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Phenolic content, volatile composition and sensory profile of red wines macerated with toasted woods from different South American botanical species

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ABSTRACT

The use of wood species from South American origin was not previously considered for wine aging. Thus, this work focuses on the comparative analysis of phenolic content, volatile composition and sensory characteristics of a red wine macerated with woods, in form of toasted cubes, from jequitibá, jaqueira, ipê, amburana and lenga species. All wines macerated with these woods showed a tendency for an increase of the phenolic parameters evaluated. This tendency was more evident in wine chromatic characteristics, especially for the wine macerated with jequitibá wood, where significantly higher color intensity and total color difference values was detected. For volatile composition, the different wood species induced significant changes on wine volatile profile. Thus, 3-hydroxy-4-phenyl-2-butanone was only detected in wine macerated with jaqueira wood, while benzophenone, ethyl pentadecanoate, D-citronellol, linalool, geranic acid and isovainillic acid were only detected in wine macerated with amburana wood. For sensory profile, wine macerated with amburana wood showed significantly higher scores for "coconut", "toasted" and "floral" aroma descriptors, while for taste and overall appreciation this wine also showed a tendency for a slightly higher score. The outcomes of this research improved the knowledge of the use of several South American wood species on red wine characteristics.

1. Introduction

The aging process stands out as an important step in wine production, contributing to improving its sensory characteristics, particularly by an increase of aromatic complexity, softening the astringency and bitterness sensations. In addition, an evolution of color properties also occurred during the wine aging. One of the options usually used during this process is the use of wood, particularly oak wood. This option may include the use of wooden barrels as well as various alternative wood products, such as chips, cubes, blocks, or tank staves, among others. Presently, for the International Organization of Vine and Wine (OIV), only oak and chestnut species are authorized for barrel manufacturing (Resolution OENO 4/2005), while for wood fragments, only wood from the *Quercus* genus is possible to use in Europe (EEC regulation in 2006, modified by the EEC Regulation No. 2019/934 of March 12, 2019 - Appendix 7). The option to use oak fragments with different toasting levels (or without toasting) and particle sizes, is a less cost-effective alternative to produce wood-flavored wines and it is an option usually used by winemakers to simulate the aging process in barrels. This option allows wineries to achieve wines with the targeted aromatic profile, good structure, and body and just the right balance between fruity and woody character (Ortega-Heras et al., 2010; Návojská et al., 2012; Oberholster et al., 2015; González-Centeno et al., 2021). In addition, it is important to note that aging in oak barrels also oxygenates wine because small quantities of oxygen can reach the wine through the pores in the wood, and the interstices between the staves (Nevares et al., 2014). This supply of oxygen is positive for red wine because it stabilizes color, reduces astringency, and removes excess vegetal notes (Tarko et al., 2020).

Therefore, over the last two decades a high number of studies were

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published related to the use of oak wood pieces in red wines during alcoholic fermentation and aging (Del Álamo et al., 2004a; 2004b; De Coninck et al., 2006; Gonçalves & Jordão, 2009; Pérez-Magariño et al., 2009; Kyraleou et al., 2016; Baiano et al., 2016; Costa et al., 2020; Muñoz-García et al., 2023). Recently, also the use of oak wood fragments in the white wines aging has been the subject of some studies (Délia et al., 2017; Sánchez-Palomo et al., 2017; Alañón et al., 2018; Del Galdo et al., 2019; Correia et al., 2023).

In recent years, there has been an interest in other wood species, other than just oak, for oenological proposes. The high demand for oak wood products may have an ecologically negative impact on harvesting oak trees in forests, where their replacement is not totally guaranteed. On the other hand, the increasing demand for oak wood by the cooperages could induce a remarkable increase in costs due to the limited availability of this material (Martínez-Gil et al., 2018).

Thus, recently some studies have been carried out using several other wood species, such as acacia (Fernández de Simón et al., 2014; Délia et al., 2017; Tavares et al., 2017; Lisanti et al., 2021; Correia et al., 2023), cherry (Délia et al., 2017; Tavares et al., 2017; Del Galdo et al., 2019; Costa et al., 2020), chestnut (Gambuti et al., 2010; Lisanti et al., 2021; Correia et al., 2023), walnut (Costa et al., 2021), mulberry (De Rosso et al., 2009) and ash (Fernández de Simón et al., 2014) in oenology. Recently, Bargalló-Bargalló-Guinjoan et al. (2023) also reported results from several Mediterranean wood species for the accelerated aging of alcoholic beverages, such as olive (*Olea europaea* L.), almond (*Prunus dulcis*) and common grape vine (*Vitis vinífera* L.). In general, according to these different research works published, the use of woods from other botanical species than oak may contribute to obtaining wines with changes in their composition and sensory profile (Alañón et al., 2013). However, most of these species are from temperate zones of the northern hemisphere and not from tropical or semi-tropical regions.

The literature published describes the use of different wood species from South American origin, such as amburana, jatobá, loro vermelho, ipê, among others, in aging process of several alcoholic beverages, namely sugar cane spirit (Faria et al., 2003; Spoto et al., 2011; Simioni et al., 2018, Silveira et al., 2022; Maia et al., 2023) and beer (Guimarães et al., 2020). However, for wines, there is very scarce research about the impact of the use of these wood species of South American origin (particularly from Brazil) on wine quality. Thus, to the best of our knowledge, the present study is the first to compare the changes in phenolic content, color parameters, detailed volatile composition and sensory profile of red wines stored in contact with five different wood species (jequitibá, jaqueira, ipê, amburana and lenga) from South American origin during a brief maceration time. The outcomes of our study would be of practical interest to state regulatory organizations, cooperages, and winemakers, allowing them to have more data about the potential use of other no oak wood species in oenology.

2. Material and methods

2.1. Red wine

The red wine used in this experiment was a varietal wine made from the Portuguese *Vitis vinifera* red grape variety Touriga Nacional harvested in 2020. Grapes were harvested in a healthy condition at the technological stage of ripeness in September from vineyards located in the wine Douro Appellation of Origin (Northern Portugal). The wine was elaborated at Sabrosa Cooperative winery (Sabrosa, Portugal) following standard red winemaking technology with a maceration time of 7 days at 24 ± 2 °C. The sulfitation of the grape mash (50 mg/L of SO_2) was followed by alcoholic fermentation, which was carried out on an industrial scale using a closed stainless-steel tank (36,000 L) and a standard *Saccharomyces cerevisiae* yeast strain (Fermol Cru, AEB Group, Brescia, Italy) inoculated at 20 g/hL. After alcoholic and malolactic fermentation, the wines were kept in the stainless-steel tanks under controlled conditions (temperature about 18 °C) and analysed for the free SO_2 level and volatile acidity regularly.

2.2. Woods species

The wood species used in this research in form of cubes (dimensions: 1.5×1.0×1.2 cm; length x height x width) were: jequitibá (*Cariniana micranta*), jaqueira (*Artocarpus heterophyllus*), ipê (*Handroanthus* sp.), and amburana (*Amburana acreana*) from Brasilein forests, supplied by Dornas Havana Cooperage (Taiobeiras - Minas Gerais State, Brazil), and lenga (*Nothofagus pumilio)* from Patagonia region (Southern Argentina), supplied by TN Coopers (Curacaví, Chile). Oak wood (*Quercus petraea*) from France forests, supplied by AEB Bioquímica S.A. (Viseu, Portugal) was also used as a reference because it is the most used wood in oenology.

According to information provided by the cooperages, all wood cubes used were previously submitted to drying process (until a humidity value between 12 % and 13 %) followed by a medium toasting level (20–22 min at 170–180 °C on the wood surface).

2.3. Experimental conditions

The red wine samples were macerated with the different wood species in stainless steel containers (20 L each, in duplicate) during two different contact days (15 and 30 days) at cellar temperature (14–15 °C). Each wood cube species was placed in an inert perforated bag (food grade) and suspended inside the central part of each stainless-steel container. A red wine without wood cube contact was also kept as a control wine. For each assay, after 15 and 30 wood maceration days, the wood cubes were removed, and the wines were immediately analyzed. Before laboratory analysis, the red wine samples were filtered with a Whatman-Cytiva Europe (Velisy-Villacoublay, France) cellulose filter with a pore diameter of 3 μm.

The concentration of the wood pieces used in this experimental work (2 g/L) considered previous works carried out on red wines, particularly produced from the Touriga Nacional variety (Tavares et al., 2017; Costa et al., 2020; 2021) and following the technical information received from the cooperages that supplied the different wood samples used.

2.4. General wine physicochemical characterization

The general red wine physicochemical characterization (reducing substances, alcohol content, pH, total and volatile acidity) was performed using an FTIR WineScan® (Foss Analytics, Hilleroed, Denmark) previously calibrated using a spectra region between 926 and 5012/cm. This characterization followed the specific guidelines for infrared analyzers established by the Resolution OIV-OENO 390/2010 (OIV, 2010). Total and free sulfur dioxide was determined according to the analytical methods described by the Resolutions of OIV-OENO 591B-2018 (OIV 2018a) and 591A-2018 (OIV 2018b), respectively. For each experiment, all measurements were performed in triplicate.

2.5. Phenolic and chromatic parameters analysis

Total polyphenolic content was determined according to Ribéreau-Gayon (1970) methodology, while non-flavonoid and flavonoid phenols were determined using the modified method described by Kramling & Singleton (1969). Briefly, the quantification of non-flavonoid phenols was based on the determination of the phenolic content before and after the precipitation of flavonoids through reaction with formaldehyde under certain conditions (low pH, room temperature and darkness). After 24 hours, a dilution with distilled water (1:10) was carried out and the absorbance was read at 280 nm. Flavonoid phenols were calculated by subtracting non-flavonoid phenols from total phenols. The results obtained were expressed as gallic acid equivalents through calibration curve with the standard gallic acid (purity > 99 %, Extrasynthese, Genay, France). Total pigments, total and colored anthocyanins, and polymeric pigments were quantified according to Somers & Evans (1977). For total and colored anthocyanins, the results were expressed as malvidin-3-monoglucoside equivalents through the calibration curves with the standard of this individual monomeric anthocyanin (purity > 99 %, Extrasynthese, Genay, France). Total tannins were quantified according to the Bate-Smith assay which is based on proanthocyanidin depolymerization through the breakdown of their intra-flavonols bonds in an acidic heat medium (Ribéreau-Gayon & Stonestreet, 1966).

Color intensity (abs 420, abs 520 and abs 620 nm) and color hue were determined following the methodology OIV-MA-AS2–07B (OIV, 2009). In addition, using the CIELab method OIV-MA-AS2–11 (OIV, 2006), chromatic characteristics (scanned from a range of 380–770 nm) were also determined by the calculation of several chromatic parameters: L^* (%) (lightness), a^* (redness), b^* (yellowness) and chroma $[C^* = [(a^*)^2 + (b^*)^2]^{1/2}]$ according to OIV (2014) method. To distinguish the color more accurately, the color difference was also calculated using the following formula: $(\Delta E=[(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2]^{1/2})$. For all these phenolic and chromatic parameters, a spectrophotometer model Genesys 50 UV-Vis (Thermo Scientific, Illkirch-Graffenstaden, France) accoupled to VISIONlite Wine Analysis software program version 5.0 (Thermo Fisher Scientific, Waltham, MA, USA) was used. All measurements were performed in triplicate.

