OENO One
vine & wine

DOI: https://doi.org/10.20870/oeno-one.2025.59.4.9523

OPEN ACCESS

ENOLOGY ORIGINAL RESEARCH ARTICLES

Effect of high hydrostatic pressure treatment and vine-shoot chips on the volatile fraction and sensorial profile of Chardonnay wines

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Article number: 9523

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Associate editor:
Stamatina Kallithraka

Received:
13 August 2025

Accepted:
16 October 2025

Published:
20 November 2025

ABSTRACT

This study evaluates the impact of toasted vine-shoot chips and high hydrostatic pressure (HHP), applied either separately or in combination, on the volatile composition and sensory properties of Chardonnay wines to investigate their individual and synergistic effects on wine quality. Five treatments were carried out: (i) untreated wine as a control (W), (ii) wine macerated for 35 days with vine-shoot chips (12 g L^{-1}) (WCM), (iii) wine treated with HHP at 600 MPa for 30 minutes (WP), (iv) wine treated with HHP in the presence of vine-shoot chips, which were removed immediately after pressurization (WPC), and (v) wine treated with HHP and subsequently macerated for 35 days with vine-shoot chips (WPCM). Results show that maceration with vine-shoot chips (WCM) had a limited effect on volatile composition but increased astringency and structure. HHP application significantly altered the aromatic profile, increasing oxidation-related compounds, leading to sensory attributes such as bitterness and acidity. In contrast, the combined treatment of WPC and WPCM promoted the development of aged, woody, and balsamic notes associated with higher levels of acetates, alcohols, aldehydes, and ketones, without the negative oxidative effects observed in HHP-only wines. These findings indicate a synergistic effect between vine-shoot chip maceration and HHP, offering a promising strategy for accelerating wine ageing while preserving sensory quality. Optimizing processing parameters is critical in tailoring outcomes for specific varietals and desired wine styles.

KEYWORDS: white wine, volatile compounds, sensorial analysis, wood

INTRODUCTION

Chardonnay is one of the oldest and most globally cultivated grape varieties, known for its remarkable adaptability to diverse terroirs across nearly all winegrowing regions. This versatility has resulted in a wide range of Chardonnay styles, each distinguished with unique aroma, flavour, sweetness, bitterness, and acidity profiles (Gambetta *et al.*, 2014). In an increasingly globalized wine market, oak barrel ageing has become a widely adopted technique to enhance wine complexity. Oak and other woods impart both volatile and non-volatile compounds that significantly influence the wine's organoleptic properties (Liberatore *et al.*, 2010). However, this method has several limitations, as it is time-consuming, expensive, and demands substantial storage space. Moreover, barrels have a limited lifespan due to continuous contact with wine which leads to wood degradation. Microbial contamination is another concern. Spoilage yeasts such as *Brettanomyces* and *Dekkera* may develop during barrel ageing, producing ethyl phenols that impart undesirable aromas reminiscent of horse sweat or medicinal notes (Oelofse *et al.*, 2008). Additionally, evaporation losses during ageing—commonly referred to as the "angel's share"—can lead to significant economic losses (Meusinger *et al.*, 2013). Given these constraints, current research efforts focus on developing alternative ageing strategies that preserve or improve wine quality, while reducing time, cost, and spoilage risks. (Ma *et al.*, 2022).

In this context, High Hydrostatic Pressure (HHP) is a promising and environmentally friendly technology that has been widely applied in the food industry in recent years (Aganovic *et al.*, 2021; Chiozzi *et al.*, 2022; Huang *et al.*, 2017), due to its low energy consumption and minimal contamination impact (Tsevdou *et al.*, 2019). HHP is a non-thermal processing technology which applies isostatic high pressure (100–600 MPa) transmitted through a liquid medium (typically water), to liquid or solid foods, usually at temperatures below 30 °C for durations ranging from a few seconds to over 20 minutes (Huang *et al.*, 2017). In oenology, high hydrostatic pressure (HHP) has been investigated for various applications, such as enhancing the extraction of phenolic compounds from grapes, inactivating undesirable microorganisms and improving wine preservation. HHP has also been employed to modify the physicochemical and sensory properties of wine (Buzrul, 2012; Morata *et al.*, 2017; Nunes *et al.*, 2017; Van Wyk & Silva, 2019). Notably, HHP can induce reactions such as the synthesis, decomposition, and oxidation of phenolic compounds, as well as Maillard reactions similar to those occurring during traditional wine ageing, but at a faster rate and lower cost (Ma *et al.*, 2022; Santos *et al.*, 2012; Santos *et al.*, 2013a; Santos *et al.*, 2013b; Santos *et al.*, 2015; Santos *et al.*, 2016; Solar *et al.*, 2021). These transformations are driven by the physical energy supplied during HHP treatment, which is converted into activation energy that accelerates the ageing process (Liu *et al.*, 2018). Moreover, HHP is considered an emerging technology for improving solid-liquid extraction processes (Ninčević Grassino *et al.*, 2020; Scepankova *et al.*, 2018).

The use of oak chips is a well-established practice in winemaking, commonly employed during the ageing process to impart distinctive sensory characteristics to wine (Gómez-Plaza & Bautista-Ortín, 2019; Petrozziello *et al.*, 2020). Numerous studies have shown that chips made from different wood species (Jordão & Cosme, 2022; Sánchez-Gómez *et al.*, 2016) and crushed and toasted vine-shoots obtained post-pruning can be used as a novel oenological practice (Cebrián-Tarancón *et al.*, 2018a; Cebrián-Tarancón *et al.*, 2019a; Cebrián-Tarancón *et al.*, 2019b; Cebrián-Tarancón *et al.*, 2022a; Cebrián-Tarancón *et al.*, 2022b; Fanzone *et al.*, 2021; Noviello *et al.*, 2024). Aligned with the current trend of recycling oenological waste and by-products (Troilo *et al.*, 2021), reusing vine-shoots obtained after pruning represents an innovative alternative with both environmental and economic benefits for wineries. In fact, vine-shoot chips have an interesting phenolic and volatile profile comparable to that of oak chips, particularly after the toasting process (Cebrián-Tarancón *et al.*, 2018a; Cebrián-Tarancón *et al.*, 2018b; Delgado de La Torre *et al.*, 2012; Delgado de La Torre *et al.*, 2015; Sánchez-Gómez *et al.*, 2016). The effect of vine-shoot chip treatments on the volatile and sensorial composition of wines, considered safe for humans (Cebrián-Tarancón *et al.*, 2021), depends on several factors such as wine type (white or red), chip format and dose (6, 12, 24 g L^{-1}), timing of the addition during the winemaking process (before, during, or after alcoholic fermentation) and duration of contact (Cebrián-Tarancón *et al.*, 2019a; Cebrián-Tarancón *et al.*, 2019b; Cebrián-Tarancón *et al.*, 2022a).

In this context, several studies have explored the use of HHP to improve the release of oak-derived compounds from oak chips. Tao *et al.* (2016) reported that HHP enhanced the extraction of phenolic compounds from oak chips into young Merlot and Sangiovese red wines, and Valdés *et al.* (2021) demonstrated that the addition of holm oak (*Quercus ilex* L.) chips (5 g L^{-1}) to cv. Cayetana white wines treated with HHP (400 MPa, 5 and 30 minutes) modified the sensorial characteristics. However, while this ageing effect was observed in Cayetana white wine, only minimal effects were detected in the Tempranillo variety, suggesting the effect may depend on wine type.

Wine aroma is one of the most critical factors influencing perceived quality and consumer acceptance (Bakker & Clarke, 2011; Martínez-Pinilla *et al.*, 2013). Volatile organic compounds (VOCs) play a fundamental role in defining the aroma and flavour profile of wines. In Chardonnay wines, the balance and concentration of these volatile compounds are key determinants of freshness and the overall aromatic character. However, the effects of HHP and vine-shoot chip treatments on the aromatic profile of Chardonnay wines remains scarcely researched, and, to the best of our knowledge, have never been studied in combination. The aim of this work was thus to investigate the effect of HHP and vine-shoot applications, both individually and in combination, on the volatile composition and aromatic characteristics of cv. Chardonnay A.O.C. Ribera del Guadiana (semiarid region of southwest Spain).

MATERIALS AND METHODS

1. Vine-shoot chips preparation

Vine shoots cv. Chardonnay were pruned randomly from a vineyard located in A.O.C. Ribera del Guadiana (Extremadura, southwest Spain) in January 2022, four months after grape harvest. A total of 5 kg of vine shoots was collected and dried in a forced-air oven (Memmert, Schwabach, Germany) at 40 °C for 24 hours. The shoots were then stored in the dark at ambient room temperature (18 ± 3 °C) for four months, following the method of Cebrián-Tarancón *et al.* (2017) with some modifications. After this period, the shoots were cut into 3–4 cm pieces, ground using a hammer miller (Ventura Forestry Machines, Aiguaviva, Girona, Spain) to a particle size of 2–20 mm, similar to that of commonly used oak chips, and toasted at 180 °C for 45 minutes in a muffle furnace (Hobersal Furnaces & Ovens Technology, Caldes de Montbui, Barcelona, Spain) according to the procedure described by Cebrián-Tarancón *et al.* (2018b).

2. Samples

Monovarietal white cv. Chardonnay wine (W) from the 2021 vintage was supplied by Romale winery (Almendralejo, Badajoz, Spain) located in A.O.C. Ribera del Guadiana. The study was conducted at the experimental plant, and the samples analysed in the laboratories, both part of CICYTEX-INTAEX (Agri-Food Technology Institute, Extremadura Centre for Scientific and Technological Research). The oenological characteristics of cv. Chardonnay were: 13.2 alcohol degree (% *v/v*), 21.9 g L^{-1} dry extract, pH 3.6, total acidity 5.0 g L^{-1} (tartaric acid,) volatile acidity 0.4 g L^{-1} (acetic acid), and 28.7 and 158 mg L^{-1} of free and total SO_2 respectively. These values are consistent for the monovarietal wines produced in this region.

3. Experimental design

The Chardonnay wine was distributed in 40 L portions into plastic bags (Mod. COEX3soldas 350 × 550 cm; Plasacar S.L., Sevilla, Spain). The bags were vacuum-packed and placed in a semi-industrial hydrostatic pressure unit with 55 L of capacity (Hiperbaric Wave 6000/55; Burgos, Spain) then subjected to a 600 MPa HHP treatment for 30 minutes. The initial water temperature inside the vessel was 10 °C.
The following treatments were carried out (Figure 1):

- W: wine untreated and considered as control;
- WCM: wine (W) with 35 days of contact (M) with 12 g L^{-1} vine-shoot chips (C) in tanks;
- WP: wine (W) treated with HHP (P);
- WPC: wine (W) with 12 g L^{-1} of vine-shoot chips (C) treated with HHP (P), and removal of chips after the HHP treatment;
- WPCM: wine (W) with 12 g L^{-1} of vine-shoot chips (C), treated with HHP (P) and 35 days of contact with vine-shoot chips in tank (M).

Following the treatments, all wine samples were bottled in 350 mL dark glass bottles and stored in darkness at 20 °C for 35 days then analysed. All the experiments were carried out in triplicate. Table S1 shows the chemical composition of samples following this period.

