC1, whereas visual parameters were oriented towards the opposite direction along PC2. The relatively low proportion of variance explained by PC2 suggests that most sensory attributes vary together rather than independently. In particular, nose ageing aromas and palate ageing notes show similar orientations, indicating a consistent sensory perception for both attributes. A similar pattern is observed for visual hue and visual intensity.

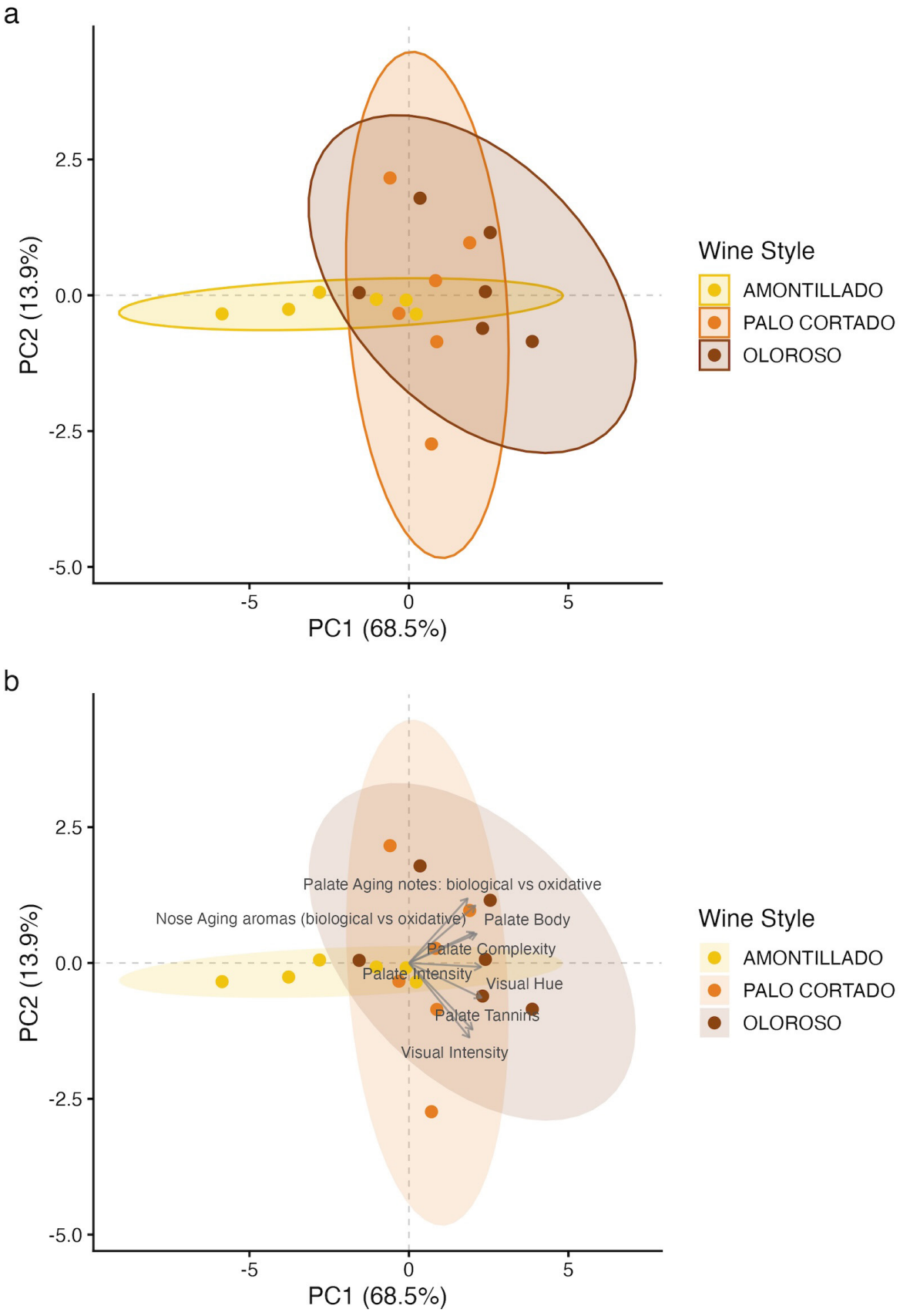


FIGURE 4. Principal Component Analysis (PCA) of sensory attributes.

