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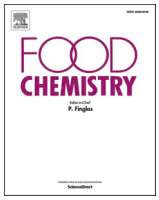

Exploring fermentative skin contact effects and post-fermentative oxidation on phenolics, aroma, and sensory characteristics in white wine

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ABSTRACT

Fermentative skin contact is increasingly applied in white winemaking, yet its compositional and sensory consequences remain underexplored. This study evaluated Arneis and Erbaluce wines produced under four maceration regimes (0, 2, 7, and 14 days), as well as the effect of post-fermentative oxygenation for each wine obtained. Phenolic composition was quantified by LC-MS/MS and spectrophotometry, volatile compounds by GC–MS, and sensory attributes through a trained panel using a Rate-All-That-Apply (RATA) approach. Extended maceration substantially increased proanthocyanidins, flavan-3-ols, hydroxycinnamates, and flavonols, reaching levels comparable to red wines, while color shifted toward deeper yellow hues. Oxygenation reduced monomeric flavanols and esters and amplified oxidative notes. Sensory evaluation revealed heightened astringency and dryness in long-macerated samples, alongside diminished fruity aromas. These findings demonstrate that fermentative maceration strongly modulates the phenolic and aroma profiles of white wines, with oxygen exposure further refining their sensory expression.

1. Introduction

White winemaking has traditionally been defined by the rapid separation of grape juice from skins to preserve relevant aroma compounds and avoid excessive phenolic extraction. However, in recent years, different maceration techniques have been proposed to increase the concentration of phenolic compounds and antioxidant activity, while also impacting wine aroma characteristics (Olejar et al., 2015). Among these, fermentative skin contact has gained increasing attention in both research and practice (Buican et al., 2023).

Skin contact in white winemaking is widely practiced, though typically restricted to the pre-fermentative stage, whose effects have been investigated in extensive literature (Arenas et al., 2021; Bestulić et al., 2022). Pre-fermentative maceration, also known as cryomaceration, consists of maintaining the grape must in contact with skins and seeds at low temperatures (usually 5–15 °C) prior to fermentation, lasting a few hours. During this process, phenolic compounds migrate from the grape solids into the grape must. Skin contact increases the content of total phenols, particularly gallic, caftaric, caffeic, and *p*-hydroxybenzoic acids, along with flavonoids (Gómez-Míguez et al., 2007), and modifies wine color (Hernanz et al., 2007). Several studies reported that pre-fermentative maceration improves wine aroma, enhancing the concentration of key compounds such as terpenes, norisoprenoids, and varietal thiols (Machado dos Santos & Kempka, 2025; Tomašević et al., 2017).

One of the main objectives of fermentative maceration is the extraction of compounds from the solid parts of the grape, with a particularly strong impact on the phenolic fraction. White wines produced through this process exhibit markedly higher total phenolic concentrations compared to those conventionally produced (Bestulić et al., 2022), reaching levels that may approach those typically found in red wines (Prezioso et al., 2024). The extraction of phenolic compounds is greatly facilitated by the presence of ethanol formed during alcoholic fermentation, which acts as a powerful solvent, enhancing the extraction of flavan-3-ols from skins and seeds (Gonzalez-Manzano

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et al., 2004).

Maceration is generally considered beneficial for aromatic grape varieties due to the high abundance of skins-extractable aroma precursors such as monoterpenes (Prezioso et al., 2024). In white wines, extended maceration not only enhances the extraction of these precursors but also influences the availability in the grape must of compounds, such as amino acids and fatty acids, involved in the formation of fermentative aroma (Buican et al., 2023).

Sensory studies showed that fermentative maceration tends to increase bitterness and astringency (Aleixandre-Tudo et al., 2015; Bestulić et al., 2022), while extended maceration can modulate overall complexity and balance. Long skin-contact treatments improved the aroma complexity of white wines with floral typicity (Radeka et al., 2023). Prezioso et al. (2024) observed in a free-choice profile task that wines macerated for 4 and 6 months displayed more flavour descriptors resulting more complex. These previous findings highlight how both the chemical and sensory impacts of maceration are crucial in determining the style and quality of white wines.

After maceration, oxygen exposure can further alter wine composition by oxidizing phenolic and volatile compounds, promoting oxidative aromas, browning, and phenolic polymerization or degradation. Phenolics extracted during maceration, particularly hydroxycinnamic acids, readily form reactive *o*-quinones, which condense or polymerize into yellow-brown pigments that drive browning and contribute to the color of orange wines (Machado dos Santos & Kempka, 2025). Oxygen also accelerates the loss of fresh fruity aromas through thiol degradation and favors the formation of aging-related compounds (Culleré et al., 2007; Ugliano, 2013). Nonetheless, the combined effects of oxygen exposure and fermentative maceration on wine composition and sensory properties require further study.

'Arneis' and 'Erbaluce', two indigenous white grape varieties from Piemonte region (Italy), are valuable models for the proposed study. Given that both are traditionally linked to fresh, fruit-forward wines, investigating alternative winemaking approaches for these varieties may provide insights into their potential to yield novel wine styles. This study examines how fermentative maceration duration and post-fermentative oxygen exposure affect the chemistry and sensory properties of Arneis and Erbaluce wines. By integrating LC-MS/MS, GC–MS, and RATA analysis, it offers new insight into how skin contact and oxygen management can shape and enhance white wine styles.

2. Materials and methods

2.1. Chemicals

Analytical-grade reagents and solvents were purchased from VWR (Radnor, PA, USA). Volatile compounds standards, sodium hydroxide, sodium metabisulphite, methyl cellulose, ammonium sulphate, phloroglucinol, ascorbic acid, sodium acetate, and anhydrous sodium chloride 99.0% were obtained from Sigma-Aldrich (St. Louis, MO, USA). Phenolic standards were supplied by Extrasynthese (Genay, France). Deionized water was prepared using a Milli-Q system (Merck, Darmstadt, Germany).

2.2. Lab-scale winemaking: maceration and oxygenation treatment

Approximately 30 kg each of *Vitis vinifera* L. cv. Arneis and Erbaluce grapes (*Vitis* International Variety Catalogue variety number *VIVC*: 626, 3925; Röckel et al., 2026) respectively from Roero and Canavese (Piemonte, Italy), were manually harvested and destemmed. The vinification protocol followed the method described by Ferrero et al. (2025) adapted for the winemaking with fermentative maceration of grapes from white varieties. After manual destemming, 'Arneis' and 'Erbaluce' berries were each divided into 12 replicates of 1.5 kg each. Berries were manually crushed into 1.5-L glass vessels previously saturated with nitrogen, then sealed using stainless steel caps fitted with airlock valves (Enolandia, Fidenza, Italy). Alcoholic fermentation was initiated by inoculating the must with 200 mg/kg *Saccharomyces cerevisiae* yeasts (FERMOL® Chardonnay, AEB SpA, Brescia, Italy) rehydrated in presence of 50 mg/kg FERMOPLUS® Energy Glu 3.0 (AEB SpA). Fermentations were conducted at 18 °C in temperature-controlled incubators (FOC200E, Velp Scientifica, Usmate Velate, Italy) and monitored daily.

For each variety, four maceration treatments were applied, differing in duration: control (CT, no maceration), short maceration (SM, 2 days), medium maceration (MM, 7 days), and long maceration (LM, 14 days). All treatments were performed in three independent replicates. At the end of each maceration period, the fermenting must was separated from the pomace using a laboratory peristaltic pump (SP 311, Velp Scientifica). The pomace was then manually pressed to recover the remaining liquid fraction. The resulting wine was transferred into 1-L glass vessels saturated with nitrogen and sealed with stainless-steel caps equipped with airlock valves, where fermentation continued. The CT treatments were pressed immediately after crushing to simulate conventional white winemaking. During maceration, two daily punch-downs were conducted using a stainless-steel plunger to submerge the pomace cap and homogenize the must. For treatments already racked, only gentle stirring was performed. At the completion of alcoholic fermentation (after 15 days for all treatments), wines were racked again and bottled in glass bottles hermetically sealed under inert conditions using a peristaltic pump (SP 311, Velp Scientifica). To ensure minimal oxygen exposure, the pump tubing, the receiving container, and the original fermentation vessel were all saturated with nitrogen before use.

After two months of storage at 4 °C (FOC200E, Velp Scientifica), the wines were subjected to an oxygenation treatment. Each sample was transferred into a 1-L beaker and stirred for 20 min at 400 rpm with a magnetic stirrer (ARE, Velp Scientifica) to achieve air saturation, defined as a dissolved oxygen concentration greater than 7 mg/L. To establish the optimal agitation duration and speed necessary to attain the target saturation, preliminary trials were performed using independent wine aliquots level. Dissolved oxygen concentrations were monitored continuously using a NomaSense O_2 P300 detector (Nomacorc, Zebulon, NC, USA) with the probe immersed directly in the liquid during mixing. Agitation was terminated once the desired concentration was reached; subsequently, the oxygenated wines were re-bottled and stored at 4 °C for two months.

2.3. Wine analysis

Wine analyses were conducted two months after the completion of fermentation (prior to oxygenation, Pre-Ox), and two months following the oxygenation treatment (Post-Ox). Basic and spectrophotometric analyses were performed on untreated wine. For high performance liquid chromatography (HPLC) and liquid chromatography-tandem mass spectrometry (LC-MS/MS) analysis, phenolic compounds were extracted from 10 mL wine aliquots (diluted to reach less than 4% v/v ethanol in the liquid) using solid-phase extraction with 1-g Sep-Pak C18 cartridges (Waters Corporation, Milford, MA, USA), preconditioned with 4 mL methanol and rinsed with 8 mL deionized water. Phenolics were eluted with 10 mL methanol, evaporated to dryness using a rotary evaporator (Laborota 4011, Heidolph Instruments, Schwabach, Germany), and reconstituted in 1 mL of methanol. The purified wine extract obtained was stored at −20 °C until analysis.

2.3.1. Wine basic parameters

Wine samples were centrifuged at 2700 ×*g* for 15 min at 20 °C (Heittich 32R, Tuttlingen, Germany) before analysis. Total acidity and pH were determined according to OIV-MA-AS313-01 and OIV-MA-AS313-15 methods (OIV, 2022), using an InoLab 730 pH meter (WTW, Weilheim, Germany). Ethanol was determined using HPLC (Agilent 1260, Agilent Technologies, Santa Clara, USA) following the method described by Giordano et al. (2009). In brief, the sample was filtered using a 0.45 µm polytetrafluoroethylene (PTFE) filter in a HPLC vial, and

Table 1
LC-MS/MS parameters for the identification and quantification of phenolic compounds.

Compound	Retention time (min)	Precursor ion (*m/z*)	Product ions (*m/z*)	DP (V)	CE (V)
(−)-Epicatechin	4.77	289	245; 109*	−85	−10; −37
(−)-Epicatechin gallate	7.30	441	289; 169*	−25	−10; −27
(−)-Epigallocatechin	3.44	305	125; 179*	−85	−10; −23
(+)-Catechin	3.80	289	245; 109*	−85	−10; −36
(+)-Catechin gallate	7.47	441	289; 169*[a]	−40	−10; −30
(+)-Gallocatechin	2.17	305	125; 179*[b]	−40	−10; −25
Caffeic acid	4.40	179	135; 134*	−50	−10; −34
Caftaric acid	2.80	311	179*; 149	−48	−10; −16
Fertaric acid	4.40	325	193; 149*[c]	−48	−10; −28
Ferulic acid	6.80	193	134*; 178	−55	−10; −19
Gallic acid	1.14	169	125; 124*	−60	−10; −34
Grape Reaction Product (GRP)	2.50	616	149*[c]; 167	−48	−10; −40
Isorhamnetin	9.90	315	151*; 271	−10	−10; −28
Isorhamnetin-3-*O*-glucoside	8.06	477	314; 243*	−48	−10; −56
Kaempferol	9.75	285	185; 117*	−115	−10; −54
Kaempferol-3-*O*-glucoside	7.94	447	284*; 227	−15	−10; −66
p-Coumaric acid	5.70	163	119; 93*	−45	−10; −49
p-Coutaric acid	3.70	295	163; 149*[c]	−48	−10; −24
Procyanidin A2	7.65	575	449*; 285	−130	−10; −40
Procyanidin B1	3.50	577	289*[d]; 425	−100	−10; −24
Procyanidin B2	4.50	577	289*; 407	−105	−10; −34
Quercetin	9.10	301	151*; 179	−100	−10; −27
Quercetin-3-*O*-glucoside	7.44	463	300; 271*	−105	−10; −59
Quercetin-3-*O*-glucuronide	7.34	477	301; 151*	−60	−10; −50

Retention times, precursor ions (*m/z*), product ions (*m/z*), declustering potential (DP, V), and collision energies (CE, V) are listed for each compound analyzed. Transitions marked with an asterisk (*) were used for quantification. Compounds labelled with superscript letters were quantified using the corresponding reference compounds: ([a]) quantified as epicatechin gallate, ([b]) as epigallocatechin, ([c]) as caftaric acid through its 2nd transition, and ([d]) as procyanidin B2.

