



Profile of red wine partially dealcoholized with a membrane-based technique and strategies to mitigate the loss of volatile compounds

Giuseppe Montevecchi^a, Arianna Ricci^b, Francesca Masino^{a,*}, Valentina Ferrari^a, Andrea Versari^b, Andrea Antonelli^a

^a Department of Life Sciences (Agro-Food Science Area), BIOGEST - SITEIA Interdepartmental Centre, University of Modena and Reggio Emilia, Piazzale Europa 1A, 42124, Reggio Emilia, Italy

^b Dipartimento di Scienze e Tecnologie Agro-Alimentari, University of Bologna, Piazza Goidanich 60, 47521, Cesena, Italy

ARTICLE INFO

Handling Editor: Professor Aiqian Ye

Keywords:

Climate change
Oenology
Evaporative pertraction
Ethanol reduction
Flavor
GC-MS
Sensory analysis

ABSTRACT

In recent years, climate change has led to higher grape must sugar content and, consequently, increased alcohol by volume. Evaporative or pertraction is a common method for post-fermentation ethanol removal from wines, but it selectively removes some less polar volatile compounds along with ethanol.

To mitigate volatile substance loss, this study investigates blending of the red wine (Marzemino-Cabernet blend) with obtained dealcoholized samples from it by industrial evaporative pertraction system, while maintaining the final product within a two-percentage-point reduction in ethanol. Thus MIX 1 and MIX 2 blends were prepared, reducing the ABV of the initial wine (12.5% alcohol by volume) to 10.5% and 9.5%.

Chemical analyses highlighted that most alcohols, acetates, and ethyl esters of fatty acids decreased with alcohol by volume reduction. However, compounds with polar groups (acetoin and acetovanillone), C₁₃-nor-isoprenoids, and certain lactones showed increasing trends. Sensory analysis indicated high scores for sweetness and smoothness in the blended wines, with a decrease in acidic taste. Floral scents notably increased, particularly in MIX 2, closely resembling the initial wine's sensory profile.

The blending of initial wine with appropriately dealcoholized wine samples has proven to be an effective strategy for preserving bouquet and color of dealcoholized wines. This approach broadens the consumer base by catering to people who prefer low-alcohol options, have dietary restrictions, or are health-conscious, but who still wish to savor wines with aromatic quality rather than a flat taste. This strategy is crucial in the wine industry as it successfully addresses technical challenges and ensures economic viability.

1. Introduction

Over the past twenty years, global warming has had a considerable impact on viticulture and oenology worldwide. In general, high temperatures, drought, and dry wind are all factors that hinder viticulture (Panceri et al., 2017). Recent models predict the disappearance of 25%–73% of wine areas by 2050 and consequently outline a new geographical distribution of wine production regions (Hannah et al., 2013; Mozell and Thach, 2014). The increase in temperatures is already leading to an increase of viticulture in northern European countries and the cultivation of many grape varieties outside their territory of origin will give rise to new issues, including the change of the denomination of origin. Grapevines in territories characterized by warm climates, such as

southern Spain and the Australian hinterland, are already facing a hard and unsustainable growth (Jones et al., 2005).

In the decades 1981–2007, the rise in temperatures caused an anticipation of two weeks in the harvesting (Cook and Wolkovich, 2016). As a consequence of climate change, some characteristics of the grapes are changing, such as the increase in the sugar content, the reduction of acidity, and the misalignment between technological and phenolic maturity with negative impact on the features of the must and wine. High sugar grape musts can lead to prolonged or arrested primary and secondary fermentations, higher levels of residual sugars, with consequent microbiological spoilage, loss of SO₂ and oxidation, increase in alcohol by volume (ABV), and change of the sensory profile (Wollan, 2010; Palliotti et al., 2014).

* Corresponding author. Department of Life Sciences (Agro-Food Science Area), BIOGEST – SITEIA Interdepartmental Centre, University of Modena and Reggio Emilia, Piazzale Europa 1A, 42124, Reggio Emilia, Italy.

E-mail address: francesca.masino@unimore.it (F. Masino).

<https://doi.org/10.1016/j.crfs.2024.100776>

Received 30 January 2024; Received in revised form 21 May 2024; Accepted 23 May 2024

Available online 24 May 2024

2665-9271/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

In this context of climate changes that the wine sector is facing, it is of paramount importance to optimize the procedures in order to manage one of the main problems affecting the wines produced in the hottest regions, namely the increase in ABV. Over the past few years, wine production has been evolving to try and satisfy consumers' demand for healthier products. Organic practices are having great commercial success and the research effort to reduce the amount of sulfur dioxide in wine has been intensified (Castro-Marín et al., 2018; Castro-Marín et al., 2019; Castro-Marín et al., 2020). Indeed, high ABV makes the wine of difficult consumption and food pairing. Further, massive government campaigns set up to raise awareness about alcohol consumption are having their effects on several sectors of society, such as schools, workplaces, and local communities (Rehn et al., 2001; Liguori et al., 2018). Furthermore, serious and mild health along with strict regulatory constraints for alcohol consumption in specific contexts contribute to the scarce appeal that this product is having on consumers (Sorbinini and Aragrande, 2013).

The harvest of unripe grapes as well as being a traditional practice for the production of 'agresto' (sour grape sauce) (Vasile Simone et al., 2013), an acidic seasoning, is acquiring interest for the possibility of extracting bioactive substances in large quantities and obtain grape musts with a reduced sugar content (Fia et al., 2022). Aside from vineyard, technological procedures as pre-fermentation practice, and microbiological strategies aimed at reducing the sugar concentration in the berries and the selection of less alcoholic yeasts in the fermentation phase (Montecchi et al., 2021; Teslić et al., 2018, 2019), post-fermentation techniques of subtraction of ethanol from wine are being used. Partial alcohol removal is an oenological practice approved by EU regulation, also considering that high-alcohol content wines are taxed at a higher rate in many countries (EU regulation no. 606/09, 2009). The maximum ethanol reduction allowable is 2% v/v, while the minimum absolute reachable ABV is 8.5–9.0% v/v, according to the wine-growing area. However, since the dealcoholization process consists in the removal of a more or less significant part of the alcohol, this raises doubts about the identification, labelling, and loss of sensory characteristics in the final products.

Different post-fermentation technological approaches were explored, namely distillation-based, membrane-based techniques, and their combination, as well as solvent supercritical extraction (Liguori et al., 2018). Distillation-based techniques damage many wine components, and the most volatile fraction is stripped from the wine. However, some innovative technological processes are currently being applied. An example is spinning cone column which is a vertical distillation that works in two phases: in the first one, the aromatic fraction is trapped for its recovery and a possible reintroduction into wine, while in the second one the ethanol is removed (Varavuth et al., 2009; Wollan, 2010).

The membrane-based techniques, notably osmotic distillation, pervaporation, and reverse osmosis can be coupled with the distillation of the permeate (Smith, 1996) or be applied with cutting-edge modifications. One of the most interesting innovations in the field is called osmotic distillation or evaporative pertraction (EP) (Hogan et al., 1998; Diban et al., 2013; Liguori et al., 2015; Longo et al., 2018). It consists of the partial removal of ethanol through a hydrophobic semipermeable microporous membrane into a water flow. During this process, although volatile compounds have a lower vapor pressure in alcoholic solutions, their loss is more limited than that which occurs using other techniques (Liguori et al., 2018). However, some strategies have been tested to control such a loss. In particular, the addition of grape juice to low-alcohol wine and the recovery of the volatile compounds from the stripper solution after the dealcoholization process and their restoration into low-alcohol beverages (Liguori et al., 2018).

The idea behind this study is to blend the dealcoholized product with its original wine in order to compensate for the losses of volatile substances and at the same time to keep the final product within 2% of ethanol reduction. This study is aimed at assessing the performance of an industrial dealcoholization system based on EP on red wine. The samples

collected during the dealcoholization process of 450 L of red wine were subjected to chemical and sensory analyses, to establish the main quality parameters, in particular the volatile compounds, of the different dealcoholized samples. A couple of blends of dealcoholized wine, realized by mixing the initial wine with two dealcoholized samples, were analyzed as well.

2. Materials and methods

2.1. Dealcoholization process and collection of the dealcoholized wine samples

The dealcoholization process was tested on a blend of Marzemino and Cabernet wines (BMC, control). The ethanol removal was performed on 450 L wine through an EP dealcoholization system (Alcoflex 15, DIEMME Enologia, Lugo, Ravenna, Italy) at Emilia Wine soc. coop. agri. company (Arceto, Reggio Emilia, Italy).

The EP dealcoholization system works on two separate circuits: the first one is dedicated to wine recirculation and the second one to water counter-flow recirculation. Each of the two circuits consists of a recirculation pump, filter, pressure sensors for temperature and flow rate, and a deoxygenation system. The two circuits are separated by a hydrophobic membrane made of a polypropylene hollow fiber, with pores narrower than 1 μm , through which ethanol permeates from wine to water.

During the whole process (226 min), samples of wine were withdrawn at the following times: 16 min, 65 min, 95 min, 118 min, 161 min, 196 min, and 226 min. Finally, samples are alphanumerically labeled D1 to D7. Ethanol removed throughout the process was collected in an appropriate tank containing water (about 1000 L) added with SO_2 . For each sampling (D1–D7), the withdrawal schedule and the alcohol by volume (ABV) were recorded.

Moreover, two blended wines (MIX 1 and MIX 2) were prepared in the laboratory in order to obtain an ABV of about 10.5% v/v and 9.5% v/v by mixing respectively BMC with the sample D4 collected after 2 h (8.6% v/v) and BMC with the sample D7 collected after 3.5 h (6.6% v/v).

2.2. Chemical analyses

ABV was carried out through the method OIV-MA-AS312-01B (type IV) using an automatic distillation apparatus (distiller DEE PV, Gibertini Elettronica Srl, Novate Milanese, MI, Italy) and a hydrostatic balance (Superalcomat, Gibertini Elettronica Srl). The pH was determined through a pH-meter (OIV-MA-AS313-15, type I). Aldehydes were determined through iodometric titration (OIV-MA-AS315-01, type IV). Total acidity was determined through potentiometric titration with a solution of NaOH 0.1 N up to pH 7 and is expressed as g/L of tartaric acid (OIV-MA-AS313-01, type I). Volatile acidity was determined through steam distillation (Vade 4 and distiller DEE PV, Gibertini Elettronica Srl) and acid-base titration of the distillate (OIV-MA-AS313-02, type I). Total and free sulfur dioxide were calculated via acid-base titration (OIV-MA-AS323-04A, type IV). The total phenolic content was determined using spectrophotometry by measuring the optical density at 280 nm and expressed as mgGAE (gallic acid equivalent)/L.

2.3. Optical density and color indices

Different color indices were calculated using the absorbance values at wavelengths 420, 520, 580, and 620 nm (OD) (OIV-MA-AS2-07B, type IV), through the following formulas (A = absorbance):

- Color intensity (CI) = $(A_{420} + A_{520} + A_{620})$
- Hue = A_{420}/A_{520}
- Copigmentation = A_{580}/A_{520}

2.4. Extraction and concentration of volatiles

The free volatile fraction was isolated using solid-phase extraction (SPE) technique (Montecchi et al., 2015). Each sample (50 mL) was spiked with 50 μ L of internal standard (2-octanol, 10,000 mg/L in ethanol) and eluted through a 5 g C₁₈-endcapped cartridge (Isolute, Biotage, Uppsala, Sweden), previously activated with 25 mL of methanol followed by 50 mL of water. After the sample was loaded, the cartridge was washed with 100 mL of water to remove the hydrophilic compounds (organic acids, glycerol, residual sugars, polyalcohols). Free aroma compounds were recovered with 20 mL of dichloromethane.

