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Sensory patterns and oxygen consumption kinetics in the oxidation of white, *rosé* and sparkling wines

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ABSTRACT

The present work studies the sensory changes caused by the consumption of oxygen of two whites, one *rosé* and one sparkling wine. Wines were subjected to different doses of O_2 (0, 6, 12 and 35 mg/L over the stoichiometric amount needed to consume total SO_2) and incubated at 35 °C for 28 days. Oxygen was consumed in all cases following pseudo-first order kinetics with differences between the fastest (Verdejo) and the slowest (Cava) by a factor of four. Oxygen consumption rates were significantly and negatively related to the wine redox potential. Oxygen consumption first caused a decrease of fruity notes. At low or intermediate oxygen levels, the "cooked vegetables" note reached its maximum intensity, acting as an intermediate stage. At the highest oxygen doses, this note became masked as "honey" and "cider/overripe apple" notes emerged as dominant oxidative descriptors. Wines consuming oxygen faster did not develop clear oxidative notes, just significant decreases in fruity notes, while slower consumers developed intense oxidative notes. Preference was well explained by a PLS model in which floral and fruity attributes had positive coefficients and oxidative notes ("cooked vegetables", "honey" and "cider/overripe apple") had negative coefficients.

KEYWORDS: oxygen consumption, white, sparkling, *rosé*, redox potential, sensory changes, fruitiness

INTRODUCTION

The role of oxygen during wine ageing is a critical parameter affecting its quality (Caillé et al., 2010; Lopes et al., 2006). On the one hand, a certain amount of oxygen is required in order to avoid the accumulation of volatile sulfur compounds responsible for reductive faults (Bekker et al., 2016; Siebert et al., 2010), but, on the other hand, too much oxygen can be detrimental to wine aroma (Ugliano, 2013; Ugliano et al., 2009). First, too much oxygen can provoke the oxidation of oxygen-sensitive powerful aroma compounds, such as polyfunctional thiols (Lyu et al., 2021; Roland et al., 2016). These compounds are crucial for the varietal expression of Sauvignon blanc, Verdejo or Muller-Thurgau wines (Carlin et al., 2022; Lund et al., 2009; Mateo-Vivaracho et al., 2010) but, in general, they are also essential for the perception of freshness in neutral white wines (Escudero et al., 2004) or for a wide range of "citrus", "fruity", and "empyreumatic" aroma subqualities (Ferreira et al., 2022; Picard et al., 2015; Tominaga et al., 2003) via perceptual interaction phenomena. Second, too much oxygen will first oxidise free SO_2, causing the release of acetaldehyde and Strecker aldehydes accumulated as hydroxy-alkyl-sulfonates (Bueno et al., 2016), and, eventually, will produce more aldehydes by the Fenton-induced oxidation of ethanol and by the quinone-induced Strecker degradation of amino acids (Bueno et al., 2018; Escudero et al., 2025).

Therefore, the dose of oxygen received during ageing seems to be a critical parameter determining the sensory properties of wines. This subject has been addressed, mostly from the chemical point of view in reds (Carrascon *et al.*, 2015; Carrasco-Quiroz *et al.*, 2023; Dai *et al.*, 2022; Gambuti *et al.*, 2018; Petrozziello *et al.*, 2018) and also in white and *rosé* wines (Carrascón *et al.*, 2017), but the sensory effects of the dose of oxygen received have been scarcely studied. Although a previous work has compared the differential sensory response of 16 different red wines (Sáenz-Navajas *et al.*, 2014), studies in white or *rosé* wines have been limited to just one wine type (Coetzee *et al.*, 2016; Wirth *et al.*, 2012), making difficult to observe the existence of differential patterns. This is a limitation, considering that in these types of wine, oxidation is yet more critical than in red wines.

Because of this, the main objective of the present study is to perform preliminary research about the differential sensory responses elicited by four different wines (two dry whites, one *rosé,* and one sparkling wine), when exposed to different amounts of oxygen.

MATERIALS AND METHODS

1. Reagents, solvents and standards

Sodium hydroxide (0.01 M, mixed indicator methyl red-methylene blue), orthophosphoric acid (85 %) and hydrogen peroxide (3 %) were supplied by Panreac (Barcelona, Spain).

2. Wines

A total of 4 wines (two whites, one *rosé* and one sparkling) presented in Table 1 were chosen for the study. All wines underwent the oxidation treatments simultaneously. The experimental part of the study began in November 2021 with the oxidation process and ended in December 2021 with redox potential and sensory analysis. These dates are specified to indicate that, at the time of the experiment, most wines were approximately one year old and had been recently released from the wineries. The only exception was the sparkling wine (Cava, vintage 2018), which, although recently commercialised, had remained longer in the winery due to the second fermentation and lees aging typical of its production process.

3. Sparkling wine degassing

Particularly for Cava, a degassing process based on the combination of shaking and vacuum cycles was performed prior to oxidation. Two-thirds of a 275 mL bottle were filled with Cava and were vacuum sealed with a VacuVin. Afterwards, 15 cycles of manual shaking for 5 seconds, each of them followed by vacuum with VacuVin were applied to decrease carbon dioxide concentrations. Finally, bottles were horizontally shaken at 320 RPM for 15 minutes with vacuum degassing every 90 seconds (10 cycles).

4. Total sulfur dioxide determination

This determination was conducted using the aspiration-titration method described by Rankine and Pocock (1970), following the guidelines recommended by the International Organisation of Vine and Wine (OIV) (OIV, 2009).

5. Accelerated oxidation

In this procedure, two bottles of each wine were uncorked and mixed, and the wine was then spiked with 200 mg/L of X Velcorin® (dimethyl dicarbonate, E-242) from Enartis

TABLE 1. General commercial information from the wines of study.

Variety	Type	% EtOH	Vintage	Winery	D.O.
Garnacha	*Rosé*	13.5	2020	Bodegas Aragonesas	Campo de Borja
Macabeo-Parellada-Xarel·lo	Sparkling "Cava"	11.5	2018	Cava Vilarnau	Cava
Verdejo	White	13.0	2020	Bodega Emina Rueda	Rueda
Chardonnay	White	13.5	2020	Bodega Laus	Somontano

(Alcázar de San Juan, Spain). This process was conducted under oxygen-protected conditions as each wine was uncorked inside an anoxic chamber (Jacomex, Dagneux, France), with O_2 levels under 0.002 % (*v/v*).