2.6. Individual anthocyanin analysis by HPLC

Individual monomeric anthocyanins grouped into 3 main groups (monoglucosides, acetylglucosides and coumarylglucosides), were analyzed by high-performance liquid chromatography (HPLC) using a Dionex Ultimate 3000 Chromatographic System (Sunnyvale, CA, USA) equipped with a quaternary pump Model LPG-3400 A, an auto sampler Model ACC-3000, a thermostatted column compartment (adjusted to 25 °C) and a multiple Wavelength Detector MWD-300. The column (250 ×4.0 mm, particle size 5 µm) was a C_{18} Nucleodur (100–5 ec, Macherey - Nagel, Germany) protected by a guard column of the same material. The solvents were: (A) 40 % (v/v) formic acid, (B) pure acetonitrile and (C) bi-distilled water. The HPLC conditions was based in the original method described by Dallas & Laureano (1994). Thus, initial conditions were 25 % (A), 10 % (B), and 65 % (C), followed by a linear gradient from 10 % to 30 % (B), and 65–45 % (C) for 40 min, with a flow rate of 0.7 mL/min. The injection volume was 40 µL, the detection was made at 520 nm and a Chromeleon software program version 6.8 (Dionex, Sunnyvale, CA, USA) was used. Individual anthocyanins were quantified by using a calibration curve obtained with diverse standard solutions containing different concentrations of malvidin-3-monoglucoside (Oenin purity > 99 %, Extrasynthese, Genay, France). The chromatographic peaks of anthocyanins were identified according to reference data previously described by Dallas & Laureano (1994). All measurements were performed in triplicate.

2.7. Volatile composition analysis by SPME-GC-MS

Volatile compounds were analysed by the gas-liquid chromatography method described previously by Santos et al., (2019). In summary, two hundred and fifty millilitres of wine with 75 µL of 2-octanol, used as an internal standard of 500 mg/L in absolute ethanol, were extracted with 5 mL of dichloromethane. Extraction occurred in an ice bath with continuous stirring for three hours. The organic phase was separated by centrifugation (10,000 *g* for 10 min at Temperature < 4 ºC) and analysed according to the following conditions: A Carbowax 20 M column (60 m x 0.32 mm, 0.25 µm film thickness) from Quadrex Corporation (Symta, Madrid, Spain), was used for separation. The carrier gas was helium, and the flow was 0.8 mL/min. The oven temperature was initially 40 ºC for 8 min, then increased to 85 ºC at 10 ºC/min and held for 1 min, then increased to 230 ºC at 2 ºC/min and held for 35 minutes. The gas chromatography-mass spectrometry (GC-MS) was performed on a Hewlett-Packard HP 6890 coupled with a HP 5973 mass selective detector. The ionization of the samples was achieved at 70 eV under the SCAN mode. The mass range studied was from 30 to 250 m/z. MS spectra data were checked with a Chem-station equipped with the library NIST 08. Volatile contents were quantified with the internal standard quantification method. Then, the relative areas (peaks' areas/internal standard area) were interpolated in the calibration curves built from results obtained with pure or equivalent reference compounds (Table S1), and quantitative data were expressed in mg/L. All analyses were done in quadruplicate.

2.8. Sensory evaluation

The wines were evaluated immediately after 15 and 30 days in contact with the different wood cube species and were presented (samples of 25 mL from each red wine sample) to panelists (8 expert judges; 6 men and 2 women between 40 and 60 years old and with over 15 years of wine tasting experience) in randomized order at 20–22 °C, in ISO standard wine glasses (marked with three-digit numbers), in isolated booths, and under daylight-type lighting. All expert judges had been previously selected and trained to assess the sensorial attributes of wines produced in the Douro Appellation of Origin, particularly for red wines produced from Touriga Nacional grape variety. During the training period and under the supervision of the panel leader, several sessions were carried out to train judges about the meaning of each attribute and to achieve reliable intensity ratings. In summary, the panellists were trained during 8 training sessions with the objective to differentiate olfactory and gustatory wine attributes. The standards of the compounds used in sensory training of the judges for the olfactory and gustatory attributes are described in Table S2. The standards used for olfactory and gustatory attributes training were added in different concentrations to 100 mL of a neutral wine. The different olfactory and gustatory attributes were evaluated using a quantitative descriptive analysis on a structured scale from 1 (absent) to 5 (high intensity). All these procedures were carried out in accordance with the standards previously described by ISO 11132 (2012a) and ISO 8586 (2012b).

In the end, the sensorial attributes used were grouped in the following way: color ("red" and "brown"), aroma ("fruity", "floral", "vanilla", "spice", "toasted", "coconut" and "balance"), taste ("body", "bitterness", "astringency", "persistence" and "balance") and global appreciation. The experts scored each sensory attribute on a scale of 1–5 (1 = "absence"; 2 = "little intensity"; 3 = "moderate intensity"; 4 = "intense"; 5 = "high intensity") according to the training. Aroma balance, taste balance and global appreciation were also scored on a scale of 1–5 (1 = "bad"; 2 = "pleasant"; 3 = "good"; 4 = "very good"; 5 = "excellent").

2.9. Statistical analysis

The data are presented as mean ± standard deviation. The statistical difference between the mean values of the parameters studied was estimated by analyses of variance (ANOVA, one-way). In this research, Duncan multiple range test (p<0.05) was applied to determine significant differences between red wines macerated with the different wood species for the different variables studied.

Principal component analysis (PCA) was also used to analyze the data and to study the relationships between the red wines macerated with the different wood species and their chemical composition (phenolic and volatile), chromatic characteristics and sensory profile. Since variables with different scales were used, the PCA analysis was performed with a previous standardization of the initial variables and conducted using a correlation matrix. All analyses were performed using SPSS software version 27.0 (SPSS Inc., Chicago, IL, USA).

3. Results and discussion

3.1. General red wine characterization

The red wine used in this study showed acceptable physicochemical standards, showing a low volatile acidity (0.35 g/L acetic acid) and adequate SO_2-free values (35 mg/L) (Table 1). It should be noted that malolactic fermentation was developed in this red wine. In addition, the wine showed a pH of 3.60, a total acidity of 4.10 g/L tartaric acid and low levels of reducing substances (0.5 g/L). Considering these general physicochemical characteristics, it was assumed that wine was in good stability conditions to be subjected to a brief wood maceration. On the other hand, this wine showed a high phenolic content (total phenols of 1950 mg/L gallic acid equivalent and total anthocyanins of 527 mg/L malvidin 3-monoglucoside equivalent), which is characteristic of red wines produced from Touriga Nacional grape variety.

3.2. Global phenolic parameters

In general, data seems to indicate that the maceration with the different wood species for 15 days was not enough to change the global phenolic parameters analyzed (Table 2). However, an exception was observed in terms of polymeric pigments contents. In this case, all wines macerated with different woods showed significantly lower values compared to the control wine.

After 30 contact days, an opposite trend was detected (Table 2). Therefore, in general for control wine a slight decrease of the different phenolic parameters occurred, while for the wines macerated with the different woods, a tendency for an increase of the several phenolic parameters studied was detected (except for anthocyanins and total pigments, for which no relevant changes occurred). Thus, wines macerated with the different wood species showed significantly higher values, particularly for non-flavonoid phenols (varied between 155 and 187 mg/L gallic acid equiv.), total tannins (varied between 3.81 and 3.95 g/L catechin equiv.) and polymeric pigments (varied between 1.78 and 1.85 abs. units), compared to control wine. However, among the wines macerated with the different wood species, there was no significant difference between them for all global phenolic parameters studied. Probably, longer maceration time and higher concentrations of wood cubes could lead to a potential differentiation between wines.

The results obtained allowed to verify that the variability of the phenolic levels of the wines macerated with the different South American wood species were in general similar to that observed in wine macerated with oak wood. It is well known that phenolic compounds extraction from wood to wines is dependent on several factors such as natural wood richness in phenolics, wood structure (related to wood porosity that could determine the extraction of phenolics from wood to wine) and the contact time between wood and wine (Jordão et al., 2007; Garcia et al., 2012; Jordão & Cosme, 2022). Several authors reported previously, differences in total phenolic content in sugar cane spirits aged in oak and different South American wood specie barrels. Thus, Bortoletto and Alcarde (2013) reported higher total phenolic content found in cane spirits aged in oak and grápia barrels compared to the others aged in ipê and jequitibá barrels. Other authors also reported high concentrations of phenolic compounds found in sugar cane spirits aged in amburana barrels compared with oak barrels (Santiago et al., 2014a). According to Santiago et al., (2017), these high concentrations may be explained by morphological differences and chemical characteristics between the different wood species.

Table 1
General physicochemical and global phenolic parameters of the Touriga Nacional red wine used in this experimental work.

Parameters	Values*
Alcohol content (%, v/v)	13.8 ± 0.1
pH	3.60 ± 0.01
Total acidity (g/L tartaric acid)	4.10 ± 0.03
Volatile acidity (g/L acetic acid)	0.35 ± 0.02
Free sulfur dioxide (mg/L)	35 ± 1
Total sulfur dioxide (mg/L)	75 ± 2
Reducing substances (g/L) **	0.5 ± 0.1
Total phenols (mg/L gallic acid equiv.)	1951 ± 8
Flavonoid phenols (mg/L gallic acid equiv.)	1857 ± 4
Non-flavonoid phenols (mg/L gallic acid equiv.)	93.6 ± 3.1
Total anthocyanins (mg/L malv. 3-monogluc. equiv.)	527 ± 3

* Average values of three replicates ± standard deviation; ** containing mainly residual sugar

3.3. Individual monomeric anthocyanins

Similar to those noted for total anthocyanins (Table 2), control wine showed higher levels for most individual monomeric anthocyanins. This trend was particularly evident for petunidin-3-glucoside, malvidin-3-glucoside and malvidin-3-acetylglucoside. Del Álamo-Sanza et al., (2004a) reported that both, acetylated and non-acetylated anthocyanins, showed higher content in wines without wood contact than in wines aged in contact with wood chips and staves. Several authors reported a lower value of anthocyanin content in red wines stored in contact with wood for several months because of oxidation and condensation reactions. These last reactions occur between wine anthocyanins and certain wood molecules, involving or not ethanal bridges and generate large, insoluble, and precipitable polymers (Jordão et al., 2019; Laqui-Estaña et al., 2019). Other authors also reported a reduction of anthocyanins due to their absorption (Barrera-García et al., 2007; Lisanti et al., 2021) and adsorption (Nan et al., 2019) by wood fragments. For Cheng et al., (2023) wood contact can reduce the content of monomeric anthocyanins and increase polymeric anthocyanins over a short-term period. This fact could help to explain the significant increase of polymeric pigments found in all wines macerated with woods compared to control wine (Table 2).