5 μL of sample were injected into the HPLC system. An Aminex HPX-87H (Bio-Rad, Hercules, CA, USA) column was used and maintained at 65 °C temperature during analysis, with a mobile phase composed by H_2SO_4 0.0013 mol/L at 0.7 mL/min flow. Ethanol was quantified with a refractive index detector (Agilent Technologies) using external standard calibration.

2.3.2. Spectrophometric analysis

Total phenolic content and color parameters were analyzed using a UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan). The total phenolic index (TPI) was assessed by recording the absorbance at 280 nm of wine samples diluted 1:100 with deionized water, using 10-mm quartz cuvettes and with prior calibration against deionized water. Results were expressed as mg/L of (−)-epicatechin based on an external calibration curve. Color analysis was performed from the absorbance value at 420 nm on a 10-mm path length, with deionized water used as blank (De Paolis et al., 2025). Acetaldehyde was determined using a colorimetric kit (SQPE059576) with a Hyperlab Smart automatic analyzer (Steroglass, San Martino in Campo, Italy).

2.3.3. Proanthocyanidin analysis

Proanthocyanidins (PA) content in wines was quantified using the methyl cellulose precipitation assay (Sarneckis et al., 2006). HPLC analysis for the PA compositional parameters, mDP (mean degree of polymerization) and G% (percentage of galloylation), based on Kennedy and Jones (2001), was performed only on samples where PA were detectable by the spectrophotometric assay. For phloroglucinolysis, 200 μL of the purified wine extract previously obtained was mixed with 200 μL of a methanolic solution containing 0.1 mol/L HCl, 50 g/L phloroglucinol, and 10 g/L ascorbic acid. The reaction was carried out at 50 °C for 20 min and stopped by adding 1 mL of 40 mmol/L aqueous sodium acetate. After 0.45 μm filtration, 20 μL of the reaction mixture was injected into an Agilent 1260 HPLC system equipped with a LiChrospher® 100 RP-18 column (250 × 4 mm, 5 μm particle size). The mobile phases consisted of solvent A (1% formic acid in water) and solvent B (methanol), delivered at 1.0 mL/min. Gradient elution started at 5% solvent B for 10 min, increased to 20% at 20 min, and to 40% at 25 min. Detection was performed at 280 nm using a diode array detector. Data acquisition and processing were conducted using Agilent ChemStation software.

2.3.4. Phenolic composition through LC-MS/MS

The phenolic profile of the samples was analyzed using a Nexera LC-40D XR system (Shimadzu Corporation, Kyoto, Japan) coupled to a QTRAP 4500 mass spectrometer (SCIEX, Framingham, MA, USA), operated under SCIEX OS software. Chromatographic separation was achieved on a reversed-phase Zorbax RRHD Eclipse Plus C18 column (100 × 2.1 mm, 1.8 μm particle size, Agilent Technologies), protected with a corresponding Zorbax Eclipse Plus UHPLC guard column (5 × 2.1 mm, 1.8 μm particle size, Agilent Technologies). The mobile phase consisted of solvent A (0.1% formic acid in water) and solvent B (0.1% formic acid in acetonitrile), delivered at a flow rate of 0.40 mL/min. The column temperature was maintained at 40 °C. The gradient elution program was as follows: 5% B at 0 min, linearly increased to 15% B over 3 min, held at 15% B from 3 to 5 min, then increased to 70% B from 5 to 11 min. This was followed by a 2-min hold at 70% B for column washing and a subsequent 3-min isocratic equilibration step. For analysis, each wine purified extract was diluted 10 times with methanol, filtered using 0.22 μm PTFE membrane filters in an LC vial, and injected. The injection volume for all analyses was 2 μL.

The column effluent was introduced into the mass spectrometer, and analyte detection was carried out using multiple reaction monitoring (MRM) mode, based on the MS/MS transitions listed in Table 1. All analytes were ionized in negative electrospray ionization (ESI−) mode. The ion source parameters were configured as follows: spray voltage −4500 V, source temperature 550 °C, Curtain Gas at 30 psi, and Ion Source Gases 1 and 2 at 40 psi. Optimization of these parameters was performed via flow injection analysis (FIA) using a mixed standard solution comprising all target analytes. Compound-specific parameters, including declustering potential, collision energy, and collision cell exit potential, were individually optimized by direct infusion, and are detailed in Table 1. For compounds without available standards, the tentative identification was done using MRM transitions based on PubChem database (https://pubchem.ncbi.nlm.nih.gov/). For each

compound, the quantifier transition was selected as the one with higher repeatability in wine, determined by multiple injections of the same set of samples.

Calibration curves were generated from multi-level standard mixtures analyzed in triplicate. LOD and LOQ were estimated from signal-to-noise ratios at the lowest concentration, using S/N = 3 for LOD and S/N = 10 for LOQ. Validation parameters and calibration data are reported in **Table S1**. When pure standards were unavailable, structurally similar surrogates were used for quantification. Data were acquired and processed with the SCIEX OS Analytics module. Method precision, evaluated through injection repeatability, showed interday RSD values below 4%.

2.3.5. Volatile organic compounds through GC–MS

The volatile composition was determined following the method reported by Slaghenaufi and Ugliano (2018) with some modifications. Into a 20 mL headspace vial, 3.0 g of NaCl were added, followed by 5.0 mL of wine, 5.0 mL of deionized water, and 50 μL of internal standard (1-heptanol, 60 mg/L in 10% v/v ethanol). A triple-phase 50/30 μm divinylbenzene–carbon wide range–polydimethylsiloxane SPME fiber (DVB/C-WR/PDMS, Agilent Technologies) was activated into the injector at 270 °C. An automated Gerstel MultiPurpose Sampler MPS 2 (Gerstel GmbH & Co., Mülheim an der Ruhr, Germany) was used for volatile compounds extraction and injection. Samples were incubated at 40 °C for 10 min, then volatiles were extracted and adsorbed onto the SPME fiber for 60 min at 40 °C under continuous agitation (250 rpm). Desorption was performed into the GC injector at 250 °C for 5 min in splitless mode.

Volatile compounds were analyzed using an 7890A GC with a DB-WAX column (30 m × 0.25 mm, 0.25 μm, Agilent Technologies) and helium at 1.0 mL/min. The oven run (104 min) was programmed from 40 °C (5 min hold) to 200 °C at 2 °C/min, then 10 min hold and to 220 °C at 5 °C/min, then 5 min hold. Detection was performed with an Agilent 5975C MS in EI mode (70 eV), scanning *m/z* 30–350. Data was processed using Agilent ChemStation. Compounds were identified by comparison with standards, literature, and the NIST database (https://webbook.nist.gov/chemistry/). Quantification was based on external calibration and expressed as μg/L; when standards were unavailable, results were reported as μg equivalents of the internal standard (1-heptanol) per L.

2.4. Wine sensorial evaluation

Prior to the sensory sessions, participants provided informed consent to take part in the study. The study was approved by the University of Torino Ethics Committee (Approval number: 0781289).

2.4.1. Descriptor generation, training, and panel validation

Seven preparatory sensory sessions were completed before formal evaluation. Firstly, ten commercial macerated wines (vintage 2021–2022) were used to generate descriptors through individual assessment and group discussion. Panel training then familiarized assessors with aroma, taste, and mouthfeel attributes using specific references, selected fruit extracts and essential oils (**Table S2**), and a series of identification and ranking exercises; each standard was evaluated at least twice. Training concluded when at least 75% of panelists reliably identified or ranked each descriptor. A validation session with three wines confirmed panel readiness. Fourteen trained judges then conducted replicated tastings using a RATA method (0–5 intensity scale; Ares et al., 2018). Data were collected with Fizz software (version 2.7, Biosystèmes, Couternon, France) and evaluated using three-way ANOVA, which showed no significant interactions, confirming panel consistency.

2.4.2. Formal evaluation

Two formal evaluation sessions were conducted for Erbaluce and Arneis wines on consecutive days. Wines were assessed two months after alcoholic fermentation and two months after oxygenation. For each session, two types of evaluation booths were used: one for visual assessment of wine color (using transparent ISO 3591:1977 glasses; Lehmann, Reims, France), and the other for aroma, taste, and mouthfeel evaluation (using black ISO 3591:1977 glasses, Lehmann, to eliminate visual bias). For each evaluation, an aliquot of 20 mL of wine was poured in glasses coded with random three-digit numbers, covered with a petri dish and served at 18 °C. *Color intensity* and hue were rated using a 10 cm unstructured scale, with *color intensity* ranging from pale to deep, and *hue* from straw to brown. The finalized sensory sheet comprised 18 aroma descriptors (*citrus, pineapple, white pulp fruit, yellow pulp fruit, white flowers, hay/chamomile, honey, prune, dry apricot, dry figs, nuts/almond, vanilla, clove, white pepper, liqueur, cotton candy, toasted, smoked*) and 5 in-mouth descriptors (*acidity, astringency, bitterness, body, dryness*). Each treatment was presented in a randomized order with two replicates, resulting in four evaluation sets per judge.

2.5. Statistical analysis

Statistical analyses of chemical data were performed using R software (R Foundation for Statistical Computing, Vienna, Austria). To evaluate the effect of maceration duration and oxygenation, a two-way analysis of variance (ANOVA) with interaction was conducted for each variable. Where significant effects were observed, differences among maceration levels were further examined using Tukey's Honestly Significant Difference (HSD) post-hoc test, while comparisons between pre- and post-oxygenation conditions were assessed using specific *t*-test contrasts. Statistical significance was set at $p < 0.05$. Assumptions of normality and homogeneity of variances were verified using the Shapiro-Wilk and Levene tests, respectively.

Sensory data were analyzed using Fizz and R through SensoMineR package (Lê & Husson, 2008). For the analysis of aroma and in-mouth attributes evaluated using the Rate-All-That-Apply (RATA) method, a three-way ANOVA was performed, with sample, judge, and replicate treated as fixed effects, the same was applied on color descriptors on a 10-point basis. Post-hoc comparisons on the sample effect were conducted using Tukey's HSD test ($p < 0.05$). Results are expressed as mean values ± standard deviation across two replicates for each wine.

3. Results and discussion

3.1. Effect of maceration and oxygenation on wine basic parameters

Alcoholic fermentation was completed within 15 days for all treatments, yielding Arneis wines with alcohol contents ranging 11.85–12.46% *v*/v, and no significant differences among treatments. The same behavior happened in Erbaluce wines, with alcohol contents ranging 13.79–14.21% v/v. Maceration length significantly influenced most compositional parameters in both Arneis and Erbaluce wines (Table 2). It led to consistent increases in pH and corresponding reductions in total acidity, confirming previous studies (Reynolds et al., 2001; Sánchez Palomo et al., 2007), likely due to potassium extraction from grape skins and subsequent precipitation of potassium bitartrate. Notably, LM treatments resulted in acidity decreases of 24.3% in Arneis and 20.3% in Erbaluce compared to CT. As previously reported by Sancho-Galán et al. (2021), the presence of white grape skins and seeds during fermentation significantly enhances the extraction of phenolic compounds. In the present study, the Total Polyphenol Index (TPI) increased progressively with the duration of maceration, reaching its highest values in the LM treatments (4.46-fold and 4.76-fold higher than the CT samples in Arneis and Erbaluce, respectively) and attaining concentrations comparable to those typically reported for monovarietal Italian red wines (Giacosa et al., 2021). This trend is consistent with literature findings, where maceration has been shown to increase the phenolic content of white wines. Short pre-fermentative maceration periods have been associated with more modest increases of 1.8-fold in

Table 2
Characterization of wines produced with different maceration time before and after oxygenation.