Each wine was divided into six aliquots: two control aliquots (without oxygen) stored in the dark at 4 °C, and four aliquots exposed to varying oxygen doses and stored in the dark at 35 °C. For the different oxygen doses, each aliquot received the stoichiometric amount of oxygen require to consume all the sulfur dioxide present in the wine, plus an additional oxygen dose of 0,6, 12, and 35 mg/L. The stoichiometric relationship used for the calculations assumes a 2:1 molar ratio between SO_2 and O_2; that is, for each mole of oxygen entering the accepted oxidation mechanism (Bueno *et al.*, 2018), two moles of SO_2 are consumed (one reacting with the H_2O_2 formed and the other with quinones). Each aliquot was prepared in duplicate for whites and sparkling wines and in quadruplicate for the *rosé* wine, resulting in a total of 60 containers (3 wines × 6 aliquots × 2 containers + 1 wine × 6 aliquots × 4 containers).

The accelerated oxidation methodology followed in this study was described by Marrufo-Curtido *et al.* (2018). In brief, oxygen doses were achieved by varying the exact air headspace volume of the container used once the samples to be oxidised were out of the anoxic chamber. The containers for the experiment were wine-in-tubes (WITs, from WIT-France, Bordeaux) of a total volume of 65 mL and negligible air permeability (12 µg O_2/day) for this study. Each WIT was equipped with a PSt3 O_2 sensor (Vinventions S.A., Thimister-Clermont, Belgium) to monitor dissolved oxygen levels in the liquid phase, which were measured several times during the treatment using the Fibox 3 OxyMeter LCD (PreSens, Germany). To ensure the equilibrium between the liquid and gas phases, the WITs were continuously shaken at 100 RPM along the 28-day treatment. After the treatment period, samples exposed to oxygen were allowed to equilibrate to room temperature, and then stored along with their controls at 4 °C for 24 hours, when their redox potential and sensory evaluation was conducted.

Experimental oxygen data were fitted to pseudo-first order kinetic models to determine the corresponding decay functions, where $1-e^{-k}$ represents the daily percent of O_2 consumed (details can be found in the Supplementary data Equation S1). The percentage of total oxygen consumed, and consumption kinetics data were evaluated using a two-way analysis of variance (ANOVA) taking into account wines and doses as fixed factors.

6. Determination of redox potential

The redox potential was measured with a commercial electrode integrated by a Pt electrode and a Ag−AgCl(s) reference electrode (HI 3148 model from HANNA Instruments, USA). The signal was obtained using a HI 98191 device from HANNA. The complete system was located inside the anoxic chamber. After the 28-day oxidation period, the WITs were opened outside the anoxic chamber under an argon flow to take an aliquot for redox potential analysis. This aliquot was transferred to a 4 mL vial completely filled (without headspace) and immediately placed inside the anoxic chamber. These vials were opened, manually shaken, and kept open within the argon atmosphere for 30 min to allow any remaining dissolved oxygen to evaporate. The redox potential was measured in these vials without agitation, using a stabilisation time of 35 min, as described in Vela *et al.* (2018). Due to the large number of samples and the time required for each measurement, one replicate of each sample was analysed on the first day, and the second replicate on the following day. All aliquots for redox potential analysis were stored inside the anoxic chamber until measurement. The remaining sample, intended for sensory analysis, was not introduced into the chamber. Sensory evaluation was carried out in parallel on the same day to prevent further uncontrolled changes.

7. Description analysis

This task was developed in two steps: first, panel training, and second, the evaluation of the samples. In all sessions, 10 mL samples were served in dark ISO-approved wine glasses (ISO, 1977), labelled with a three-digit random code, covered by a Petri dish and presented randomly to each judge. Throughout all sessions, panellist was first asked to orthonasally smell all the samples and then taste them searching for mouthfeel sensations. Ethical approval for the involvement of human subjects in the present study was granted by the Research Ethics Committee of the Consejo Superior de Investigaciones Científicas (CSIC), Ref. 150/2021, in August 2021.

7.1 Participants

The sensory analysis was carried out by ten trained panellists (an equal number of males and females, aged between 24 and 53, with an average of 36 years old), all of whom were wine consumers and staff members of the research group. Participants were informed that samples had been prepared in the laboratory. They were also required to sign a consent form prior to undertaking the sensory testing. They were neither informed about the objective of the study nor paid for their participation.

7.2 Panel training

Panel training was carried out through seven sessions following the procedure described by de-la-Fuente-Blanco *et al.* (2024). The first session focused on the identification of 18 aromatic references ("spirit-like alcohol", "citrus", "spiced", "floral", "yellow fruit", "white fruit (apple)", "white fruit (pear)", "black fruit", "red fruit (strawberry)", "red fruit (raspberry)", "tropical fruit (lychee)", "tropical fruit (pineapple)", "honey", "reduction (olive broth)", "reduction (rotten eggs)", "cider/overripe apple", "cooked vegetables" and "vinegar") and three in-mouth sensations ("acidity", "bitterness" and "astringency") and to relate them with descriptors from a list. These attributes were selected for being the most commonly used to describe the wines studied (Campo *et al.*, 2008; Niimi *et al.*, 2018; Ortega-Heras *et al.*, 2024; Rodríguez-Nogales *et al.*, 2009;

Wang *et al.*, 2016). Training references were commercially available products such as fruits or beverages, which were prepared at the beginning of the session as described in Sáenz-Navajas *et al.* (2011).

The second session involved identifying the common descriptor within four sets of four glasses and ranking them from low to high, according to their perceived intensity. Each set corresponded to a different descriptor previously trained in the first session. Within each set, the hydroalcoholic solutions were spiked with increasing concentrations, following a logarithmic scale to produce distinct intensity levels.

The third session repeated the same task as in the second session, but with four sets of four glasses containing different attributes selected from those previously trained in the first session and not used in the second. This time, the intensity levels were evaluated using a 10 cm structured scale ranging from 0 (absence) to 10 (very intense) with 1 cm increments.

In the fourth session, the selection of discriminant attributes was carried out. For this purpose, four wines similar to those that would be used in the study (including oxidised wine samples) were presented to the panellists, who were asked to identify the aroma and mouthfeel descriptors that differentiated them as described in de-la-Fuente-Blanco *et al*. (2024). Panellists were free to choose as many terms as they considered appropriate from a structured list of 121 aroma terms (families, subfamilies, and specific terms). Finally, the terms were selected according to the number of citations, with a minimum of 25 % of the panellists mentioning each term.

In the fifth session, four wines similar to those used in the study (oxidised and not oxidised) were presented to the panellists once more. The wines were evaluated using the 10 cm structured scale to familiarise the judges with the type of samples and the extensive set of attributes to be assessed (12 aromatic attributes via orthonasal and 3 in-mouth sensations obtained from the previous session).