Between the wines macerated with the different wood species similar values for the three anthocyanins group were detected. In addition, all the wines maintained an almost constant anthocyanin profile, where the most abundant being the group of 3-monoglucosides, followed by the acetylglucoside and coumarylglucoside groups.

After 30 contact days, the ratio of total acetylated/coumarylated derivatives was higher for the wines macerated with ipê and jetquitibá woods (1.57 and 1.58, respectively) compared to the remaining wines (values varied between 1.31 and 1.51). According to Malien-Aubert et al., (2001), acylated anthocyanins are very important for wine color since they participate in intramolecular copigmentation processes, thus increasing in the further the red color stability. Other authors reported that anthocyanin acetylation helps to improve the stability of anthocyanins (Cheng et al., 2023).

3.4. Chromatic characteristics

Color intensity, in general, showed a slight tendency for a decrease over the contact time (Table 4). However, for wines macerated with oak and jequitibá woods, a slight increase in color intensity values was observed. In fact, after 30 contact days, these were the two wines with significantly highest values.

For color hue results, an increase of the values, particularly evident for control wine (ranging from 0.69 to 0.74) and wines macerated with ipê and amburana woods (ranging from 0.65 to 0.73) was detected (Table 4). A similar tendency was also detected for h^o values. It is important to emphasize that color hue increase was a result of an improvement of yellow color and brown components, which was confirmed by the increase of b^* coordinate values. After 30 contact days these wines also showed the significantly highest b^* values. These changes may be a consequence of the oxidation reactions involving the different wine phenolic compounds during the storage process, but also a result of extractable wood components, such as several phenolic

Table 2
Global phenolic parameters quantified in Touriga Nacional red wines macerated with different wood species after 15 and 30 contact days.

Wines	Total phenols (mg/L gallic acid equiv.)	Flavonoid phenols (mg/L gallic acid equiv.)	Non-flavonoid phenols (mg/L gallic acid equiv.)	Total Tannins (g/L catechin equiv.)	Total anthocyanins (mg/L malv. 3-monogluc.)	Colored anthocyanins (mg/L malv. 3-monogluc.)	Total Pigments (abs. units x 10)	Polymeric pigments (abs. units x 10)
15 contact days								
Control Wine	$1930\pm20^{a*}$	1838 ± 18^{a}	91.9 ± 1.7	3.52 ± 0.11	520 ± 9	59.40 ± 1.11	22.21 ± 0.24^{ab}	2.16 ± 0.06^{a}
W + French	1893 ± 88^{abc}	1801 ± 38^{ab}	91.9 ± 10.0	3.20 ± 0.20	490 ± 16	56.02 ± 1.99	21.24 ± 0.79^{ab}	1.15 ± 0.02^{b}
W + Lenga	1927 ± 10^{ab}	1823 ± 4^{ab}	103.2 ± 4.1	3.76 ± 0.44	488 ± 14	55.82 ± 1.70	22.62 ± 1.01^{ab}	1.16 ± 0.02^{b}
W + Jequitibá	1915 ± 10^{ab}	1820 ± 13^{ab}	95.7 ± 3.6	3.45 ± 0.21	494 ± 2	56.57 ± 0.30	24.21 ± 1.30^{b}	1.18 ± 0.02^{b}
W + Jaqueira	1911 ± 12^{abc}	1803 ± 4^{ab}	107.6 ± 7.4	3.23 ± 0.13	504 ± 11	57.63 ± 1.33	30.12 ± 0.95^{a}	1.16 ± 0.01^{b}
W + Ipê	1889 ± 12^{abc}	1780 ± 15^{ab}	109.6 ± 3.3	3.10 ± 0.13	492 ± 1	56.21 ± 0.16	22.27 ± 0.26^{ab}	1.16 ± 0.03^{b}
W + Amburana	1876 ± 15^{bc}	1769 ± 13^{bc}	106.6 ± 8.5	3.29 ± 0.48	492 ± 13	56.28 ± 1.60	22.91 ± 0.24^{ab}	1.15 ± 0.04^{b}
30 contact days								
Control Wine	1910 ± 19	1822 ± 17^{a}	88.7 ± 8.1^{b}	3.10 ± 0.25^{b}	518 ± 1^{ab}	60.00 ± 0.30^{ab}	21.44 ± 1.00	1.67 ± 0.07^{c}
W + French	1925 ± 12	1734 ± 13^{abc}	187.9 ± 8.7^{a}	3.91 ± 0.06^{a}	503 ± 16^{ab}	57.55 ± 1.90^{ab}	22.22 ± 0.51	1.85 ± 0.01^{ab}
W + Lenga	1950 ± 6	1780 ± 13^{abc}	169.3 ± 7.6^{a}	3.88 ± 0.02^{a}	507 ± 9^{ab}	57.99 ± 1.08^{ab}	23.42 ± 2.75	1.79 ± 0.02^{b}
W + Jequitibá	1950 ± 22	1773 ± 4^{abc}	177.0 ± 7.0^{a}	3.95 ± 0.27^{a}	499 ± 7^{ab}	57.00 ± 0.80^{ab}	21.55 ± 0.33	1.80 ± 0.04^{b}
W + Jaqueira	1962 ± 17	1807 ± 18^{abc}	155.0 ± 1.2^{a}	3.83 ± 0.06^{a}	517 ± 1^{ab}	59.11 ± 0.24^{ab}	23.11 ± 1.62	1.79 ± 0.02^{b}
W + Ipê	1968 ± 23	1813 ± 23^{ab}	155.0 ± 3.9^{a}	3.81 ± 0.12^{a}	511 ± 2^{a}	60.77 ± 0.11^{a}	23.51 ± 1.91	1.79 ± 0.05^{b}
W + Amburana	1981 ± 21	1819 ± 21^{a}	162.0 ± 2.9^{a}	3.86 ± 0.23^{a}	504 ± 2^{ab}	57.60 ± 0.26^{ab}	22.92 ± 0.87	1.78 ± 0.02^{b}

Two essays of wines macerated with the same wood specie for each contact time were analyzed in triplicate; the results represent the average values; ± standard deviation; Control wine - wine without wood maceration; W+ French - wine macerated with French oak wood; W + Lenga - wine macerated with lenga wood; W + Jequitibá - wine macerated with jequitibá wood; W + Jaqueira - wine macerated with jaqueira wood; W + Ipê - wine macerated with ipê wood; W + Amburana - wine macerated with amburana wood; *Values with different letter (in column) for each phenolic parameter and contact time are significant different (Duncan test $p < 0.05$).

compounds which contribute to an increment of yellow and brown colors (Del Álamo-Sanza et al., 2004b). Moreover, these wines macerated with ipê and amburana woods were the ones that also showed the highest values of total phenolic compounds (Table 2), then the wood-extracted phenols could have contributed to these color changes. According to Dias et al., (2009), amburana and ipê woods are characterized by high contents of several phenolic compounds, such as vanillic and syring acids, sinapaldehyde and coniferaldehyde.

The results obtained for the a^* coordinate (redness) followed the same trend already detected for total and colored anthocyanins values (Table 2). Thus, over the 30 days of maceration, control wine and the wine macerated with ipê wood showed higher values of the a^* coordinate. This trend was particularly evident after 30 contact days, where these 2 wines showed the significantly highest values (a^* values varied between 11.54 and 12.05).

In general, an intensification of the clarity and brightness of most of the studied wines was observed. After 30 contact days, the wines macerated with amburana and ipê woods, as well as the control wine, showed for L^* and h^o, the significantly highest values (between 6.15 and 7.00 for L^* values and between 17.76 and 18.91 for h^o values). These characteristics seem to indicate that these wines were visually more evolved. On the other hand, wines macerated with oak and jequitibá woods showed an opposite trend compared to all others, i.e. a decrease in L^*, h^o and b^* values after 30 contact days, corresponding to wines visually less evolved. According to Heras-Roger et al., (2016), these changes could be a consequence of copigmentation phenomena which improve the wine color, resulting in purplish and darker wine. These results, particularly for the wine macerated with jequitibá, may also be associated with the higher values of the total ratio of acylated/coumarylated derivatives that were detected (Table 3). In this way, they showed higher values of acetylated anthocyanins, which contribute to higher stability of wine-red color.

Finally, wines macerated with oak and jequitibá woods were also the ones that showed significantly higher total color difference values compared to the control wine (ΔE values varied between 8.24 and 9.58). According to Martínez et al., (2001), for red wines, ΔE values around 3.0 CIElab units indicate that the color differences obtained could be detected by human eyes.

3.5. *Volatile composition*

3.5.1. *Global volatile content*

One hundred and twenty volatiles including, seven acids, sixteen alcohols, two aldehydes, three ketones, thirty-eight esters (eight acetates, twenty-seven ethyl esters, two methyl esters, one isobutyl ester), nine lactones, twelve terpenoids, eighteen phenols, six furfural derivates, five nitrogenated volatiles, and four sulphur compounds, were identified and had in count in this study. The volatiles were quantified in wines after 30 maceration days with the different wood species and in the control wine stored for the same time (Table S3). Esters were the group of volatile compounds quantified in higher concentrations in all wines (total values varied from 403 to 814 mg/L), followed by alcohols (total values varied from 111 to 148 mg/L) and lactones (total values varied from 35 to 41 mg/L). Aldehydes (total values varied from 0.007 to 0.020 mg/L) and terpenes (total values varied from 0.046 to 0.074 mg/L) were the lowest compounds group quantified.

Wood species influenced the number of total compounds detected in wines. Thus, for wine macerated with jaqueira wood, 109 different individual volatile compounds were detected, while for wines macerated with oak, lenga and ipê woods between 99 and 100 different individual volatile compounds were detected (Table S3). Control wine and wine macerated with amburana wood showed the lowest number of individual volatile values quantified (85 and 86 compounds, respectively).

The scientific literature contains a large amount of data related to volatile composition of different wood species and their impact in wine volatile composition, in particular oak (Cerdán et al., 2004;

Table 3
Individual monomeric anthocyanins quantified in Touriga Nacional red wines macerated with different wood species after 15 and 30 contact days.