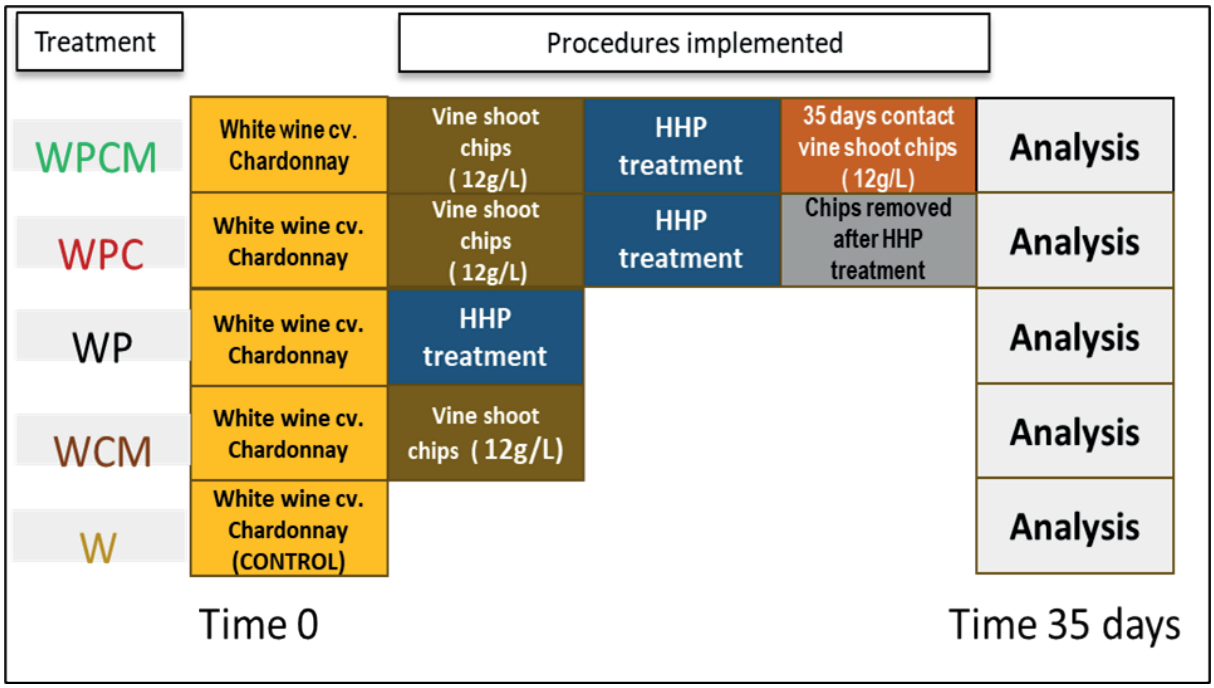

FIGURE 1. Experimental design of white Chardonnay wines treated with toasted vine-shoot chips and high hydrostatic pressure (HHP). Abbreviations: W, white wine not treated; WCM, wine (W) with 35 days of contact (M) with 12 g L^{-1} vine-shoot chips (C) in tanks; WP, wine (W) treated with HHP (P); WPC, wine (W) with 12 g L^{-1} of vine-shoot chips (C) treated with HHP (P), and removal of chips after the HHP treatment; WPCM, wine (W) with 12 g L^{-1} of vine-shoot chips (C), treated with HHP (P) and 35 days of contact with vine-shoot chips in tanks (M).

4. Volatile compounds: extraction, identification, and quantification

4.1. Extraction of volatile compounds

HS-SPME-GC-ToFMS was used to analyse the volatile profile of the different experimental wines. Volatile compounds were extracted via SPME using a 50/30 µm, 1 cm divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) fibre supplied by Supelco (Bellefonte, PA, USA). 5 mL samples of wine and 0.6 g of sodium chloride were placed into 20 mL glass vials fitted with silicon septums (Honeywell Fluka, Germany). The vials were equilibrated at 40 °C for 5 minutes, after which the SPME fibre was exposed to the vial headspace for volatile extraction for 30 minutes at the same temperature. Following extraction, the fibre was inserted into the GC-ToFMS injection port and desorbed at 260 °C for 3 minutes in split mode, with a split ratio of 50:1. Sample preparation was performed using a CTC Analysis autosampler PAL-System (SepSolve Analytical, Zwingen, Switzerland). Fibre blanks were run periodically to ensure the absence of contaminants or carryover. All wines were analysed in triplicate.

4.2. Identification and quantification of volatile compounds

GC-ToFMS analysis was carried out using an Agilent 8890 GC System (Agilent Technologies, UK) coupled to a Bench TOF-Select detector (Markes International, China). Data acquisition and analysis were performed using TOF-DS 4.1 software (Markes International). Chromatographic separation was performed on a Zebron ZB-WAX capillary column (60 m × 0.25 mm I.D. and 0.25 µm df; Phenomenex, Torrance, CA, USA). The oven temperature program started at 40 °C for 5 minutes, increased by 4 °C per minute to 240 °C, and then held for 5 minutes. Helium was used as the carrier gas. The MS transfer line and source temperatures were set at 250 °C. To determine the retention times and characteristic mass fragments of the analytes, mass spectra were recorded at 70 eV electron ionization (EI) on full scan mode over a range of 30 to 400 Da. Linear retention index values were calculated using a commercial hydrocarbon mixture (C_7–C_{30}) (Sigma-Aldrich, Shanghai, China), analysed under identical chromatographic conditions. The volatile compounds were tentatively identified by matching their mass spectra with reference spectra from the NIST mass spectral library (NIST MS Search Program version 2020), taking into account molecular structure and weight, and by comparing linear retention indices (LRI) with those reported in the literature (Bianchi *et al.*, 2007; Oliveira *et al.*, 2008; Mateus *et al.*, 2010; Di Mattia *et al.*, 2015; Santos *et al.*, 2020; Pereira *et al.*, 2021). The relative abundance of each compound was calculated as a percentage of its respective peak area relative to the total chromatographic peak area (% A).

For samples subjected to HHP treatments and samples stored in thanks, three independent replicates were collected for each treatment. All analyses were performed in triplicate.

5. Sensorial analysis

Sensory evaluation of the Chardonnay wines was conducted by the Vincalab-certified sensory panel of the A.O.C. Ribera del Guadiana, accredited under the UNE-EN ISO/IEC 17025 standard. The panel consisted of eight professional tasters, each with over five years of experience and subject to regular training to ensure consistent performance and calibration. The analysis was carried out in a dedicated sensory evaluation room equipped with individual booths, under controlled environmental conditions (20–22 °C) to minimize external interferences.

All procedures adhered to the ISO 3591:1977 standard for wine tasting, ensuring methodological rigor. Olfactory and gustatory descriptors were not generated *ad hoc* during the sessions but were selected from a validated, standardised list used in professional white wine sensory analysis. The descriptors included fruity notes such as citrus (lemon, orange, lime), yellow fruits (peach, apricot), white fruits (apple, pear), and exotic fruits (pineapple, mango). The panel also evaluated the presence or absence of secondary and tertiary aromas and flavours, including woody, smoky, tobacco, yeast, balsamic (eucalyptus, menthol), grassy (fresh-cut grass), and oxidative notes (bruised apple, sherry). In addition, the panellists rated overall aromatic intensity (low, medium, high) and persistence (duration of aroma perception post-tasting). To ensure reproducibility and minimise variability, each wine sample was assessed in duplicate by each panellist, and the results were averaged for final analysis.

6. Statistical analysis

The data were analysed using one-way ANOVA to assess the significance of treatments and two-way ANOVA to evaluate the effects of HHP (P), chips (C), and maceration (M), and as well as the combinations (P × C and P × M). Significance levels were set at $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$ and Tukey's test was applied as a *post hoc* test for parametric samples. Partial least squares regression (PLSR) was applied to show the relationship between chemical variables (X data) and sensory descriptors (Y data) of the wines. This is a data reduction technique that transforms the X variables into a set of uncorrelated factors that describe the variation in the dataset. Calculations were performed using XLStat-Pro (Addinsoft, Paris, 2009). Finally, clustering analysis coupled with a polar heatmap was used to analyse the volatile composition (considering compounds with area ≥ 0.1 %). OriginPro 2020 (OriginLab Corporation, Northampton, MA, USA) was used for this statistical analysis.

RESULTS

1. Volatile organic compounds (VOCs) identified in cv. Chardonnay: effect of treatments

As shown in Table 1, the analysed samples contained comparable quantities of volatile organic compounds (VOCs): 141 in W, WCM, and WPCM, 134 in WP, and 143 in WPC.

For all samples, the relative abundance of each compound was calculated as the percentage ratio (PRA) of its peak area in relation to the total peak area of the chromatogram. The identified compounds accounted for 100 % of the total chromatographic peak area.

In wines not subjected to High Hydrostatic Pressure (HHP), specifically W and WCM, the most abundant volatile compounds were primarily esters and acetates. Among these, octanoic acid, ethyl ester (E19) exhibited the highest Perceived Relative Aroma (PRA) values: 29.75 in W and 43.88 in WCM. Other relevant esters included hexanoic acid, ethyl ester (E11) and decanoic acid, ethyl ester (E26), while the major acetates were ethyl acetate (AC2), 1-butanol-3-methyl acetate (AC6), and acetic acid, hexyl ester (AC10). Dodecanoic acid, ethyl ester (E38) showed a significantly lower PRA value in WCM compared to W ($p < 0.05$). Several compounds were exclusively detected in W, including acetic acid, octyl ester (AC13), dodecanoic acid, methyl ester (E36), 3-methylbutyl dodecanoate, and hexanoic acid, 2-phenylethyl ester (E44 and E45).

In contrast, wines treated with HHP (WP, WPC, and WPCM) were dominated by alcohols and acetates, particularly 1-butanol, 3-methyl (AL4) and 1-butanol-3-methyl acetate/isoamyl acetate (AC6), which showed the highest PRA values, with values approaching 20. Ethyl acetate (AC2) also showed elevated levels, exceeding 5 %, and was significantly more abundant in treated wines than in untreated ones ($p < 0.05$). Conversely, esters such as octanoic acid, ethyl ester (E19), decanoic acid, ethyl ester (E26), and dodecanoic acid, ethyl ester (E38) were significantly less abundant in HHP-treated wines compared to W ($p < 0.05$), with E38 showing PRA values consistently below 1 across all treated samples.

Certain compounds were generated exclusively in treated samples, while others were only detected in the untreated samples. Specifically, 1-octen-3-ol (AL11), aldehydes (AD2, AD4, AD5, AD10, AD11, and AD14), ketones (K3, K6, K9, and K11), and *trans*-caryophyllene (T3) were present in WPMC but were not detected in the control sample W.

Figure 2 shows a polar heatmap with a circular dendrogram generated from hierarchical cluster analysis. This clustering approach groups wines and volatile compounds based on similarities in their profiles. The samples were clustered into two distinct groups (red and blue) based on their volatile compositions while the volatile compounds were clustered into five distinct groups (red, blue, green, violet, and brown). Wines treated with HHP (WP, WPC, WPCM) exhibit a volatile profile different from that of W and WCM. The first cluster (red), associated with HHP-treated wines, contains 38 VOCs, primarily alcohols, esters, and acetates (12, 7 and 6 VOCs respectively). The second and third clusters contain predominantly terpenes, norisoprenoids, and fatty acids. The fourth cluster (violet) consists of 11 VOCs, mainly ethyl esters, which are most abundant in W and WC wines. The fifth cluster (brown) comprises 5 VOCs, predominantly ethyl esters and aldehydes, which are characteristic of WCM wines. The polar heatmap demonstrates that the different treatments significantly alter the volatile compound profile. The wines treated with HHP exhibit a distinct profile, with higher concentrations of certain compounds such as furfural. The clustering of compounds suggests well-defined patterns in VOC distribution according to the applied treatment.

2. Effect of treatments on family compounds

The VOCs detected in W, WP, WPC, WPCM, and WCM were grouped into the following chemical classes: acetates (14, 12, 13, 12, and 13 compounds, respectively), alcohols (21, 21, 21, 22, and 20), aldehydes (9, 11, 14, 15, and 14), aromatic hydrocarbons (2 compounds in all treatments), esters (51, 44, 46, 44, and 48), fatty acids (9, 9, 8, 9, and 8), furans (5, 3, 4, 3, and 5), ketones (9, 10, 11, 12, and 9), norisoprenoids (4 in all samples), and terpenes (4, 5, 5, 4, and 5, respectively).

Figure 3 presents the PRA values of VOCs and the effects of treatments on the chemical classes detected in the Chardonnay samples. In W and WCM, esters, alcohols, and acetates exhibited the highest PRA values, in that order, whereas norisoprenoids and aromatic hydrocarbons showed the lowest values (< 0.1 in all cases). In WP, WPC, and WPCM, the most abundant classes were alcohols > esters > acetates.