Panel performance was evaluated in the sixth and seventh sessions. In both sessions panellists had to evaluate the attributes previously selected using one 10 cm structured scale for each attribute, whereas an additional scale was included for the preference. The goal was to assess the panellists' ability to discriminate between samples as well as their consistency and reproducibility. For this objective, the same four wines were used in both sessions: a white wine (Garnacha Blanca – Maturana Blanca-Viura), an oxidised white wine (Garnacha Blanca-Malvasía-Viura), a *rosé* wine (70 % Garnacha Tinta – 30 % Viura) and a degassed Cava (Chardonnay-Macabeo-Parellada).

7.3 Evaluation of the samples

Before sensory analysis, samples were allowed to equilibrate to room temperature, and two WITs of the same wine and oxygen dose were mixed. Regarding samples stored in anoxic conditions, two treatments are differentiated: the first was evaluated directly and it is considered the main control (Cr) while the other was aerated (Ca). The aeration process involved manually shaking the wine for 30 seconds once served in the glass. Altogether, 30 samples were evaluated (5 wines under 6 treatments each) as the *rosé* wine had a replicate to be valued sensorially for each treatment.

Evaluation sessions were conducted exclusively by the panellists who demonstrated consistency and reproducibility in the previous sessions (n = 8). Sample evaluation was carried out over three sessions of 10 glasses each. All sessions took place on the same day, with a 30-minute break (or longer, if necessary) to avoid fatigue. All the attributes were evaluated using the same intensity structured scale than in the fifth training session and these were: "spirit-like alcohol", "citrus", "floral", "yellow fruit", "white fruit", "cooked vegetables", "black fruit", "red fruit", "tropical fruit", "honey", "reduction", "cider/overripe apple", "acidity", "bitterness", and "astringency", as well as the additional scale for preference.

7.4 Sensory data treatment

Panel performance

In order to corroborate panel performance a three-way ANOVA taking into account sample (S), judge (J) and replicate (R) as fixed factors, and including first order interactions was carried out. Panel performance was assessed using the Panelcheck software (version 1.4.2, Matforsk).

Samples characterisation

Initially, sample scores assigned by the panellists to each attribute were analysed in a two-way ANOVA (judges as random and sample as fixed factor) to determine panel's ability to discriminate between samples.

For those attributes found to be significant in the first ANOVA ($p < 0.05$), a three-way ANOVA (judges as random and wine and treatment as fixed factors) was conducted on the sample scores to establish the influence of oxidation.

In addition, a principal component analysis (PCA) was performed using the average scores of each significant attribute ($p < 0.05$) for treatment (T) or the interaction with wine (W × T) obtained from the previous three-way ANOVA. Preference scores were projected as a supplementary variable.

Afterwards, two-way ANOVAs (judges as random and treatment as fixed factor) were performed individually for each of the wines studied, to report those attributes with significant variations within a specific wine context.

Thereafter, ratios ("tropical fruit" + "yellow fruit")/("cooked vegetables" + "honey" + "cider/overripe apple") were calculated for each sample and panellists. A three-way ANOVA (judges as random factor, and wine and treatment as fixed factors) was then performed on these data to assess the overall effect of the ratio. Finally, the correlation between initial and maximum-relativised potentials, and ratios with preference was assessed by calculating the significance of Pearson's linear correlation.

For all the analysis, ANOVAs were combined with Fisher's LSD to identify significant differences between samples. Partial least squares (PLS) regression was performed to approach preference changes by means of those attributes with significant changes during oxidation. Jackknife Leave One Out cross-validation method was performed to address the predictive performance. All statistical analyses were conducted using XLSTAT (Addinsoft, version 2024.4.0).

RESULTS AND DISCUSSION

1. Oxygen consumption

Four different wines were subjected to a forced oxidation procedure involving four different doses of oxygen (see section 2.5) and a pre-defined time of storage of 28 days at 35 °C. To assign the desired oxygen level for each wine and treatment (Table 2), it was first necessary to determine the total sulfur dioxide concentration. Once the procedure was completed, five different samples were obtained from each wine, differing mainly in the amount of oxygen consumed and the corresponding expected depletion of sulfur dioxide, as reported previously (Carrascón *et al.*, 2017). The chosen procedure (Marrufo-Curtido *et al.*, 2018) is highly reproducible and avoids excessive sample manipulation, since oxygen is quantitatively introduced into the sealed systems at the beginning of the process, without requiring the reopening of the sealed systems, as in other procedures (Carrascón *et al.*, 2017; Coetzee *et al.*, 2016). In addition to the undoubted operational advantage that this represents, this procedure better emulates the accidental oxidation processes undergone by real wines during their bottle-ageing, although the dose of oxygen actually consumed by the wine depends on its own capacity to consume it. To ensure that the observed oxygen consumption and resulting sensory oxidative changes were not biased by microbial activity (*e.g.*, formation of volatile acidity or aldehydes), X Velcorin® was added to the wines at the beginning of the procedure, following the OIV (OIV, 2021) recommendations. This addition effectively prevented microbial growth, ensuring that the observed oxidation originated exclusively from chemical processes.

The oxygen consumption plots for each sample, which can be found in Figure S1, confirmed the high repeatability of the experimental procedure. Experimental data were fitted to pseudo-first order kinetic models. It should be noted, however, that these processes do not correspond to strict

TABLE 2. Total SO_2 levels and O_2 doses applied to each sample as well as total and relative oxygen consumptions and kinetics coefficients expressed as $1-e^{k}$ ($days^{-1}$). R^2 are the determination coefficients when analysing data as a pseudo-first order decay function.