Parameter	Oxygenation	Arneis wines							Erbaluce wines						
		Maceration treatment				*Sign M*	*Sign O*	*Sign MxO*	Maceration treatment				*Sign M*	*Sign O*	*Sign MxO*
		CT	SM	MM	LM				CT	SM	MM	LM			
Total acidity	Pre-Ox	6.78 ± 0.57 a	5.45 ± 0.04 b	5.28 ± 0.11 b	5.13 ± 0.04 b	***	*	*ns*	4.08 ± 0.04 a	3.41 ± 0.04 b	3.15 ± 0.11 c	3.25 ± 0.04 c	***	*ns*	*ns*
	Post-Ox	6.30 ± 0.01 a	5.18 ± 0.08 b	5.18 ± 0.08 b	5.00 ± 0.04 b				4.10 ± 0.02 a	3.40 ± 0.08 b	3.18 ± 0.02 c	3.20 ± 0.04 c			
	Sign	*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
pH	Pre-Ox	3.12 ± 0.02 c	3.49 ± 0.02 b	3.52 ± 0.02 ab	3.55 ± 0.01 a	***	*ns*	*ns*	2.93 ± 0.01 c	3.21 ± 0.02 b	3.25 ± 0.02 b	3.29 ± 0.01 a	***	*ns*	*ns*
	Post-Ox	3.13 ± 0.02 c	3.49 ± 0.02 b	3.51 ± 0.01 ab	3.54 ± 0.01 a				2.92 ± 0.02 c	3.21 ± 0.03 b	3.24 ± 0.01 b	3.30 ± 0.01 a			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
Acetaldehyde	Pre-Ox	18.0 ± 7.2 a	5.7 ± 3.8 b	1.7 ± 1.2 b	–	***	*ns*	*ns*	13.3 ± 9.5	10.3 ± 6.7	–	–	*ns*	*ns*	*ns*
	Post-Ox	9.0 ± 1.0 a	8.7 ± 3.5 b	0.7 ± 0.6 c	2.0 ± 0.1 c				12.3 ± 5.8	10.3 ± 4.7	1.0 ± 0.1	1.0 ± 0.1			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
TPI	Pre-Ox	351 ± 34 d	646 ± 9 c	1408 ± 97 b	1566 ± 145 a	***	*ns*	*ns*	496 ± 58 d	1049 ± 112 c	2073 ± 124 b	2350 ± 78 a	***	*ns*	*ns*
	Post-Ox	381 ± 5 c	688 ± 29 b	1399 ± 25 a	1514 ± 25 a				509 ± 41 d	1112 ± 47 c	2111 ± 58 b	2431 ± 16 a			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
Absorbance at 420 nm	Pre-Ox	0.15 ± 0.01 b	0.25 ± 0.03 b	0.44 ± 0.11 a	0.31 ± 0.02 a	***	***	*ns*	0.19 ± 0.06	0.27 ± 0.02	0.25 ± 0.03	0.28 ± 0.02	***	***	*
	Post-Ox	0.18 ± 0.01 b	0.43 ± 0.07 a	0.58 ± 0.10 a	0.50 ± 0.13 a				0.27 ± 0.10 c	0.43 ± 0.08 b	0.58 ± 0.10 a	0.52 ± 0.04 a			
	Sign	*ns*	*	*	**				*ns*	***	***	***			
PAs	Pre-Ox	–	–	382 ± 64 b	514 ± 46 a	**	*ns*	*ns*	–	–	515 ± 70 b	709 ± 10 a	**	***	*ns*
	Post-Ox	–	–	460 ± 11 b	513 ± 47 a				–	–	746 ± 62 b	922 ± 98 a			
	Sign			*ns*	*ns*						**	**			
mDP	Pre-Ox	–	–	3.38 ± 0.12	3.69 ± 0.09	*ns*	*ns*	*ns*	–	–	3.91 ± 0.13	3.82 ± 0.25	*ns*	*ns*	*ns*
	Post-Ox	–	–	3.49 ± 0.24	3.59 ± 0.11				–	–	3.73 ± 0.09	3.95 ± 0.07			
	Sign			*ns*	*ns*						*ns*	*ns*			
G%	Pre-Ox	–	–	2.77 ± 0.30 a	2.18 ± 0.12 b	***	*	*ns*	–	–	2.43 ± 0.22	2.49 ± 0.53	*ns*	*ns*	*ns*
	Post-Ox	–	–	3.25 ± 0.27 a	2.48 ± 0.08 b				–	–	2.60 ± 0.37	2.54 ± 0.08			
	Sign			*	*ns*						*ns*	*ns*			
(−)-epicatechin	Pre-Ox	< 0.04	1.00 ± 0.19 c	8.19 ± 0.29 b	16.10 ± 1.12 a	***	***	*ns*	< 0.04	1.62 ± 0.28 c	7.29 ± 0.20 b	13.12 ± 0.83 a	***	***	*ns*
	Post-Ox	–	0.69 ± 0.21 c	6.12 ± 0.47 b	14.28 ± 0.01 a				< 0.04	1.29 ± 0.43 c	4.67 ± 1.08 b	10.37 ± 1.17 a			
	Sign		**	***	*					***	***	*			
(−)-epicatechin-gallate	Pre-Ox	–	–	0.05 ± 0.01 b	0.08 ± 0.02 a	**	*ns*	*ns*	–	–	0.08 ± 0.01 b	0.44 ± 0.02 a	***	***	***
	Post-Ox	–	–	< 0.04	0.07 ± 0.02				–	–	0.07 ± 0.03 b	0.31 ± 0.04 a			
	Sign			*ns*	*ns*						*ns*	***			
(−)-epigallocatechin	Pre-Ox	–	–	1.02 ± 0.34 a	1.50 ± 0.11 a	**	**	*ns*	–	<0.02	1.27 ± 0.09 a	1.32 ± 0.04 a	***	**	*ns*
	Post-Ox	–	–	0.31 ± 0.15 b	0.92 ± 0.26 a				–	<0.02	0.91 ± 0.29 a	1.12 ± 0.04 a			
	Sign			**	*						**	*			
(+)-catechin	Pre-Ox	0.14 ± 0.09 d	7.56 ± 1.11 c	30.77 ± 0.39 b	43.41 ± 2.33 a	***	**	*ns*	0.21 ± 0.08 d	16.08 ± 1.53 c	36.07 ± 1.47 b	45.62 ± 1.22 a	***	**	*ns*
	Post-Ox	0.05 ± 0.02 d	6.00 ± 1.23 c	27.01 ± 0.88 b	41.94 ± 1.58 a				0.15 ± 0.03 d	14.09 ± 3.40 c	28.56 ± 5.41 b	40.75 ± 1.89 a			
	Sign	*ns*	*ns*	**	*				*ns*	*ns*	**	*			
(+)-catechin-gallate	Pre-Ox	–	–	–	< 0.04	*	*	*ns*	–	–	0.09 ± 0.02	0.07 ± 0.04	*	*ns*	*ns*
	Post-Ox	–	–	–	< 0.04				–	–	0.08 ± 0.07	0.06 ± 0.04			
	Sign										*ns*	*ns*			
(+)-gallocatechin	Pre-Ox	–	<0.02	6.09 ± 1.01	6.92 ± 0.33	***	*	*	–	0.19 ± 0.15 b	5.62 ± 0.34 a	4.92 ± 0.02 a	***	*	*ns*
	Post-Ox	–	<0.02	3.88 ± 1.11 b	6.41 ± 0.68 a				–	0.18 ± 0.16 b	4.45 ± 1.20 a	5.36 ± 0.22 a			
	Sign			*	*ns*					*ns*	*ns*	*ns*			
Gallic acid	Pre-Ox	–	0.07 ± 0.03 c	2.59 ± 0.14 b	4.46 ± 0.24 a	***	*ns*	*ns*	–	0.48 ± 0.08 c	2.59 ± 0.25 b	3.73 ± 0.66 a	***	*ns*	*ns*
	Post-Ox	–	0.06 ± 0.05 c	2.63 ± 0.26 b	5.09 ± 0.64 a				–	0.50 ± 0.21 c	2.46 ± 0.53 b	3.63 ± 0.33 a			
	Sign		*ns*	*ns*	*ns*					*ns*	*ns*	*ns*			
Procyanidin A2	Pre-Ox	–	–	–	–				–	–	0.21 ± 0.01	0.26 ± 0.01	*	***	*ns*
	Post-Ox	–	–	–	–				–	–	0.10 ± 0.04	0.13 ± 0.02			
	Sign										***	***			
Procyanidin B1	Pre-Ox	–	2.64 ± 0.72 c	25.72 ± 0.13 b	28.78 ± 0.65 a	***	*ns*	*ns*	–	7.91 ± 2.14 b	34.32 ± 1.8 a	38.46 ± 0.35 a	***	**	*ns*
	Post-Ox	–	1.45 ± 0.83 c	25.52 ± 0.92 b	31.71 ± 0.90 a				–	5.75 ± 2.41 c	26.17 ± 5.97 b	34.56 ± 1.40 a			
	Sign		*ns*	*ns*	*ns*					*ns*	*	*			
Procyanidin B2	Pre-Ox	–	0.12 ± 0.04 c	2.47 ± 0.05 b	5.54 ± 0.60 a	***	*ns*	*ns*	–	0.46 ± 0.11 c	3.12 ± 0.16 b	5.74 ± 0.31 a	***	*ns*	*ns*

(*continued on next page*)

Table 2 (*continued*)