Compared to W, HHP treatment had a significant impact on the aromatic profile, resulting in WP, WPC, and WPCM showing: (i) a considerable and significant decrease in ester PRA values; (ii) an increase in alcohol and acetate PRA values; and (iii) an increasing trend in the remaining VOC families, except for norisoprenoids and aromatic hydrocarbons. In contrast, the WCM treatment (35 days of contact with vine-shoot chips in a tank) had a minimal effect on the aromatic profile, with PRA values in W and WCM samples remaining similar, although an increase in terpene PRA values was observed.

The two-way ANOVA indicated the effect of HHP (P), was stronger than vine-shoot chips (C) and maceration (M). In fact, P significatively modified the PRA values of seven chemical classes, whereas C and M affected only 2 and 3, respectively. Interactions P × C and P × M were only significant for aldehydes and terpenes. The effects also appear class-dependent: PRA of aldehydes was significatively influenced by P, C, and M, whereas norisoprenoid PRA values remained unaffected.

3. Discrimination of samples

Principal component analysis (PCA) was performed to investigate potential differentiation among treatments based on aromatic profile. The PCAs included only VOC classes showing significant results. Figure 4 shows that the first two principal components, F1 and F2, accounted for 90.71 % of the total variance (76.12 % and 14.59 %, respectively). F1 was positively associated with acetates, ketones, fatty acids, alcohols, and furans, and negatively associated with esters. F2 was characterized by positive loadings for norisoprenoids and negative loadings for aldehydes.

TABLE 1. Effect of treatments on aromatic composition of white Chardonnay wine. [1]RT (min): retention time in minutes; [2]LRI_{Calc}: the linear retention index values were calculated through analysis of the commercial hydrocarbon mixture (C_8–C_{20}); [3]LRI_{Lit}: the linear retention index values from the literature; values are expressed as the mean of three replicates ± standard deviation. Abbreviations: W, untreated wine; WCM, wine (W) with 35 days of contact (M) with 12 g L^{-1}vine-shoot chips (C) in tanks; WP, wine (W) treated with HHP (P); WPC, wine (W) with 12 g L^{-1} of vine-shoot chips (C) treated with HHP (P), and removal of chips after the HHP treatment; WPCM, wine (W) with 12 g L^{-1} of vine-shoot chips (C), treated with HHP (P) and 35 days of contact with vine-shoot chips in tanks (M). Values are expressed as the mean of three replicates ± standard deviation; n.d.: not detected; n.c.: not calculated; n.f.: not found. Values followed by different letters are statistically different at $p < 0.05$. (part 1/7)

Number compound	Compounds	[1]RT (min)	[2]LRI_{Calc}	[3]LRI_{Lit}	W	WCM	WP	WPC	WPCM
					Acetates				
AC1	Acetic acid, methyl ester	4.9	n.c.	822	0.012 b ± 0.005	0.013 b ± 0.001	0.026 a ± 0.002	0.027 a ± 0.001	0.029 a ± 0.001
AC2	Acetic acid, ethyl ester	5.90	n.c.	888	2.471 b ± 0.962	2.778 b ± 0.068	5.721 a ± 0.342	5.707 a ± 0.095	6.190 a ± 0.098
AC3	Acetic acid, propyl ester	8.17	n.c.	973	0.024 b ± 0.007	0.029 b ± 0.002	0.062 a ± 0.005	0.059 a ± 0.005	0.064 a ± 0.004
AC4	Acetic acid, 2-methylpropyl ester	9.40	n.c.	1012	0.077 b ± 0.029	0.093 b ± 0.003	0.190 a ± 0.012	0.182 a ± 0.007	0.199 a ± 0.020
AC5	Acetic acid, butyl ester	11.52	n.c.	1074	0.002 b ± 0.001	0.005 b ± 0.002	0.023 a ± 0.014	0.017 ab ± 0.008	0.012 ab ± 0.001
AC6	1-Butanol, 3-methyl- acetate	13.42	n.c.	1123	8.686 b ± 3.295	9.991 b ± 0.173	20.229 a ± 1.214	19.713 a ± 0.352	19.674 a ± 0.189
AC7	Acetic acid, pentyl ester	15.36	n.c.	1176	0.010 b ± 0.003	0.011 b ± 0.001	0.023 a ± 0.002	0.023 a ± 0.001	0.023 a ± 0.001
AC8	2-Buten-1-ol, 3-methyl- acetate	17.31	n.c.	1238	0.001 b ± 0.000	0.001 b ± 0.00	0.003 a ± 0.001	0.003 a ± 0.001	0.003 a ± 0.001
AC9	Acetic acid, hexyl ester	17.50	n.c.	1265	0.024 c ± 0.008	0.022 c ± 0.002	0.042 a ± 0.003	0.039 ab ± 0.002	0.035 b ± 0.001
AC10	Acetic acid, hexyl ester	19.07	1272	1274	2.092 bc ± 0.761	1.665 c ± 0.808	3.393 a ± 0.196	3.192 a ± 0.181	2.991 ab ± 0.070
AC11	3-Hexen-1-ol, acetate, (isomer)	20.70	1319	1322	0.067 b ± 0.027	0.059 b ± 0.029 b	0.149 a ± 0.008	0.142 a ± 0.006	0.135 a ± 0.008
AC12	Acetic acid, heptyl ester	22.66	1376	1384	0.018 a ± 0.008	0.015 a ± 0.005	n.d.	0.014 a ± 0.004	n.d.
AC13	Acetic acid, octyl ester	26.04	1478	1475	0.009 a ± 0.004	n.d.	n.d.	n.d.	n.d.
AC14	Acetic acid, phenylmethyl ester	33.85	1737	1722	0.003 b ± 0.001	0.005 b ± 0.001	0.008 a ± 0.002	0.008 a ± 0.001	0.008 a ± 0.001
AC15	Benzeneacetic acid, ethyl ester	35.41	1794	1783	0.004 c ± 0.002	0.007 b ± 0.001	0.010 a ± 0.001	0.009 a ± 0.001	0.010 a ± 0.001
AC16	Acetic acid, 2-phenylethyl ester	36.23	1824	1820	0.574 b ± 0.201	0.613 b ± 0.042	1.133 a ± 0.122	0.995 a ± 0.072	1.049 a ± 0.050
					Alcohols				
AL1	1-Propanol	10.22	n.c.	1043	0.125 ab ± 0.080	n.d.	0.269 a ± 0.025	0.262 a ± 0.120	0.207 a ± 0.125
AL2	1-Propanol, 2-methyl-	12.17	n.c.	1092	0.417 b ± 0.175	0.490 b ± 0.041	0.962 a ± 0.064	0.976 a ± 0.093	0.957 a ± 0.461
AL3	1-Butanol	14.16	n.c.	1142	0.016 c ± 0.009	0.019 c ± 0.001	0.039 ab ± 0.003	0.038 b ± 0.002	0.045 a ± 0.003
AL4	1-Butanol, 3-methyl-	16.56	n.c.	1209	8.510 c ± 3.644	11.060 c ± 0.630	21.334 b ± 0.959	21.213 b ± 1.637	25.246 a ± 1.248
AL5	1-Pentanol, 4-methyl-	20.49	1313	1315	0.010 b ± 0.005	0.014 b ± 0.001	0.029 a ± 0.002	0.023 a ± 0.007	0.030 a ± 0.003

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AL6	2-Hexanol, 3-methyl-	20.68	1318	1331	0.004 a	±	0.003	0.005 a	±	0.001	0.011 a	±	0.002	0.021 a	±	0.029	0.010 a	±	0.004
AL7	1-Pentanol, 3-methyl-	20.94	1326	1326	0.035 d	±	0.015	0.047 c	±	0.002	0.093 b	±	0.006	0.093 b	±	0.002	0.106 a	±	0.003
AL8	1-Hexanol	21.85	1352	1355	0.790 c	±	0.307	1.014 c	±	0.016	2.178 b	±	0.148	2.069 b	±	0.010	2.391 a	±	0.046
AL9	3-Hexen-1-ol, (isomer)	22.25	1364	1382	0.016 d	±	0.006	0.021 c	±	0.001	0.037 ab	±	0.002	0.037 b	±	0.001	0.041 a	±	0.001
AL10	3-Hexen-1-ol, (isomer)	22.97	1385	1386	0.036 b	±	0.017	0.049 b	±	0.002	0.087 a	±	0.042	0.106 a	±	0.002	0.119 a	±	0.005
AL11	1-Octen-3-ol	25.18	1451	1450	n.d.			0.010 c	±	0.006	0.023 b	±	0.002	0.024 b	±	0.009	0.037 a	±	0.002
AL12	1-Hexanol, 2-ethyl-	26.45	1490	1486	0.010 b	±	0.004	0.013 b	±	0.001	0.027 a	±	0.004	0.031 a	±	0.011	0.034 a	±	0.001
AL13	(s)-3-Ethyl-4-methylpentanol	27.07	1510	1506	0.017 b	±	0.006	0.023 b	±	0.005	0.063 a	±	0.005	0.051 a	±	0.010	0.059 a	±	0.009
AL14	2-Nonanol	27.36	1519	1521	0.006 c	±	0.002	0.010 bc	±	0.002	0.017 a	±	0.002	0.013 b	±	0.001	0.019 a	±	0.002
AL15	1-Octanol	28.57	1558	1557	0.063 c	±	0.022	0.087 bc	±	0.007	0.168 a	±	0.013	0.131 ab	±	0.060	0.174 a	±	0.003
AL16	Ethanol, 2-(2-ethoxyethoxy)	30.51	1622	1610	0.013 c	±	0.005	0.009 c	±	0.001	0.023 ab	±	0.003	0.019 b	±	0.003	0.027 a	±	0.003
AL17	1-Decanol	34.55	1763	1760	0.029 ab	±	0.011	0.023 abc	±	0.001	0.029 a	±	0.003	0.020 bc	±	0.006	0.017 c	±	0.001
AL18	Benzenemethanol	37.85	1885	1870	0.037 b	±	0.015	0.050 b	±	0.004	0.094 a	±	0.009	0.085 a	±	0.008	0.093 a	±	0.007
AL19	Phenylethyl alcohol	38.75	1919	1907	2.065 b	±	0.752	2.513 b	±	0.195	5.386 a	±	1.530	4.270 a	±	0.353	4.595 a	±	0.450
AL20	1,4-Butanediol	38.88	1924	1911	0.002 b	±	0.001	n.d.			n.d.			n.d.			0.006 a	±	0.004
AL21	1-Dodecanol	39.97	1967	1960	0.007 a	±	0.002	0.006 a	±	0.002	0.010 a	±	0.004	0.009 a	±	0.004	0.008 a	±	0.006
	Aldehydes																			
AD1	Acetaldehyde	3.77	n.c.	702	0.058 c	±	0.008	0.071 c	±	0.018	0.220 a	±	0.017	0.152 b	±	0.031	0.160 b	±	0.050
AD2	Propanal, 2-methyl-	4.67	n.c.	810	n.d.			0.002 b	±	0.000	n.d.			0.002 ab	±	0.001	0.002 a	±	0.000
AD3	Ethane, 1,1-diethoxy	5.95	n.c.	892	0.048 c	±	0.023	0.092 bc	±	0.012	0.120 b	±	0.041	0.126 b	±	0.028	0.222 a	±	0.019
AD4	Butanal, 2-methyl-	6.45	n.c.	877	n.d.			0.002 a	±	0.000	n.d.			0.004 a	±	0.001	0.024 a	±	0.043
AD5	Hexanal	11.86	n.c.	1083	n.d.			0.011 b	±	0.006	n.d.			0.011 b	±	0.002	0.023 a	±	0.006
AD6	Nonanal	23.37	1396	1391	0.005 a	±	0.001	0.299 a	±	0.298	0.042 a	±	0.015	0.207 a	±	0.199	0.056 a	±	0.009
AD7	Furfural	25.87	1472	1461	0.048 b	±	0.019	0.067 b	±	0.003	0.107 ab	±	0.007	0.090 b	±	0.068	0.147 a	±	0.007