Wines	Df gluc	Pt gluc	Pn gluc	Mv gluc	Df acet-gluc	Cy acet-gluc	Pt acet-gluc	Pn acet-gluc	Mv acet-gluc	Pt coum-gluc	Pn coum-gluc	Mv coum-gluc
15 contact days												
Control wine	30.47 ±1.11^{b*}	37.19 ±1.12^{a}	20.18 ±1.15^{a}	292.89 ±7.06^{a}	1.99 ±0.35^{a}	6.81 ±1.31^{a}	1.73±0.46	12.92 ±0.60^{a}	45.07 ±3.36^{a}	4.47 ±0.51^{a}	3.86 ±0.07^{a}	41.63 ±2.16^{a}
W + French	26.81 ±0.63^{c}	30.91 ±0.51^{b}	14.17 ±0.42^{b}	285.62 ±3.23^{ab}	0.81 ±0.09 ^{cd}	4.92 ±0.18^{bcd}	0.94±0.50	5.23 ±0.26^{e}	32.75 ±5.57^{b}	2.90 ±0.25^{b}	3.07 ±0.15^{b}	31.01 ±1.23^{b}
W + Lenga	34.73 ±0.70^{a}	28.80 ±1.90^{b}	17.38 ±0.41^{a}	257.63 ±3.52 ^{cd}	1.70 ±0.26^{ab}	5.41 ±0.39^{bcd}	0.89±0.59	6.19 ±0.60 ^{cd}	35.28 ±0.31^{b}	2.04 ±0.29^{b}	2.81 ±0.51^{bc}	32.91 ±0.86^{b}
W + Jequitibá	24.35 ±0.14 ^{cd}	29.79 ±2.61^{b}	14.17 ±0.09^{b}	218.01 ±12.42 ^{g}	1.65 ±0.35^{ab}	4.60 ±0.02^{d}	0.91±0.27	6.51 ±0.10^{bc}	31.83 ±2.67^{b}	1.84 ±0.01^{b}	2.57 ±0.02^{bc}	29.79 ±0.55^{b}
W + Jaqueira	25.44 ±1.05 ^{cd}	30.75 ±3.94^{b}	19.90 ±2.50^{a}	243.39 ±3.30^{de}	1.07 ±0.06 ^{cd}	4.71 ±0.17 ^{cd}	1.47±0.33	7.34 ±0.63^{b}	37.57 ±0.16^{b}	2.16 ±0.13^{b}	2.13 ±0.74^{c}	30.96 ±0.34^{b}
W + Ipê	22.44 ±2.63^{de}	31.67 ±0.93^{b}	13.84 ±1.00^{b}	270.89 ±1.22^{bc}	1.20 ±0.04^{bcd}	6.04 ±0.23^{ab}	0.74±0.09	5.48 ±0.41^{de}	38.80 ±3.17^{b}	2.72 ±0.63^{b}	2.53 ±0.06^{bc}	29.40 ±1.41^{b}
W + Amburana	19.81 ±3.28^{e}	30.19 ±2.54^{b}	14.23 ±2.11^{b}	237.72 ±3.41^{ef}	0.97 ±0.32 ^{cd}	5.88 ±0.27^{abc}	1.70±0.07	5.09 ±0.23^{e}	39.44 ±1.11^{b}	2.79 ±0.41^{b}	2.28 ±0.22^{c}	29.88 ±2.98^{b}
30 contact days												
Control wine	30.25 ±3.32^{a}	36.41 ±0.21^{a}	18.14 ±0.16^{a}	287.34 ±1.09^{a}	1.58±0.15^{a}	5.12 ±0.03^{a}	1.58 ±0.02	8.75 ±1.75^{ab}	34.33 ±2.89^{a}	2.89 ±0.52	2.65 ±0.70^{a}	28.44 ±0.40^{a}
W + French	27.74 ±2.83^{ab}	28.29 ±0.62^{c}	13.92 ±2.27^{bc}	228.14 ±8.36^{bc}	0.68±0.18 ^{cd}	4.94 ±0.47^{a}	1.02 ±0.02	5.73 ±0.76 ^{cd}	29.84 ±5.57^{bc}	2.44 ±1.15	2.16 ±0.07^{ab}	22.30 ±0.66^{bc}
W + Lenga	30.83 ±5.33^{a}	29.57 ±0.94^{bc}	18.05 ±1.10^{a}	216.05 ±3.42^{de}	1.32±0.32^{ab}	5.65 ±0.36^{a}	0.45 ±0.04	6.08 ±0.40^{bcd}	29.48 ±0.20^{c}	2.08 ±0.50	2.45 ±0.39^{ab}	27.86 ±1.22^{a}
W + Jequitibá	20.26 ±1.28^{c}	29.19 ±1.93^{bc}	11.13 ±2.43^{cde}	208.38 ±4.96^{e}	1.02±0.15^{bc}	4.23 ±0.23^{a}	0.48 ±0.15	4.62 ±0.70^{d}	25.61 ±2.67^{c}	1.44 ±0.46	1.65 ±0.07^{bc}	19.65 ±0.24^{c}
W + Jaqueira	22.86 ±0.58^{bc}	27.83 ±5.15^{c}	17.11 ±0.24^{ab}	236.16 ±3.43^{b}	1.25±0.22^{ab}	4.64 ±0.52^{a}	0.34 ±1.26	5.51 ±0.64 ^{cd}	24.82 ±0.50^{d}	2.32 ±0.47	2.19 ±0.01^{ab}	23.19 ±0.01^{bc}
W + Ipê	21.41 ±3.90^{bc}	29.83 ±1.57^{bc}	8.53 ±0.81^{e}	231.50 ±1.16^{b}	1.17±0.24^{ab}	5.67 ±0.34^{a}	0.99 ±0.06	8.25 ±2.58^{abc}	35.82 ±3.17^{ab}	2.66 ±0.24	2.54 ±0.07^{ab}	27.75 ±2.76^{a}
W + Amburana	17.93 ±1.55^{c}	25.56 ±1.32^{c}	9.15 ±0.66^{de}	206.54 ±3.94^{e}	0.43±0.07^{d}	2.41 ±0.24^{b}	1.07 ±0.22	3.28 ±0.15^{d}	31.45 ±1.19^{bc}	2.98 ±0.28	1.05 ±0.37^{c}	25.35 ±1.46^{ab}

Two essays of wines macerated with the same wood specie for each contact time were analyzed in triplicate; the results represent the average values; ± standard deviation; individual anthocyanins expressed in malvidin-3-glucoside equivalents (mg/L); Control wine - wine without wood maceration; W+ French - wine macerated with French oak wood; W + Lenga - wine macerated with lenga wood; W + Jequitibá - wine macerated with jequitibá wood; W + Jaqueira - wine macerated with jaqueira wood; W + Ipê - wine macerated with ipê wood; W + Amburana - wine macerated with amburana wood; Df gluc, delphinidin-3-glucoside; Pt gluc, petunidin-3-glucoside; Pn gluc, peonidin-3-glucoside; Mv gluc, malvidin-3-glucoside; Cy acet-gluc, cyanidin-3-acetylglucoside; Pt acet-gluc, petunidin-3-acetylglucoside; Pn acet-gluc, peonidin-3-acetylglucoside; Mv acet-gluc, malvidin-3-acetylglucoside; Pt coum-gluc, petunidin-3- *p*-coumaroyl glucoside; Pn coum-gluc, peonidin-3-*p*-coumaroyl glucoside; Mv coum-gluc, malvidin-3-*p*-coumaroyl glucoside; *Values with different letter (in column) for each phenolic parameter and contact time are significant different (Duncan test $p < 0.05$).

Ortega-Heras et al., 2007; Santos et al., 2019; Călugăr et al., 2020; Miljić et al., 2023) and in the last years also for other species, such as chestnut, cherry and acacia (Martínez-Gil et al., 2022; Jordão & Cosme, 2022; Correia et al., 2023). However, there is scarce information about the impact of South American wood species on wine volatile composition because these woods are not frequently used in oenology. Nevertheless, they are involved in the production of other fermented beverages, such as beers (Guimarães et al., 2020) and particularly for sugar cane spirits aging, commonly known as cachaça (Bortoletto & Alcarde, 2013; Santiago et al., 2016; Bortoletto et al., 2021; Ferreira et al., 2021).

In this research and under the experimental conditions considered, some individual volatile compounds were only detected in a single wine, which could be considered as a characteristic of the wood specie used. Thus, 3-hydroxy-4-phenyl-2-butanone was only detected in wine macerated with jaqueira, while benzophenone, ethyl pentadecanoate, D-citronellol, linalool, geranic acid and isovainillic acid were only detected in wine macerated with amburana wood. Furthermore, the last wine had high levels of coumarin (8.46 mg/L), a compound that only was detected in the wine macerated with jaqueira but in a very low concentration (0.048 mg/L). This result agrees with other previous works pointed out the presence of high levels of coumarin, in different products derived from amburana wood (Pereira et al., 2017; Silveira et al., 2022). The presence of high coumarin values has been previously detected on sugar cane spirits aged in amburana barrels by other authors (Maia et al., 2023). Bortoletto et al. (2021) also reported that amburana contains several specific compounds that may determine some differentiation in beverages stored in contact with this wood. These authors also reported the presence of some specific compounds only detected in sugar cane spirits aged in amburana barrels, such as hexyl acetate and ethyl heptanoate Table 4.

Wines macerated with ipê and lenga woods were differentiated from the others because of the presence of Δ-tridecalactone and *cis*-isoeugenol, respectively, while the two isomers of lactone (*trans* and *cis* whiskey lactones), α-terpinene and L-limonene were characteristic of the wine macerated with oak wood (Table S3).

3.5.2. Main volatile compounds group

To better understand the effect of different wood species on the volatile composition of wines through multivariate analysis, volatiles of the same chemical group and with similar abundances in all the studied wines were grouped. Thus, forty-seven volatile variables instead of the initial one hundred and twenty were considerate (Table 5). The major reduction of variables was due to the aggrupation of the different individual volatile compounds in the following different chemical groups: esters, alcohols, furfural derivates, phenols and nitrogenated compounds.

According to the results obtained, wine maceration with the different South American wood species produced significant quantitative effects on many volatiles groups, and individuals. This fact agrees with previous works which reported a release of volatile and phenolic compounds from the wood into the wine during the aging process (Ortega-Heras et al., 2007; Tao et al., 2014; Jordão & Ricardo-da-Silva, 2021; Carpene et al., 2021; Jordão & Cosme, 2022). In addition, wood also favours in wines the transformation of volatiles in other molecules and can retain

Table 4

Chromatic characteristics of Touriga Nacional red wines macerated with different wood species after 15 and 30 contact days.