The organic extracts containing free aroma compounds were first concentrated with a Kuderna-Danish condenser up to a volume of 2–3 mL. Finally, this volume was further reduced to about 0.5 mL with a gentle pure nitrogen flow.

2.5. GC-MS analysis of volatile compounds

The concentrated sample (1 μ L) was injected into a gas chromatograph (6890 series, Hewlett-Packard, Waldbronn, Germany) coupled with a mass spectrometer (5973 series, Hewlett-Packard), equipped with a Stabilwax-DA 30 m capillary column (Restek, Milan, Italy), having an internal diameter of 0.25 mm and film thickness of 0.25 μ m. The initial temperature of the oven was set at 45 °C and increased of 4.25 °C/min up to 230 °C, and then held for 20 min. Subsequently, the temperature was increased to 245 °C with an increase of 15 °C/min and, finally, held for 10 min (66 min in total).

The injection was performed through a split/splitless injection port in split mode (split ratio 80:1), the temperature of the injection port and the transfer line were both set at 240 °C. The carrier gas was ultrapure helium (constant flow rate of 0.9 mL/min). The molecular fragmentation was obtained by electron ionization. The chromatograms were obtained in full-scan mode and the mass to charge ratio (m/z) was recorded between 33 and 500 at 70 eV.

Chromatograms were acquired and processed using the software Enhanced Chem Station (G1701AA vA.03.00, Hewlett Packard). Identification was performed by comparing retention times and quantifying and qualifying ions of all the available pure standards. In the absence of pure standards, the volatile compounds were tentatively identified by comparing the mass spectra with those present in the data system libraries (Wiley 7th Edition Library and NIST14). Whenever it was possible, the presence of volatiles was also verified in the literature. Quantification was carried out by measuring the relative peak area of each quantifying ion in relation to that of the internal standard. Each sample was analyzed in duplicate strictly following the same procedure.

2.6. Sensory analysis: judges' training and evaluation, and vocabulary development

Sensory analysis was carried out in a sensory lab (UNI-ISO 8589:1990) at room temperature (20 \pm 2 °C) and uniform artificial light, without shades, was used. The inclusion criteria for candidates were: (i) elder than 21, (ii) no oral disorders or specific allergies to wine, (iii) no teetotalers, and all regular red wine consumers, (iv) ability to discriminate wines during training sessions, (v) and personal interest to sensory analysis.

The official panel was composed of ten judges as volunteers, both men (5) and women (5), aged between 22 and 46, including students and staff from the University of Modena and Reggio Emilia. Moreover, all assessors (indicated by abbreviations from ASS1 to ASS10) had previously attended various panel sessions regarding different foodstuffs, and they had already been trained on the visual appearance, smell, taste, and general sensory analysis rules, as reported in the standard methods (ISO 3972:2011; ISO 8586:2023).

A specific training session on the selected attributes in the study was conducted, following a procedure similar to that reported by Masino

et al. (2022). Standard references (including taste compounds, floral and fruit pure aromatic compounds) and model wines with various ABV contents prepared in the laboratory according to the method described by Montecchi et al. (2021) were used to familiarize the panel with aromatic and alcoholic sensations. Recognition and ranking tests were employed.

The panel performance among the sessions was assessed by evaluating: i) discriminant ability, ii) agreement among judges, and iii) repeatability between sessions were assessed. To assess the panel's performance, a sensory evaluation of Marzemino and Cabernet wines was carried out. These commercial wines were selected because they are identical to those present in the BMC.

Regarding sample evaluation, assessors were instructed to record the intensity of each attribute on the evaluation card for each sample. Furthermore, the evaluation session was repeated on another day, during the same morning time and under similar conditions.

2.7. Quantitative descriptive analysis

The sensory evaluation consisted in a quantitative descriptive analysis (QDA) which was carried out by marking the score of different attributes along an interval scale 10-cm long (Meilgaard et al., 1999) on the evaluation card generated by the Smart Sensory Box (Smart Sensory Solution S. r.l., Sassari, Italy).

The selected attributes were color (COL), brightness (BRGH), saturation (SAT), fluidity (FLU), clarity (CLA), smell-like fruitiness (S-FRU), smell-like floweriness (S-FLO), and smell-like vegetable/herbaceous (S-VEG). As for the mouth perceptions, sweet (SWE), bitter (BIT), sour (SOUR), smooth (SMO), astringent (AST), full-bodied (BOD), alcoholic (ALC), flavor-like fruitiness (F-FRU), flavor-like floweriness (F-FLO), and flavor-like vegetable/herbaceous (F-VEG) were selected. Finally, off flavors (off-F) were also included, their absence or presence was indicated with a 0 or 1 value, respectively.

Two official evaluation sessions, conducted over two consecutive weeks, at the same morning time and under similar conditions, were carried out in individual sensory booths to avoid any exchanges of opinions among judges. Each assessor participated to both sessions.

The tested wines (15 mL) were poured 5 min before tasting and served to the assessors in covered clear "ISO standard wine testing glasses" at room temperature (20 \pm 2 °C). All samples were coded with three-digit random numbers. In order to reduce potential fatigue and adaptation, a 1-min break was allowed after each wine. Between each sample, participants were instructed to rinse their mouth with water and eat an unsalted cracker to minimize any carryover effects (Ross et al., 2007).

In each session, ten wines (BMC, samples from D1 to D7, and MIX 1 and MIX 2) were presented to the ten assessors following a randomized incomplete block design and a balanced order (Meilgaard et al., 1999). In the block, each assessor evaluated a reference wine (RWM, Marzemino) and four samples. The block was repeated two times. At the end of the two sessions each sample was evaluated eight times in total.

2.8. Statistical analysis

The dataset underwent both univariate and multivariate analyses. In the context of the GC-MS and sensory analyses, the one-way ANOVA was employed to evaluate significant differences among replicate wine samples. Upon detecting a significant effect (at least $p < 0.05$), comparative analyses were conducted using the post-hoc Tukey's multiple comparison test. Finally, Principal Component Analysis (PCA) of the autoscaled values was performed. All statistical analyses were executed using Statistica v8.0 software (formerly Stat Soft Inc., now TIBCO Software Inc., Palo Alto, USA).

3. Results and discussion

3.1. Dealcoholization kinetic

The trend of the curve followed a second-degree equation (Fig. 1), which approached an equilibrium value, consistent with the literature (Ferrarini et al., 2016). At 226 min, the ABV decreased from an initial 12.5% v/v to approximately 6.3% v/v.

3.2. Evaluation of chemical parameters

Table 1 shows the results of chemical analyses. In general, with the progress of the dealcoholization process, no major variations in the chemical parameters were noticed in the wine samples when compared to BMC.

A slight increase in free and total SO₂ was found. Being present in the water circle, SO₂ went to a balance during the process. Its presence protected the product during this delicate process so that there was no actual need to reintegrate the SO₂. A slight decrease in the samples' total acidity was recorded, presumably due to fixed acidity (as the volatile acidity is stable). The trend of the color indices remained similar in the dealcoholized samples and did not reflect the findings reported in the literature, which indicate a general increase in color intensity and a decrease in wine hue (Kumar et al., 2024). For this reason, the peculiar color evolution of the initial wine (blended Marzemino and Cabernet) during dealcoholization deserves further investigation. The concentration of aldehydes showed a slight increase in the dealcoholized samples. Regarding MIX 1 and MIX 2 samples, chemical parameters like OD and CI showed a slight increase in comparison with BMC.

3.3. Evaluation of the aromatic profile

3.3.1. Volatile profile of the dealcoholized wine samples

Table 2 shows the average concentrations of each volatile (GC-MS analysis) following the EP process with PP membrane. One-way ANOVA and Tukey's test were performed for each volatile substance on all samples collected during the dealcoholization process, as well as on the two MIXES prepared after the process. For this reason, the statistical results are not exactly representative of the progress of the process, and sometimes are not consistent with an evident observed trend.

It can be noticed that most of the alcohols, namely isobutyl alcohol, 1-butanol, isoamyl alcohols, 1-pentanol, 3-methyl-3-buten-1-ol, 4-

methylpentanol, 3-methylpentanol, 1-octen-3-ol, 1-heptanol, 2-phenylethanol, 1-hexanol, *trans*-3-hexenol, *cis*-3-hexenol, and *trans*-2-hexenol showed a considerable decrease according to the ABV removal kinetics. Conversely, 3-ethoxy-propanol, 3-methylthio-1-propanol, 2,3-butane-diol gradually increased during the process, due to the presence of two polar groups in these molecules. Also 3-oxo- α -ionol and 3-oxo-7,8-dihydro- α -ionol, which are two C₁₃-norisoprenoids showed a tendency to accumulate due to the presence of two polar groups in their structures.

The comparison among benzyl alcohol, 4-hydroxybenzenethanol (tyrosol), and 2-phenylethanol is rather interesting, although the latter is normally present in much higher concentrations. Indeed, the first two compounds showed a tendency to increase throughout the process, while in lower extent 2-phenylethanol slightly decreased.

As regards the esters, they showed much more diversified behaviors. All the acetates (isobutyl acetate, isoamyl acetate, hexyl acetate, *cis*-3-hexenyl acetate, ethylphenethyl acetate, and tryptophan acetate) showed a considerable decrease during the dealcoholization process. Also, the ethyl esters of fatty acids, such as ethyl butyrate, ethyl isovalerate, ethyl hexanoate, ethyl octanoate, ethyl decanoate, ethyl laurate, as well as isoamyl lactate, and diethyl succinate displayed a decreasing trend. On the other hand, ethyl lactate, ethyl 3-hydroxybutanoate, and ethyl 4-hydroxybutanoate were present in increasing concentrations during the dealcoholization process in comparison with BMC, probably given their higher polarity due to the presence of the hydroxyl group. A similar behavior was shown by diethyl malate, ethyl 2-hydroxy-3-phenyl-propanoate, mono ethyl succinate, and ethyl vanillate.

Diban et al. (2008) measured the percentage of loss of key compounds belonging to alcohol and ester classes, using model solutions and a real wine sample. Although the authors limited the reduction of ABV to 2% compared to the initial ABV, some interesting parallels can be drawn. Ethyl esters (especially ethyl octanoate) and acetates were lost in proportions exceeding 30%. In the present study, isoamyl acetate and ethyl octanoate were lost at the rate of 39.7% and 38.5%, respectively, while ethyl hexanoate was just below 30%. Regarding alcohols, isoamyl alcohols (calculated as a sum) were lost at a rate of 43.9%, while linalool was completely lost. The data obtained in the present work do not reflect those obtained by Diban et al. (2008), although this discrepancy can be explained. As for isoamyl alcohols, the uncertainty in quantifying their saturated and tailed peak may have affected the accuracy of their concentration, while linalool was present in very low concentrations (as the grape varieties in question were not aromatic).

Similarly to what was observed in the present work, Varavuth et al. (2009) reported that the dealcoholization process resulted in a reduction of approximately 44% in the initial concentration of isoamyl alcohol in model solutions. The reduction rates of ethyl phenylacetate (14.9%) and 2-phenylethanol (7.9%) were perfectly in line with those observed by Diban et al. (2008).

Some lactones (such as γ -butyrolactone, γ -caprolactone, and γ -nonalactone), which are cyclic esters with pleasant fruit flavors, also behaved in an interesting way by showing an increasing trend during the dealcoholization process, differently from linear esters.

Fatty acid class showed a behavior consistent with the polarity of the specific molecule. Acetic acid, which is a very polar substance, tended to accumulate during the process, 2-methylpropanoic and 3-methylbutanoic acids showed slight reductions, although with trend not always stable, while hexanoic, *trans*-2-hexenoic, octanoic, decanoic, and dodecanoic acids, which are gradually less polar, showed a drastic reduction.