Parameter	Oxygenation	Arneis wines							Erbaluce wines						
		Maceration treatment				*Sign M*	*Sign O*	*Sign MxO*	Maceration treatment				*Sign M*	*Sign O*	*Sign MxO*
		CT	SM	MM	LM				CT	SM	MM	LM			
	Post-Ox	–	0.07 ± 0.06 c	2.05 ± 0.14 b	5.62 ± 0.53 a				–	0.38 ± 0.16 c	2.44 ± 0.8 b	5.51 ± 0.58 a			
	Sign		*ns*	*ns*	*ns*					*ns*	*ns*	*ns*			
Caffeic acid	Pre-Ox	0.25 ± 0.06 d	1.08 ± 0.12 c	1.58 ± 0.11 b	1.85 ± 0.07 a	***	*ns*	*ns*	0.33 ± 0.08 d	0.84 ± 0.01 c	1.12 ± 0.05 b	1.14 ± 0.04 a	***	*ns*	*ns*
	Post-Ox	0.25 ± 0.02 d	1.11 ± 0.10 c	1.61 ± 0.12 b	2.00 ± 0.03 a				0.24 ± 0.08 d	0.89 ± 0.16 c	1.15 ± 0.27 b	1.30 ± 0.02 a			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
Ferulic acid	Pre-Ox	0.12 ± 0.01 d	0.15 ± 0.01 c	0.25 ± 0.02 b	0.20 ± 0.01 a	***	*ns*	*ns*	0.47 ± 0.10 c	0.57 ± 0.06 bc	0.92 ± 0.10 ab	0.97 ± 0.11 a	***	*ns*	*ns*
	Post-Ox	0.12 ± 0.01 b	0.15 ± 0.01 b	0.24 ± 0.02 a	0.21 ± 0.01 a				0.35 ± 0.12 b	0.58 ± 0.16 b	0.96 ± 0.32 a	0.98 ± 0.07 a			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
p-Coumaric acid	Pre-Ox	0.15 ± 0.02 b	0.42 ± 0.07 a	0.48 ± 0.07 a	0.41 ± 0.03 a	***	*ns*	*ns*	0.46 ± 0.13	0.34 ± 0.04	0.52 ± 0.08	0.53 ± 0.1	*	*ns*	*ns*
	Post-Ox	0.17 ± 0.01 b	0.47 ± 0.07 a	0.52 ± 0.08 a	0.47 ± 0.02 a				0.39 ± 0.12	0.39 ± 0.10	0.61 ± 0.19	0.58 ± 0.07			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
Caftaric-acid	Pre-Ox	5.3 ± 0.76 c	19.04 ± 2.4 b	35.27 ± 0.95 a	31.26 ± 3.34 a	***	*ns*	*ns*	12.54 ± 6.22 c	42.53 ± 1.89 b	68.73 ± 3.03 a	67.46 ± 7.03 a	***	*	*ns*
	Post-Ox	3.04 ± 2.73 c	15.88 ± 1.97 b	32.16 ± 7.17 a	32.11 ± 5.01 a				8.60 ± 4.12 b	42.01 ± 9.35 a	56.05 ± 10.99 a	55.52 ± 2.70 a			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*	*			
Fertaric acid	Pre-Ox	0.78 ± 0.04 c	1.17 ± 0.05 b	1.56 ± 0.04 a	1.47 ± 0.08 a	***	*ns*	*ns*	1.45 ± 0.4 b	1.76 ± 0.13 ab	2.49 ± 0.26 a	2.65 ± 0.05 a	***	*ns*	*ns*
	Post-Ox	0.76 ± 0.05 c	1.17 ± 0.01 b	1.54 ± 0.02 a	1.61 ± 0.10 a				1.03 ± 0.37 b	1.8 ± 0.41 ab	2.09 ± 0.79 a	2.66 ± 0.16 a			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
p-Coutaric-acid	Pre-Ox	3.87 ± 0.07 c	14.1 ± 0.50 b	19.28 ± 0.99 a	17.41 ± 0.95 a	***	*ns*	*ns*	5.07 ± 1.26 c	13.75 ± 1.01 b	19.21 ± 1.15 a	19.49 ± 0.30 a	***	*ns*	*ns*
	Post-Ox	2.77 ± 1.32 c	13.74 ± 1.04 b	18.98 ± 0.99 a	18.36 ± 2.05 a				3.78 ± 1.14 b	14.06 ± 2.39 a	16.41 ± 3.44 a	17.92 ± 0.79 a			
	Sign	*ns*	*ns*	*ns*	*ns*				*ns*	*ns*	*ns*	*ns*			
GRP	Pre-Ox	0.42 ± 0.10 b	0.68 ± 0.09	1.03 ± 0.22	0.63 ± 0.19	***	*	*ns*	0.29 ± 0.12 b	1.00 ± 0.17 a	0.72 ± 0.08 a	0.75 ± 0.21 a	***	*ns*	*ns*
	Post-Ox	0.19 ± 0.21 b	0.34 ± 0.10 b	0.70 ± 0.14 ab	0.54 ± 0.13 a				0.32 ± 0.20 b	0.97 ± 0.03 a	0.62 ± 0.16 a	0.80 ± 0.28 a			
	Sign	*ns*	*	*	*ns*				*ns*	*ns*	*ns*	*ns*			
Quercetin	Pre-Ox	0.02 ± 0.01 b	0.03 ± 0.03 b	0.27 ± 0.06 a	0.26 ± 0.17 a	**	***	*	0.01 ± 0.01 c	0.22 ± 0.03 bc	0.63 ± 0.19 a	0.60 ± 0.12 ab	***	*ns*	*ns*
	Post-Ox	–	0.01 ± 0.01	0.04 ± 0.03	0.01 ± 0.01				0.01 ± 0.01 b	0.10 ± 0.06 b	0.56 ± 0.40 a	0.77 ± 0.13 a			
	Sign		*ns*	***	***				*ns*	*ns*	*ns*	*ns*			
Isorhamnetin	Pre-Ox	0.01 ± 0.01	0.02 ± 0.01	0.03 ± 0.02	0.04 ± 0.01	*	*ns*	*ns*	0.01 ± 0.01	0.19 ± 0.04	0.25 ± 0.08	0.20 ± 0.02	**	*ns*	*ns*
	Post-Ox	–	–	–	–				0.02 ± 0.01 c	0.06 ± 0.04 bc	0.25 ± 0.17 ab	0.33 ± 0.08 a			
	Sign								*ns*	*ns*	*ns*	*ns*			
Kaempferol	Pre-Ox	–	–	0.15 ± 0.05	0.12 ± 0.09	*ns*	*ns*	*ns*	–	0.11 ± 0.02	0.09 ± 0.03	0.17 ± 0.17	*ns*	*ns*	*ns*
	Post-Ox	–	–	–	–				–	<0.08	0.17 ± 0.21	0.22 ± 0.24			
	Sign										*ns*	*ns*			
Quercetin-3-*O*-glucoside	Pre-Ox	–	0.22 ± 0.09 c	6.83 ± 0.33 b	6.14 ± 0.12 a	***	***	***	–	<0.06	7.95 ± 0.35 b	11.43 ± 0.87 a	***	**	*
	Post-Ox	–	–	5.36 ± 0.29	5.3 ± 0.42				–	–	5.43 ± 2.23 b	8.74 ± 0.76 a			
	Sign			***	***						**	**			
Quercetin-3-*O*-glucuronide	Pre-Ox	–	0.93 ± 0.06 c	5.23 ± 0.18 a	3.30 ± 0.28 a	***	*	*	–	2.36 ± 0.12 b	10.16 ± 0.71 a	8.79 ± 0.32 a	***	*ns*	*ns*
	Post-Ox	–	0.97 ± 0.10 c	4.65 ± 0.13 a	3.17 ± 0.31 b				–	1.95 ± 0.28 b	9.14 ± 3.38 a	7.99 ± 0.28 a			
	Sign		*ns*	*	*ns*					*ns*	*ns*	*ns*			
Kaempferol-3-*O*-glucoside	Pre-Ox	–	<0.10	0.72 ± 0.08	0.68 ± 0.01	***	***	*ns*	–	–	0.36 ± 0.01 b	1.11 ± 0.24 a	***	***	*ns*
	Post-Ox	–	–	0.47 ± 0.07	0.49 ± 0.07				–	–	0.15 ± 0.11 b	0.48 ± 0.13 a			
	Sign			**	**						**	***			

Values are presented as average ± standard deviation ($n = 3$). Sign.: *ns*, *, **, and *** indicate not significant and significant differences at $p < 0.05$, 0.01, and 0.001, respectively. Different letters within the same row indicate significant differences among values (according to two-way ANOVA and Tukey HSD post-hoc test). For oxygenation, Sign indicates the difference among values within the same column (according to two-way ANOVA and specific contrast). Sign M, O, and MxO indicate the significance levels associated with the variables maceration time, oxygenation, and their interaction (maceration × oxygenation), respectively, as determined by a two-way ANOVA.

Total acidity is expressed in g of tartaric acid/L of wine; Acetaldehyde is expressed as mg of free acetaldehyde/L; TPI: total polyphenol index is expressed as mg of (+)-catechin/L; PA are expressed as mg of (−)-epicatechin/L; mDP: mean degree of polymerization; G%: percentage of galloylation. Individual phenolic compounds are expressed as mg/L of the reference compound.

phenolics (Sánchez Palomo et al., 2007), while extended maceration resulted in a markedly greater increase, exceeding 10 times (Prezioso et al., 2024), promoted, among other factors, by the presence of ethanol during fermentation, which facilitates cell wall degradation and enhances compound diffusion.

Similarly, absorbance at 420 nm, a clear indicator of the yellow color intensity in white wines, rose markedly with extended maceration mainly up to 7 days. It is consistent with increased extraction of phenolic compounds (Bestulić et al., 2022), resulting in a higher susceptibility in the formation of oxidable *o*-quinones and other yellow pigments (Carbone & Fiordiponti, 2016). In Arneis, acetaldehyde concentrations were higher in CT wines, suggesting that the greater abundance of phenolic compounds in macerated samples may have reduced acetaldehyde accumulation, possibly through enhanced oxygen consumption by polyphenols during processing.

The effect of oxygenation on wine chemical and phenolic parameters is reported in Table 2. For pH and total acidity, post-oxygenation induced only minimal changes. TPI values were not significantly affected by the oxygenation treatment in either Arneis or Erbaluce. In both cultivars, post-oxygenation significantly enhanced the values of absorbance at 420 nm, indicating accelerated pigment oxidation following exposure to oxygen (Silva Ferreira et al., 2002). Overall, although oxygenation influenced specific oxidative markers, its effects were generally subordinate to those induced by maceration.

3.2. Effect of maceration and oxygenation on wine phenolic composition

3.2.1. Proanthocyanidins

Proanthocyanidins (PA), as quantified by the methyl cellulose precipitation assay, ranged 382–514 mg/L in Arneis and were higher in Erbaluce, with values 515–922 mg/L, considering also the Post-Ox treatments. These concentrations were lower than the average PA levels typically reported for Italian red wines (Giacosa et al., 2021). Methyl cellulose precipitable proanthocyanidins were found in detectable amounts exclusively in the MM and LM treatments, highlighting the essential role of extended maceration in promoting their extraction (Ferrero et al., 2025). This pattern was further reinforced by the consistently higher PA concentrations observed in LM compared to MM wines across both varieties, indicating that prolonged contact with grape skins and seeds enhances PA release (Prezioso et al., 2024).

The mean degree of polymerization (mDP) in white wines has been scarcely investigated in the existing literature. In this study, mDP was assessed only in samples where PA were detectable, and ranged 3.38–3.95, considering also Post-Ox treatments, which are consistent with those commonly observed in red wines (Ferrero et al., 2025). In contrast with previous results (González-Manzano et al., 2006), mDP values remained statistically unchanged across maceration times in both varieties, indicating that the duration of skin contact did not markedly influence the average polymer size of PAs for these varieties. In Arneis, the percentage of galloylation (G%) significantly decreased with increasing maceration time. This trend contrasts with previous studies on other varieties, where prolonged maceration typically increases G% due to enhanced extraction of seed-derived tannins, facilitated by greater seed hydration and permeability (Busse-Valverde et al., 2012; Martínez-Moreno & Bautista-Ortín, 2025). In contrast, no significant variation in G% was observed in Erbaluce.

PA content increased following oxygenation, particularly in Erbaluce, which may be associated with oxidative polymerization or stabilization mechanisms. Literature reports suggest that monomeric flavanols can undergo condensation reactions mediated by acetaldehyde (Cucciniello et al., 2021), forming higher molecular weight compounds that may be detectable by the methyl cellulose precipitation assay. Despite these changes in PA content, oxygenation had no statistically significant effect on mDP in either variety, indicating that polymer size remained stable. In Arneis, a significant increase in G% was observed in MM samples post-oxygenation, while no consistent pattern was evident in Erbaluce.