Wine	SO_2 total (mg/L)	Dose (mg/L) *	Initial mg/L O_2 added	mg/L O_2 consumed	% consumed	$1-e^{k}$ **	R^2
Verdejo	80.0 ± 4.5	0	20.3 ± 0.3	19.3 ± 1.0	95.1 ± 4.6^{A}	0.1389 ± 0.0083^{A}	0.985
		6	25.7 ± 0.4	24.4 ± 1.2	94.9 ± 4.9^{A}	0.1093 ± 0.0052^{B}	0.990
		12	31.8 ± 0.5	29.7 ± 1.5	93.4 ± 5.7^{A}	0.0990 ± 0.0030^{C}	0.995
		35	54.8 ± 0.8	43.7 ± 2.2	79.7 ± 4.9^{B}	0.0550 ± 0.0017^{D}	0.982
Chardonnay	104.0 ± 2.3	0	26.4 ± 0.4	22.4 ± 1.1	84.8 ± 5.2^{A}	0.0623 ± 0.0037^{A}	0.977
		6	32.0 ± 0.5	25.5 ± 1.3	79.7 ± 4.9^{A}	0.0540 ± 0.0026^{B}	0.979
		12	38.1 ± 0.5	31.4 ± 1.6	82.4 ± 5.0^{A}	0.0508 ± 0.0015^{B}	0.988
		35	61.8 ± 0.9	38.5 ± 1.9	62.3 ± 3.8^{B}	0.0342 ± 0.0011^{C}	0.986
Cava	54.4 ± 4.5	0	13.4 ± 0.2	11.0 ± 0.6	82.1 ± 5.0^{A}	0.0319 ± 0.0019^{A}	0.994
		6	19.9 ± 0.3	13.3 ± 0.7	66.8 ± 4.1^{B}	0.0226 ± 0.0011^{B}	0.978
		12	25.2 ± 0.4	15.7 ± 0.8	62.3 ± 3.8^{B}	0.0187 ± 0.0006^{C}	0.973
		35	49.4 ± 0.7	16.8 ± 0.8	34.0 ± 2.1^{C}	0.0119 ± 0.0004^{D}	0.933
Rosé	91.2 ± 2.3	0	23.1 ± 0.7	17.6 ± 1.0	76.2 ± 7.0^{A}	0.0381 ± 0.0023^{A}	0.988
		6	29.5 ± 0.1	20.0 ± 0.1	67.8 ± 0.4^{AB}	0.0308 ± 0.0015^{B}	0.977
		12	34.7 ± 0.2	20.9 ± 1.9	60.2 ± 5.0^{B}	0.0268 ± 0.0008^{C}	0.975
		35	57.7 ± 1.0	22.7 ± 1.1	39.3 ± 2.5^{C}	0.0174 ± 0.0005^{D}	0.973

Different capitals indicate differences between oxygen doses within each wine (Fisher test $p < 0.05$).

* The dose expressed is the extra O_2 added over the stoichiometric amount needed to consume total SO_2.

** $1-e^{k}$ represents the fraction of dissolved O_2 consumed by the wine in one day (Marrufo-Curtido *et al.*, 2018).

first-order kinetics. The wine matrix evolves as oxygen is consumed, so a sample reaching a given dissolved oxygen concentration after receiving a higher initial dose does not have the same chemical composition (for example in terms of phenols, metals or sulfur compounds among others) as a sample that starts directly at that lower oxygen concentration. For this reason, the apparent consumption rates depend on the wine's oxygen-exposure history, and the fitted constants must be interpreted as pseudo-first-order parameters. These data, expressed as $1-e^{-k}$, which represent the daily percent of O_2 consumed, together with the doses of oxygen applied and the amounts of oxygen consumed in the period can be found in Table 2. As can be seen, the wines significantly differed in their ability to consume O_2. A two-way ANOVA revealed that Verdejo consumed a higher percentage of oxygen than Chardonnay, and both wines consumed percentages significantly higher than *rosé* and Cava, regardless of the applied dose. Specifically, only Verdejo consumed consistently more than 90 % of the oxygen supplied, except at the highest dose. Chardonnay was able to consume around 80 % in the three lower doses, while *rosé* and Cava consistently consumed less than 68 %, except in the lowest dose. These two wines consumed hardly one third of the O_2 provided at the highest dose.

It is most remarkable that, in contrast to what was reported in red wines (Marrufo-Curtido *et al.*, 2018), no evidence of multiple kinetic steps was observed here. Fits to pseudo-first order decay functions were very good, as can be observed in Table 2. The $1-e^{-k}$ coefficient reveals that Verdejo consumes O_2 two times faster than Chardonnay and four times faster than the Cava and the *rosé* wine. These differences are much higher than those observed among red wines, which hardly differed more than a factor of two (Aragón-Capone *et al.*, 2025; Marrufo-Curtido *et al.*, 2018). As expected, due to their lower phenolics content (Jackson, 2016), the oxygen consumption rates in these wines were, on average, one order of magnitude smaller than those reported for red wines (Aragón-Capone *et al.*, 2025; Marrufo-Curtido *et al.*, 2018). Although the oxidation method is different, both trends are also consistent with the findings of Pérez-Magariño *et al.* (2023) and with the combined results reported by Ferreira *et al.* (2015) and Carrascón *et al.* (2017).

Regarding redox potential, to ensure the reliability of the measurements, preliminary tests showed that opening the WITs outside the anoxic chamber while protected by an argon flow produced equivalent redox potential results compared to direct opening inside the chamber (p-value > 0.05, t-test, n = 5). The redox potential of the 20 different wine samples obtained in the study are shown in Figure 1. Verdejo had the smallest redox potentials, followed by Chardonnay, then by the *rosé*, and finally by the Cava. The figure suggests the existence of close relationships between the ability of each wine to consume oxygen and its initial redox potential. In fact, the percentages of oxygen consumed at the two lowest doses are negatively and significantly correlated to the initial redox potential of the wine (r = −0.975 and −0.971, $p < 0.05$) and at higher doses, correlations are also negative, although the level of significance is not reached. The overall correlation for the 16 pairs initial redox potential, and % of oxygen consumed, is also negative and significant (r = −0.688, $p < 0.01$). As expected, the figure also shows that within each wine, redox potential increases with the level of oxygen consumed, and such an increase is also significantly correlated (r = 0.543, $p < 0.05$) to the amount of oxygen consumed. Redox potential