Benzoic and benzeneacetic acids, as already observed for benzyl alcohol, tended to increase. Regarding minor compounds, acetoin stood out, having two polar functions (ketone and alcohol) and despite its small size, tended to increase. Acetovanillone, which also has several polar functions, showed a similar behavior.

Unravelling among volatile phenols is essential as they can

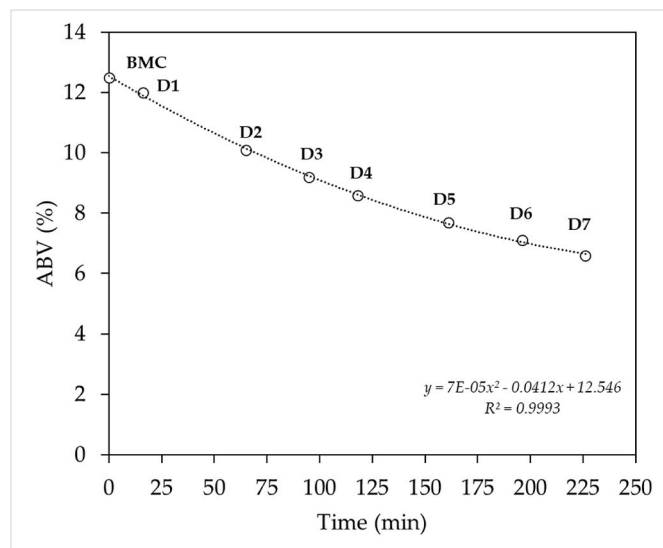


Fig. 1. Time course (min) of dealcoholization (ABV % v/v) of red wines. BMC: control wine; D1-D7: dealcoholized wine samples 1 to 7.

Table 1
Results of chemical analyses.

Samples	BMC	D1	D2	D3	D4	D5	D6	D7	MIX 1	MIX 2
ABV (%)	12.5	12.0	10.1	9.2	8.6	7.7	7.1	6.6	10.4	9.2
Free SO ₂ (mg/L)	24.3	28.2	29.4	29.4	28.2	29.4	29.4	29.4	14.1	10.2
Total SO ₂ (mg/L)	74.2	74.2	74.2	76.8	74.2	74.2	74.2	76.8	79.4	69.1
pH	3.6	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.7	3.5
Titrate acidity (g/L)	6.3	5.0	4.7	4.7	4.7	4.8	4.7	5.3	6.2	6.5
Volatile acidity (g/L)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	–	–
Aldehydes (mg/L)	28.6	30.8	30.8	30.8	39.6	31.0	30.8	30.8	–	–
TPC 280 (mg _{GAE} /L)	1152.5	1149.5	1152.5	1149.5	1149.5	1155.4	1155.4	1146.6	1070.5	1078.0
OD 420 (nm)	2.7	2.6	2.6	2.7	2.6	2.6	2.6	2.6	2.7	3.0
OD 520 (nm)	3.3	3.3	3.2	3.3	3.3	3.3	3.3	3.3	4.1	4.8
OD 580 (nm)	2.1	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.4	2.8
OD 620 (nm)	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	1.2
CI	6.9	6.7	6.7	6.8	6.7	6.8	6.8	6.8	7.8	8.9
Hue	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.6
Copigmentation	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Dry residue (g/L)	24.2	–	–	–	–	–	–	24.5	24.2	24.2

BMC: control wine; D1-D7: dealcoholized wine samples 1 to 7; MIX 1 and MIX 2: blended wines obtained from BMC with D4, and BMC with D7 respectively; ABV: Alcohol by volume; TPC: Total phenolic content as mg_{GAE} (gallic acid equivalent)/L; OD: optical density; CI: color intensity.

significantly impact the overall aroma profile of wine. For instance, 4-ethylphenol can produce an unpleasant note resembling horse sweat when its concentration exceeds 0.4 mg/L (Rapp and Versini, 1996). However, in the examined samples, this threshold was never reached, and 4-ethylphenol showed a tendency to remain stable in dealcoholized wines.

Unlike the previously mentioned substances, vinyl phenols, which have very low perception thresholds (10 µg/L), tend to release more pleasant notes during wine aging (Bertrand and Anocibar Beloqui, 1996). In the present work, 2-methoxy-4-vinylphenol and 4-vinylphenol exhibited an accumulation with potential sensory consequences.

In general, severe changes have been reported in wine volatile compounds resulting from various dealcoholization processes (Sam et al., 2021), including those employing membranes. Recent reviews have indicated that a certain loss in the volatile fraction is unavoidable during dealcoholization due to the concentration gradients produced for these components between both sides of the membrane (Kumar et al., 2024). In particular, Catarino and Mendes (2011) have stated that the dealcoholization process based on the membrane technology can cause a reduction that varies considerably (from 30% to 90%) according to process parameters, membrane material, and manufacturing. In addition, the physico-chemical properties of the volatiles involved (including chemical features, water affinity, hydrophobicity, and boiling point) strongly influence their interaction with the wine matrix during dealcoholization, as well as their affinity to the membrane and the alcohol concentration (Esteras-Saz et al., 2023).

3.3.2. Volatile profile of blends MIX 1 and MIX 2

The volatile compounds found in MIX 1 and MIX 2 (Table 2) matched the profiles of D2 and D3, respectively, which were also the dealcoholized samples with ABV values most similar to MIX 1 and MIX 2. The trends observed for the different volatile classes were consistent with those described for D2 and D3, except for the esters, where some differences were noted between the MIX 1-MIX 2 pair and the D2-D3 pair. In particular, ethyl hexanoate, hexyl acetate, isoamyl acetate, and ethyl octanoate showed higher concentrations in MIX 1 and MIX 2, while ethyl lactate, ethyl 3-hydroxybutanoate, ethyl 4-hydroxybutanoate, and mono-ethyl succinate displayed decreased concentrations in the same samples.

3.4. Principal component analysis applied on chemical and volatile profile analyses

Principal component analysis (PCA) was applied to the autoscaled data set resulting from the chemical analyses and from the

determination of the aromatic profile in order to gather information about the relationship among variables and about the overall distribution of samples on score plots. The first three principal components (PCs), all with eigenvalues >1.0 (Kaiser, 1958), explained 83.16% of the total variance.

In Fig. 2A (PC1 vs PC2, 55.27% and 19.42% of the total variance, respectively), BMC (control wine) and the seven dealcoholized samples (D1-D7) are placed according to the progress of the dealcoholization process. BMC is located in the lower right side of the plot, while the other samples follow one another in an almost linear way on the left along the PC1. On the contrary, MIX 1 and MIX 2 clearly diverge on PC2.

The loading plots (Fig. 3A and B) show the contribution of the chemical parameters and of the volatiles within each PC and help understand which parameters have the most significant influence on the dataset. PC1 vs PC2 loading plot (Fig. 3A) allows to separate the dealcoholized wine samples into three categories according to the progress of the process, i.e., BMC, D1, and D2 having high content in ABV; D3, D4, and D5 having middle content in ABV; while D6 and D7 having low content in ABV. Indeed, BMC, D1, and D2 are positively correlated with a high ABV and the presence of other alcoholic molecules (including fusel oils), as it can be expected at the beginning of a process of ABV reduction. The dealcoholized samples are negatively correlated with γ -caprolactone and 2,3-butanediol. The obtained clusters confirm the results of the volatile compounds profile.

D3, D4, and D5 are positively correlated with the concentrations of some esters, such as ethyl 2-hydroxy-3-phenylpropanoate, ethyl vanillate, 1H-indole-3-ethanol acetate (tryptophol acetate). The same samples are negatively correlated with those chemical parameters which, instead, have a positive effect on the two MIX blends, in particular the parameters linked to the sample color.

D6 and D7 follow a completely opposite trend in comparison with BMC and the samples collected at the beginning of the dealcoholization process. In fact, they are positively correlated with 2,3-butanediol and ethyl lactate. Post-fermentative aromatic compounds, such as 3-oxo- α -ionol and 3-oxo-7,8-dihydro- α -ionol, are more concentrated in the most dealcoholized samples, thus showing an increasing trend in their concentrations with the process ongoing. Conversely, D6 and D7 are negatively correlated with alcohols, such as 2-phenylethanol and *cis*-3-hexenol, some acetates such as isobutyl acetate, fatty acids such as octanoic acid and hexanoic acid, and ABV.

The two MIX blends are positively correlated with color parameters, such as OD 420, OD 520, OD 620, and color intensity, as well as some volatile substances, such as *cis*-2-pentenol, acetic acid, and citronellol. They are also negatively correlated with TPC 280, free SO₂, 2-methylpropanoic acid, and hue.

Table 2

Results of the analysis of volatile compounds (mg/L) expressed as mean values of two replicates. BMC: control wine; D1-D7: dealcoholized 1 to dealcoholized 7; MIX 1: wine obtained by mixing BMC + D4; MIX 2: wine obtained by mixing BMC + D7.