3.2.2. Flavan-3-ols

The concentrations of (−)-epicatechin and (+)-catechin increased progressively and significantly with maceration time, reflecting enhanced extraction from grape skins and seeds. Among all flavan-3-ols, (−)-epicatechin and (+)-catechin were the most abundant. Their concentrations in MM and LM wines remained below those typically reported in red wines after two weeks of maceration (Gambuti et al., 2004; Kocabey et al., 2016; Kovač et al., 1992). However, the levels observed were comparable to those found in other commercial Italian red wines (Arapitsas et al., 2022) and still exceeded the average concentrations reported for commercial non-macerated white wines (Goldberg et al., 1999). This highlights how the higher flavanol content in red wines is largely a consequence of extended maceration together with intrinsic varietal differences. Our results align with Bestulić et al. (2022), who reported a tenfold increase in (+)-catechin and (−)-epicatechin concentrations after 21 days of maceration of 'Malvazija istarska' grapes. Similar maceration-dependent trends were observed for (+)-gallocatechin and (−)-epigallocatechin, particularly in the MM and LM treatments; these compounds were either absent or present only in trace amounts in CT and SM wines, indicating that their presence is linked with longer maceration times. Galloylated flavan-3-ols, (−)-epicatechin-gallate and (+)-catechin-gallate, also showed increased concentrations with extended maceration, although to a lesser extent. These forms were more abundant in Erbaluce, particularly in LM wines, suggesting a varietal influence on the extractability of galloylated compounds, potentially due to differences in seed composition or structure. Galloylated forms were consistently the least abundant, never exceeding 0.5 mg/L, suggesting a limited contribution to the overall phenolic profile of white wines, even under prolonged maceration conditions. The sum of detected monomeric flavan-3-ols, expressed as mg of catechin equivalent/L is reported in Fig. 1A. Maceration exerted a pronounced effect on flavan-3-ols, with concentrations increasing by over two orders of magnitude from CT to LM treatments. Maceration significantly increased also procyanidin B1 and B2 concentrations in both Arneis and Erbaluce, with the highest levels observed in MM and LM treatments. In contrast, procyanidin A2 was not detected in Arneis wines and was only found at later maceration stages in Erbaluce, suggesting limited extractability or lower initial abundance.

Oxygenation led to a significant decrease in (−)-epicatechin and (+)-catechin levels in both varietals tested, suggesting oxidative degradation or condensation reactions (Cucciniello et al., 2023), as evidenced by the increase in methyl cellulose precipitable PA content. The decline was more evident in MM and LM treatments, where these compounds were more abundant. A slight decline was observed for (+)-gallocatechin, notably in Arneis, whereas (−)-epigallocatechin was less consistently affected by oxidation, showing a significant reduction only in Arneis MM. The sum of flavan-3-ols was significantly reduced in both varieties following oxygenation (Fig. 1A), particularly in the MM and LM treatments, where pre-oxidation concentrations were highest. In Arneis, reductions of 18.8% and 6.8% were observed in MM and LM, respectively, while in Erbaluce, the corresponding decreases were 25.4% and 13.9%.

3.2.3. Hydroxycinnamic acids and derivatives

White grape varieties typically exhibit higher concentrations of hydroxycinnamic acids (HCA) than red varieties (González de Peredo et al., 2021). These compounds are present in wines both as free acids and as tartaric acid esters (HCTA). In the present study, free hydroxycinnamic acids (namely caffeic, *p*-coumaric, and ferulic acids) showed moderate but consistent increases with maceration in both Arneis and Erbaluce, with the highest concentrations generally observed in the LM treatments. Among the tartaric esters, caftaric and *p*-coutaric acids were the most abundant, with significantly elevated levels in the MM and LM wines of both varieties. Fertaric acid also increased with maceration,

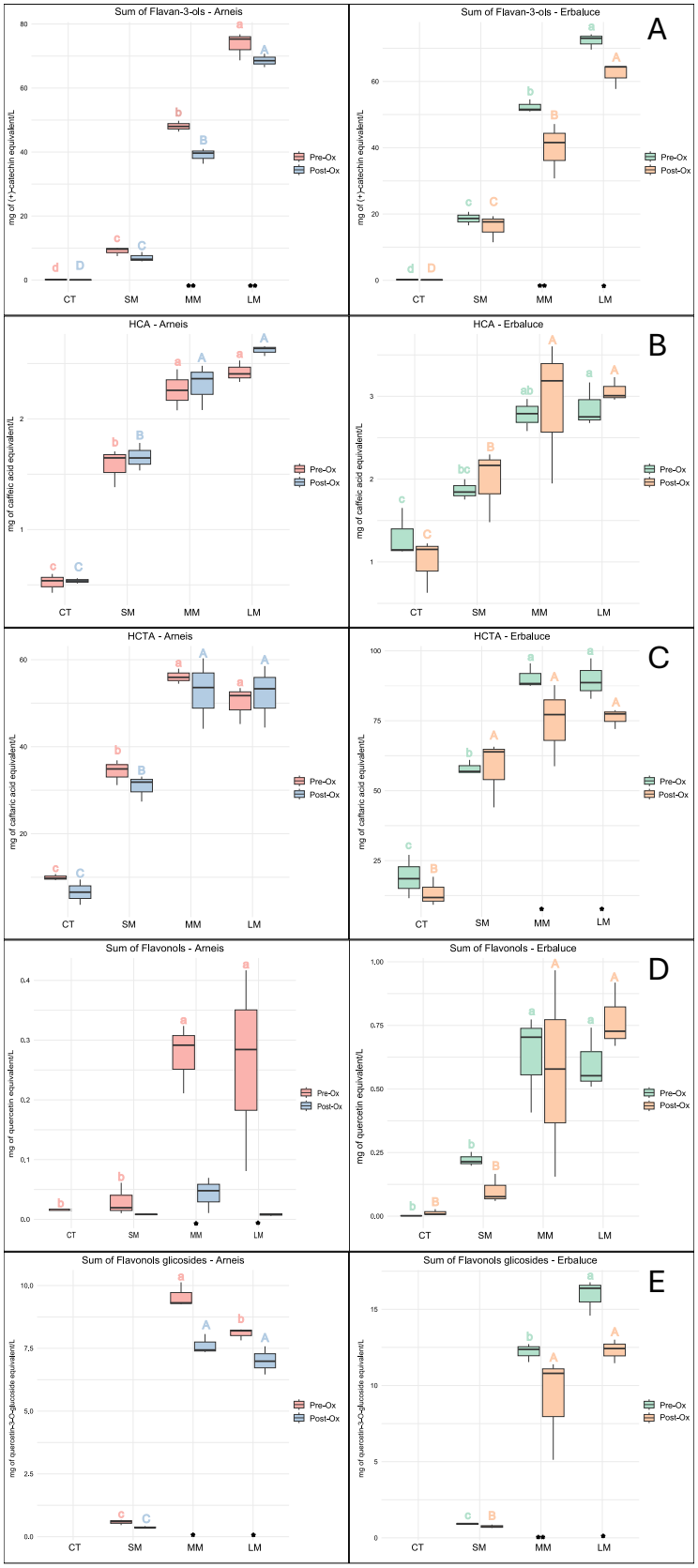

Fig. 1. Phenolic composition of Arneis and Erbaluce wines before and after post-fermentative oxygenation, determined through LC-MS/MS analysis and grouped according to their phenolic class: (A) flavan-3-ols, (B) hydroxycinnamic acids, (C) tartaric esters of hydroxycinnamic acids, (D) flavonol aglycones, and (E) flavonol glycosides. Letters indicate significant differences ($p < 0.05$) among maceration treatments, with red lowercase letters referring to Pre-Ox and blue uppercase letters to Post-Ox in Arneis wines, and green lowercase letters referring to Pre-Ox and orange uppercase letters to Post-Ox in Erbaluce wines. Asterisks denote significant

differences between Pre-Ox and Post-Ox at each maceration level (* $p < 0.05$; ** $p < 0.01$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

although to a lesser extent, particularly in Erbaluce. The total concentrations of HCA and HCTA increased progressively with maceration time (Fig. 1B–C), with LM treatments consistently exhibiting the highest values. This pattern indicates enhanced extraction from grape skins and pulp, more markedly in Erbaluce. These findings are consistent with previous reports showing that caftaric acid undergoes significant extraction already after 24 h of maceration (Gómez-Míguez et al., 2007), while extended fermentative maceration leads to even higher concentrations (Bestulić et al., 2022; Korenika et al., 2014), confirming the progressive extraction of these compounds with prolonged skin contact.

The effect of oxygenation on HCAs and HCTAs was generally limited (Fig. 1B-C). A significant reduction was observed only for caftaric acid in Erbaluce wines, particularly in the MM and LM treatments, where this compound was most abundant. In these samples, sum of HCTAs decreased by 17.8% and 15.1%, respectively. Our findings are consistent with those of Bestulić et al. (2022), who reported a decline in caftaric acid concentrations in wines produced with maceration lasting up to 21 days due to oxygen contact. This reduction may be attributed to enzymatic oxidation, as caftaric acid serves as a primary substrate for such reactions. Notably, the other HCAs and HCTAs remained largely unaffected by oxygen exposure, indicating a relative stability of these compounds under the applied oxidative conditions. This limited response may be explained by the higher oxidation susceptibility of caftaric acid, which acts as the primary substrate for polyphenol oxidase-mediated reactions and quinone formation. Once caftaric acid is depleted or converted, the oxidative cascade may slow down or effectively stop, leaving the other cinnamic derivatives largely unaffected.

3.2.4. *Flavonols and flavonol glycosides*

Quercetin, kaempferol, and isorhamnetin were significantly influenced by maceration in both Arneis and Erbaluce. Although individual concentrations remained very low (always below 1 mg/L), levels increased with maceration time, with the highest values consistently observed in LM treatments, reflecting progressive extraction from grape skins. Kaempferol was not detected in CT wines, while quercetin and isorhamnetin were generally more abundant in Erbaluce, indicating a possible varietal influence on flavonol composition. These findings align with previous studies reporting low levels of quercetin even in wines subjected to fermentative maceration (Aleixandre-Tudo et al., 2015), while kaempferol and isorhamnetin were often absent or detected only in trace amounts (Korenika et al., 2014).

Kaempferol-3-*O*-glucoside was detected only in MM and LM treatments, indicating its extraction requires extended skin contact. Quercetin-3-*O*-glucuronide and quercetin-3-*O*-glucoside were absent in CT wines and accumulated with maceration. Among these, quercetin-3-*O*-glucoside was the most abundant form, particularly in Erbaluce, which exhibited overall higher levels of flavonol glucosides than Arneis. Notably, the concentration of quercetin-3-*O*-glucuronide peaked in MM treatments but declined in LM, suggesting a potential degradation of this compound during prolonged maceration. The sum of flavonol aglycones (i.e., quercetin, kaempferol, and isorhamnetin, expressed as quercetin equivalents) also showed significant increases with maceration (Fig. 1D). A similar maceration-dependent pattern was observed for flavonol glucosides (Fig. 1E).

Flavonols exhibit extraction dynamics comparable to those of anthocyanins; however, due to the lower polarity of their backbone structures, their release into the wine occurs more gradually under typical winemaking conditions (Casassa & Harbertson, 2014; Morel-Salmi et al., 2006). However, Hernanz et al. (2007) demonstrated that even short periods of pre-fermentative skin contact can facilitate the extraction of quercetin glycosides into white wines. Consistent with these findings, the present study showed that MM and LM resulted in free and glycoside flavonol concentrations approaching those commonly reported in Italian red wines (Simonetti et al., 1997), highlighting the efficiency of extended skin contact in promoting the transfer of these phenolic compounds from grape skins into the wine.

In Arneis, isorhamnetin and kaempferol aglycones were no longer detectable following oxygenation, regardless of maceration length, showing a high susceptibility to oxidative degradation. Quercetin aglycone also decreased significantly in Arneis MM and LM, suggesting susceptibility to oxidation (Castellari et al., 2000) or a possible insolubilization of this compound, potentially with a similar process as evidenced in red wines (Gambuti et al., 2020). In contrast, flavonol aglycones concentration remained stable in Erbaluce, suggesting greater oxidative stability in this cv. Therefore, the sum of flavonol aglycones (Fig. 1D) showed significant decreases only in Arneis MM and LM, while flavonol contents in Erbaluce remained largely stable.

Quercetin-3-*O*-glucoside showed a reduction upon oxygenation in both cultivars, while quercetin-3-*O*-glucuronide concentrations remained stable, indicating differing sensitivities to oxidation. Kaempferol-3-*O*-glucoside decreased post-oxygenation in both varietals, reinforcing the notion that certain glycosylated flavonols are more susceptible to oxidative loss. The sum of flavonol glycosylated forms (Fig. 1E) were overall more susceptible to oxidation, showing significant reductions in MM and LM treatments in both varieties. In Arneis, flavonol glucosides decreased by 20.4% and 13.3% in MM and LM, respectively, whereas in Erbaluce, reductions of 25.5% and 22.7% were observed.