Wines	**Color intensity (abs. units) ***	**Color hue**	**CIELab coordinates**					
			L*	***a****	***b****	h^0	***C****	**ΔE**
15 contact days								
Control wine	$12.1\pm0.01^{b**}$	0.69 ± 0.04^{a}	6.17 ± 0.78^{ab}	33.07 ± 2.06^{ab}	10.58 ± 1.35^{ab}	17.62 ± 0.17^{a}	34.73 ± 2.37^{a}	—
W + French	13.0 ± 0.01^{a}	0.65 ± 0.02^{bcd}	5.60 ± 0.14^{ab}	31.85 ± 0.38^{ab}	9.61 ± 0.20^{ab}	16.62 ± 0.01^{b}	33.27 ± 0.43^{ab}	0.62 ± 0.14^{c}
W + Lenga	13.2 ± 0.01^{a}	0.66 ± 0.01^{b}	5.00 ± 0.28^{b}	29.80 ± 1.25^{b}	8.58 ± 0.58^{b}	16.33 ± 0.41^{c}	31.01 ± 0.37^{cd}	2.91 ± 0.14^{b}
W + Jequitibá	13.1 ± 0.01^{a}	0.65 ± 0.04^{bcd}	5.60 ± 0.28^{ab}	31.82 ± 0.84^{ab}	9.60 ± 0.48^{ab}	16.90 ± 0.40^{c}	33.24 ± 0.94^{ab}	1.14 ± 0.25^{c}
W + Jaqueira	13.3 ± 0.01^{a}	0.65 ± 0.03^{bcd}	5.00 ± 0.10^{b}	29.95 ± 0.04^{b}	8.61 ± 0.02^{b}	16.04 ± 0.01^{d}	31.16 ± 0.04^{cd}	6.50 ± 0.04^{a}
W + Ipê	13.1 ± 0.02^{a}	0.65 ± 0.01^{cd}	5.90 ± 0.28^{a}	32.98 ± 0.76^{a}	10.19 ± 0.46^{a}	17.14 ± 0.02^{b}	34.52 ± 0.86^{a}	3.01 ± 0.92^{b}
W + Amburana	13.1 ± 0.01^{a}	0.65 ± 0.01^{d}	6.00 ± 0.14^{a}	33.17 ± 0.35^{a}	10.30 ± 0.23^{a}	17.19 ± 0.05^{b}	34.73 ± 0.40^{a}	2.77 ± 0.44^{b}
30 contact days								
Control wine	11.6 ± 0.05^{e}	0.74 ± 0.02^{a}	7.00 ± 0.14^{a}	35.11 ± 0.32^{a}	12.05 ± 0.29^{a}	18.91 ± 0.02^{ab}	37.11 ± 0.40^{a}	—
W + French	13.1 ± 0.05^{a}	0.70 ± 0.05^{cd}	4.55 ± 0.07^{e}	28.09 ± 0.39^{f}	7.81 ± 0.14^{f}	15.47 ± 0.01^{g}	29.16 ± 0.42^{g}	8.24 ± 0.42^{b}
W + Lenga	12.3 ± 0.09^{bc}	0.72 ± 0.04^{abc}	5.85 ± 0.06^{bc}	32.44 ± 0.07^{cd}	10.08 ± 0.05^{cd}	17.19 ± 001^{e}	33.97 ± 0.09^{d}	3.19 ± 0.11^{de}
W + Jequitibá	13.5 ± 0.04^{a}	0.69 ± 0.05^{d}	3.90 ± 0.14^{f}	25.25 ± 0.71^{g}	6.77 ± 0.23^{g}	14.90 ± 0.10^{h}	26.14 ± 0.75^{h}	9.58 ± 0.74^{a}
W + Jaqueira	12.7 ± 0.01^{b}	0.71 ± 0.08^{bcd}	5.20 ± 0.14^{d}	30.30 ± 0.52^{e}	8.87 ± 0.27^{e}	16.33 ± 0.41^{f}	31.57 ± 0.58^{f}	2.95 ± 0.60^{c}
W + Ipê	11.9 ± 0.01^{de}	0.73 ± 0.01^{ab}	6.75 ± 0.07^{a}	34.50 ± 0.07^{ab}	11.54 ± 0.09^{ab}	18.33 ± 0.05^{c}	36.38 ± 0.09^{b}	1.44 ± 0.13^{fg}
W + Amburana	12.1 ± 0.04^{cd}	0.73 ± 0.01^{ab}	6.15 ± 0.07^{b}	33.20 ± 0.27^{bc}	10.59 ± 0.17^{bc}	17.76 ± 0.01^{d}	34.85 ± 0.31^{c}	1.04 ± 0.33^{ef}

Two essays of wines macerated with the same wood specie and for each contact time were analyzed in triplicate; the results represent the average values; ± standard deviation; Control wine - wine without wood maceration; W+ French - wine macerated with French oak wood; W + Lenga - wine macerated with lenga wood; W + Jequitibá - wine macerated with jequitibá wood; W + Jaqueira - wine macerated with jaqueira wood; W + Ipê - wine macerated with ipê wood; W + Amburana - wine macerated with amburana wood; * absorbance values expressed for an optical path of 1 cm optical path; ** Values with different letter (in column) for each phenolic parameter and contact time are significant different (Duncan test $p < 0.05$).

volatiles, mainly by absorption (Coelho et al., 2019; 2021).

3.5.2.1. Acids. Levels of principal acids showed effects of wood contact very variables among wood species studied (Table 5). Thus, while wine macerated with jequitibá produced an intense reduction of the total of major acids (83 % respect control wine), wines macerated with other woods (jaqueira, oak, ipê and amburana) resulted in a significant increase (126, 118, 115 and 111 %, respectively), which were mainly associated with increments of hexanoic and acetic acids. The last effect seems to agree with a previous work pointed out that wood, mainly after the toasting process, can contain a significant quantity of acetic acid (Paiva et al., 2019). Wood contact also induced an increase of decanoic acid in most of the wines (except for the wine macerated with jequitibá). This result was particularly evident for the wine macerated with amburana wood. This tendency agrees with higher levels of decanoic acid found in sugar cane spirit aged in contact with different Brazilian woods (Nascimento et al., 2000). In addition, 5-benzoyl pentanoic acid was detected in similar values for wines macerated with oak, lenga and jaqueira woods.

3.5.2.2. Alcohols and aldehydes. For the major alcohols, in general, wines with wood maceration showed lower values than the control (Table 5), especially the wines macerated with oak and amburana (81 % and 87 % of control wine, respectively). These results could be associated with the possible adsorption of the alcohols by these woods and agree with those found by other authors in a red wine aged with oak wood chips (Del-Barrio-Galan et al., 2012). However, exceptionally, wine macerated with lenga showed higher levels of major alcohols and phenethyl alcohol than the control (Table 5). This fact seems to suggest a possible extraction of these alcohols from lenga wood; however, no information about the presence of alcohols in lenga wood has been found, then more studies are necessary to clarify the observed data.

For benzyl alcohol, wood maceration induced an increase of this individual volatile, particularly for the wines macerated with oak, jaqueira and ipê woods (0.413, 0.431 and 0.435 mg/L, respectively). However, wines with jetiquibá and amburana maceration showed a slight decrease in the content of this alcohol. Concerning to total of benzenic aldehydes derivates, similar values were detected between all wines, except for the wine macerated with amburana wood, which showed the significantly highest value.

3.5.2.3. Ketones and esters. For ketones, wines macerated with oak and ipê woods showed notably lower levels of acetoin (from 65 % to 77 % than control wine values). In this case, these woods may have had a subtraction effect on this compound through greater absorption of this ketone. Regarding esters content, the major ethyl esters showed significant differences among wines (Table 5). Wines macerated with jaqueira, ipê and amburana woods induced a significant increase of major ethyl esters (between 1,4 and 1,5 times more than levels in control wine), while the maceration with lenga and jequitibá woods induced a significant decrease (between 1.2 and 1.3 times lower than control wine). Several authors reported a significant increase of esters in sugar cane spirits aged in amburana barrels compared to the remaining aged in oak barrels (Santiago et al., 2014b; 2016). Other authors reported similar ester values for sugar cane spirits aged in oak and jequitibá barrels but lower values when ipê barrels were employed (Alcarde et al., 2010). On the other hand, wine stored in contact with oak cubes did not show significant changes concerning the control wine. In previous research, Santos et al. (2019) reported variable effects of diverse wood species (oak, acacia, and cherry) on wine ester volatiles content. However, the impact of the different wood species did not show any clear tendency for wine esters composition.

The results of major ethyl esters contrast with those observed for minority ethyl esters, whose levels were always minor in wines macerated with the different wood species than in control wine. These last results corroborate the previous data found by Del-Barrio Galán et al. (2012), who reported a decrease in esters levels in wines macerated with oak chips. In addition, other authors also reported that wood, mainly oak, adsorbs several volatile compounds, especially esters, from beers (Coelho et al., 2021; Correia et al., 2023).

3.5.2.4. Lactones and terpenes. Levels of lactones were significantly higher in wine macerated with oak than in control wine (which corresponded to an increase of 2.8 times). On the other hand, wines macerated with jaqueira, ipê and jequitibá woods showed levels around 1.3 times higher than control wine (Table 5). The use of lenga cubes did not modify the levels of lactones, and wine macerated with amburana showed a decrease of around 89 % of the content of lactones compared to the control wine. Notable were the content of dihydromevalonic lactone in wines macerated with amburana (0.767 mg/L), oak (0.390 mg/L), jaqueira (0.306 mg/L) and ipê (0.234 mg/L) woods, whiles was not detected in wines macerated with lenga and jequitibá

Table 5
Main individual volatile compounds and groups that differentiated the Touriga Nacional red wines macerated in contact with different wood species after 30 contact days.