	BMC	±SD	D1	±SD	D2	±SD	D3	±SD	D4	±SD	D5	±SD	D6	±SD	D7	±SD	MIX 1	±SD	MIX 2	±SD	F _{value}
Alcohols (mg/L)																					
1-Butanol	0.460 ^a	0.021	0.402 ^b	0.005	0.399 ^{ab}	0.056	0.347 ^{bc}	0.006	0.269 ^{cde}	0.011	0.254 ^{cde}	0.034	0.225 ^{de}	0.013	0.185 ^e	0.026	0.30 ^{bced}	0.030	0.261 ^{cde}	0.347	22.883 ^{***}
Isobutyl alcohol	10.462 ^a	0.054	9.755 ^{ab}	0.149	9.084 ^{abc}	1.066	8.854 ^{abc}	0.199	8.687 ^{abc}	0.681	8.062 ^{bc}	0.063	7.067 ^c	0.667	7.036 ^c	0.285	8.655 ^{abc}	0.571	8.435 ^{abc}	0.972	6.575 ^{**}
Isoamyl alcohols (sum)	117.72 ^a	0.89	71.31 ^b	1.23	65.96 ^b	2.86	54.37 ^c	2.00	44.20 ^d	0.85	33.59 ^e	1.01	28.85 ^{ef}	2.74	26.36 ^f	1.60	68.70 ^b	0.57	54.50 ^c	1.84	485.0 ^{***}
Amyl alcohol	0.045 ^a	0.005	0.034 ^b	0.002	0.032 ^b	0.004	0.025 ^{bc}	0.001	0.019 ^c	0.001	0.018 ^c	0.002	0.019 ^c	0.000	0.017 ^c	0.001	0.033 ^b	0.003	0.031 ^b	0.002	28.278 ^{***}
3-Methyl-3-buten-1-ol	0.056 ^c	0.005	0.079 ^{ab}	0.010	0.090 ^a	0.002	0.079 ^{ab}	0.002	0.061 ^{bc}	0.002	0.062 ^{bc}	0.001	0.056 ^c	0.008	0.051 ^c	0.004	0.058 ^c	0.003	0.059 ^c	0.002	13.996 ^{***}
4-Methyl-1-pentanol	0.036	0.002	0.029	0.000	0.025	0.002	0.023	0.000	0.017	0.002	0.016	0.002	0.016	0.000	0.015	0.001	0.028	0.001	0.024	0.026	n.s.
3-Methylpentanol	0.041 ^a	0.002	0.035 ^{ab}	0.001	0.030 ^{bc}	0.001	0.027 ^{cd}	0.001	0.014 ^e	0.002	0.020 ^{de}	0.002	0.019 ^e	0.002	0.017 ^e	0.002	0.030 ^{bc}	0.003	0.031 ^{bc}	0.000	43.657 ^{***}
cis-2-Pentanol	0.008	0.001	0.009	0.001	0.009	0.001	0.009	0.000	0.009	0.000	0.009	0.000	0.007	0.001	0.010	0.001	0.012	0.002	0.012	0.006	n.s.
3-Ethoxypropanol	0.026 ^d	0.001	0.031 ^{dc}	0.004	0.040 ^{abc}	0.001	0.035 ^{bc}	0.001	0.036 ^{abc}	0.003	0.042 ^{ab}	0.004	0.045 ^a	0.001	0.045 ^a	0.001	0.025 ^d	0.000	0.023 ^d	0.000	25.156 ^{***}
3-(Methylthio)-1-propanol	1.614 ^{cd}	0.088	2.353 ^{bcd}	0.113	2.755 ^{abc}	0.048	2.782 ^{abc}	0.134	3.187 ^a	0.164	2.870 ^{ab}	0.029	3.352 ^a	0.197	3.421 ^a	0.050	2.058 ^{cd}	0.028	2.083 ^{cd}	0.493	20.666 ^{***}
1-Heptanol	0.036	0.000	0.029	0.001	0.025	0.001	0.024	0.001	0.021	0.000	0.020	0.000	0.021	0.000	0.017	0.000	0.029	0.001	0.027	0.020	n.s.
1-Octen-3-ol	0.014 ^a	0.002	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.003 ^{bc}	0.000	0.000 ^c	0.000	0.011 ^{ab}	0.008	0.000 ^c	0.000	9.064 ^{***}
2-phenylethanol	48.78 ^a	0.68	46.56 ^{ab}	0.79	44.91 ^{ab}	0.51	41.66 ^{bc}	1.25	31.84 ^d	0.53	35.52 ^d	1.74	34.86 ^d	0.83	36.41 ^{cd}	3.05	47.04 ^{ab}	1.65	42.18 ^b	1.52	33.24 ^{***}
4-Hydroxy-benzeneethanol (Tyrosol)	2.802 ^e	0.203	5.051 ^{cd}	0.115	6.093 ^{bc}	0.160	4.783 ^d	0.216	6.457 ^{abc}	0.794	7.079 ^{ab}	0.086	7.608 ^{ab}	0.165	7.952 ^a	0.502	2.873 ^c	0.228	2.256 ^e	0.667	56.580 ^{***}
Benzyl alcohol	0.708 ^d	0.062	0.930 ^{bcd}	0.023	0.962 ^{abcd}	0.042	1.101 ^{abc}	0.051	1.226 ^{ab}	0.085	1.277 ^a	0.049	1.134 ^{abc}	0.154	1.114 ^{abc}	0.082	0.839 ^{abcd}	0.041	0.960 ^{cd}	0.152	8.451 ^{**}
∑Alcohols	182.80		136.61		130.42		114.11		96.05		88.84		83.28		82.64		130.7		110.89		
C6 Alcohols (mg/L)																					
1-Hexanol	2.392 ^a	0.142	1.982 ^b	0.077	1.703 ^{bc}	0.078	1.494 ^{cd}	0.007	1.210 ^{de}	0.079	1.105 ^e	0.099	1.126 ^{de}	0.051	1.001 ^e	0.078	2.014 ^{ab}	0.129	1.772 ^{bc}	0.135	47.567 ^{***}
cis-3-Hexenol	0.014 ^a	0.000	0.013 ^a	0.001	0.012 ^{ab}	0.001	0.010 ^{bc}	0.000	0.007 ^{cde}	0.001	0.007 ^{de}	0.001	0.007 ^e	0.001	0.006 ^e	0.001	0.012 ^{ab}	0.001	0.010 ^{bcd}	0.000	36.563 ^{***}
trans-2-Hexenol	0.002 ^a	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.001 ^b	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.001 ^b	0.000	0.000 ^c	0.000	0.001 ^b	0.000	115.414 ^{***}
trans-3-Hexenol	0.032 ^a	0.000	0.029 ^{ab}	0.001	0.027 ^{abc}	0.002	0.023 ^{abcd}	0.000	0.016 ^{cd}	0.002	0.017 ^{bcd}	0.002	0.016 ^{cd}	0.000	0.016 ^{cd}	0.000	0.017 ^{bcd}	0.001	0.014 ^d	0.009	9.356 ^{***}
∑C6 Alcohols	2.441		2.023		1.741		1.526		1.234		1.130		1.148		1.024		2.043		1.797		
Acetates (mg/L)																					
Isobutyl acetate	0.017 ^a	0.000	0.018 ^a	0.002	0.014 ^{ab}	0.002	0.010 ^{bcd}	0.000	0.006 ^d	0.001	0.009 ^{bcd}	0.000	0.008 ^{cd}	0.000	0.008 ^{cd}	0.001	0.012 ^{abc}	0.000	0.009 ^{bcd}	0.004	15.336 ^{***}
Isoamyl acetate	0.780 ^a	0.008	0.732 ^{ab}	0.061	0.470 ^{cd}	0.046	0.463 ^{cd}	0.010	0.374 ^{cd}	0.016	0.359 ^{cd}	0.026	0.299 ^{cd}	0.002	0.263 ^d	0.006	0.521 ^{bc}	0.059	0.513 ^{bc}	0.168	15.056 ^{***}
Hexyl acetate	0.038 ^a	0.005	0.036 ^{ab}	0.004	0.028 ^{abc}	0.004	0.026 ^{bc}	0.000	0.025 ^{bc}	0.001	0.021 ^c	0.002	0.023 ^c	0.000	0.024 ^c	0.003	0.036 ^{ab}	0.004	0.032 ^{abc}	0.003	8.578 ^{**}
cis-3-Hexenyl acetate	0.042 ^a	0.001	0.001 ^b	0.000	0.000 ^b	0.000	0.001 ^b	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.001 ^{bc}	0.000	0.001 ^b	0.001	41.77 ^{***}
Ethyl phenylacetate	0.449 ^a	0.045	0.457 ^a	0.030	0.382 ^{ab}	0.028	0.330 ^{ab}	0.015	0.352 ^{ab}	0.036	0.270 ^b	0.004	0.313 ^{ab}	0.035	0.290 ^{ab}	0.031	0.398 ^{ab}	0.049	0.342 ^{ab}	0.094	4.253 [*]
∑C6 Acetates	1.326		1.244		0.894		0.829		0.757		0.658		0.643		0.585		0.967		0.897		
Esters of fatty acids (mg/L)																					
Ethyl butyrate	0.116 ^a	0.002	0.098 ^{ab}	0.009	0.072 ^{abc}	0.007	0.067 ^{bc}	0.004	0.047 ^c	0.002	0.052 ^{bc}	0.005	0.053 ^{bc}	0.005	0.052 ^{bc}	0.002	0.075 ^{abc}	0.005	0.067 ^{bc}	0.034	7.100 ^{**}
Ethyl isovalerate	0.112 ^a	0.001	0.002 ^{de}	0.000	0.006 ^e	0.000	0.004 ^d	0.000	0.001 ^e	0.000	0.003 ^d	0.000	0.001 ^e	0.000	0.001 ^e	0.000	0.008 ^b	0.001	0.005 ^c	0.001	1445 ^{***}
Ethyl hexanoate	0.606 ^a	0.008	0.541 ^{ab}	0.001	0.432 ^{bc}	0.058	0.346 ^{cde}	0.002	0.284 ^{de}	0.019	0.240 ^e	0.034	0.275 ^{de}	0.039	0.240 ^e	0.023	0.515 ^{abc}	0.061	0.412 ^{bcd}	0.052	26.006 ^{***}
Ethyl octanoate	0.670 ^a	0.054	0.561 ^{ab}	0.026	0.412 ^{bcd}	0.054	0.402 ^{cd}	0.024	0.374 ^{cd}	0.012	0.312 ^d	0.008	0.279 ^d	0.029	0.270 ^d	0.007	0.523 ^{abc}	0.020	0.514 ^{bc}	0.081	22.813 ^{***}
Ethyl 3-hydroxybutanoate	0.153 ^f	0.003	0.193 ^{def}	0.012	0.242 ^{bcd}	0.007	0.252 ^{abcd}	0.008	0.284 ^{ab}	0.037	0.266 ^{abc}	0.014	0.317 ^a	0.020	0.316 ^a	0.008	0.172 ^{ef}	0.007	0.184 ^{def}	0.033	20.435 ^{***}
Ethyl 4-Hydroxybutanoate	6.322 ^g	0.184	6.770 ^{fg}	0.068	8.029 ^{efg}	0.850	10.856 ^{bcd}	0.227	11.490 ^{abc}	1.045	11.955 ^{ab}	0.206	12.992 ^{ab}	0.993	13.390 ^a	0.145	9.460 ^{cde}	0.672	8.740 ^{def}	0.514	34.483 ^{***}
Ethyl decanoate	0.587 ^a	0.036	0.513 ^{ab}	0.069	0.354 ^{bcd}	0.033	0.317 ^{cd}	0.024	0.313 ^{cd}	0.038	0.239 ^{cd}	0.013	0.217 ^{cd}	0.002	0.181 ^d	0.002	0.385 ^{bc}	0.002	0.344 ^{bcd}	0.106	15.660 ^{***}
∑ Esters of fatty acids	8.566		8.676		9.547		12.243		12.792		13.067		14.134		14.450		11.138		10.267		
Esters of other acids (mg/L)																					
Ethyl lactate	51.04 ^b	0.09	53.08 ^b	1.048	62.99 ^{ab}	3.76	66.97 ^{ab}	1.01	62.25 ^{ab}	6.68	59.54 ^{ab}	5.38	68.68 ^{ab}	4.75	75.66 ^a	2.78	55.51 ^b	5.81	59.02 ^{ab}	6.75	5.694 ^{**}
Isoamyl lactate	0.169 ^a	0.016	0.161 ^{ab}	0.016	0.144 ^{ab}	0.005	0.128 ^{ab}	0.004	0.110 ^{ab}	0.004	0.108 ^b	0.005	0.108 ^b	0.002	0.106 ^b	0.000	0.136 ^{ab}	0.004	0.121 ^{ab}	0.041	4.534 [*]
Diethyl succinate	1.796 ^{abc}	0.155	1.842 ^{ab}	0.195	1.612 ^{abcd}	0.112	1.427 ^{bcd}	0.061	1.349 ^{bcd}	0.098	1.243 ^{cd}	0.105	1.290 ^{bcd}	0.070	1.199 ^d	0.156	2.054 ^a	0.018	1.818 ^{abc}	0.294	8.420 ^{**}
Diethyl malate	0.194 ^d	0.004	0.260 ^{cd}	0.003	0.349 ^{bc}	0.011	0.411 ^{ab}	0.013	0.437 ^{ab}	0.009	0.470 ^a	0.030	0.490 ^a	0.030	0.499 ^a	0.015	0.203 ^d	0.005	0.239 ^d	0.061	48.320 ^{***}
Mono-ethyl succinate	4.686 ^d	0.504	6.836 ^{bcd}	0.312	6.775 ^{bcd}	0.057	6.883 ^{bcd}	0.108	6.652 ^{bcd}	0.645	8.037 ^{abc}	1.131	8.577<								

Table 2 (continued)