The interaction between maceration and subsequent oxygenation was not statistically significant for most parameters (Table 2), indicating that the oxidative response was largely additive and not dependent on the extraction level. Overall, oxygenation contributed to modulating the final flavanol profile primarily through degradation and transformation of free monomeric forms rather than altering extraction efficiency.

3.3. *Effect of maceration and oxygenation on volatile organic compounds*

The comprehensive volatile profiles of the experimental wines are shown in Fig. 2, with full data available in **Table S3**. Fermentative maceration significantly influenced the aroma composition in both Arneis and Erbaluce, although the direction and extent of these modifications were highly dependent on both chemical class of volatiles and grape variety.

3.3.1. *Esters*

In Arneis, total ester concentrations generally decreased with increasing maceration time, although individual compounds exhibited distinct behavior (Fig. 2A). Isoamyl acetate, ethyl acetate, ethyl lactate, and ethyl octanoate were the most abundant esters detected (**Table S3**). In scientific literature, a general decrease in ester concentration has been consistently reported in wines subjected to skin contact or prolonged maceration. Wines fermented on skins or with pre-fermentative maceration showed significantly lower levels of total esters and individual acetate and ethyl esters compared with control wines (Aleixandre-Tudo et al., 2015). Similar reductions in straight-chain ethyl esters and acetate esters were observed in wines undergoing extended maceration and barrel maturation (Lukić et al., 2015), as well as during long maceration of Minutolo wines (Prezioso et al., 2024). These decreases have been attributed to several mechanisms, including adsorption of volatile esters onto grape skin macromolecules or yeast lees, hydrolysis of esters under acidic conditions or due to enzymatic activity (esterases released during maceration), and inhibition of biosynthesis of fatty acid precursors during fermentation in musts rich in solids (Ancín-Azpilicueta et al., 2009; Câmara et al., 2006; Liberatore et al., 2010). In

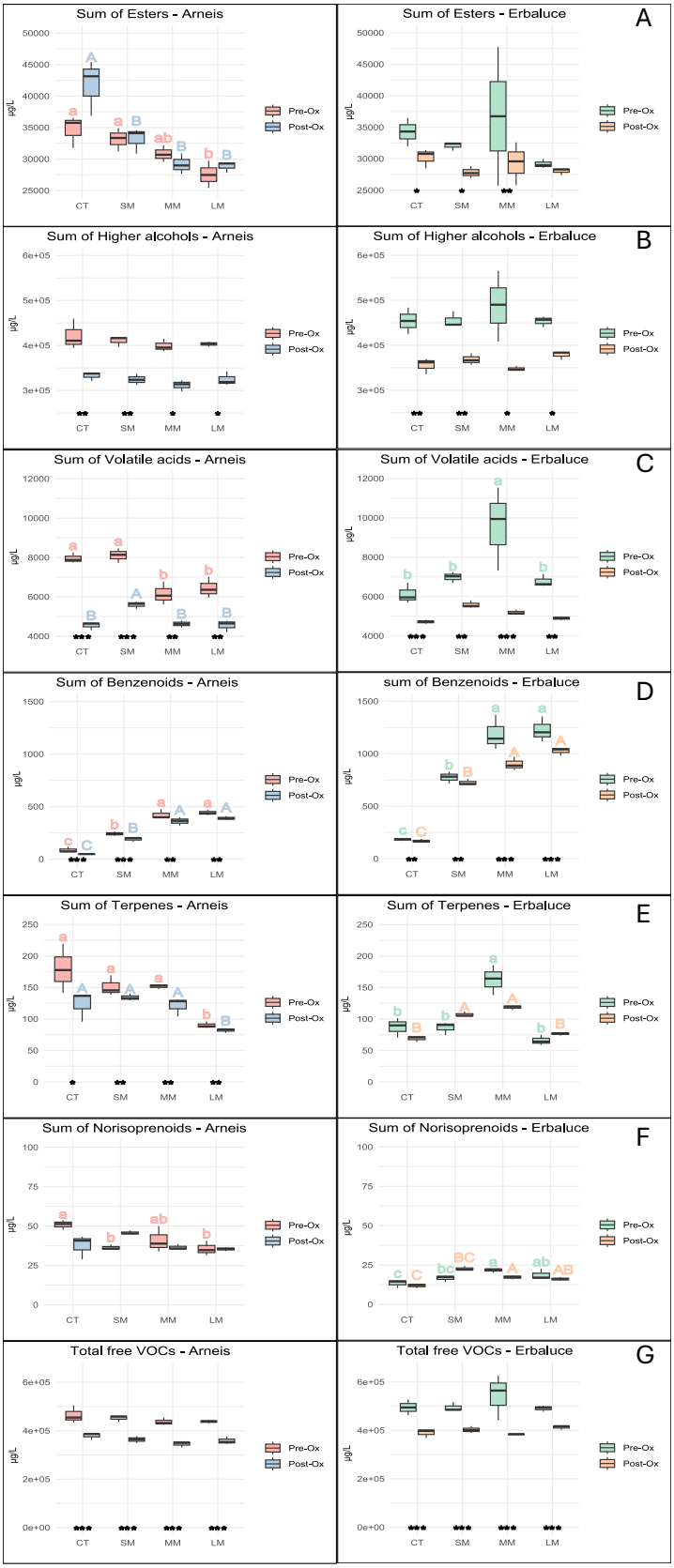

Fig. 2. Free volatile organic compounds of Arneis and Erbaluce wines before and after post-fermentative oxygenation, determined by GC–MS and grouped according to their chemical class: (A) esters, (B) higher alcohols, (C) volatile acids, (D) benzenoids, (E) terpenes, (F) norisoprenoids, and (G) sum of total free volatiles. Letters indicate significant differences ($p < 0.05$) among maceration treatments, with red lowercase letters referring to Pre-Ox and blue uppercase letters to Post-Ox in Arneis wines, and green lowercase letters referring to Pre-Ox and orange uppercase letters to Post-Ox in Erbaluce wines. Asterisks denote significant differences between Pre-

Ox and Post-Ox at each maceration level (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

contrast, Erbaluce showed greater overall ester stability. Several esters remained relatively unaffected by maceration, while some displayed moderate decreases and others accumulated during fermentation, suggesting a more balanced modulation of ester metabolism in this variety. However, some trends were similar in both varieties, showing higher concentrations of ethyl hexanoate, methyl octanoate, and methyl decanoate in all macerated wines, while other compounds (ethyl heptanoate, ethyl 9-decenoate, and isoamyl octanoate) increased at the beginning of maceration and then decreased, as well as isoamyl acetate and 2-phenylethyl acetate achieved the highest concentrations in MM samples. Prezioso et al. (2024) also reported an increase in ethyl hexanoate and isoamyl acetate in Minutolo and Verdeca white wines after 1-month maceration whereas 2-phenylethyl acetate markedly decreased. The effect of oxygenation on total ester concentration was significant only in Erbaluce, while no differences were observed in Arneis. In this latter variety, the impact of oxygen exposure varied among individual compounds. Most esters decreased following oxygenation, whereas ethyl lactate and ethyl isoamyl succinate increased, resulting in no substantial change in the overall esters content in Arneis. In Erbaluce, a similar trend was observed; however, the overall loss of esters was more pronounced, leading to post-oxidation CT, SM, and MM wines with lower total ester concentrations. The increased concentration of ethyl isoamyl succinate is in agreement with other studies that evidenced higher concentrations of branched-chain ethyl esters during aging whereas lower ones of $C_3 - C_{10}$ fatty acid esters and acetate esters (Ugliano, 2013).

3.3.2. Higher alcohols

Except for 1-hexanol and 1-propanol, which exhibited moderate decreases (**Table S3**), the concentrations of all other higher alcohols either increased or remained unchanged with increasing maceration time in Arneis wines, resulting in no significant variation in total higher alcohol content (Fig. 2B). A similar trend was observed in Erbaluce, where higher alcohol levels were largely unaffected by maceration, although in this case only propanol showed a decreased concentration. Among the most present higher alcohols in the wines studied, only 2-phenylethanol concentrations showed a significant increase in MM samples, compared to CT wine, for Erbaluce. Therefore, in contrast with previous findings reporting general increases of higher alcohols (Aleixandre-Tudo et al., 2015; Rodrıguez-Bencomo et al., 2008), the total concentration of higher alcohols remained unchanged with prolonged maceration. However, Sánchez Palomo et al. (2006) observed a significant reduction in fermentation-derived alcohols in wines produced with skin contact, likely due to the higher nitrogen content of these musts. This decrease has been attributed to the regression of the Ehrlich pathway, it being the principal pathway for higher alcohol formation during fermentation. Furthermore, Radeka et al. (2023) also observed a significant decrease in all higher alcohols for maceration times less than 21 days in Malvazija istarska white wines. Oxygenation led to a general reduction in higher alcohol concentrations in both varieties, likely due to oxidative degradation and volatilization processes promoted by increased oxygen exposure, which can accelerate the conversion of alcohols into corresponding aldehydes.

3.3.3. Volatile acids

Volatile acids exhibited variety-dependent behaviors (Fig. 2C). In Arneis, extended maceration was associated with a progressive decrease in volatile acid concentrations, with the highest levels detected in CT and SM wines, suggesting that prolonged skin contact may reduce the formation of these compounds or promote their adsorption on skins and lees (Prezioso et al., 2024). This decrease is consistent with the results reported for wines produced with different maceration times up to 42 days (Radeka et al., 2023) and also with skin-contact fermentation (Aleixandre-Tudo et al., 2015). In contrast, Erbaluce showed an opposite trend, with MM treatments often yielding elevated volatile acid levels. Following oxygen exposure, a sharp decrease in volatile acid concentrations was observed in all wines, except for hexanoic acid in CT and SM wines for Erbaluce variety. In Arneis, SM wines retained comparatively higher levels than other treatments, whereas in Erbaluce the differences among maceration treatments were no longer significant for total volatile acid concentrations, suggesting that oxidative processes may have levelled out treatment-dependent variability by promoting further chemical transformations.

3.3.4. Benzenoids

The concentrations of benzenoid compounds and volatile phenols (4-vinylguaiacol) increased progressively with maceration in both varieties (Fig. 2D), reflecting enhanced extraction of precursors from grape skins (Widhalm & Dudareva, 2015). Consistently with similar studies (Lukić et al., 2015), the accumulation of benzenoids was particularly pronounced in long macerated wine. Erbaluce LM wines showed total concentrations exceeding 1000 μg/L, indicating a substantial release of aroma compounds under extended skin contact. After oxygenation, benzenoid levels decreased across all treatments, consistent with oxidative degradation or transformation/rearrangement of these compounds. Benzenoids, like other phenolic compounds, are a key substrate for oxidation reactions. Nevertheless, the relative differences among maceration treatments were preserved, suggesting that the initial extraction patterns exerted a lasting influence on the aroma composition of the wines.