(a) PCA scores plot showing the distribution of samples according to wine style; ellipses represent the dispersion within each group. (b) PCA biplot showing both sample distribution and the contribution of sensory variables to the principal components.

Regarding sample distribution, Palo Cortado and Oloroso wines are generally located in the direction of variables associated with ageing, such as palate ageing notes, whereas Amontillado wines tend to be positioned in the opposite direction, reflecting a more biologically influenced profile. Palo Cortado samples are distributed between both groups, often overlapping with Oloroso, supporting its intermediate character and its tendency towards an oxidative profile. Oloroso wines are also located closer to structural attributes such as palate complexity, intensity, and tannins, in agreement with reported sensory characteristics of this style (Pereira *et al*., 2019).

However, the observed length of the vectors indicates that the representation of the variables in the first two principal components is limited. In addition, a substantial overlap among wine styles was observed, indicating that no clear differentiation among styles can be established based on these variables.

Hierarchical cluster analysis showed lower dispersion within style for Palo Cortado and higher dispersion in Amontillado. For between-style comparisons, greater distances were observed between Amontillado and Palo Cortado compared to other pairs. The dendrogram (Figure S9) showed mixed clustering patterns, with no clear grouping according to wine style.

7. Multiple factor analysis (MFA)

Multiple Factor Analysis (MFA) integrates multiple groups of variables, providing a global view of the dataset. According to the MFA biplot (Figure 5), the first dimension (F1) showed a separation trend among samples, which appeared to be associated with differences among wine styles. This axis is driven mostly by colour-related parameters, such as absorbance at 420 nm and CIELAB coordinates.