	BMC	±SD	D1	±SD	D2	±SD	D3	±SD	D4	±SD	D5	±SD	D6	±SD	D7	±SD	MIX 1	±SD	MIX 2	±SD	F _{value}
∑ Esters of other acids	61.064		65.979		75.183		79.069		74.237		73.511		83.052		91.408		66.512		69.844		
Miscellaneous acids (mg/L)																					
Acetic acid	0.076 ^{bc}	0.006	0.090 ^b	0.013	0.102 ^b	0.006	0.097 ^b	0.000	0.086 ^b	0.007	0.056 ^c	0.001	0.084 ^b	0.001	0.098 ^b	0.009	0.153 ^a	0.000	0.151 ^a	0.011	37.398***
2-Methylpropanoic acid	0.313 ^{bc}	0.024	0.352 ^{ab}	0.002	0.420 ^a	0.014	0.357 ^{ab}	0.005	0.330 ^b	0.004	0.364 ^{ab}	0.017	0.325 ^b	0.012	0.306 ^{bc}	0.042	0.246 ^{cd}	0.006	0.208 ^d	0.012	23.053***
3-Methylbutanoic acid	1.734 ^{abc}	0.112	2.106 ^a	0.064	2.096 ^a	0.048	1.987 ^{ab}	0.014	1.980 ^{abc}	0.147	1.968 ^{abc}	0.244	1.730 ^{abc}	0.146	1.627 ^{abc}	0.006	1.573 ^{bc}	0.018	1.488 ^c	0.180	6.574**
Hexanoic acid	2.506 ^a	0.091	2.482 ^a	0.351	2.222 ^{ab}	0.114	2.061 ^{ab}	0.057	2.020 ^{ab}	0.155	1.641 ^b	0.186	1.806 ^{ab}	0.065	1.634 ^b	0.066	2.323 ^{ab}	0.155	2.156 ^{ab}	0.324	5.800**
trans-2-Hexenoic acid	0.065 ^a	0.005	0.047 ^{ab}	0.001	0.056 ^{ab}	0.000	0.061 ^{ab}	0.002	0.047 ^{ab}	0.006	0.058 ^{ab}	0.004	0.058 ^{ab}	0.004	0.044 ^{ab}	0.000	0.041 ^b	0.000	0.047 ^{ab}	0.016	3.875*
Octanoic acid	5.931 ^a	0.187	5.848 ^{ab}	0.470	4.533 ^{bcd}	0.119	4.526 ^{bcd}	0.094	4.708 ^{abcd}	0.654	3.969 ^{cd}	0.408	3.400 ^d	0.492	3.380 ^d	0.063	5.100 ^{abc}	0.064	5.092 ^{abc}	0.262	13.361***
Decanoic acid	2.241 ^a	0.016	2.069 ^{ab}	0.026	1.862 ^{abc}	0.038	1.801 ^{abcd}	0.080	1.921 ^{abc}	0.176	1.412 ^{bcd}	0.068	1.204 ^{cd}	0.229	1.130 ^d	0.098	1.526 ^{abcd}	0.142	1.482 ^{bcd}	0.450	8.330**
Dodecanoic acid	0.078	0.009	0.043	0.006	0.042	0.002	0.051	0.003	0.056	0.005	0.055	0.002	0.053	0.006	0.042	0.002	0.047	0.006	0.057	0.078	n.s.
Benzoic acid	0.056 ^d	0.006	0.079 ^{cd}	0.008	0.082 ^{cd}	0.004	0.077 ^{cd}	0.003	0.089 ^{bc}	0.003	0.117 ^{ab}	0.001	0.128 ^a	0.009	0.145 ^a	0.014	0.081 ^{cd}	0.001	0.076 ^{cd}	0.012	27.570***
Benzeneacetic acid	0.245 ^c	0.036	0.256 ^c	0.021	0.290 ^{bc}	0.031	0.299 ^{bc}	0.009	0.367 ^{ab}	0.006	0.420 ^a	0.003	0.421 ^a	0.026	0.439 ^a	0.054	0.215 ^c	0.010	0.223 ^c	0.013	22.662***
∑ Miscellaneous acids	13.246		13.372		11.706		11.319		11.605		10.061		9.210		8.846		11.306		10.980		
Keton and diols (mg/L)																					
Acetoin	0.651 ^d	0.015	0.840 ^{bcd}	0.073	0.879 ^{bc}	0.059	0.880 ^{bc}	0.075	0.808 ^{cd}	0.025	0.816 ^{bcd}	0.059	1.025 ^{ab}	0.057	1.139 ^a	0.070	0.714 ^{cd}	0.038	0.722 ^{cd}	0.026	14.718***
2,3-Butanediol	2.417 ^{ab}	0.051	2.163 ^{ab}	0.282	2.012 ^{ab}	0.330	2.43 ^{ab}	0.406	2.307 ^{ab}	0.216	2.047 ^{ab}	0.024	2.360 ^{ab}	0.163	2.876 ^a	0.218	1.946 ^b	0.105	2.568 ^{ab}	0.197	3.058*
∑ Keton and diols	3.068		3.002		2.892		3.306		3.115		2.863		3.385		4.015		2.660		3.290		
Lactones (mg/L)																					
γ-Butyrolactone	0.068 ^d	0.006	0.084 ^{bcd}	0.008	0.099 ^{abcd}	0.001	0.096 ^{bcd}	0.002	0.121 ^{abc}	0.000	0.124 ^{ab}	0.011	0.124 ^{ab}	0.000	0.137 ^a	0.002	0.080 ^d	0.010	0.083 ^{cd}	0.027	10.446***
γ-Caprolactone	0.024 ^b	0.003	0.036 ^{ab}	0.002	0.032 ^b	0.000	0.034 ^b	0.002	0.041 ^{ab}	0.003	0.036 ^{ab}	0.005	0.058 ^a	0.003	0.040 ^{ab}	0.003	0.044 ^{ab}	0.005	0.045 ^{ab}	0.015	5.208**
γ-Nonalactone	0.033 ^{ab}	0.001	0.036 ^a	0.003	0.030 ^{abc}	0.003	0.026 ^{bc}	0.001	0.030 ^{abc}	0.004	0.021 ^c	0.000	0.037 ^a	0.001	0.025 ^{bc}	0.002	0.021 ^c	0.000	0.023 ^c	0.002	13.695***
∑ Lactones	0.126		0.156		0.162		0.156		0.191		0.182		0.219		0.202		0.144		0.151		
Terpenes (mg/L)																					
Linalool	0.004 ^a	0.001	0.003 ^{ab}	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.000 ^c	0.000	0.003 ^{ab}	0.001	0.002 ^b	0.001	33.922***
Citronellol	0.006 ^{abc}	0.000	0.009 ^a	0.001	0.005 ^{bc}	0.001	0.005 ^{bc}	0.001	0.005 ^{bc}	0.001	0.003 ^c	0.000	0.007 ^{abc}	0.000	0.004 ^{bc}	0.000	0.007 ^{ab}	0.001	0.006 ^{abc}	0.003	6.734**
3-Oxo-α-ionol	0.219 ^{bc}	0.021	0.246 ^{bc}	0.020	0.208 ^{bc}	0.013	0.216 ^c	0.002	0.277 ^{bc}	0.024	0.289 ^{ab}	0.016	0.363 ^a	0.031	0.413 ^c	0.017	0.229 ^c	0.017	0.236 ^c	0.037	19.704***
3-Oxo-7,8-dihydro-α-ionol	0.004 ^e	0.000	0.011 ^{bcd}	0.002	0.009 ^{cde}	0.001	0.010 ^{cde}	0.001	0.013 ^{abc}	0.001	0.007 ^{de}	0.001	0.018 ^a	0.001	0.017 ^{ab}	0.004	0.010 ^{cde}	0.001	0.010 ^{cd}	0.002	15.680***
Ethyl vanillate	0.177 ^{bc}	0.006	0.193 ^{bc}	0.018	0.173 ^{bc}	0.014	0.168 ^c	0.012	0.194 ^{bc}	0.010	0.222 ^{ab}	0.005	0.263 ^a	0.004	0.159 ^c	0.003	0.168 ^c	0.011	0.160 ^c	0.026	13.089***
Acetovanillone	0.090 ^c	0.004	0.122 ^{abc}	0.014	0.109 ^{bc}	0.009	0.109 ^{bc}	0.003	0.137 ^{abc}	0.013	0.157 ^{ab}	0.006	0.166 ^a	0.010	0.167 ^a	0.009	0.123 ^{abc}	0.008	0.123 ^{abc}	0.030	8.121**
∑ Terpenes	0.501		0.585		0.504		0.508		0.628		0.677		0.818		0.760		0.541		0.538		
Volatile phenols (mg/L)																					
4-Ethylphenol	0.018 ^{ab}	0.002	0.015 ^{ab}	0.001	0.016 ^{ab}	0.000	0.016 ^{ab}	0.000	0.017 ^{ab}	0.000	0.012 ^b	0.001	0.018 ^{ab}	0.001	0.016 ^{ab}	0.002	0.016 ^{ab}	0.002	0.020 ^a	0.005	3.280*
2-Methoxy-4-vinylphenol	0.170 ^c	0.003	0.233 ^c	0.021	0.235 ^c	0.053	0.228 ^c	0.026	0.365 ^b	0.054	0.404 ^b	0.007	0.651 ^a	0.011	0.701 ^a	0.004	0.166 ^c	0.011	0.157 ^c	0.040	90.083***
4-Vinylphenol	0.716 ^d	0.092	1.535 ^b	0.048	1.589 ^{ab}	0.161	1.143 ^c	0.078	1.172 ^c	0.026	1.858 ^a	0.026	1.600 ^{ab}	0.045	1.587 ^{ab}	0.085	0.929 ^{cd}	0.097	0.668 ^d	0.010	54.350***
∑ Volatile phenols	0.903		1.783		1.840		1.388		1.554		2.274		2.269		2.304		1.111		0.846		
Miscellaneous others (mg/L)																					
N-(3-Methylbutyl)-acetamide	2.215 ^a	0.075	2.139 ^a	0.129	1.976 ^a	0.159	1.329 ^b	0.083	1.213 ^{bc}	0.111	1.307 ^{bc}	0.005	1.275 ^{bc}	0.100	0.697 ^c	0.041	1.688 ^{ab}	0.035	1.135 ^{bc}	0.411	19.303***
N-(2-Phenylethyl)-acetamide	0.508 ^{cd}	0.050	0.574 ^{cd}	0.067	0.487 ^{cd}	0.024	0.475 ^d	0.001	0.552 ^{cd}	0.006	0.618 ^{bc}	0.011	0.724 ^{ab}	0.040	0.765 ^a	0.048	0.521 ^{cd}	0.006	0.510 ^{8d}	0.033	15.723***
N-Acetyltyramine	0.257 ^c	0.007	0.285 ^{bc}	0.031	0.263 ^{bc}	0.019	0.262 ^c	0.012	0.298 ^{bc}	0.023	0.344 ^{abc}	0.004	0.398 ^{ab}	0.033	0.464 ^a	0.045	0.266 ^{bc}	0.011	0.265 ^{bc}	0.081	8.404**
Ethyl 2-hydroxy-3-phenylpropanoate	0.493 ^{ab}	0.058	0.443 ^b	0.004	0.446 ^b	0.064	0.439 ^b	0.023	0.468 ^{ab}	0.006	0.456 ^{ab}	0.068	0.573 ^{ab}	0.028	0.621 ^a	0.005	0.443 ^b	0.033	0.435 ^b	0.070	4.244*
1H-Indol-3-ethanol acetate (Tryptophol acetate)	1.028 ^{bc}	0.083	1.179 ^{bc}	0.084	1.060 ^{bc}	0.125	1.032 ^c	0.062	1.583 ^a	0.063	1.302 ^{ab}	0.067	1.052 ^{bc}	0.068	0.969 ^c	0.051	1.061 ^{bc}	0.023	1.030 ^{bc}	0.061	19.915***
1H-Indol-3-ethanol (Tryptophol)	5.774 ^{bcd}	0.509	7.367 ^{abcd}	0.684	6.960 ^{abcd}	0.402	6.740 ^{abcd}	0.328	8.343 ^{ab}	0.491	8.201 ^{abc}	0.074	8.043 ^{abcd}	0.148	8.643 ^a	0.130	5.432 ^d	0.181	5.260 ^d	1.908	6.354**
∑ Miscellaneous others	10.276		11.988		11.193		10.271		12.457		12.228		12.065		12.159		9.411		8.632		

ANOVA results were expressed as F_{values} and p_{values}. ***p ≤ 0.001; **p ≤ 0.01; *p ≤ 0.05; n.s.: not significant. Results of the Tukey's test are also reported as superscript letters, where different letters identify samples significantly different (p ≤ 0.05) g < f < e < d < c < b < a.