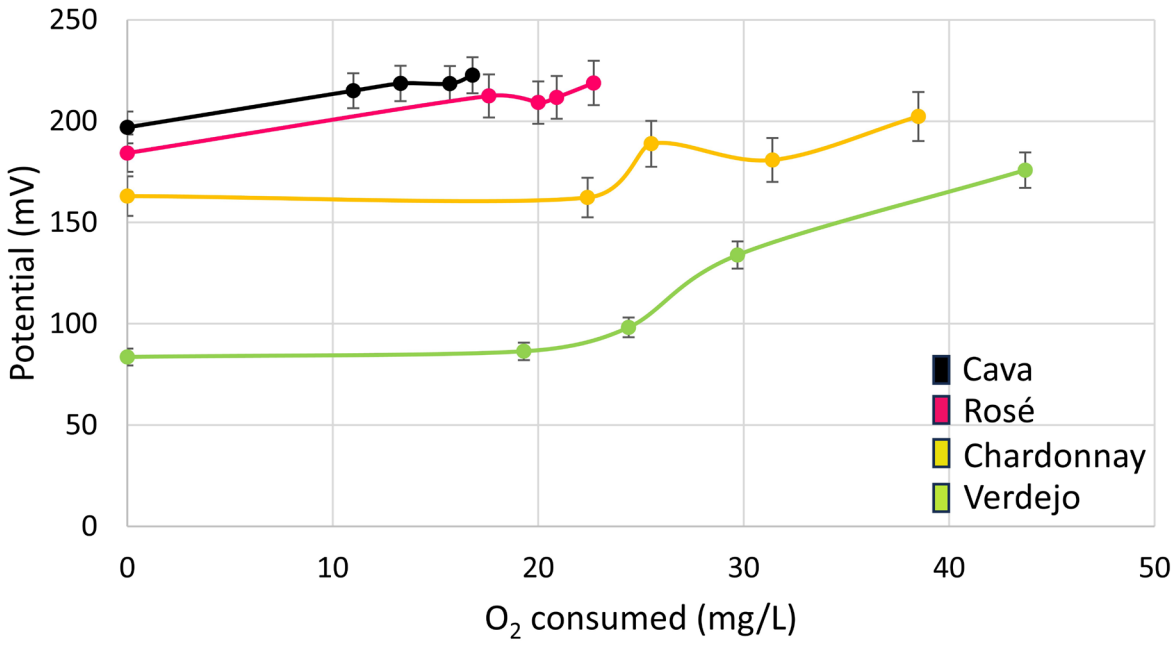


FIGURE 1. Redox potential levels once finished the oxidative treatment after the 28-day period.

The points from left to right for each wine correspond to the control samples and doses of O_2 of 0, 6, 12 and 35 mg/L over the stoichiometric amount needed to consume total SO_2, respectively. Error bars are expressed as ± standard deviation.

of Verdejo increased by nearly 100 mV, while that of Cava barely increased 25 mV. It is out of the scope of this paper to explain the chemical bases of these interesting observations which suggest that sulfur compounds, such as polyfunctional thiols, glutathione, cysteine and hydrogen sulfide, have a major role on wine oxygen consumption. These substances, which are antioxidants (Romanet *et al.*, 2019) and strong nucleophiles, react readily with quinones (Nikolantonaki & Waterhouse, 2012) and interact with metals (Kreitman *et al.*, 2016). Under low oxygen conditions, these sulfur-containing compounds contribute to the redox potential measured with a Pt electrode (Ferreira *et al.*, 2018; Kilmartin & Zou, 2001), while polyphenols do not (Danilewicz *et al.*, 2019).

2. Sensory analysis

The 20 samples from 4 different wines were sensorially characterised by a Descriptive Analysis using a trained panel. The performance of the panel was assessed by studying the judge × sample interactions, to assess the consistency in the use of the scales, the judge × replicate interactions, which measures repeatability, and the sample × replica interactions, which measures reproducibility. All these interactions, except the judge × sample for the "spirit-like alcohol" attribute, were non-significant (see Table S1), which demonstrates the consistency of the sensory evaluation carried out.

Eleven out of the 16 studied sensory attributes differed significantly between samples, as can be seen in Table 3, which summarises the results of the 2-way ANOVA, with sample as main factor and judges as random factor. As can be seen, only terms related to red and black fruits and to in-mouth properties, did not significantly vary between samples. The effects of the oxidation are shown in Table 4, which summarises the results of the three-way ANOVA, with wine and treatment (level of oxidation) as fixed factors. As can be seen, "cooked vegetables", "tropical fruit", "honey", "cider/overripe apple" and "preference" were significantly and consistently related to the level of oxygen (treatment), while the for terms "citrus", "floral", "yellow fruit" and "cooked vegetables" the interaction wine × treatment was significant, indicating that in these cases the effects of the treatment were wine-dependent.

These results are complemented with the PCA plot shown in Figure 2. The plot represents the first two components (eigenvalue > 1), which retain 68.5 % of the variance and shows through the first component a sharp opposition between the "tropical fruit" descriptor, and to a lower extent also "yellow fruit", and "honey" and "cider/overripe apple". The second component is essentially dominated by the "cooked vegetables" note, which emerges as a variable completely independent to the other sensory notes. The plot also shows that "preference" is positively correlated with "tropical fruit" and negatively correlated to "honey" and

TABLE 3. F and *p* values from 2-way ANOVA (judges as random and sample as fixed factor) regarding sample discrimination. In bold those attributes with significant variations ($p < 0.05$) among samples.

Attribute	F	*p*
Spirit-like alcohol	**1.759**	**0.016**
Citrus	**1.892**	**0.008**
Floral	**1.795**	**0.016**
Yellow fruit	**1.638**	**0.036**
White fruit	**1.648**	**0.025**
Cooked vegetables	**2.082**	**0.003**
Black fruit	1.106	0.333
Red fruit	0.708	0.865
Tropical fruit	**2.462**	**< 0.001**
Honey	**2.011**	**0.003**
Reduction	**1.619**	**0.030**
Cider/overripe apple	**1.707**	**0.025**
Acidity	0.842	0.697
Bitterness	0.915	0.594
Astringency	0.809	0.740
Preference	**2.018**	**0.003**

TABLE 4. F and *p* values from three-way ANOVA (judges as random and wine and treatment as fixed factors). In bold those attributes with significant variations ($p < 0.05$) because of the oxidative treatments.

Attribute	Wine		Treatment		W × T	
	F	*p*	F	*p*	F	*p*
Spirit-like alcohol	**10.113**	**< 0.0001**	0.774	0.570	0.756	0.724
Citrus	**4.960**	**0.003**	1.194	0.315	**2.377**	**0.004**
Floral	**4.993**	**0.003**	1.620	0.160	**1.855**	**0.034**
Yellow fruit	1.868	0.139	1.621	0.159	**1.744**	**0.047**
White fruit	**3.193**	**0.025**	1.436	0.212	1.284	0.214
Cooked vegetables	**5.229**	**0.002**	**2.769**	**0.021**	1.737	0.048
Tropical fruit	**14.304**	**< 0.0001**	**3.647**	**0.004**	1.458	0.125
Honey	**10.340**	**< 0.0001**	**2.751**	**0.021**	1.087	0.373
Reduction	**6.912**	**< 0.0001**	1.251	0.286	1.381	0.159
Cider/overripe apple	**3.988**	**0.001**	**3.467**	**0.006**	1.198	0.282
Preference	**5.675**	**0.001**	**3.388**	**0.006**	0.778	0.701