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AD8	Decanal	26.84	1502	1498	0.005 b	±	0.001	0.054 a	±	0.023	0.016 b	±	0.003	0.028 b	±	0.007	0.027 b	±	0.004
AD9	Benzaldehyde	27.77	1532	1534	0.079 b	±	0.026	0.072 b	±	0.051	0.151 a	±	0.019	0.157 a	±	0.009	0.151 a	±	0.015
AD10	2-Furancarboxaldehyde, 5-methyl	29.30	1582	1567	n.d.			0.003 c	±	0.001	0.004 bc	±	0.000	0.008 ab	±	0.003	0.009 a	±	0.003
AD11	Benzaldehyde, 2-methyl-	30.84	1633	1632	n.d.			0.001 bc	±	0.001	0.003 a	±	0.001	0.001 b	±	0.000	0.002 b	±	0.000
AD12	Safranal	31.42	1653	1636	0.006 b	±	0.001	0.008 b	±	0.003	0.009 b	±	0.001	0.009 b	±	0.003	0.018 a	±	0.009
AD13	Benzeneacetaldehyde	31.45	1654	1640	0.002 b	±	0.000	0.003 b	±	0.001	0.018 a	±	0.004	0.010 ab	±	0.006	0.014 a	±	0.007
AD14	Dodecanal	33.20	1714	1709	n.d.			0.014 a	±	0.008	n.d.			0.002 b	±	0.000	0.017 a	±	0.001
AD15	2,4-Dimethylbenzaldehyde	34.16	1749	1733	0.002 b	±	0.001	n.d.			0.002 b	±	0.000	n.d.			0.004 a	±	0.001
	Aromatic hydrocarbons																		
AR1	Benzene, 1,4-dimethyl	14.05	n.c.	1139	0.012 a	±	0.004	0.010 a	±	0.001	0.011 a	±	0.001	0.012 a	±	0.001	0.009 a	±	0.001
AR2	Benzene, 1,2-dimethyl	15.74	n.c.	1187	0.002 b	±	0.000	0.002 b	±	0.001	0.006 a	±	0.001	0.005 a	±	0.001	0.006 a	±	0.001
	Fatty acids																		
FT1	3-Pentenoic acid, 4-methyl-	4.72	n.c.	n.f.	0.003 bc	±	0.001	0.002 c	±	0.000	0.006 ab	±	0.003	0.006 a	±	0.001	0.007 a	±	0.001
FT2	Acetic acid	26.08	1479	1463	0.028 b	±	0.024	0.030 b	±	0.011	0.054 ab	±	0.031	0.097 a	±	0.046	0.084 a	±	0.029
FT3	Propanoic acid, 2-methyl-	29.48	1587	1570	0.002 c	±	0.000	0.003 c	±	0.000	0.003 c	±	0.001	0.005 b	±	0.001	0.008 a	±	0.001
FT4	Pentanoic acid	31.29	1649	1634	0.002 a	±	0.002	0.038 a	±	0.083	0.011 a	±	0.004	0.013 a	±	0.002	0.015 a	±	0.002
FT5	Hexanoic acid	37.31	1864	1846	0.207 b	±	0.174	0.175 b	±	0.056	0.432 a	±	0.024	0.368 a	±	0.066	0.455 a	±	0.041
FT6	Octanoic acid	42.69	2077	2065	0.404 b	±	0.124	0.576 b	±	0.072	1.057 a	±	0.144	0.936 a	±	0.225	1.051 a	±	0.197
FT7	Nonanoic acid	45.19	2184	2170	0.007 b	±	0.007	0.012 b	±	0.012	0.019 b	±	0.015	0.221 a	±	0.162	0.005 b	±	0.001
FT8	Decanoic acid	47.58	2289	2290	0.253 a	±	0.126	0.097 b	±	0.046	0.252 a	±	0.113	0.207 ab	±	0.065	0.227 ab	±	0.040
FT9	Dodecanoic acid	52.07	2502	2496	0.057 a	±	0.009	n.d.			0.032 a	±	0.065	n.d.			0.034 a	±	0.002
	Furans																		
F1	Furan, 3-methyl-	5.59	n.c.	870	0.008 bc	±	0.003	0.005 d	±	0.001	0.011 ab	±	0.001	0.011 a	±	0.001	0.006 cd	±	0.001
F2	Ethylfuran	7.56	n.c.	951	0.001 c	±	0.000	0.002 b	±	0.000	n.d.			0.003 a	±	0.001	n.d.		

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F3	2-Methylbenzofuran	29.95	1603	1589	0.008 a	±	0.003	0.006 b	±	0.001	n.d.			n.d.			n.d.		
F4	2-Furancarboxylic acid, ethyl ester	30.75	1630	1618	0.026 c	±	0.011	0.033 c	±	0.001	0.061 ab	±	0.005	0.057 b	±	0.003	0.067 a	±	0.004
F5	2-Furanmethanol	31.81	1666	1665	0.014 ab	±	0.007	0.005 c	±	0.001	0.009 bc	±	0.005	0.013 ab	±	0.002	0.016 a	±	0.001
								Esters											
E1	Formic acid, ethyl ester	4.87	n.c.	820	0.003 c	±	0.002	0.004 c	±	0.001	0.006 b	±	0.001	0.010 a	±	0.001	0.011 a	±	0.001
E2	Propanoic acid, ethyl ester	7.66	n.c.	953	0.035 b	±	0.014	0.040 b	±	0.001	0.081 a	±	0.007	0.076 a	±	0.003	0.087 a	±	0.005
E3	Propanoic acid, 2-methyl- ethyl ester	7.90	n.c.	961	0.034 b	±	0.010	0.041 b	±	0.002	0.084 a	±	0.006	0.078 a	±	0.006	0.084 a	±	0.006
E4	Butanoic acid, ethyl ester	10.21	n.c.	1036	0.453 b	±	0.164	0.615 b	±	0.025	1.111 a	±	0.172	1.127 a	±	0.110	1.259 a	±	0.097
E5	Butanoic acid, 2-methyl- ethyl ester	10.76	n.c.	1052	0.001 a	±	0.000	0.003 a	±	0.002	0.003 a	±	0.000	0.003 a	±	0.001	0.003 a	±	0.000
E6	Butanoic acid, 3-methyl- ethyl ester	11.36	n.c.	1060	0.018 b	±	0.006	0.023 b	±	0.001	0.041 a	±	0.003	0.037 a	±	0.004	0.038 a	±	0.005
E7	Pentanoic acid, ethyl ester	13.89	n.c.	1134	0.013 b	±	0.005	0.018 b	±	0.001	0.030 a	±	0.004	0.031 a	±	0.002	0.035 a	±	0.002
E8	2-Butenoic acid, ethyl ester	14.98	n.c.	1160	0.012 c	±	0.004	0.022 bc	±	0.005	0.039 ab	±	0.021	0.043 a	±	0.012	0.034 abc	±	0.003
E9	Hexanoic acid, methyl ester	15.87	n.c.	1189	0.018 c	±	0.007	0.021 bc	±	0.002	0.035 ab	±	0.003	0.031 abc	±	0.015	0.035 a	±	0.005
E10	1-Butanol, 3-methyl-, propanoate	15.97	n.c.	1192	0.016 a	±	0.018	0.007 a	±	0.001	0.011 a	±	0.001	0.011 a	±	0.001	0.011 a	±	0.001
E11	Hexanoic acid, ethyl ester	17.63	n.c.	1242	6.141 b	±	5.883	10.092 a	±	0.349	13.113 a	±	0.824	12.382 a	±	0.495	12.442 a	±	0.136
E12	Butyric acid, isopentyl ester	18.81	1265	1264	0.014 a	±	0.005	0.015 a	±	0.001	0.012 a	±	0.001	0.013 a	±	0.002	0.013 a	±	0.001
E13	3-Hexanoic acid, ethyl ester (isomer)	20.15	1303	1292	0.021 b	±	0.008	0.027 b	±	0.004	0.049 a	±	0.003	0.034 ab	±	0.023	0.048 a	±	0.006
E14	Hexanoic acid, propyl ester	20.73	1320	1325	0.012 a	±	0.004	0.014 a	±	0.001	0.010 a	±	0.005	0.010 a	±	0.002	0.009 a	±	0.002
E15	Heptanoic acid, ethyl ester	21.26	1335	1331	0.056 a	±	0.019	0.063 a	±	0.002	0.034 b	±	0.002	0.036 b	±	0.003	0.040 b	±	0.004
E16	Propanoic acid, 2-hydroxy- ethyl ester	21.62	1346	1347	0.129 b	±	0.059	0.141 b	±	0.025	0.292 a	±	0.021	0.310 a	±	0.052	0.336 a	±	0.053
E17	2-Hexenoic acid, ethyl ester	21.68	1347	1353	0.067 b	±	0.026	0.088 b	±	0.011	0.128 a	±	0.012	0.137 a	±	0.006	0.146 a	±	0.009
E18	Octanoic acid, methyl ester	23.21	1392	1391	0.157 a	±	0.052	0.140 a	±	0.004	0.063 b	±	0.006	0.064 b	±	0.003	0.059 b	±	0.002

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E19	Octanoic acid, ethyl ester	24.73	1438	1435	29.752 ab	±	25.731	43.887 a	±	0.692	11.408 c	±	5.569	14.590 bc	±	0.917	12.739 bc	±	0.561
E20	Octanoic acid, 3-methylbutyl ester	25.51	1461	1451	0.128 a	±	0.036	0.101 b	±	0.002	0.026 c	±	0.002	0.033 c	±	0.001	0.023 c	±	0.003
E21	Octanoic acid, propyl ester	27.45	1522	1515	0.046 a	±	0.015	0.045 a	±	0.005	0.050 a	±	0.015	n.d.			0.020 b	±	0.004
E22	Nonanoic acid, ethyl ester	27.97	1539	1538	0.098 b	±	0.029	0.175 a	±	0.048	0.019 c	±	0.003	0.060 bc	±	0.029	0.022 c	±	0.004
E23	Pentanoic acid, 2-hydroxy-4-methyl- ethyl ester	28.24	1547	1547	0.006 b	±	0.002	0.008 b	±	0.001	0.018 ab	±	0.010	0.017 ab	±	0.008	0.028 a	±	0.015
E24	Octanoic acid, ethyl ester	28.47	1555	1552	0.027 a	±	0.007	0.015 ab	±	0.001	0.008 bc	±	0.001	0.015 ab	±	0.016	n.d.		
E25	Decanoic acid, methyl ester	29.80	1598	1580	0.091 a	±	0.026	0.038 b	±	0.001	0.022 c	±	0.003	0.024 c	±	0.001	n.d.		
E26	Decanoic acid, ethyl ester	31.08	1641	1631	29.375 a	±	7.972	9.511 b	±	0.424	5.724 bc	±	0.518	5.652 bc	±	0.857	2.114 c	±	0.173
E27	Octanoic acid, 3-methylbutyl ester	31.67	1662	1655	0.294 a	±	0.063	0.182 b	±	0.010	0.128 c	±	0.018	0.133 c	±	0.017	0.046 d	±	0.003
E28	Benzoic acid, ethyl ester	32.06	1675	1667	0.017 c	±	0.006	0.021 bc	±	0.001	0.030 a	±	0.006	0.026 ab	±	0.003	0.025 ab	±	0.002
E29	Butanedioic acid, diethyl ester	32.23	1680	1668	0.554 d	±	0.203	0.802 c	±	0.050	1.361 ab	±	0.141	1.241 b	±	0.109	1.486 a	±	0.074
E30	9-Decenoic acid, ethyl ester	32.62	1694	1684	0.380 a	±	0.111	0.236 b	±	0.014	0.066 c	±	0.005	0.069 c	±	0.010	0.033 c	±	0.004
E31	Decanoic acid, propyl ester	33.52	1726	1720	0.011 a	±	0.002	0.002 b	±	0.000	n.d.			0.003 b	±	0.002	n.d.		
E32	Undecanoic acid, ethyl ester	34.01	1743	1730	0.004 ab	±	0.003	0.013 a	±	0.002	0.001 b	±	0.000	0.009 ab	±	0.012	n.d.		
E33	n-Capric acid isobutyl ester	34.41	1758	1751	0.010 a	±	0.002	0.032 a	±	0.064	n.d.			0.002 a	±	0.001	n.d.		
E34	Pentanedioic acid, diethyl ester	35.14	1784	1774	0.010 c	±	0.003	0.017 b	±	0.001	0.028 a	±	0.004	0.025 a	±	0.004	0.027 a	±	0.002
E35	Benzoic acid, 2-hydroxy-, methyl ester	35.22	1787	1781	0.003 b	±	0.001	0.004 ab	±	0.001	0.004 ab	±	0.001	0.004 ab	±	0.001	0.004 a	±	0.000
E36	Dodecanoic acid, methyl ester	35.71	1804	1800	0.004 b	±	0.001	n.d.			n.d.			n.d.			0.006 a	±	0.000
E37	Ethyl 4-hydroxybutanoate	35.80	1808	1819	0.026 c	±	0.007	0.035 c	±	0.009	0.087 a	±	0.007	0.058 b	±	0.010	0.058 b	±	0.014
E38	Dodecanoic acid, ethyl ester	36.81	1846	1838	3.549 a	±	0.875	0.247 b	±	0.193	0.200 b	±	0.031	0.143 b	±	0.016	0.334 b	±	0.067
E39	Pentadecanoic acid, 3-methylbutyl ester	37.32	1865	1860	0.135 a	±	0.100	0.066 ab	±	0.009	0.045 bc	±	0.033	0.066 ab	±	0.033	n.d.		
E40	Ethyl 3-hydroxyoctanoate	38.09	1894	1884	0.002 bc	±	0.001	0.004 ab	±	0.001	n.d.			0.004 b	±	0.001	0.006 a	±	0.003
E41	Butanedioic acid, ethyl-(3-methyl-1-butyl) ester	38.39	1905	1895	0.019 a	±	0.007	0.032 a	±	0.008	0.035 a	±	0.006	0.030 a	±	0.004	0.029 a	±	0.013