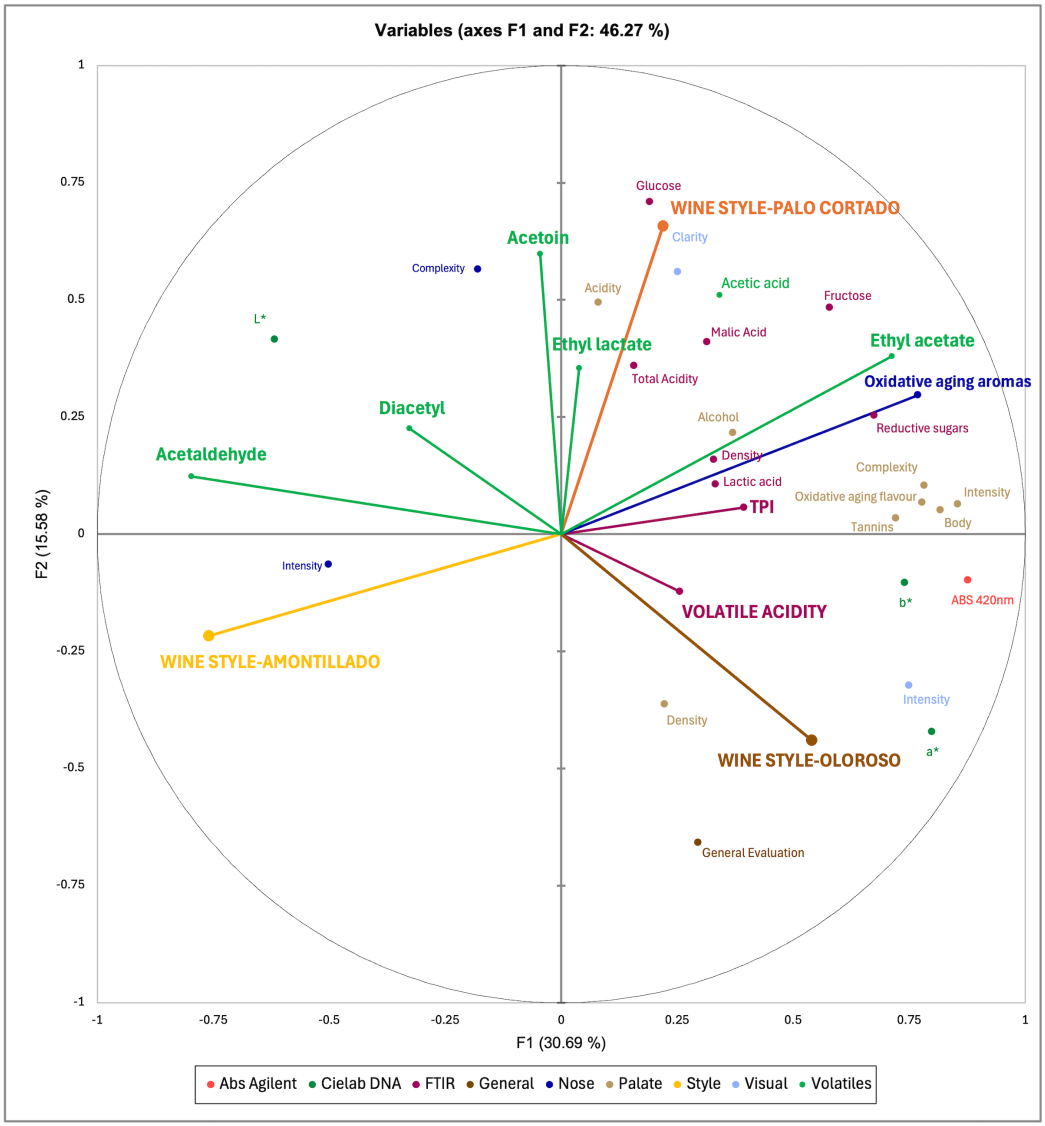


FIGURE 5. Multiple factor analysis (MFA) biplot integrating sensory, colour, FTIR, and volatile compound data for Amontillado, Palo Cortado, and Oloroso wines.

The analysis is presented for exploratory purposes to visualise relationships among samples and groups of variables. The first two dimensions illustrate the distribution of the wine styles and their associations with sensory and physicochemical parameters. Proximity among samples reflects similarities in their profiles, with Palo Cortado tending to appear closer to Oloroso.

Amontillado samples were generally positioned on the negative side of F1 and were associated with compounds such as acetaldehyde, typically considered a biological ageing marker (García-García *et al*., 2025), as well as diacetyl and acetoin. In contrast, Oloroso samples were located towards the positive side, showing associations with variables such as TPI, oxidative ageing aromas, and ethyl acetate, as well as colour parameters such as absorbance at 420 nm, and CIELAB coordinates (a* and b*). Palo Cortado samples were distributed between both styles, with a tendency towards the Oloroso region. The second dimension (F2) was predominantly associated with sensory attributes including clarity and general evaluation, as well as sugar-related parameters, although it contributed less to the overall structuring of the samples.

Overall, the MFA biplot revealed tendencies in the distribution of wine styles and their associated variables, although some overlap among samples remained. The structuring observed in MFA was more defined than in PCA, allowing clearer observation of grouping tendencies among wine styles and their associated variables.

DISCUSSION

The main goal of this research was to characterise Palo Cortado in comparison with Amontillado and Oloroso based on sensory and physicochemical parameters, including oenological parameters, pH, Total Polyphenol Index (TPI) and volatile compound quantification. Overall, univariate analysis revealed that only a limited number of parameters showed significant differences among styles, suggesting a broadly similar chemical composition. In contrast, sensory evaluation provided slightly clearer differentiation patterns, particularly regarding ageing profiles, which are especially relevant in these wines. Principal Component Analysis (PCA) was therefore used as an exploratory tool, while Multifactorial Analysis (MFA) was used to integrate the different variables, including chemical and sensory parameters. However, the discriminative power of multivariate approaches remained limited due to the low number of significant variables and the high intra-style variability.