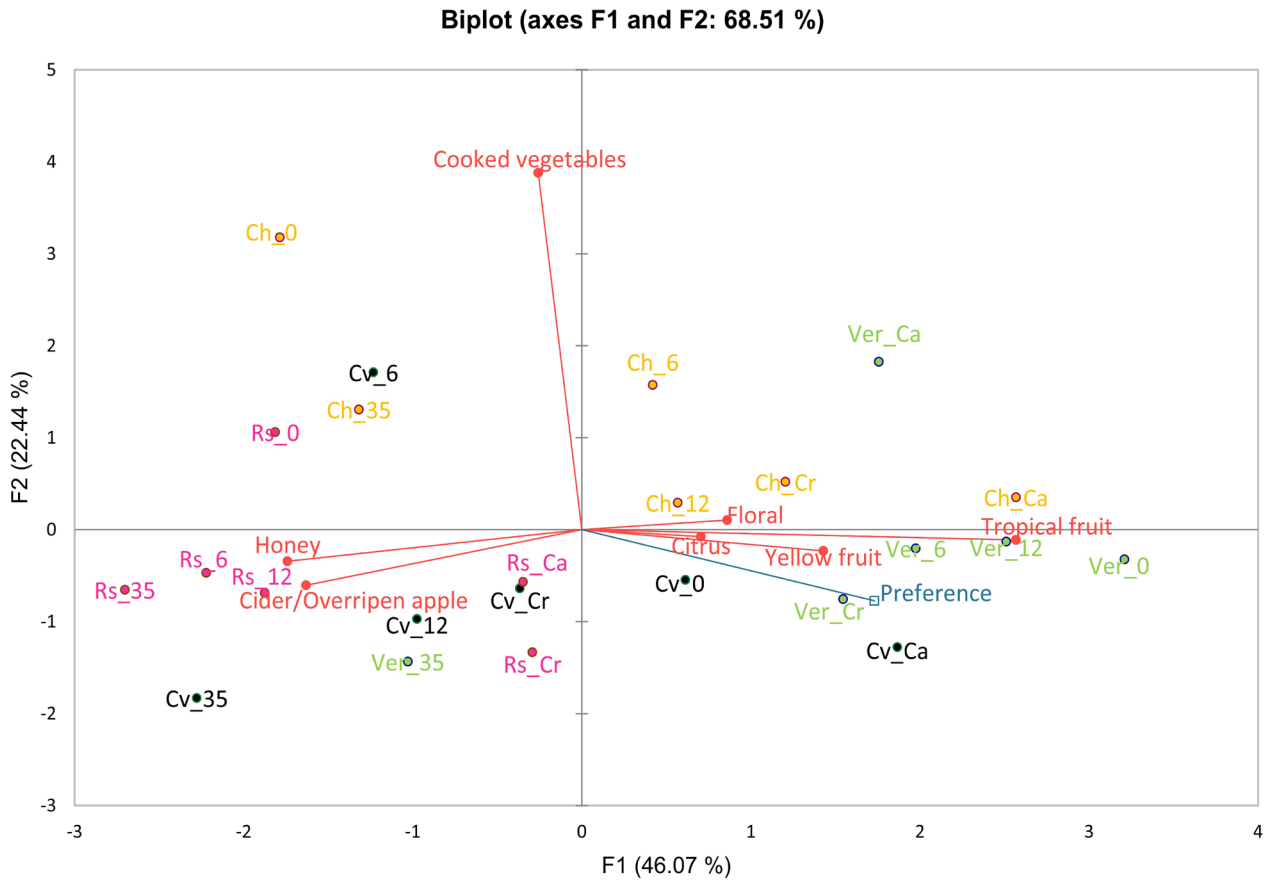


FIGURE 2. PCA from the scores of those significant attributes in the global sensory space and the preference set as supplementary variable.

Cr represents controls (stored in anoxic conditions at 4 °C) and Ca controls aerated (manually aerated in the glasses for 30 s).

"cider/overripe apple" and, secondarily, also to "cooked vegetables", which will be later discussed. The plot suggests that the sensory space is either "tropical fruit" (right), neutral (centre), or "honey-cider/overripe apple" (left), and that, within each category, different levels of "cooked vegetables" note can be observed, from null (samples in the lower half) to high (samples in the upper part).

The plot in Figure 2 also reveals that, while in general, samples are arranged from right to left attending to the level of oxygen supplied, the specific relationships between oxygen exposure and the sensory attributes are complex and sample-dependent. In all cases, one of the samples of the series, never the most oxygenated, contained relatively high levels of "cooked vegetables" (see average scores in Table S2). For Verdejo, only the aerated control (Ver_Ca), and the sample with highest levels of oxygen (Ver_35) are markedly different to the other Verdejo subsamples, which retained high levels of "tropical fruit". The aerated control (Ver_Ca) had relatively high levels of "cooked vegetables" and Ver_35 of "honey" and "cider/overripe apple". For Chardonnay, the aerated control (Ch_Ca) showed maximal "tropical fruit", the anoxic control (Ch_Cr) and samples with intermediate doses of oxygen, showed moderate "tropical fruit", and the oxidised samples with the lowest (Ch_0) and highest (Ch_35) levels of oxygen showed moderate levels of "honey" and "cider/overripe apple", with moderate (Ch_6 and Ch_35) or highest (Ch_0) intensities of "cooked vegetables". In the case of Cava, leaving aside the anoxic control, samples are roughly arranged by level of oxygen from right (aerated control) to left (Cv_35), with the sample Cv_6 showing levels of "cooked vegetables" much higher than the others. Finally, samples from *rosé* are also arranged from right to left, with the two controls in the "neutral" area, and the oxygenated samples in the "honey"-"cider/overripe apple" area, with the subsample Rs_0 containing moderate levels of "cooked vegetables" (see also in Table S2).

These effects can be better interpreted with the results of the two-way ANOVA carried out with each one of the wines, as can be seen in Table 5, and in the radar plots given in Figure 3. Additionally, classical lineal plots can be also seen in the Supplementary data (Figures S2-S5). A first observation in Table 5 is that oxidation exerted more significant effects on most sensory descriptors, especially in Cava and *rosé* wines, than on those of Verdejo and Chardonnay, in spite of the fact that these latter two consumed more oxygen.