TABLE 1. Effect of treatments on aromatic composition of white Chardonnay wine. [1]RT (min): retention time in minutes; [2]LRI_{Calc}: the linear retention index values were calculated through analysis of the commercial hydrocarbon mixture (C_8–C_{20}); [3]LRI_{Lit}: the linear retention index values from the literature; values are expressed as the mean of three replicates ± standard deviation. Abbreviations: W, untreated wine; WCM, wine (W) with 35 days of contact (M) with 12 g L^{-1}vine-shoot chips (C) in tanks; WP, wine (W) treated with HHP (P); WPC, wine (W) with 12 g L^{-1} of vine-shoot chips (C) treated with HHP (P), and removal of chips after the HHP treatment; WPCM, wine (W) with 12 g L^{-1} of vine-shoot chips (C), treated with HHP (P) and 35 days of contact with vine-shoot chips in tanks (M). Values are expressed as the mean of three replicates ± standard deviation; n.d.: not detected; n.c.: not calculated; n.f.: not found. Values followed by different letters are statistically different at $p < 0.05$. (part 6/7)

E42	Tetradecanoic acid, 1-methylethyl ester	41.73	2038	2027	0.019 ab	±	0.005	0.010 b	±	0.002	0.023 a	±	0.009	0.024 a	±	0.012	0.009 b	±	0.003
E43	Tetradecanoic acid, ethyl ester	42.03	2050	2050	0.102 a	±	0.038	0.044 b	±	0.028	0.012 b	±	0.007	0.017 b	±	0.010	0.018 b	±	0.002
E44	Dodecanoic acid, 3-methylbutyl ester	42.47	2068	2062	0.004 a	±	0.001	n.d.			n.d.			n.d.			n.d.		
E45	Hexanoic acid, 2-phenylethyl ester	45.04	2177	2164	0.003 a	±	0.000	n.d.			n.d.			n.d.			n.d.		
E46	Hexadecanoic acid, ethyl ester	46.81	2255	2251	0.183 a	±	0.119	0.070 b	±	0.039	0.053 b	±	0.026	0.019 b	±	0.011	0.060 b	±	0.020
E47	Linoleic acid ethyl ester	52.64	2531	2521	0.009 b	±	0.009	0.008 b	±	0.008	n.d.			n.d.			0.042 a	±	0.006
	Ketones																		
K1	3-Pentanone	8.23	n.c.	980	0.002 b	±	0.000	0.002 b	±	0.000	0.003 ab	±	0.001	0.005 a	±	0.001	0.005 a	±	0.002
K2	2,3-Butanedione	8.35	n.c.	913	0.002 b	±	0.000	0.002 b	±	0.000	0.004 a	±	0.001	0.004 a	±	0.000	0.004 a	±	0.002
K3	3-Heptanone	14.54	n.c.	1158	n.d.			n.d.			0.007 b	±	0.001	0.009 a	±	0.001	0.009 a	±	0.000
K4	2-Heptanone	15.66	n.c.	1182	0.003 e	±	0.000	0.005 d	±	0.001	0.009 c	±	0.001	0.012 b	±	0.001	0.014 a	±	0.001
K5	3-Octanone	18.37	n.c.	1253	0.002 a	±	0.000	0.002 a	±	0.000	0.009 a	±	0.010	0.005 a	±	0.001	0.005 a	±	0.001
K6	2-Octanone	19.51	1285	1281	n.d.			n.d.			n.d.			n.d.			0.004 a	±	0.000
K7	2-Butanone, 3-hydroxy-	19.58	1287	1285	0.013 ab	±	0.007	0.009 b	±	0.004	0.020 ab	±	0.015	0.033 a	±	0.017	0.033 a	±	0.011
K8	5-Hepten-2-one, 6-methyl-	21.42	1340	1339	0.039 c	±	0.016	0.066 b	±	0.022	0.114 a	±	0.007	0.113 a	±	0.004	0.119 a	±	0.003
K9	3-Nonanone	22.06	1358	1360	n.d.			n.d.			0.066 b	±	0.004	0.068 b	±	0.001	0.073 a	±	0.004
K10	2-Nonanone	23.18	1391	1390	0.018 b	±	0.014	0.021 b	±	0.004	0.026 ab	±	0.002	0.028 ab	±	0.003	0.032 a	±	0.003
K11	3-Octen-2-one	23.82	1410	1411	n.d.			0.002 b	±	0.000	n.d.			0.003 b	±	0.000	0.006 a	±	0.002
K12	3-Buten-2-one, 4-phenyl-	40.85	2002	2032	0.010 b	±	0.004	0.011 b	±	0.002	0.017 a	±	0.002	0.019 a	±	0.001	0.016 a	±	0.002
	13C-norisoprenoid																		
N1	Vitispirane	27.76	1532	1530	0.015 a	±	0.006	0.042 a	±	0.057	0.063 a	±	0.083	0.005 a	±	0.001	0.016 a	±	0.005
N2	Vitispirane	27.85	1535	1530	0.024 a	±	0.011	0.023 a	±	0.007	0.007 b	±	0.005	0.011 b	±	0.001	0.006 b	±	0.003
N3	Naphthalene, 1,2-dihydro-1,4,6-trimethyl-	34.30	1754	1750	0.072 a	±	0.022	0.034 b	±	0.005	0.057 a	±	0.004	0.055 a	±	0.007	0.033 b	±	0.009
N4	β-Damascenone	36.34	1828	1823	0.019 b	±	0.007	0.020 b	±	0.014	0.030 ab	±	0.005	0.031 ab	±	0.004	0.035 a	±	0.003

TABLE 1. Effect of treatments on aromatic composition of white Chardonnay wine. [1]RT (min): retention time in minutes; [2]LRI_{Calc}: the linear retention index values were calculated through analysis of the commercial hydrocarbon mixture (C_8–C_{20}); [3]LRI_{Lit}: the linear retention index values from the literature; values are expressed as the mean of three replicates ± standard deviation. Abbreviations: W, untreated wine; WCM, wine (W) with 35 days of contact (M) with 12 g L^{-1}vine-shoot chips (C) in tanks; WP, wine (W) treated with HHP (P); WPC, wine (W) with 12 g L^{-1} of vine-shoot chips (C) treated with HHP (P), and removal of chips after the HHP treatment; WPCM, wine (W) with 12 g L^{-1} of vine-shoot chips (C), treated with HHP (P) and 35 days of contact with vine-shoot chips in tanks (M). Values are expressed as the mean of three replicates ± standard deviation; n.d.: not detected; n.c.: not calculated; n.f.: not found. Values followed by different letters are statistically different at $p < 0.05$. (part 7/7)

Terpenes																			
T1	D-Limonene	16.17	n.c.	1199	0.008 bc	±	0.002	0.111 b	±	0.044	0.252 a	±	0.056	0.242 a	±	0.109	0.003 c	±	0.000
T2	Linalool	28.29	1549	1550	0.015 d	±	0.005	0.024 cd	±	0.010	0.046 ab	±	0.006	0.037 bc	±	0.017	0.055 a	±	0.004
T3	*trans*-Caryophyllene	29.90	1601	1584	n.d.			0.016 ab	±	0.013	0.035 a	±	0.024	0.036 a	±	0.018	n.d.		
T4	α-Terpineol	32.81	1700	1697	0.004 c	±	0.001	0.007 bc	±	0.001	0.010 ab	±	0.002	0.010 ab	±	0.002	0.011 a	±	0.002
T5	β-Citronellol	34.68	1768	1765	0.005 c	±	0.002	0.009 b	±	0.001	0.015 a	±	0.003	0.012 a	±	0.001	0.015 a	±	0.001
Other compounds																			
O1	Methanethiol	3.66	n.c.	688	0.002 ab	±	0.000	0.001 b	±	0.000	0.002 a	±	0.000	0.002 a	±	0.000	0.002 a	±	0.000
O2	Dimethyl sulfide	4.06	n.c.	741	0.004 b	±	0.002	0.003 c	±	0.000	0.007 a	±	0.001	0.007 a	±	0.000	0.006 a	±	0.000
O3	Styrene	18.55	1257	1272	0.057 a	±	0.022	0.046 a	±	0.003	0.027 b	±	0.004	0.025 b	±	0.008	0.024 b	±	0.004
O4	Pyrazine, methyl-	18.76	1263	1276	n.d.			0.008 a	±	0.003	n.d.			0.010 a	±	0.002	0.012 a	±	0.004
O5	Furfuryl ethyl ether	19.69	1290	1291	0.010 a	±	0.004	0.050 a	±	0.047	0.031 a	±	0.005	0.049 a	±	0.027	0.036 a	±	0.004
O6	Pyrazine, 2,6-dimethyl-	20.98	1327	1328	n.d.			n.d.			n.d.			0.007 a	±	0.001	0.008 a	±	0.002
O7	1-Propanol, 3-(methylthio)-	33.42	1722	1710	0.033 b	±	0.007	0.036 b	±	0.005	0.083 a	±	0.016	0.070 a	±	0.008	0.069 a	±	0.006
O8	Phenol	41.24	2018	2015	0.006 bc	±	0.002	0.004 c	±	0.003	0.011 ab	±	0.005	0.012 ab	±	0.005	0.016 a	±	0.001
O9	4-Vinylphenol	50.10	2406	2379	0.005 c	±	0.002	0.003 c	±	0.000	0.011 a	±	0.001	0.008 b	±	0.001	0.005 c	±	0.001