3.3.5. Terpenes and norisoprenoids

Total concentration of terpenes and norisoprenoids exhibited non-linear responses to maceration that were variety-dependent (Fig. 2E–F). In Arneis, LM treatments showed a significantly lower content of these compounds compared to CT, likely attributable to oxidative degradation, enzymatic conversion, chemical rearrangements, or interactions with other matrix components during extended skin contact (Yang et al., 2023), whereas MM treatments yielded the highest concentrations in Erbaluce. However, different compounds showed diverse trends with skin maceration. Specifically, monoterpenols (linalool, α-terpineol, and β-citronellol) achieved the highest concentrations in MM wines for both varieties, but they were not significantly different to those in LM wines, except for linalool. Nerolidol and farnesol are sesquiterpene alcohols increasing in MM wines and decreasing for longer skin contact, but this increase was significant only for Erbaluce. Terpene hydrocarbons, such as α-ionene, decreased with increasing skin-contact time for both varieties. Individual norisoprenoids also showed different trends, decreasing the concentrations of TDN and β-damascenone with maceration whereas increasing those of β-ionone in both varieties. These trends are consistent with the evolution of terpenes and norisoprenoids during fermentative maceration of white grapes cv. Malvazija istarska, although the increase observed in the monoterpenol concentrations was linear from 7 to 42 days of skin contact, probably due to higher precursor concentrations in the skin of this aromatic variety (Radeka et al., 2023). Oxygen exposure had no significant impact on the total terpenes and norisoprenoids contents, except for Arneis where a general reduction in the terpene content was observed post-oxygenation, as previously reported for white wines by Silva Ferreira et al. (2002). In all other cases, oxygenation did not modify the overall abundance of these two compound classes, although shifts in individual compound distributions were evident, suggesting compound-specific susceptibilities to oxidative reactions. Furthermore, the molecular rearrangement may influence the different behavior of

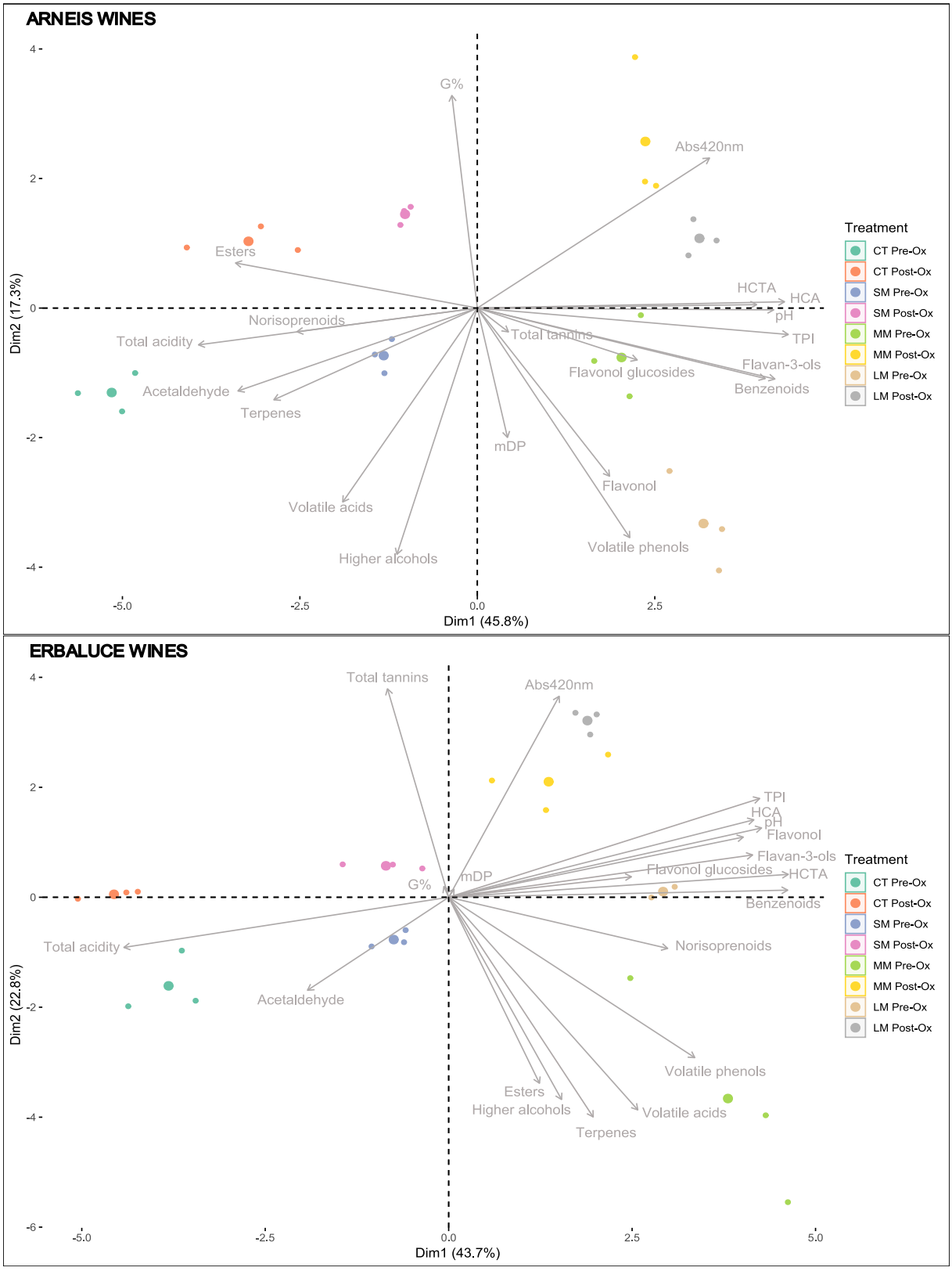

Fig. 3. Principal component analysis (PCA) of key compositional and color parameters in Arneis and Erbaluce wines as affected by maceration length (CT, SM, MM, LM) and oxygenation (Pre-Ox, Post-Ox). Vectors represent major compositional and color variables; small points indicate treatment replicates, while the larger point indicates the average among replicates of the same condition (maceration length and oxygenation).

Table 3
Sensory characteristics of produced Arneis and Erbaluce wines.

Parameter	Arneis wines						Erbaluce wines					
	Oxygenation	Maceration treatment				Sign M	Maceration treatment				Sign M
		CT	SM	MM	LM		CT	SM	MM	LM	
Acidity	Pre-Ox	3.12 ± 0.05 a	2.58 ± 0.16 b	2.65 ± 0.05 ab	2.69 ± 0.01 a	*	3.25 ± 0.05	2.82 ± 0.05	2.96 ± 0.15	2.79 ± 0.20	ns
	Post-Ox	2.92 ± 0.24	2.50 ± 0.35	2.92 ± 0.24	2.58 ± 0.12	*	3.40 ± 0.14	3.00 ± 0.01	2.75 ± 0.35	3.00 ± 0.01	ns
Bitterness	Pre-Ox	1.77 ± 0.33	1.92 ± 0.22	2.23 ± 0.11	2.08 ± 0.01	ns	1.39 ± 0.05	1.68 ± 0.25	1.36 ± 0.20	1.50 ± 0.40	ns
	Post-Ox	1.58 ± 0.12	1.58 ± 0.35	1.58 ± 0.24	2.08 ± 0.01	ns	1.77 ± 0.32	1.82 ± 0.01	1.36 ± 0.01	1.91 ± 0.13	ns
Dryness	Pre-Ox	1.88 ± 0.38	2.04 ± 0.05	1.96 ± 0.05	2.08 ± 0.22	ns	2.04 ± 0.15	2.04 ± 0.35	2.07 ± 0.20	2.29 ± 0.10	ns
	Post-Ox	1.60 ± 0.06 b	1.7 ± 0.26 b	2.20 ± 0.13 a	2.30 ± 0.45 a	***	2.91 ± 0.39	2.41 ± 0.19	2.45 ± 0.13	2.68 ± 0.06	ns
Astringency	Pre-Ox	1.62 ± 0.01 b	1.42 ± 0.16 b	1.96 ± 0.16 ab	2.31 ± 0.01 a	***	1.68 ± 0.15 b	1.61 ± 0.25 b	2.04 ± 0.35 ab	2.54 ± 0.25 a	***
	Post-Ox	1.67 ± 0.24 b	1.75 ± 0.12 b	2.63 ± 0.06 a	2.79 ± 0.06 a	***	1.89 ± 0.16 b	1.72 ± 0.08 b	2.78 ± 0.31 a	2.89 ± 0.47 a	***
Body	Pre-Ox	1.88 ± 0.16	2.08 ± 0.11	1.85 ± 0.11	1.73 ± 0.16	ns	1.93 ± 0.20 ab	1.71 ± 0.10 b	2.11 ± 0.05 a	1.79 ± 0.10 b	**
	Post-Ox	1.92 ± 0.01	1.75 ± 0.24	2.08 ± 0.01	2.00 ± 0.12	ns	1.68 ± 0.19	1.91 ± 0.51	2.05 ± 0.19	1.86 ± 0.06	ns
Color intensity	Pre-Ox	2.57 ± 0.24 b	4.32 ± 0.55 a	3.98 ± 0.56 ab	4.25 ± 0.40 a	**	3.91 ± 0.66 a	3.31 ± 0.07 ab	3.05 ± 1.14 ab	2.52 ± 0.42 b	**
	Post-Ox	2.67 ± 1.06 b	2.74 ± 0.19 b	5.08 ± 0.07 a	4.57 ± 0.54 a	***	2.16 ± 0.40 b	2.46 ± 0.07 b	4.48 ± 0.05 a	4.84 ± 0.64 a	***
Hue	Pre-Ox	3.24 ± 0.05 c	5.71 ± 0.28 b	6.47 ± 0.05 a	6.31 ± 0.09 a	***	3.09 ± 0.03 c	5.90 ± 0.10 b	6.27 ± 0.03 b	7.13 ± 0.20 a	***
	Post-Ox	2.37 ± 0.10 c	6.48 ± 0.09 b	7.50 ± 0.21 a	7.30 ± 0.01 a	***	1.61 ± 0.17 c	6.42 ± 0.13 b	7.39 ± 0.01 a	7.43 ± 0.39 a	***

Values are presented as average ± standard deviation ($n = 3$). Sign.: *ns*, *, **, and *** indicate not significant and significant differences at $p < 0.05$, 0.01, and 0.001, respectively. Different letters within the same row indicate significant differences among values (according to two-way ANOVA and Tukey HSD post-hoc test). Sign M indicates the significance levels associated with the maceration time.

monoterpenols after oxygen exposure (Yang et al., 2023).

Despite these compositional shifts, the total concentration of volatiles (Fig. 2G) remained relatively constant across treatments, indicating that maceration primarily redistributed the aromatic profile rather than altering the overall volatile content. Oxygen exposure negatively affected most volatile classes, primarily through oxidative degradation, yet the relative differences among maceration treatments were largely preserved.

3.4. Multivariate evaluation of wine phenolic and chemical composition

Key compositional and color parameters, as well as phenolic and volatile classes were subjected to Principal Component Analysis evaluations for Arneis and Erbaluce wines. The PCA of Arneis wines (Fig. 3A, PC1 = 45.8%, PC2 = 17.3%) revealed a clear separation of samples according to maceration length along PC1. CT wines clustered on the negative side of PC1, associated with higher total acidity, acetaldehyde, terpenes, norisoprenoids, and esters, reflecting a fresher, fruit-driven aromatic profile with minimal phenolic extraction. In contrast, MM and LM wines were positioned on the positive side of PC1, strongly aligned with higher concentrations of phenolic and color-related compounds (flavonol glucosides, flavan-3-ols, Abs420nm, and TPI), consistent with extensive extraction during prolonged skin contact. SM wines occupied intermediate positions, reflecting a progressive compositional shift driven by maceration. PC2 primarily captured well the influence of oxygenation, with Post-Ox wines all positioned in the positive PC2 side and opposed to their Pre-Ox counterparts. Significantly, Pre-Ox LM and MM samples grouped closely together within one quadrant, while Post-Ox LM and MM wines shifted to a different quadrant, separating from their pre-oxygenation counterparts. This suggests that while maceration defined the main compositional axis, oxygen exposure introduced a secondary structuring effect, redistributing phenolic and volatile compounds in a coordinated way within the macerated wine group.