Table 5 shows that oxygen in Verdejo only significantly ($p < 0.05$) affected to the "tropical fruit" note, which comes decreased with the highest level of oxygen, as seen in Figure 3a. It is remarkable to outline that Figure 3 also reveals a trend ($p < 0.1$) for the "cooked vegetables" note, showing an apparent maximum in the aerated control (Ver_Ca), which differs from all other samples except Ver_12 (Figure S2). Likewise, a trend is observed ($p < 0.1$) (see Table 5) for the "reductive" note, which shows higher values in the anoxic control (Ver_Cr) compared with some of the higher O_2 doses (Ver_6 and Ver_35) (Figure S2). In addition, no significant increases were observed for the other two oxidative attributes (Table 5), "cider/overripe apple" and "honey", although both showed a slight increase at the highest oxygen dose (Ver_35) (Figure 3a and Table S2). In summary, the most notable effect of oxidation in Verdejo is the degradation of the "tropical fruit" note, rather than of

TABLE 5. F and *p* values from two-way ANOVA (judges as random and treatment as fixed factor) for each wine. In bold those significant ($p < 0.05$) values and in italic those related to a *p*-value < 0.1.

Attribute	Treatment							
	Verdejo		Chardonnay		Cava		*Rosé*	
	F	*p*	F	*p*	F	*p*	F	*p*
Spirit-like alcohol	0.342	0.882	0.607	0.695	1.004	0.436	1.497	0.226
Citrus	2.011	0.132	0.490	0.743	**4.181**	**0.013**	0.629	0.647
Floral	1.210	0.338	1.030	0.416	**3.802**	**0.019**	1.033	0.415
Yellow fruit	0.970	0.446	**2.860**	**0.047**	**2.886**	**0.046**	0.818	0.529
White fruit	0.832	0.568	1.547	0.184	1.320	0.270	1.259	0.299
Cooked vegetables	2.629	*0.065*	0.960	0.451	**3.900**	**0.017**	**2.872**	**0.048**
Tropical fruit	**2.531**	**0.042**	**3.485**	**0.001**	0.472	0.825	1.318	0.280
Honey	1.504	0.224	1.078	0.396	2.443	*0.062*	**2.598**	**0.049**
Reduction	2.010	*0.082*	0.800	0.593	0.607	0.746	0.245	0.970
Cider/overripe apple	1.695	0.191	1.145	0.364	2.334	*0.091*	**2.878**	**0.046**
Preference	0.420	0.883	**2.662**	**0.026**	1.391	0.240	2.494	0.034

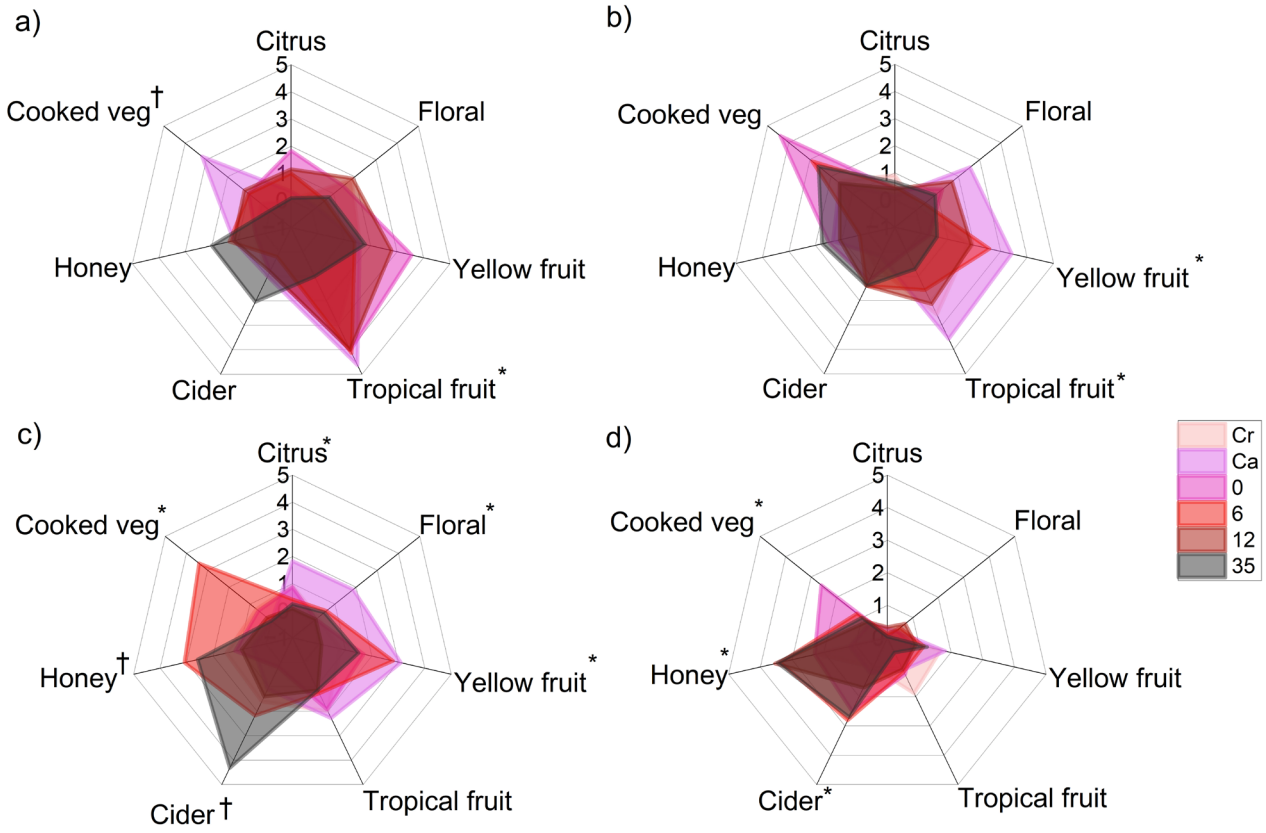


FIGURE 3. Radar graphs from the aromatic profile of (a) Verdejo, (b) Chardonnay, (c) Cava and (d) *rosé*.
Significance levels are marked as † if $p < 0.1$; * if $p < 0.05$; and y ** if $p < 0.01$.

other positive attributes such as "yellow fruit", "floral", and "citrus". In the case of Chardonnay, the most notable effects ($p < 0.05$) are also the decrease of the "tropical fruit" note, as well as the "yellow fruit" notes (Table 5, Figure 3b, and Figure S3). No significant increases of oxidation-related notes of "honey" and "cider/overripe apple" are observed. The situation differs in Cava, where one clear effect of oxidation is the significant decrease ($p < 0.05$) in the "citrus", "floral", and "yellow fruit" notes (Table 5). In parallel, a significant increase ($p < 0.05$) in "cooked vegetables" note is observed exclusively in the sample that received 6 mg/L O_2 over the stoichiometric amount needed to consume total SO_2 (Cv_6) (Figure 3c). Furthermore, the attributes "honey" and "cider/overripe apple" show increasing trends ($p < 0.1$) in the more oxidised samples (Table 5 and Figure S4). Finally, in the *rosé* wine, which already had low fruity ratings, and floral characteristics (Figure 3d), the most evident effects ($p < 0.05$) are found in the three oxidative notes. On one hand, the "cooked vegetables" notes are maximised in the sample with the lowest O_2 level (Rs_0). On the other hand, the "honey" and "cider/overripe apple" notes reach their maximum value in the samples with the highest oxygen doses (Figure S5). This unexpected character of the "cooked vegetables" notes is in agreement with other author's studies reported in different wines, since the "cooked vegetables" note makes its appearance during intermediate oxidation stages, and before the development of "honey" and "cider/overripe apple" notes (Coetzee *et al.*, 2016).