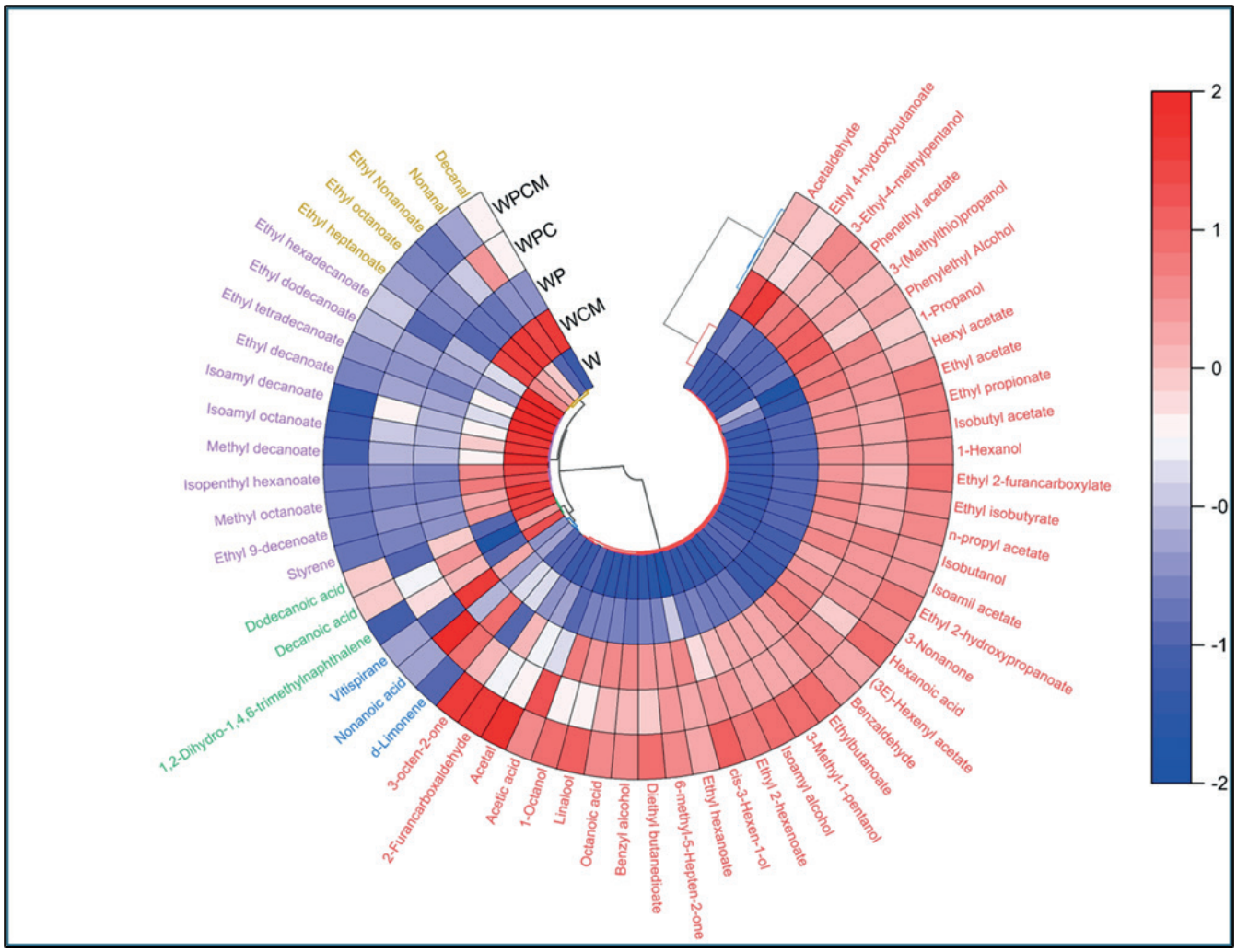


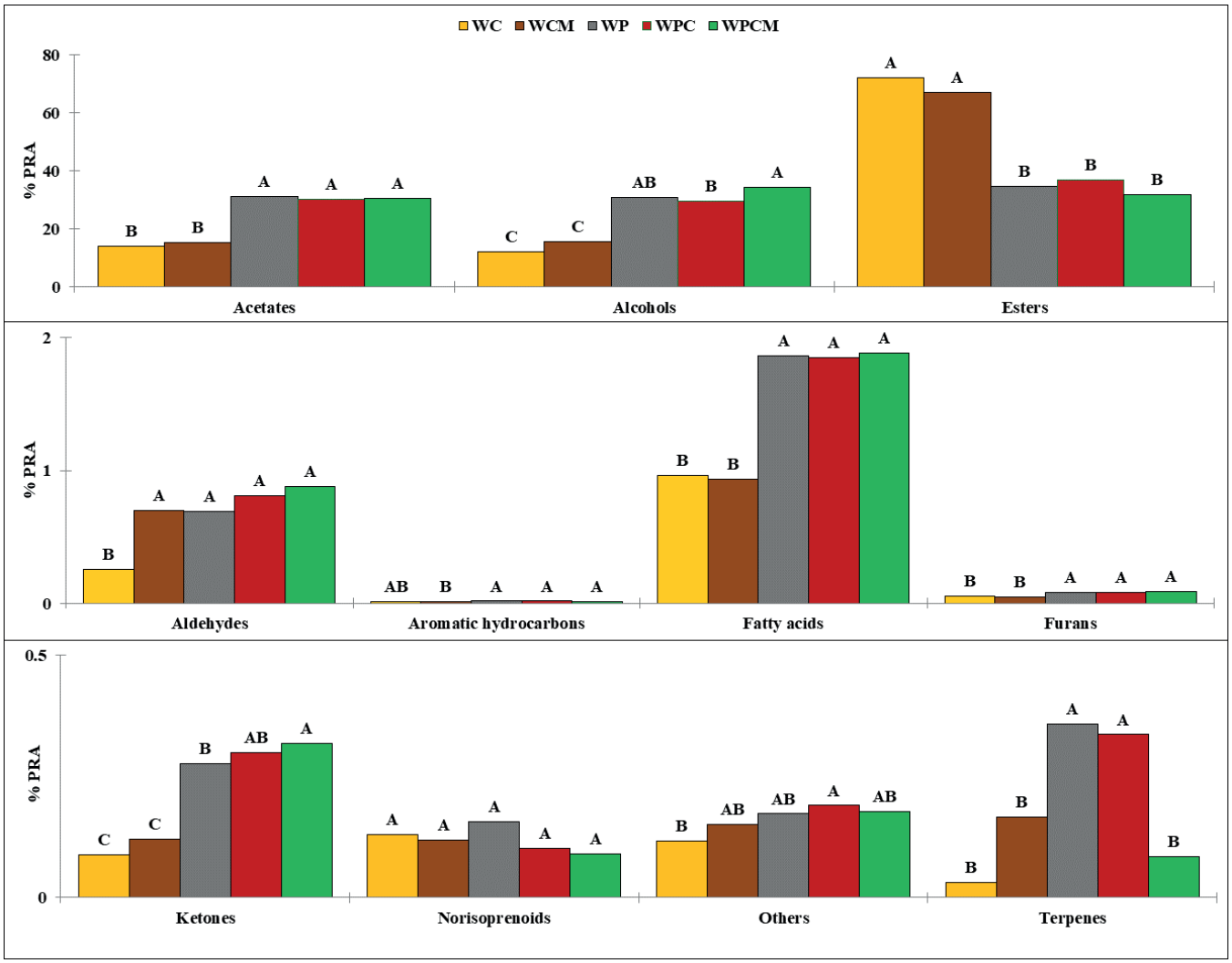
FIGURE 2. Polar heatmap with a circular dendrogram generated from a hierarchical cluster analysis of the volatile profiles of the cv. Chardonnay wine samples. Abbreviations: W, WCM, WP, WPC, and WPCM explained in Figure 1.

Figure 4 also shows clear discrimination based on HHP treatment. The PCA shows three clear groups: the first, on the negative side of F1, comprised the control wine (W) and the wines subjected to classical maceration treatment (WCM). The WP, WPC, and WPCM wines were positioned on the positive side of F1. In this group, two subgroups can be distinguished: i) WP, and ii) WPC and WPCM. Based on the PCA, the results affirm that HHP process, with or without vine-shoots, modified the aromatic profile. Specifically, W and WCM wines were mainly characterised by high PRA values of esters, whereas WPC and WPCM wines showed a predominance of acetates and ketones. This result was particularly interesting and highlights the potential of HHP to direct outcomes.

4. Sensorial analysis

The colour of all the cv. Chardonnay wines was assessed as pale golden with medium intensity. The values in Figure 5 represent the percentage of judges (% J) who perceived each descriptor in the respective wine sample, with higher values indicating a greater proportion of the panel detected a given characteristic. Yellow fruits, white fruits, and exotic fruits were frequently identified across all samples. The W sample exhibited the highest detection of white fruits, with 63 % of judges detecting this descriptor, whereas the other samples showed lower frequencies. The yeast descriptor was detected by a moderate percentage of judges (13–25 %), indicating a consistent but not dominant perception of fermentation aroma. Wood aroma was detected at varying levels, with WPCM (75 %) showing the highest % J, confirming a stronger influence of vine-shoot chips in these samples.

Balsamic aromas were less frequently perceived (≤ 25 % J), suggesting these characteristics are not dominant in these wines. Grass aroma was observed only in WCM (38 %) and WPCM (25 %), suggesting a more pronounced vegetal expression in these samples. Oxidation aromas were detected by a small percentage of judges, with slightly higher values in WP (25 % J) and WPCM (13 %), indicating a potential for greater wine evolution. With respect to the gustatory profile, acidity was identified by a low proportion of judges across all samples, with the highest detection in WP (25 % J). Bitterness was reported in WP (50 %), WCM (38 %), and WPCM (38 %), possibly linked to vine shoot influence in the latter two. Astringency was noted only in WCM (13 %), suggesting a mild perception of tannins.



Significance of effects						
		Factors			Interaction	
Compound	Treatment	P	C	M	P × C	P × M
Acetates	***	***	n.s.	n.s.	n.s.	n.s.
Alcohols	***	***	n.s.	***	n.s.	n.s.
Aldehydes	**	**	**	**	n.s.	n.s.
Aromatic hydrocarbons	*	**	n.s.	n.s.	n.s.	n.s.
Fatty acids	***	***	n.s.	n.s.	n.s.	n.s.
Furans	***	***	n.s.	n.s.	n.s.	n.s.
Esters	***	***	n.s.	*	n.s.	n.s.
Ketones	***	**	**	*	n.s.	n.s.
Norisoprenoids	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Terpenes	***	**	n.s.	*	*	n.s.
Others	*	**	n.s.	n.s.	n.s.	n.s.

FIGURE 3. Effect of treatment on % PRA of VOCs families. W, WCM, WP, WPC, and WPCM explained in Figure 1. ANOVA test significance level. In the same row, values followed by different letters are statistically different at $p < 0.05$. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s.: not significant.

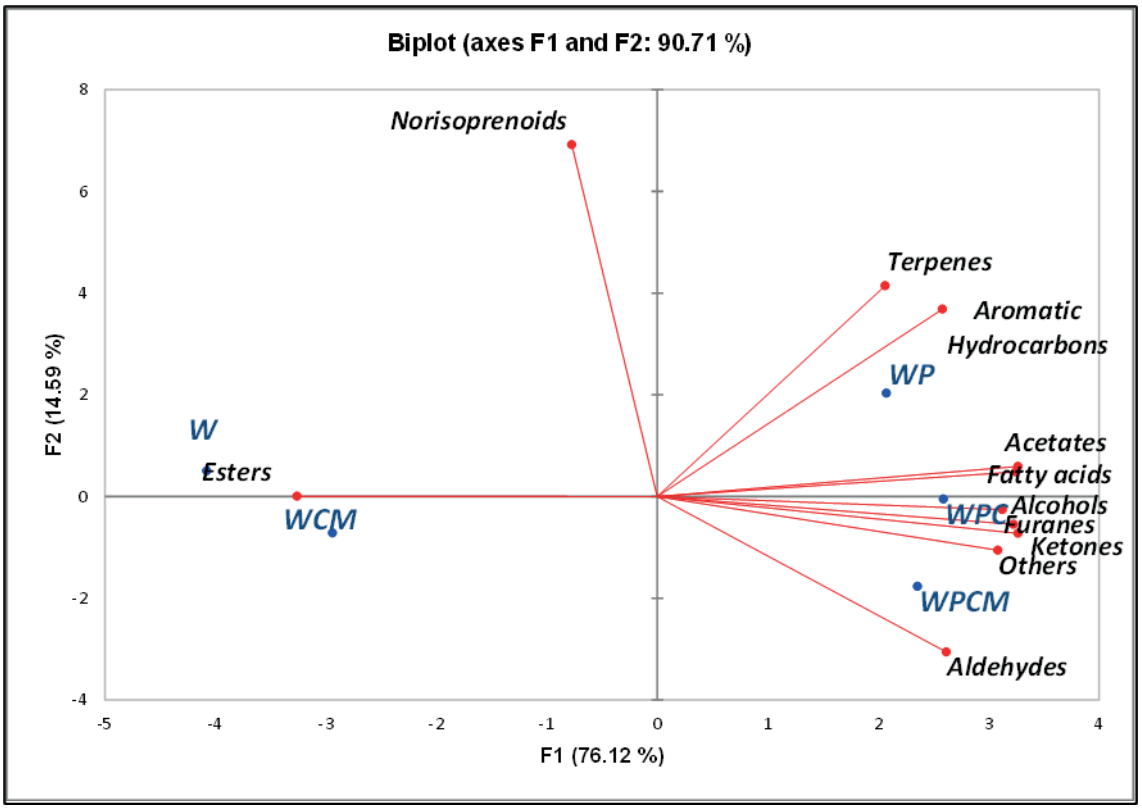


FIGURE 4. Principal component analysis of Chardonnay wines based on their aromatic profile. Abbreviations: W, WCM, WP, WPC, and WPCM explained in Figure 1.