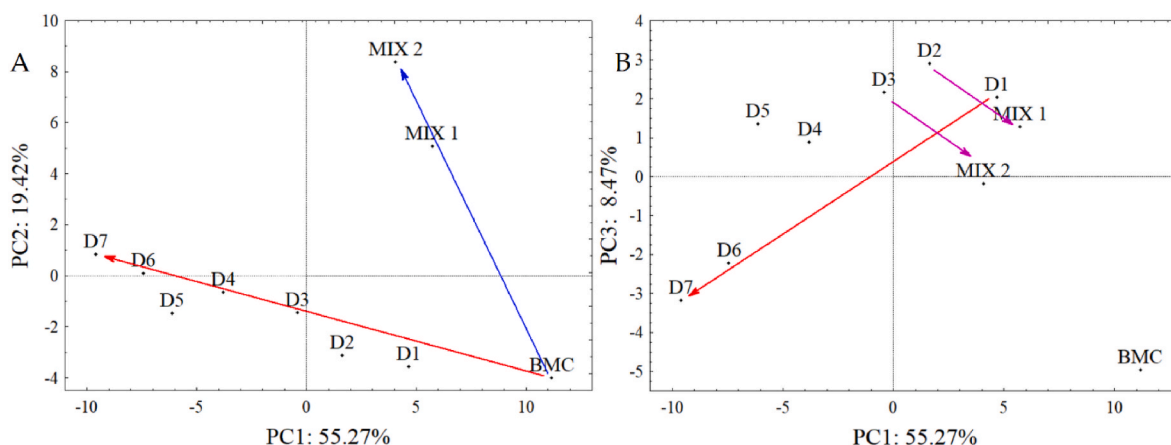


Fig. 2. PCA of the chemical dataset. Score plots of the PC1 vs PC2 (A), and PC1 vs PC3 (B) with explained variances.

BMC: control wine; D1-D7: dealcoholized wine samples 1–7; MIX 1: wine sample obtained by mixing BMC + D4; MIX 2: wine sample obtained by mixing BMC + D7.

Fig. 2B shows the score plot of PC1 vs PC3 (8.47% of the total variance). As for this combination of PCs, the progress of the dealcoholization process proceeds from the upper right quadrant and descends towards the lower left corner, except for the BMC sample which is isolated in the lower right corner. In addition, it is important to highlight an interesting parallelism. Indeed, the MIX 1 and MIX 2 samples that correspond in terms of ABV to D2 and D3, respectively, are positioned parallel to the latter and closer to the BMC.

Fig. 3B shows the loading plot of PC1 vs PC3. The color parameters, as well as some alcohols and esters, influence the placement in the Cartesian plane of the MIX 1 and MIX 2 blends. This configuration of the parameters in the loading plot PC1 vs PC3 shows that the preparation of the MIX 1 and MIX 2 blends helps enrich these samples with volatile substances otherwise lost in the corresponded dealcoholized samples, while maintaining a proximity to the latter due to the same ABV achieved.

3.5. Sensory performance evaluation

Table 3 shows the results of the sensory judges' performance evaluation on the Marzemino and Cabernet wines. There were no significant differences among the assessors for each attribute, except for SOUR ($p \leq 0.05$) and BIT ($p \leq 0.01$) tastes. Furthermore, the assessors showed excellent repeatability between the sessions for all attributes, except for F-VEG ($p \leq 0.05$), and demonstrated satisfactory discriminant ability as the samples were perceived as different by assessors for almost all attributes (Table 4), except for S-VEG, AST, and SOUR. The results regarding SOUR could be attributed to a lack of agreement among the assessors.

3.6. Results of the QDA

Table 4 shows the average scores assigned by the judges to the wine samples assessed during the two official QDA sessions. In general, the scores of some parameters showed a remarkable variability among the different samples collected during the dealcoholization process, while other parameters remained rather unchanged, and therefore these latter were not influenced by the applied process. Indeed, some appearance parameters, such as color, saturation, fluidity, and clarity did not show significant differences ($p > 0.05$), while brightness scored slightly lower during dealcoholization process. This response of the assessors is linked to the wine concentration that made these latter samples less brilliant.

As for the olfactory attributes, the S-FRU remained unchanged along the series of samples, while the S-FLO and S-VEG tended to become less perceptible with the progress of the dealcoholization process in line with the aromatic profile. However, ANOVA did not show any significant

effect for each of these attributes.

Going from BMC to D4, a remarkable decrease was observed in the alcoholic perception ($p \leq 0.001$), consistently with the ABV trend, however, in samples D5-D7 the same falling trends were not observed. Regarding other taste parameters, SWE showed slight significant differences among the samples ($p \leq 0.05$).

The control wine was dry, therefore, an increase in SWE was not expected. Some studies have described a decrease in sweetness caused by the ethanol removal (Meillon et al., 2009; Sam et al., 2021). However, wine is a complex matrix where a delicate balance among different compounds subsists, as well as interactions occur between alcohol and wine compounds. In addition, it is not obvious to detect sensory differences between dealcoholized wines using standard sensory methods. In fact, Meillon et al. (2009) compared standard descriptive analysis with the Temporal Dominance of Sensations method, which proved to be more effective than the descriptive one.

In addition, Meillon et al. (2009) have stated that the effect of the dealcoholization process varies in wines obtained from different grape varieties. As for Merlot, texture and astringency were affected by the dealcoholization process, while regarding Syrah, sweetness was the most influenced. A slight variation in the SWE attribute was highlighted, possibly stemming from the concentration of polyalcohols in dealcoholized wine. It is well known that glycerol influences the taste qualities of wine, making it softer and sweeter in relation to its concentration (Butnariu and Butu, 2019).

In the present work, SOUR scores ($p \leq 0.01$) were generally higher than SWE scores, especially in D3 and D4 samples. This clear perception of the acidic sensation could also have affected the evaluation of other attributes, such as smoothness and full-bodied, which were judged below the linear trend shown starting from sample D4. However, full-bodied did not show any statistical difference, while smoothness displayed slight differences among the samples ($p \leq 0.05$). It is likely that from BMC to D4, smoothness scores increased due to the concentration of glycerol. Indeed, considering the characteristics of this polar molecule, it is likely that it does not permeate the membrane and consequently accumulates in the wine.

BIT ($p \leq 0.05$) showed a sharp drop in values from sample D6 onwards. This is likely to be related to the reduction in ethanol content. Still, one of the most common problems in a dealcoholized wine is the increased astringency (Liguori et al., 2018). However, in this study, there was no observed increase in this attribute. Regarding floral and fruity attributes, F-FRU scores gradually increased ($p \leq 0.01$) in the samples collected throughout the process, while the F-FLO scores showed a gradual decline ($p \leq 0.01$), aligning with the results of smell scores. This behavior suggests that the volatiles responsible for floral scents were lost during the dealcoholization process, whereas more

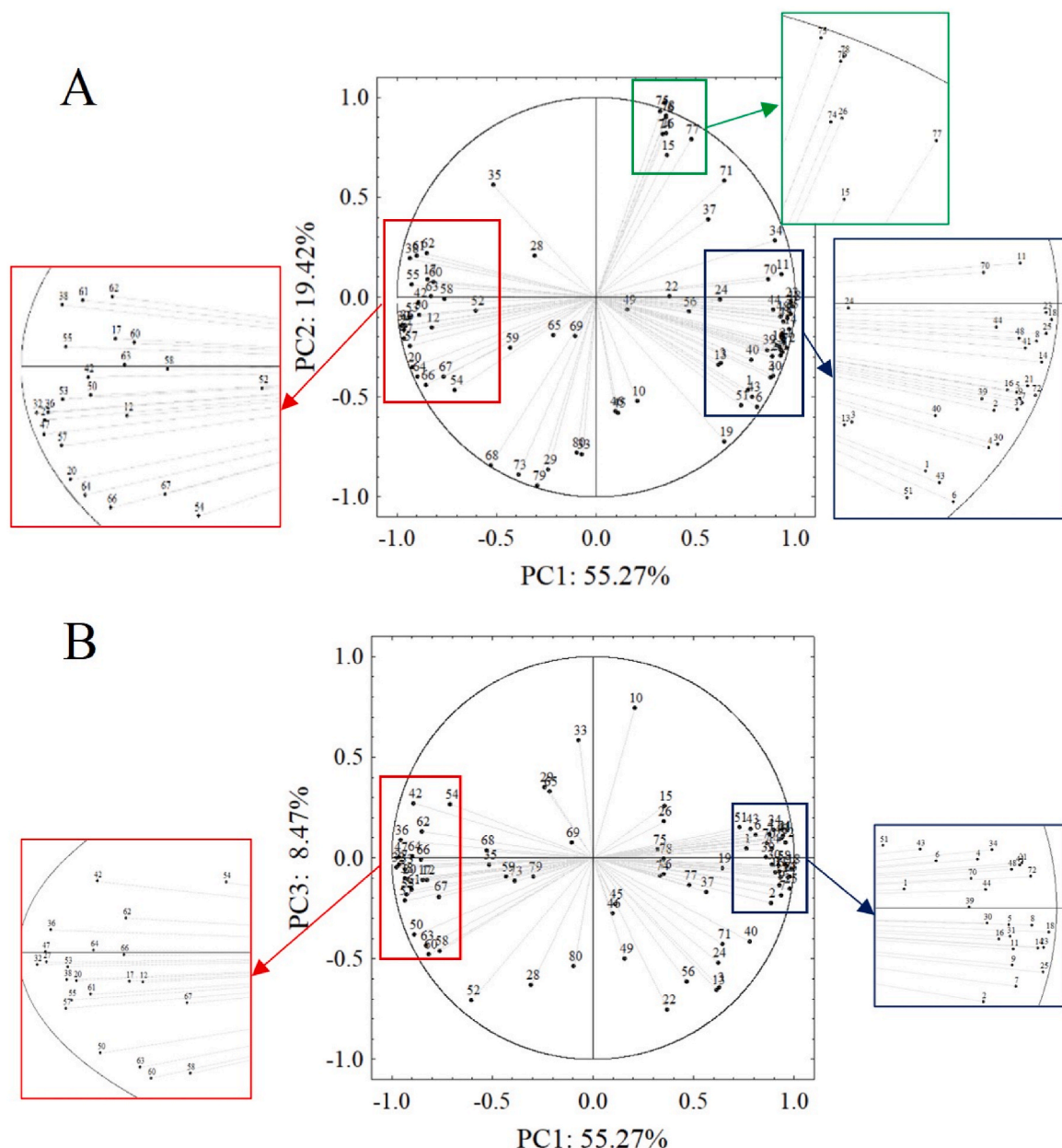


Fig. 3. PCA of the chemical dataset. Loading plots of the PC1 vs PC2 (A), and PC1 vs PC3 (B) with explained variances.