2.1 Preference and sensory notes

Preference was significantly correlated with nearly all sensory attributes except for "cooked vegetables". Moderate positive correlations were found with "citrus" ($r = 0.429$, $p < 0.05$), "floral" ($r = 0.488$, $p < 0.05$), and "white fruit" ($r = 0.453$, $p < 0.05$), while strong positive correlations were observed with "yellow fruit" ($r = 0.589$, $p < 0.01$), and "tropical fruit" ($r = 0.774$, $p < 0.0001$). In contrast, moderate negative correlations were obtained with "honey" ($r = -0.482$, $p < 0.05$), and strong negative correlations with "cider/overripe apple" ($r = -0.602$, $p < 0.01$) and "spirit-like alcohol" ($r = -0.662$, $p < 0.001$). For those attributes that showed significant differences among treatments (Table 4), this pattern of dependence can also be seen in Figure 2. The attributes "white fruit" and "spirit-like alcohol", although correlated with preference, were not included in the PCA because they did not vary significantly across treatments (see ANOVAs in Table 4). It may be surprising that the "cooked vegetables" note is not significantly correlated with preference, since its relationship with the development of oxidative notes in wine has long been established (Escudero *et al.*, 2000a; Escudero *et al.*, 2000b). However, this attribute shows a non-linear behaviour across treatments:

in most wines it reaches its highest intensity at intermediate oxygen doses and then decreases at the highest ones, which correspond to the least preferred samples. As a result, the overall linear correlation with preference is weak, however, "cooked vegetables" still contributes meaningfully to the best PLS model relating sensory attributes with preference in the wines of the study, which was:

Pref = 4.111 + 0.271 Citrus + 0.159 Floral + 0.168 Yellow fruit + 0.192 Tropical fruit − 0.121 Cooked vegetables − 0.117 Honey − 0.219 Cider/overripe apple

In such a model, "cooked vegetables" takes a negative coefficient. The model is highly significant, explaining by cross-validation 79.9 % of the original variance, and with a root mean squared error (RMSE) of only 0.416 (8.0 %). The model points out that in these wines, what is most valued is freshness, related to the floral and mainly fruity characteristics, while the appearance of any oxidative note is penalised.

In fact, preference is significantly correlated to the following ratio:

$$Pref \propto \frac{I_{yellow\ fruit} + I_{tropical\ fruit}}{1 + I_{cooked\ veg} + I_{honey} + I_{cider}}$$

Such a ratio relates fruity attributes to oxidative attributes, with a highly significant determination coefficient (r = 0.783, significant at $p < 0.0001$), confirming the relevance of the ratio between positive fruity characteristics with oxidation-related attributes.

Finally, it is important to note that redox potentials (see Figure 1) are negative and significantly related to preference (r = −0.769, $p < 0.0001$), to "tropical fruit" (r = −0.783, $p < 0.0001$), and to the ratio fruity notes/oxidised notes (r = −0.788, $p < 0.0001$). Such relationships arise because Verdejo samples, which apart from Ver_35 had small redox potentials, were most preferred, and showed high scores in "tropical fruit" as well as in the ratio fruity/oxidised notes. Additionally, also due to the fact that in all cases, samples with higher levels of oxygen (and therefore higher redox potentials; see Figure 1), were less preferred, with lower "tropical fruit" and fruity/oxidised ratios. These observations are in agreement with previous published works in several aspects: first, by reporting that perception is explained by the participation of multiple attributes, both positive and negative (Sáenz-Navajas *et al.*, 2011); and second, by revealing that sulfur-groups detectable in our redox potential analysis not only play a protector role against oxidative processes (Kreitman *et al.*, 2016; Nikolantonaki & Waterhouse, 2012; Romanet *et al.*, 2019), but also a crucial role in aromatic quality, given the impact of their related notes, such as passion fruit, grapefruit, and box tree (Carlin *et al.*, 2022; Ferreira *et al.*, 2022) on preference. On the other hand, a significant positive correlation was observed between the "spirit-like alcohol" note and the redox potential (r = 0.825, $p < 0.0001$), likely because this note is significantly and negatively correlated to both "tropical fruit" (r = −0.709, $p < 0.001$) and the fruity/oxidised ratio (r = −0.733, $p < 0.001$). Although the "spirit-like alcohol" attribute did not exhibit significant changes with oxidation in any of the four wines studied (Table 5), these strong correlations suggest it still plays a relevant role in wine oxidation, in line with a previous work indicating that this note can increase in certain wines under oxidative conditions (Aragón-Capone *et al.*, 2025).

CONCLUSIONS

This exploratory study, based on four different wines (two whites, one *rosé*, and one sparkling wine), highlights how markedly oxygen consumption behaviour and sensory evolution can differ across wines. Wines that showed higher oxygen consumption and lower redox potentials also exhibited less pronounced sensory changes, suggesting the presence of more effective antioxidant species (most likely polyfunctional thiols) capable of modulating the balance between fruity and oxidation-related attributes. Sensory changes did not progress uniformly but instead followed distinct stages: an initial decrease in fruity attributes, followed by the emergence of "cooked vegetables" as an intermediate attribute, whereas "honey" and "cider/overripe apple" became dominant at more advanced oxidation levels. Preference was closely associated with the relative contribution of fruity ("yellow fruit" and "tropical fruit") versus oxidative notes ("cooked vegetables", "honey" and "cider/overripe apple"), indicating that perception derives from the interplay of multiple positive and negative sensory dimensions rather than from individual attributes. Overall, these findings underline the importance of characterizing the oxidative behaviour of each wine, and they point toward the value of accelerated tests or predictive tools for anticipating sensory evolution and supporting decision-making during production and storage.

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