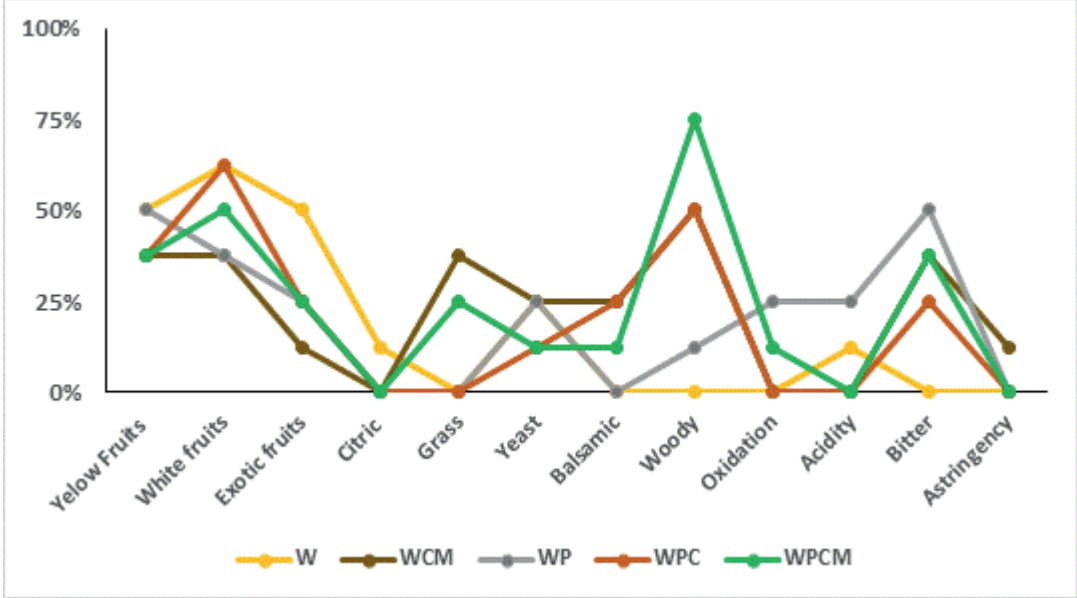


FIGURE 5. Sensorial profile of cv. Chardonnay wines. Abbreviations: W, WCM, WP, WPC, and WPCM explained in Figure 1.

Samples with higher wood influence (WPC and WPCM) showed the highest perception of wood notes, accompanied by a lower percentage of judges detecting fresh fruit aromas. Sample W was most frequently described as fruity, particularly with white and yellow fruit characteristics, while WP exhibited the highest perception of bitterness and oxidation, consistent with more advanced wine evolution. WCM and WPCM displayed a balanced profile of fruit, herbal, and wood descriptors, but also showed higher frequencies of bitterness and astringency, possibly due to tannin content. Finally, as shown in Table 2, W exhibited the highest olfactory intensity and persistence. In contrast, WP showed the lowest olfactory intensity, suggesting a less expressive aromatic profile, while WPC exhibited a moderate intensity, possibly influenced by a balance between fruitiness and wood-derived aromas.

TABLE 2. Olfactory intensity and persistence of cv. Chardonnay wines. Abbreviations: W, WCM, WP, WPC, and WPCM explained in Figure 1.

Descriptor	Samples				
	W	WCM	WP	WPC	WPCM
Olfactory intensity	Medium	Medium	Low	Low-medium	Medium
Olfactory persistence	Medium	Low-medium	Medium	Low-medium	Low

5. PLS modelling relationships between sensory descriptors and chemical composition of wines

Partial least squares regression (PLSR) was applied to examine correlations between sensory attributes and chemical compounds in Chardonnay wines subjected to different treatments. Prior to analysis, the data were standardized to ensure comparability across variables. Figure 6 presents the correlation plot based on the first two latent variables, t1 and t2, which are linear combinations of the original variables that capture the maximum covariance between the chemical (X) and sensory (Y) datasets. These components define a two-dimensional latent space in which the relationships among variables can be visualized.

The PLSR model demonstrated strong explanatory and predictive performance, with a cumulative R^2Y of 0.800 and Q^2 of 1.000. The results revealed robust associations between sensory attributes such as colour and taste, and volatile compounds. In the plot, variables are represented as coloured points: blue for chemical compounds (X variables), red for sensory attributes (Y variables), and green for active variables. The correlation circle facilitates interpretation of the direction and strength of each variable's contribution to the model. This visualization provides valuable insights into how different treatments influence both the chemical composition and sensory perception of Chardonnay wines.

According to Figure 6, esters showed a strong positive contribution to component 1 (t1), corresponding to the control wine (W), which is located in the right quadrant of the PLSR biplot. This wine was characterised by fresh and fruity sensory descriptors, including citrus, white fruits, exotic fruits, yellow fruits, olfactory persistence, and fermentation aromas. Ethyl esters, such as ethyl hexanoate (E11) and ethyl octanoate (E19), are well known for their contribution to fruity and floral aromas. Both compounds were detected in W (Table 1), with ethyl octanoate being the most abundant volatile compound. Their presence explains the strong correlation with the sensory attributes observed in the control wine (W). Furthermore, as shown in Figure 3, the % PRA of esters was highest in W, further reinforcing their role as key contributors to fruitiness and freshness in untreated Chardonnay wines.

In contrast, acetates, alcohols, volatile fatty acids, ketones, and furans exhibited a strong negative contribution to component 1 (t1), suggesting an association with less fresh and more oxidized sensory profiles. These compounds classes are typically linked to oxidative processes and contribute to complex aromatic characteristics. The higher alcohols identified-1-propanol (AL1), 1-propanol, 2-methyl (AL2), 1-butanol (AL3), and 1-butanol, 3-methyl (AL4) (Table 1), are known to impart pungent or fusel-like notes. Fatty acids, such as hexanoic and octanoic acids are frequently associated with cheesy or rancid aromas. Furans and ketones, often formed through thermal degradation or wood contact, contribute to toasty, caramel, or oxidized nuances.

The HHP-treated wine (WP), positioned in the upper-left quadrant of the PLSR biplot, was closely associated with these oxidation-related compounds, particularly acetaldehyde, furans, and volatile fatty acids, which evoke bruised apple, nutty, and oxidized aromas. As shown in Figure 3, WP exhibited the highest % PRA values for acetates, alcohols, aldehydes, furans, and terpenes, consistent with its chemical composition and sensory positioning within the oxidative spectrum. These results further support the perception of oxidative and alcoholic notes in this sample.

WPC and WPMC, located in the lower-left quadrant of the PLSR biplot, were associated with furans and sensory descriptors such as woody, balsamic, and bitterness. Furans—particularly furfural (AD7) which showed the highest % PRA in WPMC (Table 1)—are characteristic of wood ageing and are likely derived from the thermal degradation of lignin in vine-shoot chips. As shown in Figure 3, WPC also exhibited high % PRA values for furans and aldehydes, supporting its association with wood-derived compounds and the corresponding sensory attributes observed in this quadrant. The perception of balsamic notes may also be linked to aromatic hydrocarbons and phenolic aldehydes, which contribute to aromatic complexity.

WCM (maceration with chips for 35 days without HHP treatment) was positioned in the lower-right quadrant of the PLSR biplot. This wine was associated with aldehydes, astringency, olfactory intensity, and grassy sensory notes. Aldehydes such as hexanal (AD5) and nonanal (AD6), which were not detected in the untreated wines but were detected in WCM (Table 1), are known to impart green, grassy, or herbaceous aromas, consistent with the sensory profile of this wine. The pronounced astringency may be due to phenolic extraction during the extended maceration period with vine-shoot chips. As shown in Figure 3, WCM exhibited moderate % PRA values for aldehydes and fatty acids, supporting its association with green, grassy, and astringent characteristics, likely resulting from prolonged contact with vine shoot material.

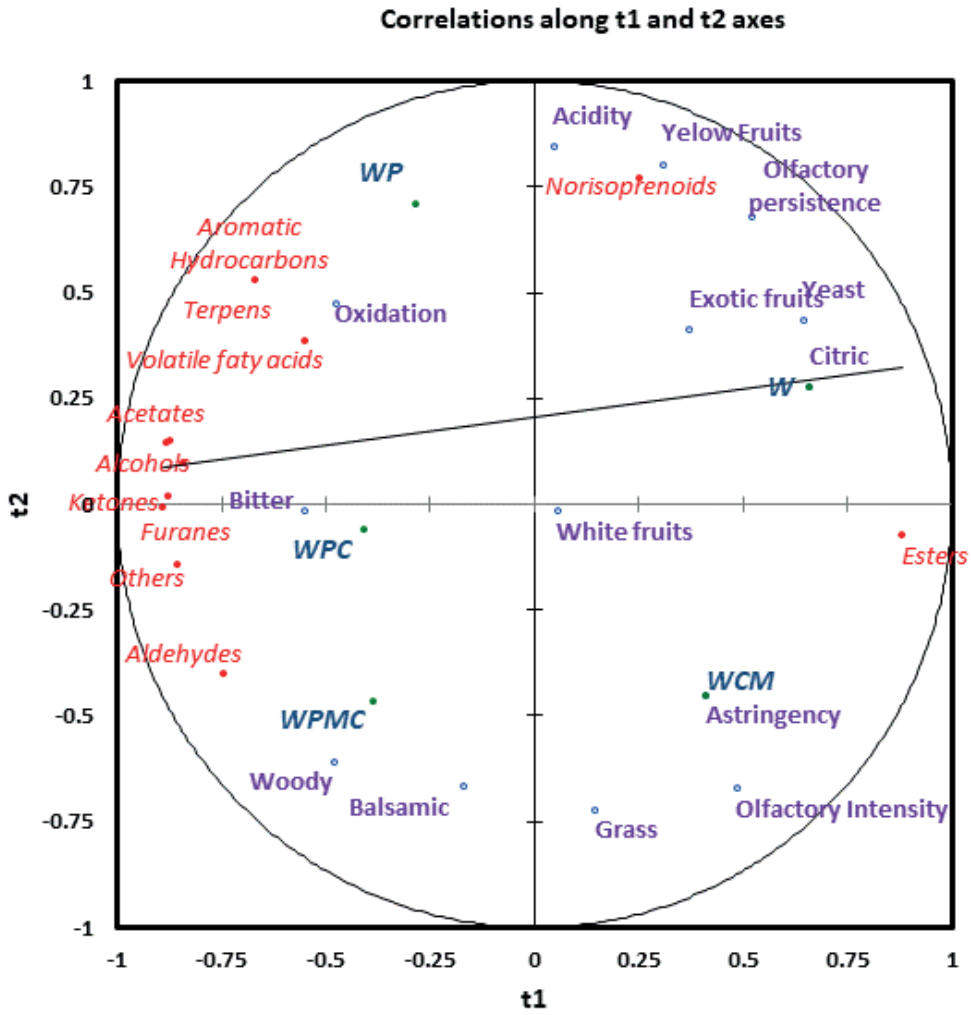


FIGURE 6. Partial least square regression of aromatic profile (in red) and sensory characteristics (in violet) of Chardonnay wines made from different treatments. Abbreviations: W, WCM, WP, WPC, and WPCM explained in Figure 1.