Compounds/groups(*)	**Red wines**						
	Control wine	**W+French**	**W+Lenga**	**W+Jequitibá**	**W+Jaqueira**	**W+Ipê**	**W+Amburana**
Acids							
Decanoic acid	0.049 ±0.008$^{c(**)}$	0.134 ±0.023^{a}	0.127 ±0.022^{a}	0.022 ±0.002^{d}	0.128 ±0.018^{a}	0.096 ±0.015^{b}	0.143 ±0.007^{a}
Isobutyric acid	0.043 ±0.003^{c}	0.050 ±0.006^{a}	0.049 ±0.003^{a}	0.041 ±0.002^{d}	0.049 ±0.005^{a}	0.046 ±0.007^{b}	0.035 ±0.008^{a}
Nonanoic acid	n.d.	0.018 ±0.001^{a}	0.018 ±0.001^{a}	n.d.	0.018 ±0.001^{a}	0.021 ±0.001^{b}	n.d.
5-Benzoylpentanoic acid	n.d.	0.013 ±0.001	0.013 ±0.000	n.d.	0.012 ±0.000	n.d.	n.d.
Total of major acids (acetic, hexanoic, octanoic acids)	4.440 ±0.297^{c}	5.255 ±0.399^{ab}	4.553 ±0.179^{c}	3.670 ±0.228^{d}	5.607 ±0.252^{a}	5.101 ±0.550^{ab}	4.919 ±0.251^{bc}
Alcohols							
Phenethyl alcohol	4.082 ±0.669^{abc}	3.122 ±0.344^{c}	4.986 ±0.665^{a}	4.266 ±0.608^{abc}	3.654 ±0.589^{bc}	3.475 ±0.367^{bc}	4.495 ±0.593^{ab}
Benzyl alcohol	0.394 ±0.039	0.413 ±0.045	0.387 ±0.070	0.343 ±0.045	0.431 ±0.029	0.435 ±0.074	0.370 ±0.040
1-Hexanol	1.360 ±0.099	1.298 ±0.092	1.266 ±0.129	1.247 ±0.117	1.341 ±0.072	1.346 ±0.011	1.351 ±0.042
Cis−3-hexen−1-ol	0.050 ±0.003	0.049 ±0.006	0.049 ±0.004	0.045 ±0.004	0.053 ±0.003	0.053 ±0.003	0.049 ±0.001
Total of major alcohols (isobutanol, 1-butanol, 2-methyl−1-butanol, isoamyl alcohol)	129.839 ±14.229^{ab}	113.553 ±8.626^{b}	142.115 ±9.695^{a}	127.354 ±8.224^{ab}	116.625 ±14.744^{ab}	120.659 ±14.601^{ab}	105.51 ±5.567^{b}
Total of minor alcohols (4-methyl−1-pentanol, 2-heptanol, 3-methyl−1-pentanol, 1-heptanol, 1-octanol, 2,3-butanediol, 1-nonanol, 4-tert-butylcyclohexanol)	0.193 ±0.009^{abc}	0.208 ±0.014^{a}	0.187 ±0.008^{abc}	0.175 ±0.011^{c}	0.202 ±0.013^{ab}	0.194 ±0.011^{abc}	0.178 ±0.005^{bc}
Aldehydes							
Total of benzenic aldehydes derivates (benzaldehyde, 4-ethyl-benzaldehyde)	0.010 ±0.001^{bcd}	0.012 ±0.001^{bc}	0.009 ±0.000^{cd}	0.007 ±0.001^{d}	0.012 ±0.002^{b}	0.011 ±0.001^{bc}	0.020 ±0.000^{a}
Compounds/groups (*)	**Red wines**						
	Control wine	**W+French**	**W+Lenga**	**W+Jequitibá**	**W+Jaqueira**	**W+Ipê**	**W+Amburana**
Ketones							
Acetoin	2.577 ±0.240^{a}	1.772 ±0.251^{c}	2.003 ±0.190^{bc}	2.396 ±0.245^{ab}	2.514 ±0.256^{a}	1.682 ±0.088^{c}	2.817 ±0.145^{a}
3-Hydroxy−4-phenyl−2-butanone	n.d.	n.d.	n.d.	n.d.	0.013 ±0.002	n.d.	n.d.
Benzophenone	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.005 ±0.001
Esters							
Ethyl pentadecanoate	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.001 ±0.000
Ethyl n-propyl succinate	n.d.	n.d.	0.015 ±0.002^{b}	n.d.	0.031 ±0.005^{a}	n.d.	n.d.
Ethyl 12- oxododecanoate	n.d.	n.d.	n.d.	n.d.	0.007 ±0.001	0.006 ±0.000	n.d.
Diethyl suberate	n.d.	0.001 ±0.000	n.d.	n.d.	0.001 ±0.000	0.001 ±0.000	n.d.
Total of acetates (isoamyl, benzyl, isobutyl, phenethyl, ethyl-phenyl, methoxy2-phenylethyl, isopentyl methoxy-acetate)	0.690 ±0.036^{ab}	0.684 ±0.018^{ab}	0.626 ±0.022^{b}	0.681 ±0.040^{ab}	0.651 ±0.032^{ab}	0.644 ±0.014^{ab}	0.695 ±0.022^{a}
Total of major ethyl esters (hexanoate, 2-hydroxy-hexanoate, lactate, phenyl-lactate, isopentyl succinate, hydrogen succinate, methyl succinate)	531.770 ±31.199^{c}	540.385 ±18.35^{c}	446.441 ±24.131^{d}	400.152 ±34.787^{d}	812.201 ±36.969^{a}	786.007 ±87.192^{ab}	737.230 ±49.96^{b}
Total of minor ethyl esters (ethyl butyrate, 3 hydroxy butyrate, isovalerate, 2-hydroxyisovalerate, levulinate, 2-hexanoate, heptanoate octanoate, 3-hydroxyoctanoate, nonanoate, decanoate, diethyl succinate, 2-hydroxy−3-methylsuccinate, glutarate, malate, malonate)	2.442 ±0.193^{a}	2.058 ±0.275^{ab}	2.183 ±0.126^{ab}	2.182 ±0.297^{ab}	1.865 ±0.138^{b}	1.985 ±0.075^{b}	2.296 ±0.166^{ab}
Total of other esters (methyl hexanoate, methyl lactate, isobutyl lactate)	0.019 ±0.001^{b}	0.019 ±0.003^{b}	0.018 ±0.002^{b}	0.017 ±0.001^{b}	0.020 ±0.001^{b}	0.022 ±0.003^{b}	1.410 ±0.129^{a}
Compounds/groups (*)	**Red wines**						
	Control wine	**W+French**	**W+Lenga**	**W+Jequitibá**	**W+Jaqueira**	**W+Ipê**	**W+Amburana**
Lactones							
Δ-Tridecalactone	n.d.	n.d.	n.d.	n.d.	n.d.	0.302 ±0.040	n.d.
Dehydromevalonic lactone	n.d.	0.390 ±0.025^{b}	n.d.	n.d.	0.306 ±0.013^{c}	0.234 ±0.022^{d}	0.767 ±0.028^{a}

(*continued on next page*)

Table 5 (*continued*)

Compounds/groups(*)	**Red wines**						
	Control wine	**W+French**	**W+Lenga**	**W+Jequitibá**	**W+Jaqueira**	**W+Ipê**	**W+Amburana**
γ-Butyrolactone	37.430 ±5.623	37.438 ±4.145	36.035 ±3.666	34.552 ±5.067	39.057 ±2.698	39.279 ±5.028	38.689 ±1.088
Total of whisky lactones (*trans*-whiskey lactone, *cis*-whiskey lactone)	n.d.	0.014 ±0.009	n.d.	n.d.	n.d.	n.d.	n.d.
Total of minor lactones (γ-octalactone, γ-nonalactone, Δ-decalactone, Δ-undecalactone)	1.031 ±0.123^{bcd}	2.834 ±0.207^{a}	0.995 ±0.50^{cd}	1.115 ±0.060^{bcd}	1.347 ±0.106^{b}	1.276 ±0.237^{bc}	0.893 ±0.065^{d}
Terpenes							
L-Limonene	n.d.	0.004 ±0.000	n.d.	n.d.	n.d.	n.d.	n.d.
Vitispirane	0.004 ±0.000^{b}	0.005 ±0.000^{a}	0.004 ±0.000^{b}	0.004 ±0.000^{b}	0.004 ±0.000^{b}	0.0048 ±0.000^{b}	0.003 ±0.000^{d}
γ-Eudesmol	n.d.	0.001 ±0.000^{a}	n.d.	n.d.	0.001 ±0.000^{a}	0.009 ±0.000^{b}	n.d.
Total of common terpenes (detected in all wines) (α-terpineol, α-terpinene, β-citronellol, dihydroactinidiolide, carvacrol, geraniol)	0.043 ±0.002^{c}	0.067 ±0.007^{a}	0.047 ±0.007^{c}	0.041 ±0.002^{c}	0.059 ±0.004^{ab}	0.049 ±0.002^{bc}	0.025 ±0.001^{d}
Total of lineal monoterpens (detected only in a single wine) (D-citronellol, geranic acid, linalool)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.023 ±0.001
Phenols							
4-Ethylphenol	0.003 ±0.000^{a}	0.002 ±0.000^{b}	0.002 ±0.000^{b}	0.002 ±0.000^{b}	0.003 ±0.000^{a}	0.002 ±0.000^{b}	0.002 ±0.000^{b}
4-Hydroxy−3-methyl acetophenone	0.126 ±0.013^{c}	0.191 ±0.017^{a}	0.157 ±0.028^{b}	0.091 ±0.012^{d}	0.139 ±0.008^{bc}	0.141 ±0.016^{bc}	0.074 ±0.008^{d}
Compounds/groups (*)	**Red wines** **Control wine**	**W+French**	**W+Lenga**	**W+Jequitibá**	**W+Jaqueira**	**W+Ipê**	**W+Amburana**
2,4-di-tert-Butylphenol	0.134 ±0.026^{a}	0.118 ±0.024^{ab}	0.032 ±0.002^{d}	0.035 ±0.009^{d}	0.068 ±0.007^{c}	0.067 ±0.012^{c}	0.096 ±0.011^{b}
Total of guaiacol derivates (guaiacol, 4-methylguaicol)	0.016 ±0.002^{d}	0.030 ±0.004^{c}	0.046 ±0.007^{b}	0.044 ±0.009^{b}	0.052 ±0.002^{b}	0.025 ±0.005^{cd}	0.132 ±0.008^{a}
Total of vanillin derivates (vanillin, ethylvanillate, isocetovanillone, isovanilic acid)	2.060 ±0.350^{b}	2.620 ±0.196^{a}	1.478 ±0.132^{c}	0.874 ±0.181^{d}	2.422 ±0.332^{ab}	2.039 ±0.319^{b}	1.533 ±0.152^{c}
Total of syringic derivates (syringol, syringaldehyde, acetosyringone, syringic acid hydrazide)	0.363 ±0.007^{d}	2.345 ±0.193^{a}	0.563 ±0.06^{c}	0.155 ±0.013^{e}	0.818 ±0.035^{b}	0.224 ±0.009^{de}	0.071 ±0.012^{e}
Total of eugenol derivates (eugenol, *cis*-isoeugenol and methoxyeugenol)	n.d.	0.001 ±0.000^{b}	0.004 ±0.000^{a}	0.001 ±0.000^{b}	0.001 ±0.000^{b}	n.d.	n.d.
Total of coumarins (coumarin, mellein)	0.181 ±0.017^{b}	0.190 ±0.026^{b}	0.056 ±0.053^{b}	0.076 ±0.020^{b}	0.200 ±0.036^{b}	0.146 ±0.033^{b}	8.577 ±1.284^{a}
Furfural derivates							
Total of furfural derivates (furfural, 5-methylfurfural, tetrahydro−2-methylfuran, 2-acetylfuran, ethyl 2-furoate, furfuryl alcohol)	0.297 ±0.025^{c}	0.302 ±0.033^{c}	0.398 ±0.020^{b}	0.385 ±0.017^{b}	0.292 ±0.002^{c}	0.327 ±0.024^{c}	0.496 ±0.060^{a}
Nitrogenated derivates							
1-Ethyl-1H-pyrrole−2-carbaldehyde	n.d.	n.d.	n.d.	0.014 ±0.003	0.016 ±0.002	0.014 ±0.001	n.d.
Total of nitrogenated derivates (1-methylpyrrole−2-carboxaldehyde, ethyl nicotinate, N-(3-methylbutyl) acetamide, ethyl 2-acetamido−4-methyl pentanoate)	0.364 ±0.055^{b}	0.411 ±0.055^{ab}	0.267 ±0.038^{c}	0.231 ±0.039^{c}	0.470 ±0.098^{a}	0.440 ±0.052^{ab}	n.d.
Sulfured derivates							
2-Methyltetrahydrothiophen−3-one	0.700 ±0.060^{ab}	0.742 ±0.141^{a}	0.662 ±0.045^{abc}	0.486 ±0.090^{c}	0.679 ±0.033^{ab}	0.539 ±0.106^{bc}	0.576 ±0.050^{abc}
Methionol	0.211 ±0.050^{ab}	0.216 ±0.051^{ab}	0.197 ±0.038^{ab}	0.220 ±0.050^{a}	0.159 ±0.010^{b}	0.092 ±0.013^{c}	0.247 ±0.017^{a}
Total of sulfured derivates (ethyl 3-(methylthio) propionate, 2,3-dihydrothiophene)	0.166 ±0.024^{a}	0.121 ±0.025^{b}	0.124 ±0.027^{b}	0.118 ±0.018^{b}	0.177 ±0.010^{a}	0.539 ±0.106^{a}	0.126 ±0.019^{b}