Colored insets have been incorporated to enhance the visibility of certain parameters.

1: isobutyl acetate; 2: ethyl butyrate; 3: ethyl isovalerate; 4: isobutyl alcohol; 5: isoamyl acetate; 6: 1-butanol; 7: isoamyl alcohols; 8: ethyl hexanoate; 9: amyl alcohol; 10: 3-methyl 3-buten-1-ol; 11: hexyl acetate; 12: acetoin; 13: *cis*-3-hexenyl acetate; 14: 4-methyl pentanol; 15: *cis*-2-pentanol; 16: 3-methylpentanol; 17: ethyl lactate; 18: 1-hexanol; 19: *trans*-3-hexenol; 20: 3-ethoxypropanol; 21: *cis*-3-hexenol; 22: *trans*-2-hexenol; 23: ethyl octanoate; 24: 1-octen-3-ol; 25: 1-heptanol; 26: acetic acid; 27: ethyl 3-hydroxybutanoate; 28: 2,3-butanediol; 29: 2-methyl propanoic acid; 30: isoamyl lactate; 31: ethyl decanoate; 32: γ -butyrolactone; 33: 3-methylbutanoic acid; 34: diethyl succinate; 35: γ -caprolactone; 36: 3-methylthio-1-propanol; 37: citronellol; 38: ethyl 4-hydroxybutanoate; 39: phenethyl acetate; 40: ethyl laurate; 41: hexanoic acid; 42: benzyl alcohol; 43: *n*-(3-methylbutyl) acetamide; 44: phenethyl alcohol; 45: *trans*-2-hexenoic acid; 46: γ -nonalactone; 47: diethylmalate; 48: octanoic acid; 49: 4-ethylphenol; 50: 2-methoxy-4-vinylphenol; 51: decanoic acid; 52: ethyl 2-hydroxy-3-phenylpropanoate; 53: monoethylsuccinate; 54: 4-vinylphenol; 55: benzoic acid; 56: dodecanoic acid; 57: benzenacetic acid; 58: *n*-(2-phenylethyl)-acetamide; 59: ethyl vanillate; 60: 3-oxo- α -ionol; 61: acetovanillone; 62: 3-oxo-7,8-dihydro- α -ionol; 63: *n*-acetyltyramine; 64: 4-hydroxy-benzenethanol (tyrosol); 65: 1H-indole-3-ethanol acetate (tryptophol acetate); 66: 1H-indole-3-ethanol (tryptophol); 67: ethyl *p*-coumarate; 68: free SO₂; 69: total SO₂; 70: pH; 71: total acidity; 72: ABV (alcohol by volume); 73: TPC (total phenolic compounds); 74: OD 420 (optical density 420 nm); 75: OD 520 (optical density 520 nm); 76: OD 580 (optical density 580 nm); 77: OD 620 (optical density 620 nm); 78: Color intensity; 79: Hue; 80: Copigmentation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

polar compounds and certain lactones with fruity scents gradually concentrated and became detectable by the judges in the most dealcoholized wine samples.

Focusing on the explanation of sensory results, the complexity of studying sensory profiling in wines arises from the multitude of interactions between the constituents of the non-volatile fraction of wine

and those of the volatile fraction (Noble, 1996). In some studies (Saenz-Navajas et al., 2010a; Sáenz-Navajas et al., 2010), the addition of volatile fruity extracts from white wine to a deodorized red wine has reduced the perception of astringency and bitterness while enhancing the perception of sweetness. Conversely, by substituting the volatile matrix of white wine with that of red wine has resulted in an increase in

Table 3One-way ANOVA for the evaluation of the judges' performance using Marzemino and Cabernet wines. Results are reported as F_{values} and p_{values} .

Attribute	DISCRIMINANT ABILITY			AGREEMENT AMONG JUDGES			REPEATABILITY BETWEEN SESSIONS		
	F_{value}	p_{value}		F_{value}	p_{value}		F_{value}	p_{value}	
COL	117.93	0.00	***	0.83	0.59	n.s.	2.64	0.13	n.s.
BRGH	46.77	0.00	***	0.55	0.77	n.s.	0.05	0.83	n.s.
SAT	33.23	0.00	***	1.80	0.21	n.s.	1.34	0.27	n.s.
FLU	8.63	0.01	**	3.41	0.05	n.s.	0.59	0.46	n.s.
CLA	13.21	0.00	***	2.65	0.10	n.s.	0.06	0.81	n.s.
S-FRU	10.61	0.00	**	3.12	0.07	n.s.	1.54	0.24	n.s.
S-FLO	49.02	0.00	***	2.14	0.15	n.s.	0.49	0.49	n.s.
S-VEG	1.18	0.29	n.s.	0.95	0.52	n.s.	3.48	0.08	n.s.
SWE	7.13	0.01	**	2.89	0.08	n.s.	0.03	0.86	n.s.
SOUR	0.13	0.97	n.s.	5.10	0.02	**	0.49	0.50	n.s.
BIT	7.45	0.01	**	5.44	0.01	**	0.31	0.59	n.s.
AST	0.42	0.98	n.s.	0.64	0.71	n.s.	0.02	0.89	n.s.
SMO	11.84	0.00	**	2.80	0.09	n.s.	0.07	0.80	n.s.
BOD	8.96	0.01	**	0.63	0.72	n.s.	2.82	0.12	n.s.
ALC	25.31	0.00	***	2.82	0.08	n.s.	0.13	0.73	n.s.
F-FRU	4.63	0.04	*	1.43	0.31	n.s.	2.07	0.17	n.s.
F-FLO	13.32	0.00	***	2.83	0.08	n.s.	0.52	0.48	n.s.
F-VEG	13.48	0.00	***	1.13	0.43	n.s.	4.71	0.05	*

Color (COL), brightness (BRGH), saturation (SAT), fluidity (FLU), clarity (CLA), smell-like fruitiness (S-FRU), smell-like floweriness (S-FLO), and smell-like vegetable/herbaceous scent (S-VEG), sweet (SWE), bitter (BIT), sour (SOUR), astringent (AST), smooth (SMO), full-bodied (BOD), alcoholic (ALC), flavor-like fruitiness (F-FRU), flavor-like floweriness (F-FLO), and flavor-like vegetable/herbaceous (F-VEG).

ANOVA was expressed as F_{values} and p_{values} . *** $p \leq 0.001$; ** $p \leq 0.01$; * $p \leq 0.05$; n.s.: not significant.

astringency perception and a decrease in sweetness.

Finally, in the present study, none of the wine samples exhibited any sensory defect. Despite the slight increase in concentrations of some volatile phenols in the dealcoholized samples, the judges did not perceive them, except occasionally.

3.6.1. Sensory scores in the blend wine samples (MIX 1 and MIX 2)

In general, the sensory attributes increased in MIX 1 and MIX 2 in comparison with the most dealcoholized samples, including the samples they were prepared from, i.e. D4 and D7, respectively. For most of the attributes, MIX 1 and MIX 2 reached almost the same values of the BMC, thus showing an almost identical sensory profile.

BRGH increased in the MIX samples, as a consequence of the BMC mixing. However, the most interesting result was recorded about taste attributes. Indeed, in the MIX wines, 'sweet' showed a tendency to increase in parallel with higher scores for smooth due to the mitigation effect of the BMC mixing. On the contrary, 'sour' taste perceived in both MIX samples decreased in comparison with the dealcoholized samples. The olfactory aspect, which is linked to the floral scent, significantly increased in both MIX wines, compared with the dealcoholized samples, until reaching the BMC values.

3.7. Principal component analysis applied on sensory analysis results

PCA was applied to the autoscaled sensory data set, which consists of the average values from the two sessions, based on the scores given by the 10 judges on 18 sensory parameters, excluding visual and gustatory defects. Three PCs were chosen based on Kaiser's criterion. PC1 explained 42.80% of the total variance, PC2 18.52%, and PC3 13.10%. PC1 vs PC2 score plot (Fig. 4A) shows that the trend of the samples traces quite faithfully that observed in the score plot (Fig. 2A) of the chemical parameters and volatile profile. In the PC1 vs PC3 score plot (Fig. 4B), it is clear that the BMC control sample approaches MIX 2.

The loading plot (Fig. 5A) of the PC1 vs PC2 shows that 'sour' taste is negatively correlated with S-FRU, F-FRU, fluidity, color, astringency, sweet, and brightness. All these attributes are positively correlated with the two MIX blends.

BMC, D1, and D2 show similar characteristics and are positively correlated with the scores of BITBIT, S-VEG, F-VEG, ALC, and BOD.

These latter, on the other hand, display a negative correlation with D5, D6, and D7. D3 and D4 are positively correlated with 'sour' taste, and negatively correlated with FLU, AST, COL, F-FRU, and SWE.

The loading plot of the PC1 vs PC3 (Fig. 5B) clearly shows that the two attributes that most influence the relationship between the PCs are 'saturation' and 'clarity', which are in diametrically opposite positions.

4. Conclusions

The needs of producers to reduce the alcohol content of wines due to climate change is combined with the market demand for products that are easier to drink and with a lower alcohol content. If on the one hand, the technological approach that exploits evaporative pertraction to reduce the alcohol content of wines is a valid option for wine producers, on the other it is necessary to mitigate some significant losses in the composition of the dealcoholized products.

The blending strategy of combining dealcoholized samples with the initial wine resulted in a remarkable increase in fermentation aromas and color intensity, as confirmed by chemical analysis. In the sensory evaluation, the MIX blends received the highest scores for sweet taste, while the sour taste was somewhat diminished. Moreover, the floral aroma significantly intensified in the MIX wines up to BMC scores.

The multivariate statistical analysis revealed that the two MIX blends significantly differed from the dealcoholized samples based on both chemical and sensory parameters. However, interestingly, the sensory profile of MIX 2 closely resembled that of the original initial wine.

The data obtained in the present study support the conclusion that the blending of the initial wine with volumes of appropriately dealcoholized wine, in order to bring the alcohol by volume within the limits regulated by law, is a technological strategy suitable for preserving the sensory quality (bouquet and color) of the final product. Furthermore, the wine industry, which is under pressure at the European level to reduce alcohol intake, can confidently pursue similar options to satisfy the health-conscious consumers, who are at the same time very demanding in terms of product quality.

Funding

This research was funded by the "POR FESR Emilia-Romagna

Table 4

Sensory scores expressed as mean values of eight sensory evaluations carried out during two sensory sessions (\pm standard deviation) on 10 wine samples, namely BMC: control wine; D1-D7: dealcoholized wine samples 1 to 7; MIX 1: wine obtained by mixing BMC + D4; MIX 2: wine obtained by mixing BMC + D7.