The PLSR biplot reveals a clear separation between fresh, fruity wines (right side, associated with esters and the control wine) and oxidized or wood-influenced wines (left side, associated with HHP and vine shoot treatments). This suggests that: i) esters are key markers of freshness and fruitiness, especially in W (untreated wines); ii) oxidation-related compounds including aldehydes, volatile fatty acids, ketones, reflect the effect of HHP treatment; iii) furans and aromatic hydrocarbons, likely derived from vine-shoot chips, contribute to woody and balsamic notes; and iv) aldehydes and phenolic compounds may contribute to astringency and green sensory attributes, particularly in wines subjected to extended chip contact (WCM).

DISCUSSION

Our results indicate that vine-shoot maceration, high hydrostatic pressure (HHP), and the combined application of both techniques influenced the aromatic profile of Chardonnay wines in distinct ways, with varying levels of statistical significance. The treatments affected the frequency with which trained panellists detected key sensory attributes, including fruitiness, wood-related aromas, oxidative notes, and mouthfeel properties such as bitterness and astringency.

The volatile profile of untreated Chardonnay wines was dominated by esters, which contribute a wide range of fruity notes, including apple, pear, citrus and tropical fruits, alongside notable levels of alcohols, acetals, aldehydes, ketones, and aromatic hydrocarbons. Only a limited number of monoterpenes were detected, including D-limonene, linalool, α-terpineol, and β-citronellol. The presence of norisoprenoids such as *trans*-vitispirane, *cis*-vitispirane, TDN, and damascenone was consistent with previous studies (Simpson & Miller, 1984; Cejudo-Bastante *et al.*, 2013; Gambetta *et al.*, 2014). The high % PRA values for 2-phenylethanol, ethyl hexanoate, and isoamyl alcohol supports the findings of Louw *et al.* (2010), who reported that most yeast-derived compounds—particularly alcohols, acids, and esters—were unaffected by vintage. This suggests that these compounds may be characteristic of the Chardonnay cultivar. In the untreated wines, esters predominated, positively contributing to fruit-forward aromas, leading panellists to perceive yellow and white fruit aromas typically associated with young Chardonnay wines.

In this study, vine-shoots were toasted to be applied as an oenological practice in a manner analogous to the common application of commercial oak chips. Previous studies have studied the impact of wood contact on Chardonnay wines (Guchu *et al.*, 2006; Herrero *et al.*, 2016). From an aromatic perspective, interaction with wood—particularly oak, the most frequently used species—is typically associated with the presence of furanic and benzenoid compounds, followed by whiskey lactones, and to a lesser extent, terpenes. The concentration and proportion of these compounds in wine depend on the wood's origin, the level of toasting applied, and, in the case of chips, their shape and size (Guchu *et al.*, 2006). To the best of our knowledge, this study represents the first use of toasted vine-shoots from *Vitis vinifera* cv. Chardonnay. In this context, the present study builds on the research of Cebrián-Tarancón *et al.* (2018a), who investigated the use of vine shoots as an innovative oenological practice. These researchers analysed the volatile composition of vine shoots from Airén and Cencibel cultivars toasted at 180 °C for 45 minutes. Their analysis identified furanic compounds, benzenoids, norisoprenoids, terpenes, C_6 alcohols, other volatiles, and *trans*- and *cis*-whiskey lactones in toasted Airén vine shoots. In the current study, decanal and nonanal-minimally present in the control-were detected in Chardonnay wines treated with vine-shoot chips (WCM wines). Notably. nonanal had previously been identified in vine-shoot chips from Airén and Tempranillo cultivars by the aforementioned authors.

The results (Table 1; Figures 2–6) indicated that 35 days of maceration in tank with toasted vine-shoot chips from Chardonnay vines had a limited impact on the aromatic profile. The % PRA values for most compounds were similar between W and WCM wines. The main differences were observed in the esters, with decreases in 14 compounds in WCM compared to W, and in aldehydes, where 4 compounds showed increased levels in WCM. When comparing W and WCM, statistically significant differences were detected only in aldehydes.

However, tasters perceived greater astringency in WCM, and PLSR analysis (Figure 6) indicated that longer maceration with vine-shoot chips may increase polyphenol extraction, resulting in wines that are more tannic, structured, and intense, in contrast to the fresh and fruity profile of the control wines. These findings suggest that under these conditions, both contact time and vine-shoot chip concentration require further investigation, as the parameters may not have been optimal for effective transfer of volatile compounds from the vine-shoots to the wine.

Previous studies explored the impact of different high hydrostatic pressure (HHP) conditions on the volatile composition and sensory properties of wines, demonstrating that the treatment parameters—pressure, temperature, and time—significantly influence the outcomes. Briones-Labarca *et al.* (2017) reported that HHP treatment of Sauvignon blanc wines at 300 MPa reduced microbial load, improved organoleptic properties, and induced imperceptible colour changes. In cv. Marselan wines, Yi *et al.* (2024) examined HHP treatments ranging from 100 to 600 MPa for 10 to 30 minutes, identifying 300 MPa for 20 minutes as the optimal condition for enhancing the aromatic profile and taste perception. More recently, Cheng *et al.* (2025) applied a response surface design of experiments (RSDE) on the same variety, determining optimal HHP conditions to be 470 MPa, 26 °C, for 40 minutes. Under the applied parameters, wines exhibited increased complexity, with enhanced fruity, floral, and herbaceous aromas, as well as improved drinkability. These effects were attributed to elevated concentrations of esters (*e.g.*, ethyl acetate, diethyl succinate), as well as the generation of terpenes (*e.g.*, citronellol, myrcene) and higher alcohols (*e.g.*, 2-ethylhexanol, 2-heptanol). In Chardonnay wines subjected to the experimental conditions in this study (600 MPa for 30 minutes), a significant impact on the aromatic profile was observed. HHP significantly affected the relative aromatic proportions (% PRAS) of nearly all volatile compound classes, with the exception of norisoprenoids (Figure 3). Principal component analysis (PCA) and the partial least squares regression (PLSR) clearly distinguished treated from untreated wines regardless of the presence of oak chips during processing. However, contrary to the promising results reported by previous studies, the HHP-treated wines in this study did not show improved sensory characteristics. Specifically, wines subjected to HHP (WP) were associated with oxidative, acidic, and bitter sensory attributes. This suggests that HHP may have accelerated oxidative processes, thereby diminishing fruity and fresh aromatic notes. Oxidation is known to generate aldehydes, ketones, alcohols, acetates, volatile fatty acids, and furans, which contribute to aged or stale aromas and reduce the perception of freshness (del Barrio-Galán *et al.*, 2024). The underlying mechanism likely involves the conversion of applied physical pressure into activation energy, which facilitates chemical reactions characteristic of wine ageing. This energy input can disrupt hydrogen bonds and promote both synthesis and degradation processes (Liu *et al.*, 2018; Tao *et al.*, 2014). Although pressure levels between 100 and 600 MPa are known to affect molecular dynamics—particularly polyphenol polymerisation and the distribution of volatile compounds (Nunes *et al.*, 2017)—the synergistic effects of pressure, temperature, and treatment time remain insufficiently understood in oenological applications. Temperature may also play an important role in modulating these effects, influencing both colour and aromatic stability (Liu *et al.*, 2018). Given the observed trade-off between freshness (esters, fruity notes) and oxidative or wood-derived characteristics, these findings highlight the importance of carefully controlling both HHP treatment and wood exposure during Chardonnay winemaking. Furthermore, they highlight the need for a variety-specific approach to HHP application and for further studies focused at optimising treatment conditions tailored to different wine matrices.

Finally, the combined application of high hydrostatic pressure (HHP) and wood-derived products has been extensively studied due to its potential to accelerate wine ageing processes. In the present study, wines treated with vine-shoot chips and HHP (WPC and WPCM) exhibited

significant increases in acetates, alcohols, aldehydes, fatty acids, furans, and ketones compared with the control (Figure 3). These increases were associated with sensory attributes typically found in aged wines, such as woody and balsamic notes. The correlation between woody and balsamic sensory descriptors, particularly in WPCM samples (Figures 5 and 6) suggests that the combination of HHP, vine-shoot chips, and short maceration enhances complexity and structure, without inducing the undesirable oxidative, bitter, and astringent notes observed in WP wines. The theoretical foundation of this approach lies in the synergistic interaction between HHP and wood components. Firstly, HHP can replicate certain aspects of the micro-oxygenation that occurs during traditional barrel ageing. Secondly, wood products provide key aromatic and structural compounds. Thirdly, HHP promotes the extraction (leaching) of these compounds, thereby shortening the ageing period and facilitating the incorporation of wood-derived constituents into the wine.

The results obtained in this study are of particular interest. Although not statistically significant P × M interactions were detected in the PRA of volatile compounds, sensory analysis indicated that the most effective strategy involves enhancing the extraction of wood-derived compounds through HHP, followed by a 35-day maceration. The process required only 35 days to produce notable sensory characteristics in the wines. Valdés *et al.* (2021) reported similar findings when they applied HHP in combination with holm oak *(Quercus ilex)* to white (cv. Cayetana) and red (cv. Tempranillo) wines. They observed that HHP increased polyphenol content, altered chromatic properties in white wine, and raised oxidation susceptibility, resulting in reduced fresh and fruity aromas and a rise in oxidation-associated compounds. However, the effects of accelerated ageing were more evident in the white wine, whereas only minor sensory changes were detected in the red wine. These results highlight the importance of optimizing HHP processing conditions (pressure and holding time) according to grape variety and wood chip concentrations. Further studies are therefore necessary, as modulating HHP parameters or adjusting the dose of vine-shoot chips may eliminate the need for subsequent maceration.

CONCLUSION

This study demonstrates that both vine-shoot chip maceration and HHP treatment can influence the aromatic and sensory profiles of Chardonnay wines to varying degrees. Untreated wines exhibited the fruity, fresh character typical of young Chardonnay, while HHP-treated wines (WP) showed increased levels of oxidation-related compounds and associated sensory attributes, such as bitterness and acidity, suggesting that the applied conditions may have accelerated undesirable oxidative reactions. Vine-shoot chips represent a novel oenological practice for imparting distinctive sensory attributes to wine. However, maceration with vine-shoot chips alone (WCM) had a limited effect on the volatile composition, although it enhanced astringency and structure, possibly due to polyphenol extraction. The combined application of vine-shoot chips and HHP (WPCM) promoted the development of aged, woody, and balsamic notes, increasing complexity and improving structural balance, without the oxidative drawbacks observed in HHP-only treatments.

These findings highlight the potential of combining HHP with alternative wood sources such as vine shoots to influence wine style and accelerate the ageing process. However, the variability observed across treatments indicates the need to optimise processing parameters, particularly pressure, maceration time, and wood chip composition, for each grape variety to achieve the desired oenological outcomes. Further research is required to refine these interventions and consistently enhance wine quality.

ACKNOWLEDGEMENTS

This work has been funded by the project: Valorization of natural plant-based resources. Development and digitalisation of processes to improve the sustainability and competitiveness of the productive sector in Extremadura (VAVEGEX), within the framework of the FEDER Operational Programme Extremadura 2021–2027. Action 1A1103. Development of scientific research, technological development, and innovation capacity, co-financed at 85 %. Authors also give thanks to MED—Mediterranean Institute for Agriculture, Environment and Development (DOI 10.54499/UIDB/05183/2020); CHANGE—Global Change and Sustainability Institute (DOI 10.54499/LA/P/0121/2020).

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