When compared with Erbaluce wines PCA (Fig. 3B, PC1 = 43.7%, PC2 = 22.8%), several similarities emerged. In both varieties, maceration length was the dominant driver of compositional variance, with a clear transition from fruit- and acid-driven profiles in CT wines toward phenolic- and color-enriched profiles in MM and LM wines. In both varieties, oxygen exposure emerged as a secondary factor, contributing to intra-group variability and separating clusters along the PC2 axis. However, Erbaluce wines displayed a broader distribution along both PCs, indicating greater intra-group variability and a more complex interaction between phenolic and volatile fractions. Moreover, in Erbaluce, MM and LM wines were more strongly associated with a wider set of phenolic and volatile parameters that exhibited stronger intercorrelations, whereas in Arneis these variables appeared more independent, suggesting a less integrated compositional response to maceration. These observations suggest that while the overall impact of maceration on compositional structuring is conserved between the two cultivars, the specific compounds driving this differentiation reflect underlying varietal differences in phenolic composition, aromatic precursors, and matrix interactions.

3.5. Impact of maceration on wine sensory properties

3.5.1. In-mouth attributes

The wine in-mouth sensory properties and color are reported in Table 3. As a limitation of the experimental plan performed, the sensory evaluations have been conducted in separate sessions at different times (Pre- and Post-Ox), therefore a comparison between the oxygenation cross-condition could not be reliably made. Therefore, the discussion of sensory outcomes is limited to the effects of maceration within each oxygenation condition independently.

In Arneis, significant differences in *acidity* were observed among maceration treatments in both Pre-Ox and Post-Ox. Under Pre-Ox, CT

samples exhibited the highest acidity, while acidity perception decreased in the other treatments, indicating that maceration reduced perceived acidity, as also confirmed by values reported in Table 2. After oxygenation, these differences were no longer perceived by the panel, possibly due to a masking or balancing effect. Erbaluce did not show significant differences in acidity. The limited influence of skin contact on perceived acidity in Erbaluce may be explained by the lower decrease in total acidity observed during maceration compared to that found in Arneis wines.

No significant differences in bitterness were detected across maceration levels in either Arneis or Erbaluce at the two points. Similarly, *dryness* and *body* perceptions were largely unaffected by maceration length, with few exceptions. In Arneis, a significant difference emerged under Post-Ox conditions, where wines from the MM and LM treatments were perceived as drier than those from the CT and SM treatments. In Erbaluce, body was significantly influenced by maceration, with MM samples showing higher perceived values than SM and LM. This suggests that extended maceration may impact on body and dryness, as strongly connected with the astringency perception and the PA content (Paissoni et al., 2023). In fact, astringency was the most affected sensory parameter, increasing significantly with maceration duration in both varieties in both oxygenation conditions. In Arneis, LM samples consistently exhibited the highest astringency in both Pre-Ox and Post-Ox treatments, while CT and SM samples showed lower values. Erbaluce followed a similar trend, with a progressive increase in astringency from CT to LM across both conditions. These results confirm the impact of extended maceration in the increase of phenolic compounds and their perceptible role in the wine produced. Notably, this increase persists even after oxygen exposure, in line with the PA content of the wines that were unaffected or increased (Table 2). Individual low-molecular mass phenols, decreasing in Post-Ox, are known to play a minor role in astringency perception, and in this study did not influence bitterness. Instead, maceration length significantly affected color intensity in both varietal wines.

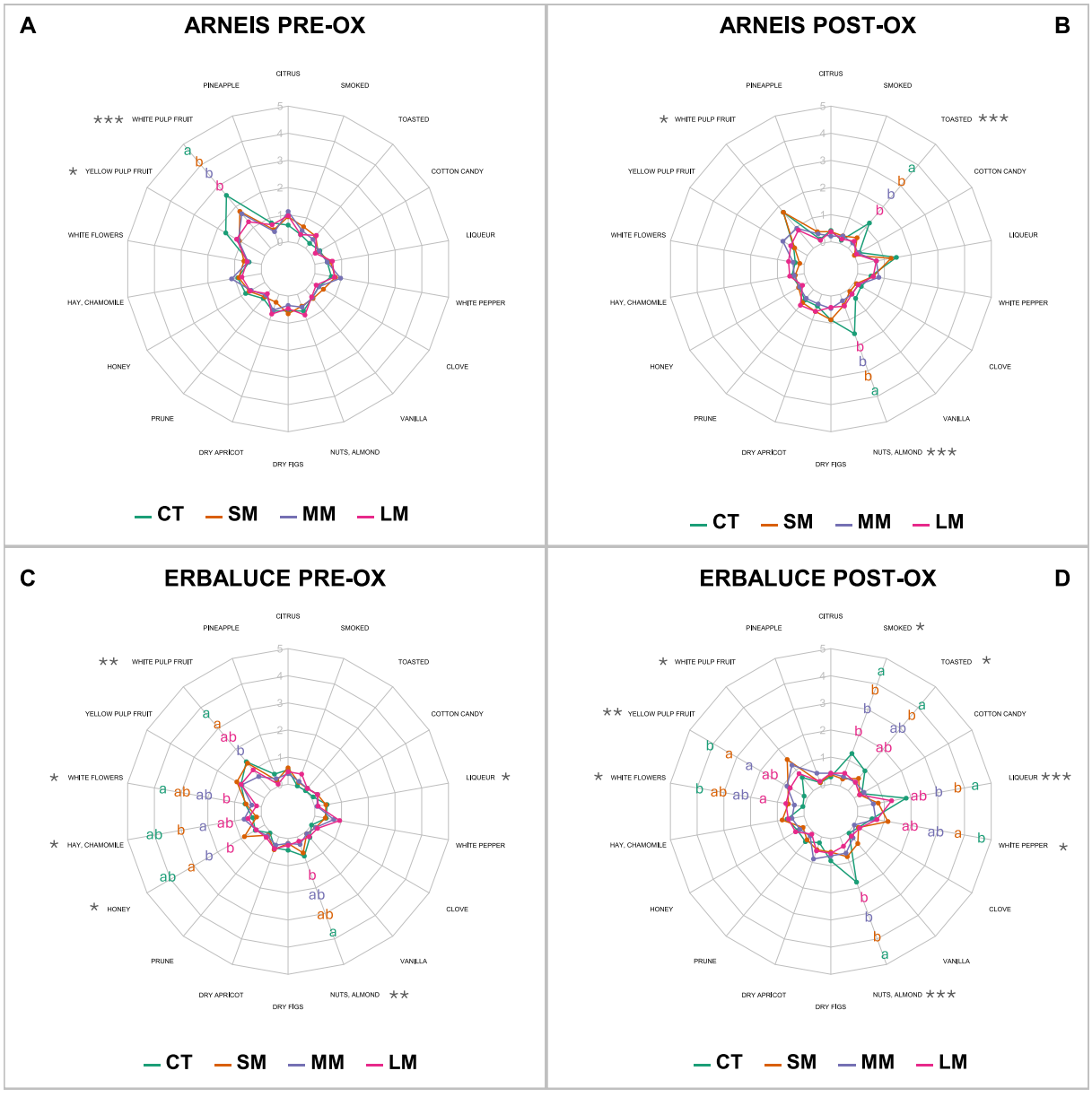

Fig. 4. Radar plot reporting sensorial and visual evaluation of Arneis and Erbaluce wines performed by the trained panel using Rate-All-That-Apply method. Inside each parameter, letters indicate significant differences ($p < 0.05$) among maceration treatments.

3.5.2. Color evaluation

In Arneis, macerated samples exhibited significantly higher *color intensity* compared to CT wines at the end of the maceration period, a trend that persisted in the Post-Ox condition. In contrast, Erbaluce showed a slight decline in *color intensity* with increasing maceration time under Pre-Ox conditions, whereas in Post-Ox, MM and LM samples displayed significantly higher *color intensity* than CT and SM, indicating a possible delayed yellow pigment development. *Hue* was also strongly influenced by maceration length. In Arneis, *hue* increased progressively with extended maceration, with MM and LM samples reaching the highest values. A similar trend was observed in Erbaluce, where *hue* values rose consistently with longer skin contact. The enhanced extraction and oxidation of phenolic compounds during prolonged maceration led to increased yellow-brown tonalities in the wines, consistently with the rise in absorbance at 420 nm (Table 2). These results further support the oxidative browning and phenolic transformations during extended maceration (Bestulić et al., 2022; Ćorković et al., 2024).

3.5.3. Aroma profile evaluation

Fig. 4 shows sensory aroma attributes. In Arneis, maceration-related differences were limited in Pre-Ox (Fig. 4A), with only minor variations observed for *yellow pulp fruit* and *white pulp fruit*, where CT samples tended to score slightly higher. This pattern suggests a better preservation of fermentative fruity aromas, consistent with the higher ester content detected in Arneis wines prior to oxygenation (Fig. 2). After oxygen exposure (Fig. 4B), however, differences among treatments became more evident. *Nuts/almond* and *toasted* notes were more pronounced in CT wines, while differences in *yellow pulp fruit* and *white pulp fruit* were no longer perceived by the panel. These results confirm that oxygen exposure led to a sensory loss or masking of fruit-related aromas, accompanied by a relative increase in oxidative sensory characters, particularly evident in varieties with a low varietal aroma content as it was observed in Arneis (De Paolis et al., 2025).

In Erbaluce, maceration exerted a clearer influence on aroma expression than in Arneis. In Pre-Ox (Fig. 4C), significant differences were observed for several descriptors, including *yellow pulp fruit*, *white flowers*, *hay/chamomile*, and *honey*, with wines subjected to shorter maceration generally showing higher intensity. Fruity and flowery descriptors were higher in CT and SM wines, whereas longer maceration increased complex notes of *hay/chamomile* and *honey*. Interestingly, *nuts/almond* descriptor was already present and different among maceration lengths in Erbaluce before oxygenation, whereas in Arneis these notes clearly emerged after. This finding may indicate a greater intrinsic predisposition of Erbaluce wines toward the development of early perception of oxidative-associated characters.

After oxygenation (Fig. 4D), the number of discriminant attributes increased, particularly for *smoked*, *toasted*, *white pepper*, *liqueur*, and *nuts/almond* notes, which were significantly less intense in MM and LM samples compared to CT and SM. This behavior may be explained by a higher impact of oxygen, in absence of phenolic compounds, toward volatile compounds. In all samples a strong decrease of higher alcohols (methionol, 2-phenylethanol, **Table S3**) was reported: it may be connected to the respective aldehydes formation, here not investigated, that are reported as *smoked*, *toasted*, *nuts/almond* contributors (Culleré et al., 2007). In contrast, *yellow pulp fruit* and *white flowers* notes remained more pronounced in maceration treatments. This outcome, particularly for *yellow pulp fruits*, is in line with the results obtained by Prezioso et al. (2024) on Minutolo and Verdeca varietal wines.

These results highlight distinct varietal responses to maceration and oxygenation, with Erbaluce showing a greater sensitivity of its aromatic profile to both skin contact and oxygenation, leading to broader sensory differentiation.

4. Conclusions

Fermentative skin contact strongly shapes the phenolic, volatile, and sensory profiles of white wines. Extended maceration increased flavan-3-ols, hydroxycinnamic acids, and flavonols to levels approaching those of red wines, and sensory responses aligned with these chemical changes: higher phenolics and polymeric tannins intensified astringency, dryness, and color, while fruity and floral notes declined with shifts in volatiles. Post-fermentative oxygenation further modified composition though its impact was smaller than that of maceration. Overall, maceration and oxygen management offer effective tools for diversifying and tailoring white wine styles.

Studies in human

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place.

This study was approved by the Università degli Studi di Torino - Comitato di Bioetica di Ateneo.

(Approval No. 0781289)

CRediT authorship contribution statement

Lorenzo Ferrero: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Lagori:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Anastasiia Kasianova:** Writing – review & editing, Investigation, Formal analysis. **Micaela Boido:** Writing – review & editing, Investigation, Formal analysis. **Giorgia Botta:** Writing – review & editing, Investigation. **Beatrice Cordero:** Writing – review & editing, Investigation. **Maria Alessandra Paissoni:** Writing – review & editing, Validation, Methodology, Data curation. **Susana Río Segade:** Writing – review & editing, Validation, Methodology, Data curation. **Luca Rolle:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Simone Giacosa:** Writing – review & editing, Supervision, Resources, Project administration, Methodology.

Informed consent and patient details

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2026.151142.

Data availability

Data will be made available on request.

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