Across analyses, Palo Cortado consistently showed intermediate behaviour, tending to align more closely with Oloroso than with Amontillado. High variability among samples was observed, likely influenced by winery-specific winemaking practices. Despite the limited number of significant differences observed in univariate analyses, correlation and regression approaches revealed relationships between chemical composition and sensory perception, highlighting that, even in the absence of strong chemical differentiation, specific compounds and parameters can be directly associated with sensory attributes.

According to previous findings, Palo Cortado has been reported as slightly more acidic than Oloroso, mainly due to a higher proportion of organic and inorganic acids from the grapes, fermentation (alcoholic/MLF), or "plastering" practices (Valcárcel-Muñoz *et al*., 2022). In the present study, pH values differed significantly among styles, particularly between Oloroso and Amontillado, suggesting relevant variations in physicochemical parameters. However, sensory results indicated that Palo Cortado showed the highest perceived acidity, although no significant difference was found at the sensory level. This apparent discrepancy highlights the complex relationship between chemical parameters and sensory perception, as pH alone does not fully reflect perceived acidity. Instead, acidity perception may be influenced by the interactions among multiple components within the wine matrix, especially in wines with complex ageing processes such as Sherry wines.

Regarding the Total Polyphenol Index (TPI), higher values were observed in Amontillado and particularly in Oloroso wines, although the differences were not statistically significant. This behaviour is consistent with the oxidative ageing process, where prolonged contact with oak casks promotes the extraction of phenolic compounds, further influenced by temperature and concentration effects during ageing (Ortega *et al*., 2003). The higher phenolic content in Oloroso wines agrees with the higher "body" and mouthfeel attributes reported during sensory evaluation. Ageing in oak has been associated with an increase in phenolic compounds, including gallic acid as a major compound, p-hydroxybenzoic acid and p-coumaric acid (García-Moreno *et al*., 2021), which tend to oxidise, contributing to the development of amber and brown colours and oxidative aromas (Oliveira *et al*., 2011).

Regarding oenological parameters, volatile, and total acidity showed higher values in Palo Cortado wines, consistent with their predominantly oxidative ageing profile. Volatile acidity tends to increase during ageing due to ethanol oxidation (Valcárcel-Muñoz *et al*., 2022), whereas Amontillado is typically expected to show lower values as a result of yeast metabolism during the biological phase (Peinado & Mauricio, 2009). Total acidity, in contrast, has been shown to increase over ageing. Correlation analyses showed a moderately significant difference between a combined acidity parameter (lactic acid, malic acid, total acidity, volatile acidity) and sensory perception of acidity. Similarly, linear regression indicated that sensory acidity was primarily explained by total acidity measured by FTIR. Malic acid in this study showed minimal differences among styles; however, slightly higher lactic acid concentrations in Amontillado and Palo Cortado may suggest the occurrence of a partial malolactic fermentation (MLF) due to microbial activity during ageing. This has been associated in previous studies with higher initial malic acid levels, contributing to the sensory deviation that characterises Palo Cortado (Valcárcel-Muñoz *et al*., 2022). Other parameters, such as density, remained relatively constant across all samples, supporting the similarity in basic composition. Glucose showed a more variable behaviour: Palo Cortado presented higher values than Oloroso, as previously reported, which may be related to the influence of the *flor* (Villamiel *et al*., 2008). In contrast, Amontillado did not consistently show higher values, which may reflect the variability among samples and differences in ageing conditions. Fructose, in contrast, showed a significant

difference between Amontillado and the other two styles, reinforcing similarity between Amontillado and Oloroso, and discrimination between styles. Overall, residual sugars were low across all wines, as expected for dry styles. This resulted in discrepancies between reducing sugar values and the sum of glucose and fructose concentrations, which can be attributed to limitations associated with FTIR-based analysis. In dry wines, the low concentration of sugars, combined with spectral overlap with major components such as ethanol and organic acids, can affect calibration accuracy and lead to deviations in predicted values (Moreira & Santos, 2004). Additionally, the calibration applied corresponded to finished wines rather than fortified wines, which may further contribute to the observed differences.