Two essays of wines macerated with the same wood specie were analyzed in quadruplicate; results represent the average values; ± standard deviation; Control wine - wine without wood maceration; W+ French - wine macerated with French oak wood; W + Lenga - wine macerated with lenga wood; W + Jequitibá - wine macerated with jequitibá wood; W + Jaqueira - wine macerated with jaqueira wood; W + Ipê - wine macerated with ipê wood; W + Amburana - wine macerated with amburana wood; $^{(*)}$ Values expressed in mg/L; n.d. no detected; $^{(**)}$ Values with different letter (in line) for each volatile compound are not significant different (Duncan test $p < 0.05$).

woods (Table 5). Wines macerated with oak, jaqueira, ipê and lenga woods showed between intense (157 % for oak) to slight (110 % for Lenga) increments of total terpenes concerning the control wine. However, wine macerated with amburana showed lower levels of these compounds (59 % of the level of the control wine), although it was the unique wine in which lineal monoterpenes (D-citronellol, geranic acid, and linalool) were detected (Tables S3 and 5). In general, these results are contrary to previous studies reported for craft beers macerated with oak, and cherry wood chips, in which results evidenced that wood maceration significantly reduced the levels of terpenes (Correia et al., 2023). γ-Eudesmol was an individual terpene detected only in wines macerated with oak, jaqueira and ipê woods, with levels significantly higher value in the last. This volatile compound was previously described in several Brazilian wood species, including ipê wood (Lima et al., 2023).

3.5.2.5. Phenols. Regarding the levels of other characteristic wood volatiles, particularly for the phenols group, wines macerated with the different wood species showed significantly higher levels of guaiacol derivates than control wine, resalting the significantly higher values found in wine macerated with amburana (Table 5).

Total vanillin derivates showed high variability among wines. Thus, the use of oak and jaqueira woods increased the levels of vanillin derivates (127 and 117 % concerning control wine), while ipê wood did not change the content of these derivates in wine (Table 5). Similar results were obtained for total syringic derivates, where wine macerated with oak showed an increase of 8 times higher level compared to the control wine, followed by wine macerated with jaqueira (2 times more) and lenga (1.6 times more). The maceration with the other woods induced a decrease in total syringic derivates levels for wines macerated with ipê (62 % of the control wine level), jequitibá (43 % of the control wine level) and amburana (20 % of the control wine level). The results obtained for syringin and vanillin derivates follow a similar trend reported by Bortoletto and Alcarde (2013) in which sugar cane spirits aged in oak barrels showed higher values of these derivates than the remaining spirits aged in several Brazilian wood barrel species.

Eugenol derivates were detected only in wines macerated with lenga, oak, jaqueira and jequitibá, with the significantly highest value in the former (Table 5). Finally, wine wood maceration induced an increase in the content of 4-hydroxy-3-methylacetophenone found for most of the wines, especially for the wines macerated with oak and lenga. An opposite tendency was detected for 2,4-di-tert-butylphenol, showing all the wines with wood maceration a decrease in the content of this phenol (especially the wines macerated with lenga and jequitibá).

3.5.2.6. Furfural derivates. Results of total furfural derivates indicated strong increases in their content in wines macerated with amburana (an increase of 167 %), lenga (an increase of 134 %) and jequitibá (an increase of 130 %) woods. These increases could be explained as a consequence of the diverse natural composition and structure of the polysaccharides of each wood species used, giving different resistance to thermodegradation and then to the formation of different content of furfural derivates (Férnandez de Simón et al., 2009; Kozlovic et al., 2010).

3.6. *Sensory evaluation*

The wine sensory evaluation results for color, aroma, taste, and global appreciation after 15 and 30 wood maceration days are shown in the form of spider diagrams which are based on the average values of the different sensory attributes studied (Fig. 1). From a statistical point of view, the results indicated low significant differences between the wines after 15 wood maceration days for most sensory attributes considered, except for coconut and vanilla aroma descriptors. Thus, for coconut aroma, wines macerated with oak and amburana woods showed the significantly highest scores, while for vanilla aroma, it was also the wine macerated with amburana which showed significantly higher scores followed by the wines macerated with jaqueira wood. Wines macerated with oak and jequitibá woods showed intermediate scores. These results follow a similar tendency already reported by other authors for beers

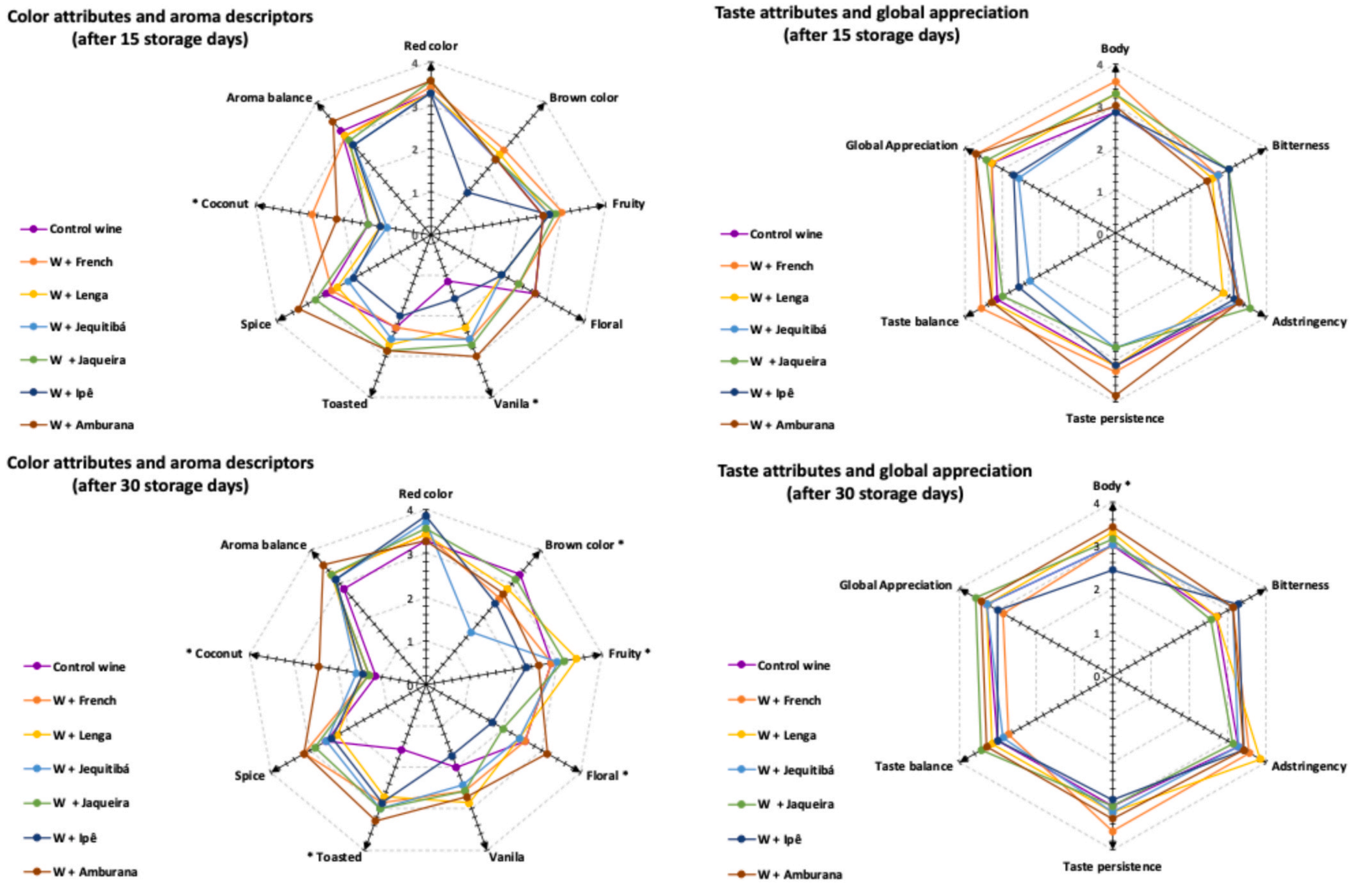

Fig. 1. Sensory profile of Touriga Nacional red wines macerated with different wood species after 15 and 30 contact days. Control wine - wine without wood maceration; W + French - wine macerated with French oak wood; W + Lenga - wine macerated with lenga wood; W + Jequitibá - wine macerated with jequitibá wood; W + Jaqueira - wine macerated with jaqueira wood; W + Ipê - wine macerated with ipê wood; W + Amburana - wine macerated with amburana wood; *Sensory parameter where there are significant differences between wines (Duncan test $p < 0.05$).

aged in amburana and oak barrels. In that case, these beers showed more sweet-like characteristics, including vanilla aroma and flavour (Guimarães et al., 2020; Silvello et al., 2020).

Most of the aroma descriptors differences increased throughout maceration time (except for vanilla aroma). This tendency was particularly evident for toasted, floral, and fruity descriptors. Thus, after 30 contact days wine macerated with amburana showed significantly higher punctuations for coconut, toasted and floral aroma descriptors. On the other hand, for these aroma descriptors wine macerated with ipê wood, and the control wine showed the lowest scores. These results, particularly for wines macerated with amburana and oak woods, may be associated with higher values of some volatile compounds found in wines macerated with these wood species after 30 days. So, data in Tables S1 and 5 noted that wines macerated with oak, and especially with amburana, showed a tendency towards higher values of furfural derivatives, some lactones and other wood volatiles (particularly from the phenols group).