At 420 nm, Palo Cortado showed the highest absorbance, indicating a greater contribution of the yellow hues. In contrast, Oloroso showed higher, red-related values, consistent with oxidative browning. This behaviour is consistent with the expected colour evolution in Sherry wines (Ferreiro-González *et al*., 2019), where oxidative ageing leads to increased absorbance at 420 nm and the development of amber and brownish tones (Ortega *et al*., 2003). Shade (tonality) scores were also highest for Palo Cortado, likely influenced by a clearer sample, with golden/yellow hues.

For CIELAB parameters, Palo Cortado showed the highest L* values, while Amontillado presented the lowest. This contrasts with typical colour descriptions reported for Amontillado wines, which are often characterised as transparent amber (Recamales *et al*., 2006). Such differences may reflect the instrument's response, particularly regarding yellow hues. Amontillado displayed higher variability. For a*, Palo Cortado appeared closer to Amontillado than to Oloroso, although more reddish tones were expected, depending on the relative proportions of oxidative and biological ageing. For b* and chroma, values were comparable for Palo Cortado and Oloroso. Significant differences were found only for hue and a*, for Amontillado and Oloroso, reflecting the dissimilarity between styles. Regarding hue angle, Amontillado showed values around 87 º, indicating less saturated yellow tones, whereas Oloroso reached values around 80 º, consistent with more oxidised, reddish hues. The higher hue values observed in Amontillado indicate a greater contribution of yellow tonalities, whereas the lower values in Oloroso suggest a shift towards darker, more evolved colour tones, often described as bronze-like. Palo Cortado showed intermediate behaviour, reflecting a transition between both profiles. The separation observed between Amontillado and Oloroso, supported by significant differences in hue and a*, highlights the impact of ageing conditions on colour development. In contrast, the overlap between Palo Cortado and Oloroso suggests shared chromatic characteristics, likely associated with oxidative processes.

The greater colour difference (ΔE) observed between Amontillado and Oloroso further supports the distinction between wines subjected to different ageing regimes. Overall, these results indicate a transition from lighter, less oxidised colour profiles in Amontillado towards more intense yellow and reddish hues in Palo Cortado and Oloroso, reflecting the progressive influence of oxidative ageing on wine chromatic characteristics (Chaves *et al*., 2007). The greater dispersion observed in Amontillado samples may reflect higher variability in ageing conditions and winemaking practices, while the more compact clustering of Oloroso indicates a more uniform evolution of colour parameters.

Colour parameters such as a*, b* hue, and absorbance at 420 nm showed significant correspondence with the visually perceived characteristics. However, no correlation was found with luminosity, for example, which may be due to other factors affecting the perception of visual clarity. Regression analysis revealed significant relationships between visual hue perception and several colour parameters, including instrumental hue, tonality/shade, red component, and absorbance at 420 nm. These results indicate that visual colour perception is primarily driven by hue-related parameters, with additional contributions from absorbance and colour intensity components, as well as supporting the correspondence between sensory and physicochemical parameters.

One limitation of this study is that volatile compounds were analysed using GC-FID, which does not allow compound identification with the same level of specificity as GC-MS. Therefore, the volatile profile presented should be interpreted as indicative rather than comprehensive. However, GC-FID remains a widely used technique for the quantitative analysis of major volatile compounds in wines (Paolini *et al*., 2022). Regarding the main volatile compounds, Palo Cortado showed the highest concentrations of acetoin, in agreement with previous reports (Palacios *et al*., 2018). Acetaldehyde and ethyl lactate are considered differentiators among styles (Pozo-Bayón & Moreno-Arribas, 2011). In this study, Amontillado presented higher acetaldehyde levels, consistent with its biological ageing phase, whereas Oloroso showed higher ethyl acetate concentrations, reflecting its oxidative ageing. These trends are in line with the metabolic activity of yeasts, which consume ethyl acetate during biological ageing (Petretto *et al*., 2023), while acetaldehyde is synthesised by yeasts, making it a marker of biologically aged wines. Ethyl lactate followed a similar trend to ethyl acetate, increasing in oxidatively aged wines as a result of esterification processes (Pozo-Bayón & Moreno-Arribas, 2016). Diacetyl showed the highest values in Amontillado, suggesting the occurrence of malolactic fermentation (MLF) (Fornachon & Lloyd, 1965).

From a sensory perspective, these compounds contribute to characteristic aroma profiles. Acetoin has been associated with bitter notes, while 2,3-butanediol contributes to typical Sherry wine aromas. Although acetoin concentrations were at the lower end of previously reported values, the higher levels observed in Palo Cortado may be linked to intermediate ageing conditions, consistent with its positioning between biologically and oxidatively aged wines. This behaviour aligns with previous findings relating acetoin formation to acetaldehyde metabolism and its decrease during prolonged biological ageing. Additionally, acetoin may increase during ageing due to evaporation effects (Durán-Guerrero *et al*., 2021). Descriptively, ethyl lactate concentrations were highest

in Oloroso, intermediate in Palo Cortado, and lowest in Amontillado, consistent with the expected increase of ester compounds during oxidative ageing. In contrast, lactic acid concentrations were highest in Palo Cortado, suggesting a more balanced profile with comparable levels of both compounds, while Amontillado showed intermediate values and Oloroso the lowest. The high variability observed across samples further supports the heterogeneous nature of Sherry wines, likely influenced by differences in ageing conditions and winemaking practices. Although mean values suggest an overall balanced profile across styles, the distribution of sensory scores revealed clearer trends. In particular, Amontillado samples tended to cluster towards the biological end of the scale, Oloroso towards the oxidative end, and Palo Cortado towards the intermediate end. This pattern, observed in the spread of the data rather than in mean values alone, reflects the inherent variability of these wines and their overlapping ageing characteristics.

Despite the limited number of statistically significant differences observed among individual volatile compounds, ethyl acetate emerged as a relevant indicator of ageing processes. Although it showed overall significant differences among wine styles, post-hoc comparisons did not reveal clear differences between specific groups. Nevertheless, its strong association with sensory perception, particularly in relation to ageing attributes, highlights its relevance as a marker of oxidative character. Ethyl acetate showed a strong correlation with sensory perception, particularly in relation to ageing attributes. In contrast, acetaldehyde showed weaker and non-significant relationships, which may reflect the influence of other interacting compounds and the complexity of aroma perception. Overall, these results highlight that despite the limited number of significant differences observed in univariate analysis, specific compounds – especially esters associated with oxidative ageing – play a key role in driving sensory differentiation among styles. This is further supported by the significant association observed for stylistic attributes related to Amontillado and Oloroso, where panellists consistently related each sample's ageing profile to these reference styles. Altogether, these findings reinforce that sensory differentiation among wine styles is supported by underlying chemical composition, particularly by compounds associated with oxidative ageing processes.