To color attributes, only for the brown color the panel detected significant differences. After 15 contact days, wine macerated with ipê wood showed significantly lower values, while after 30 days it was the wine macerated with jequitibá wood (Fig. 1). The other wines showed similar scores at two macerated times. The results obtained after 30 contact days confirm the results previously reported for color hue and *b** coordinate, where the wine macerated with jequitibá wood showed ~~the~~ significantly lower values compared to the other wines. This color differentiation also resulted from the fact that this wine was the one that showed the highest significant total color difference (ΔE) compared to the control wine (Table 4). The tendency to brown color increase, which

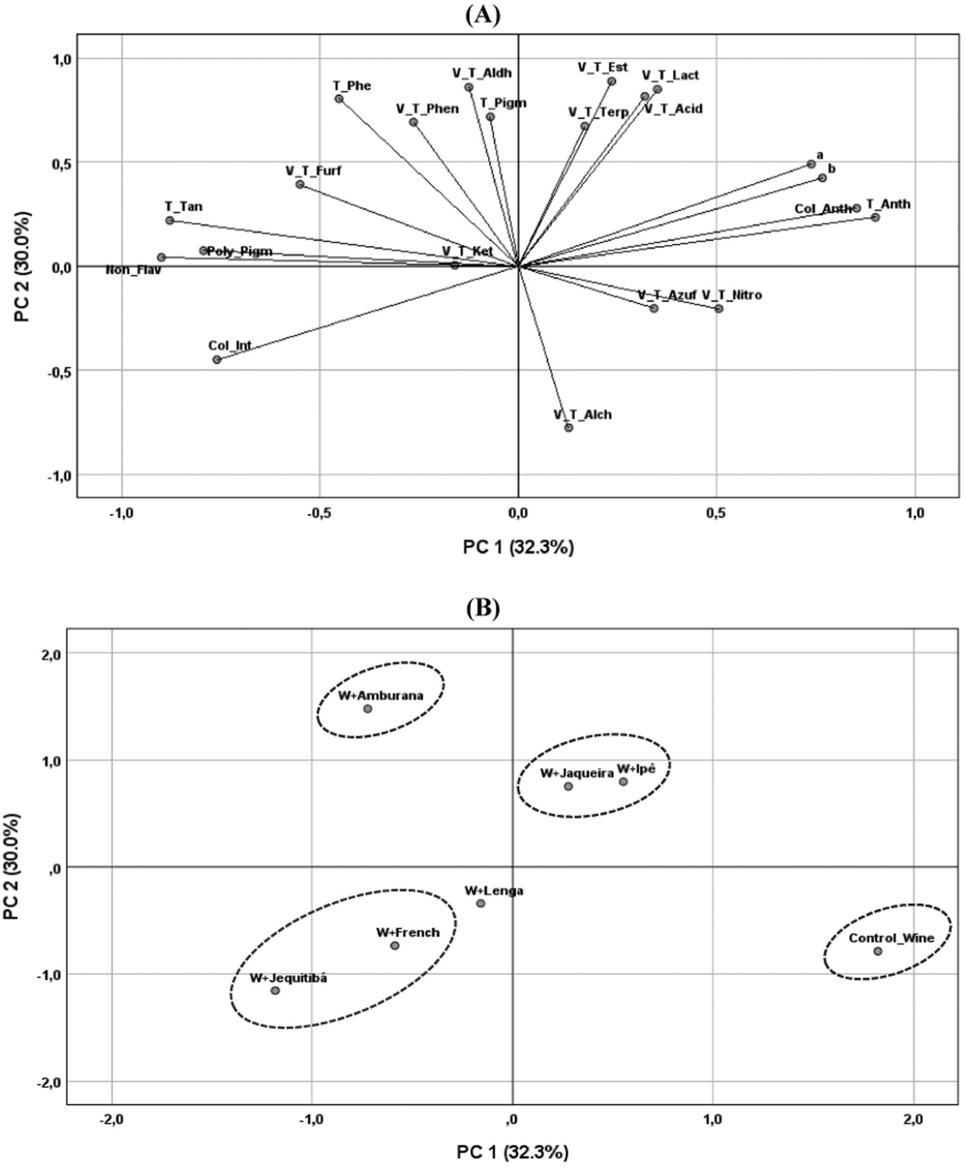

Fig. 2. Principal component analysis (PCA; PC1 and PC2) for different variables (phenolic, chromatic, and volatile variables) and Touriga Nacional red wines macerated with different wood species after 30 contact days. (A) Projection of variables; (B) Projection of red wine samples. (A) Projection of variables: *Volatile compounds* - V_T_Acid: total acids; V_T_Alch: total alcohols; V_T_Aldh: total aldehydes; V_T_Ket: total ketones; V_T_Est: total esters; V_T_Lact: total lactones; V_T_Terp: total terpenes; V_T_Phen: total phenols; V_T_Furf: total furfural derivates; V_T_Nitro: total nitrogenated derivates; V_T_Azuf: total azufrated compounds. *Phenolic parameters* - T_Phe: total phenols; Non_Flav: non flavonoid phenols; T_Tan: total tannins; T_Anth: total anthocyanins; Col_Anth: colored anthocyanins; T_Pigm: total pigments; Poly_Pigm: polymeric pigments. *Chromatic parameters* - CoI_Int: color intensity; a: component *a** (CIELab coordinate); b: component *b** (CIELab coordinate). (B) Projection of red wine samples: Control wine - wine without wood maceration; W+ French - wine macerated with French oak wood; W + Lenga - wine macerated with lenga wood; W + Jequitibá - wine macerated with jequitibá wood; W + Jaqueira - wine macerated with jaqueira wood; W + Ipê - wine macerated with ipê wood; W + Amburana - wine macerated with amburana wood.

was different among the wines, could be a consequence of oxidation reactions and interactions between wine compounds and wood components extracted, as it was previously described by other authors using model wine solutions containing different individual wine phenolic compounds and several wood components (Jordão et al., 2006; 2008; 2019).

Finally, for taste attributes and global appreciation, only the body attribute showed significant differences, among wines, after 30 contact days (Fig. 1). In that case, the wine macerated with ipê wood showed the lowest score. The other wines did not show significant differences between them, although the wine macerated with amburana wood showed a tendency for a slightly higher score compared to the others. These results generally follow a similar trend to that was detected for global phenolic parameters, where in general, no significant differences between wines were detected after 30 days of wood maceration (Table 2). Several authors reported, for short contact times, low sensory differentiation between wines stored in contact oak and other wood fragment species, namely cherry and acacia (Tavares et al., 2017; Nunes et al., 2020; Costa et al., 2021). In a previous work, Pilar Rubio-Bretón et al. (2018) reported that due to the chromatic evolution of wines and the contribution of substances which came from the oak wood, the optimal contact time between fragments and wine could be estimated as being 2 months for taste and aroma descriptors. However, at 4 months they were the ones considered with the best global characteristics. A similar trend was reported by Cano-López et al. (2008) which obtained the best sensory results in wines macerated with oak cubes after 3 and 6 months of contact. However, it should be noted that all these published works used oak wood and not woods from other species little known in terms of their oenological suitability, as was the wood species used in our research.

3.7. PCA applied to wines characterization

A Principal Component Analysis (PCA) was used to better understand the effect of the wine maceration with the different wood species in global phenolic parameters, chromatic characteristics, and volatile composition after 30 contact days (Fig. 2).

The PCA was carried out to obtain a reduced number of linear combinations of the variables that explain the greater variability in the data. Then, considering the high number of the individual volatile compounds detected in wine samples (Table A1), the total main volatile groups (acids, alcohols, aldehydes, ketones, esters, lactones, terpenes, phenols, furfural and nitrogenated derivates, and sulfured compounds) were used in the PCA analysis. Therefore, a PCA was calculated using 21 initial variables: the previous eleven cited volatile groups, seven global phenolic parameters, and three chromatic parameters.

The corresponding loading plots that established the relative importance of each variable are shown in Fig. 2A, which also shows that the first two principal components (PCs) explained 62.3 % of the total variance. The first PC (PC1, 32.3 % of the variance) was positively correlated with a^* and b^* CIELab coordinates, total anthocyanins and colored anthocyanins. However, was negatively correlated with color intensity, non-flavonoid phenols, total tannins, and polymeric pigments. The second PC (PC2, 30.0 % of the variance) was strongly positively correlated with almost all groups of volatile compounds (except for alcohols which were negatively correlated), total phenols and total pigments. The distribution of centroids of 30 days wood-macerated wines in the plane defined by the two main PCA (Fig. 2B) seems to put in evidence four different groups of wines. One group formed by red wine macerated with jaqueira and ipê woods. These wines were positively related to some of the principal volatile groups (namely, acids, terpenes, esters, lactones), and several phenolic parameters (total and colored anthocyanins). Another group comprises the wines macerated with amburana wood. In that case, this wine was characterized by higher total phenols, total pigments, and several volatile compound groups (furfural, phenols, and aldehydes derivates). The third group was formed by the red wines macerated with French oak and jequitibá woods which were positively related to color intensity. Finally, the last group comprises the control wine, which was positioned to the right side of PCA, specifically on the negative side of PC2. This wine was positively correlated with chromatic coordinates (a^* and b^* coordinates) and total and colored anthocyanins.

4. Conclusions

The results obtained in this experimental work demonstrated that the use of different South American wood species studied induced in general, an increase of the different red wine chromatic characteristics and phenolic parameters analyzed compared to wine without wood contact. This tendency was particularly evident for red wine macerated with jequitibá and oak woods. Regarding the wine volatile composition, the results also revealed that each wood specie influenced the number of total volatile compounds detected. In this case, wine macerated with jaqueira wood showed the highest number of individual volatile compounds detected. From a sensory point of view, wine macerated with amburana wood showed significantly higher scores for the majority of the several aroma and taste descriptors compared to the others.

Finally, the results obtained in our work could be of practical interest, especially when the maturation of red wines in contact with woods from other botanical species than oak may contribute to obtaining wines with potential new profiles. In any case, it is important to note that further research involving the introduction of other variables, such as the use of different wood-wine contact times, wood piece concentrations, other wood species and wood particle sizes and forms, will be necessary to improve our understanding about the potential impact of the use of South American wood species on red wine quality.

Ethics statement

The sensory evaluation section of this study involved human participants. The wine sensory evaluation did not need approval in Polytechnic University of Viseu, Portugal. Nevertheless, the privacy and rights of human subjects have been observed and informed written consent was obtained by all tasters who participated in the sensory evaluation of the wines studied.

CRediT authorship contribution statement

María L. González-SanJosé: Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation. **António M. Jordão:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ana C. Correia:** Validation, Supervision, Data curation. **Renato V. Botelho:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Miriam Ortega-Heras:** Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of consent

I declare that I accept to participate in the research study on the ***influence of the use of different woods of South American origin on the quality of red wines***, namely by participating in the wine sensory analysis sessions.

I also declare that I consent to my personal data (name, age and gender) being processed in accordance with Article 6 of European Regulation (EU) No. 2016/679 of the European Parliament relating to the protection of personnel data, and in line with the Code of Good Practices of Polytechnique University of Viseu (Portugal). In addition, I also declare that the main objectives of the research were previously explained to me by the researcher responsible for this research, and all the data obtained will be processed exclusively for research purposes (particularly in terms of the statistical treatment of the results of the wine sensory evaluation).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jfca.2024.106854.

Data Availability

Data will be made available on request.

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