From sensory evaluation results, Palo Cortado aligned more closely with Oloroso regarding oxidative descriptors (aroma and palate ageing notes), reflecting similarities in their ageing processes, while maintaining intermediate attributes that reinforce differentiation among the styles. Visual hue also emerged as a discriminating attribute, associated with precipitation of phenolic material, and its contribution to colour variations in Amontillado wines (Palacios *et al*., 2001). The darker tones observed in Oloroso are consistent with oxidative ageing in the absence of *flor*, promoting phenolic oxidation, whereas the yeast layer contributes to lighter tones in Amontillado and, to a lesser extent, in Palo Cortado. Most Amontillado samples were positioned toward the biological side of the scale; however, considerable variability was observed, with some samples showing a more balanced oxidative-biological profile. On average, Amontillado showed a balanced profile, while Palo Cortado and Oloroso leaned towards oxidative descriptors. On the palate, Oloroso showed the highest complexity and intensity, associated with higher ethanol content and fuller mouthfeel. The alcohol perception values are consistent with fortification (*encabezado)*, and the greater structural characteristics of its base wine, usually has a greater structure (*gordura*) (Perestrelo *et al*., 2016) contributing to its characteristic volume. Panellists also perceived greater body and density in Oloroso samples, in line with previous literature (Casal del Rey Barreiro *et al*., 2001). Regarding ageing notes on the palate, Amontillado and Palo Cortado showed a balance between biological and oxidative descriptors, whereas Oloroso tended to associate with oxidative notes. This behaviour may be attributed to differences in the duration of oxidative and biological ageing phases, depending on winery practices. These findings are consistent with previous reports describing fruity or cooked-apple aromas in Amontillado, associated with acetaldehyde, and weaker oxidative descriptors compared to Oloroso (Marcq & Schieberle, 2015). Again, some Amontillado samples appeared closer to Oloroso, consistent with their documented profiles. Olfactory complexity also emerged as a differentiating parameter, with compounds such as acetaldehyde, acetoin, eugenol, and 1,1-diethoxyethane contributing to the aromatic profile (Durán-Guerrero *et al*., 2021). Acetaldehyde, synthesised by *flor* yeasts, is typically higher in Amontillado than in Oloroso, while Palo Cortado presents intermediate concentrations due to its shorter biological phase. This compound is associated with pungent and ripe apple notes (Moreno *et al*., 2005), reinforcing the sensory positioning of Amontillado. Differences in alcohol perception among styles were also observed, with Palo Cortado showing the highest perceived alcohol. These differences are mainly related to ageing and fortification. Oloroso is fortified at a higher alcoholic strength from the beginning to prevent *flor* yeast development, while the other styles undergo fortification at specific stages. However, specific winery practices can influence the final ethanol content and sensory perception. Oloroso typically increases in volatile acidity during ageing due to ethanol and acetaldehyde oxidation, while Amontillado remains intermediate (Medina *et al*., 2003).

Interestingly, as mentioned before, panellists perceived the highest acidity in Palo Cortado and the lowest in Oloroso, despite limited differences in physicochemical measurements. This further supports the complex relationship between chemical composition and sensory perception, where interactions between compounds influence taste perception (Valcárcel-Muñoz *et al*., 2022). This study shows how specific chemical variables contribute to sensory attributes.

The main differentiating sensory parameters were visual hue, ageing aromas (biological *vs* oxidative), between Amontillado and Oloroso, and alcohol perception, consistent with previous references. For ageing-related notes, the relationship between chemical composition

and sensory perception was better explained through targeted associations rather than individual compound differences. In particular, oxidative-related compounds, such as ethyl acetate, showed a stronger association with sensory perception of ageing, whereas acetaldehyde presented weaker relationships. This suggests that sensory differentiation among styles is driven by the combined effect of multiple compounds rather than single markers, especially in wines undergoing partial biological ageing, such as Amontillado and Palo Cortado.

Despite limited differences in univariate analysis, this study demonstrates that the combination of chemical and sensory approaches provides a more comprehensive understanding of Sherry wine styles. In particular, compounds associated with oxidative ageing play a key role in sensory differentiation, highlighting the complexity of these wines and the importance of integrative analytical approaches.

CONCLUSION

This study aimed to identify sensory and physicochemical differences among the three Sherry styles, with particular focus on distinguishing Palo Cortado from Amontillado and Oloroso. Despite limited statistical significance in the chemical composition, several colour parameters, particularly intensity and hue, as well as volatile compounds such as ethyl acetate, showed significant differences among styles. Sensory analysis also revealed differences, especially in ageing-related attributes on the nose and palate.

Amontillado showed higher mean acetaldehyde concentrations, whereas Oloroso showed higher ethyl acetate levels, consistent with their respective ageing processes. However, the limited sample size and the high variability among samples, likely influenced by winery-specific practices, constrained the statistical robustness and hindered clear classification.

Colour-related parameters, including hue and tonality, showed consistent relationships with sensory perception, particularly in relation to oxidative processes. Overall, the results suggest tendencies of differentiation among styles and indicate the proximity of Palo Cortado to Oloroso, while maintaining its distinctive character. This study provides a useful basis for further research on the analytical and sensory characterisation of these wines.

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