	BMC		D1		D2		D3		D4		D5		D6		D7		MIX 1		MIX 2		ANOVA
	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	Mean	\pm SD	F_{value}
Visual appearance attributes																					
COL	6.8	1.4	6.5	1.5	5.5	1.0	6.5	1.3	6.0	0.5	6.5	1.0	6.5	1.7	6.3	0.5	7.0	1.0	7.3	0.5	1.05 n.s.
BRGH	6.2 ^{ab}	2.2	5.0 ^{ab}	1.0	4.5 ^{ab}	1.5	4.0 ^a	2.0	4.0 ^a	1.0	6.0 ^{ab}	1.0	5.4 ^{ab}	2.0	5.0 ^{ab}	1.0	7.0 ^b	0.9	5.8 ^{ab}	1.0	2.90 **
SAT	6.8	0.7	5.5	1.0	6.0	1.7	7.0	1.0	6.0	0.1	6.5	0.8	6.5	1.5	6.3	0.6	7.2	0.2	6.0	0.8	0.89 n.s.
FLU	4.7	1.8	4.5	1.2	5.0	1.0	5.0	1.0	4.0	1.0	5.0	1.0	5.0	1.0	4.3	1.2	6.3	0.6	5.5	0.7	1.57 n.s.
CLA	8.3	1.8	9.0	0.7	8.5	1.0	8.0	1.5	8.0	2.0	8.0	0.8	9.0	1.0	8.0	1.5	8.0	1.0	7.8	1.7	0.62 n.s.
Olfactory attributes																					
S-FRU	3.3	1.0	4.0	2.0	5.0	1.2	3.5	0.5	3.3	1.8	4.0	2.0	4.0	1.6	3.5	0.5	5.0	1.0	5.7	1.3	1.74 n.s.
S-FLO	4.1	1.6	3.5	1.0	3.6	1.5	2.5	0.8	2.0	0.8	2.0	1.5	3.2	2.0	2.3	0.5	3.0	1.0	4.8	1.1	1.31 n.s.
S-VEG	4.7	0.5	4.0	2.0	4.0	1.4	4.0	1.2	3.8	1.0	3.5	1.5	2.8	1.5	3.3	1.0	4.5	1.5	3.3	1.0	1.10 n.s.
Gustatory attributes																					
SWE	3.6 ^{ab}	1.5	4.0 ^{ab}	1.0	4.5 ^{ab}	0.3	3.5 ^{ab}	0.5	3.6 ^{ab}	1.0	3.0 ^a	0.5	3.0 ^a	1.2	3.5 ^{ab}	0.8	5.0 ^{ab}	1.5	5.4 ^b	1.3	2.31 *
SOUR	4.0 ^{ab}	1.0	4.5 ^{ab}	1.0	4.7 ^{ab}	1.9	6.7 ^b	1.0	6.8 ^b	1.0	5.0 ^{ab}	2.0	4.8 ^{ab}	1.0	4.5 ^{ab}	0.7	4.0 ^{ab}	1.0	3.3 ^a	1.3	2.75 **
BIT	4.0 ^b	1.6	3.0 ^{ab}	1.5	3.5 ^{ab}	1.5	3.0 ^{ab}	2.0	3.0 ^{ab}	1.5	3.0 ^{ab}	1.0	1.5 ^a	0.5	1.8 ^a	0.5	3.1 ^{ab}	0.3	2.6 ^{ab}	1.2	1.64 *
AST	2.4	1.3	3.0	1.0	3.0	1.2	2.5	0.7	3.0	0.8	3.0	1.0	2.7	1.3	2.6	1.5	4.0	1.5	4.0	2.0	0.81 n.s.
SMO	4.0 ^{ab}	1.8	4.0 ^{ab}	1.8	4.7 ^{ab}	1.0	4.5 ^{ab}	1.2	3.0 ^a	0.5	3.5 ^{ab}	1.0	3.0 ^a	1.0	3.0 ^a	0.7	5.0 ^b	0.6	5.0 ^b	0.8	2.15 *
BOD	4.5	1.5	4.5	1.0	4.2	1.5	4.5	1.7	3.0	1.5	3.4	0.5	3.0	2.3	3.0	1.0	5.0	0.5	3.8	0.5	1.28 n.s.
ALC	4.5 ^{bc}	1.6	4.5 ^{bc}	1.6	3.4 ^{ab}	0.4	2.5 ^{ab}	0.8	2.0 ^a	0.2	3.3 ^{ab}	1.1	2.5 ^{ab}	1.4	2.5 ^{ab}	0.8	4.8 ^c	0.5	4.1 ^{abc}	0.7	6.41 ***
F-FRU	2.5 ^a	1.0	2.5 ^a	2.0	4.6 ^{ab}	1.0	4.5 ^{ab}	1.0	4.0 ^{ab}	0.8	3.0 ^{ab}	1.6	3.3 ^{ab}	1.0	3.0 ^{ab}	0.7	5.0 ^{ab}	0.5	5.2 ^b	1.0	2.75 **
F-FLO	3.3 ^{ab}	1.6	3.5 ^{ab}	1.5	3.8 ^b	2.0	2.0 ^{ab}	0.1	2.0 ^{ab}	0.5	1.8 ^{ab}	0.5	1.6 ^a	0.6	2.0 ^{ab}	1.0	3.0 ^{ab}	1.0	3.0 ^{ab}	1.3	2.65 **
F-VEG	4.4	1.7	4.0	1.0	3.5	1.0	4.0	1.5	3.5	0.7	3.0	0.8	3.0	2.5	2.5	1.8	4.0	1.0	3.5	0.7	0.53 n.s.

Color (COL), brightness (BRGH), saturation (SAT), fluidity (FLU), clarity (CLA), smell-like fruitiness (S-FRU), smell-like floweriness (S-FLO), and smell-like vegetable/herbaceous scent (S-VEG), sweet (SWE), bitter (BIT), sour (SOUR), astringent (AST), smooth (SMO), full-bodied (BOD), alcoholic (ALC), flavor-like fruitiness (F-FRU), flavor-like floweriness (F-FLO), and flavor-like vegetable/herbaceous (F-VEG).

ANOVA was expressed as F_{values} and p_{values} . *** $p \leq 0.001$; ** $p \leq 0.01$; * $p \leq 0.05$; n.s.: not significant. Results of the Tukey's test are also reported as superscript letters, where different letters identify samples significantly different ($p \leq 0.05$) a < b < c.

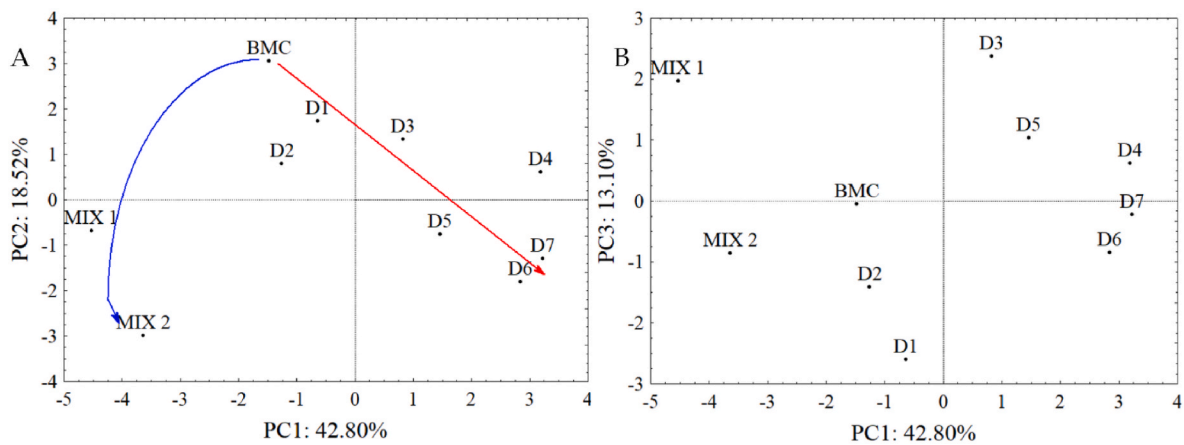


Fig. 4. PCA of the sensory dataset. Score plots of the PC1 vs PC2 (A), and PC1 vs PC3 (B) with explained variances.

BMC: control wine; D1-D7: dealcoholized wine samples 1 to 7; MIX 1: wine obtained by mixing BMC + D4; MIX 2: wine obtained by mixing BMC + D7.

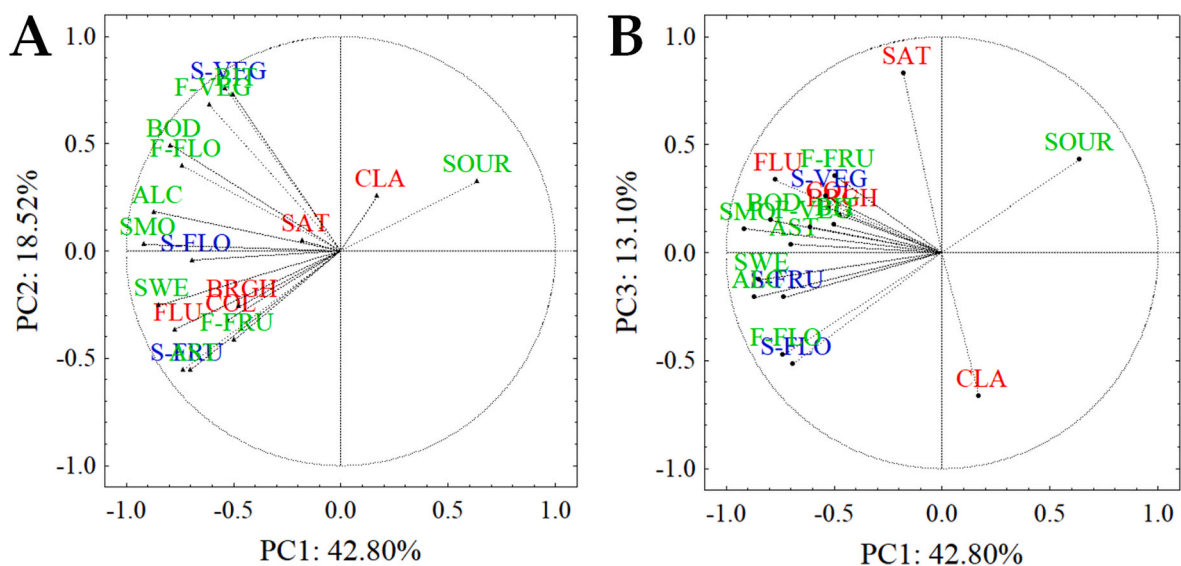


Fig. 5. PCA of the sensory dataset. Loading plots of the PC1 vs PC2 (A), and PC1 vs PC3 (B) with explained variances.

Color (COL), brightness (BRGH), saturation (SAT), fluidity (FLU), clarity (CLA), smell-like fruitiness (S-FRU), smell-like floweriness (S-FLO), and smell-like vegetable/herbaceous scent (S-VEG), sweet (SWE), bitter (BIT), sour (SOUR), astringent (AST), smooth (SMO), full-bodied (BOD), alcoholic (ALC), flavor-like fruitiness (F-FRU), flavor-like floweriness (F-FLO), and flavor-like vegetable/herbaceous (F-VEG). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2014–2020, grant number CUP: E56C18002290006” titled: ‘Sostenibilità e Innovazione Sostenibilità e Innovazione – SOSTINNOVI’.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

CRedit authorship contribution statement

Giuseppe Montecocchi: Data curation, Resources, Software, Methodology, Validation, Visualization, Roles/. **Arianna Ricci:** Data curation, Resources, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. **Francesca Masino:** Data curation, Resources, Software, Methodology, Investigation, Formal analysis, Validation, Roles/. **Valentina Ferrari:** Data curation,

Investigation, Formal analysis. **Andrea Versari:** Methodology, Resources, Validation, Visualization, Writing – review & editing. All authors have read and agreed to the published version of the manuscript. **Andrea Antonelli:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

All 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.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to thank Dr Laura Munari and Maria Rosa Pettazoni (project managers), Anna Garavaldi and Valeria Musi (CRPA), DIEMME Enologia (Lugo, RA – Italy), Emilia Wine soc. coop. agri. (Arceto di Scandiano, RE – Italy).

References

- Bertrand, A., Anocibar Belouqui, A., 1996. Essais d'utilisation d'enzymes pectolytiques à activités complémentaires de type glucosidase dans les vins. Influence sur l'arôme. *Rev. Fr. Enol.* 157, 19–24.
- Butnariu, M., Butu, A., 2019. Qualitative and quantitative chemical composition of wine. In: Grumezescu, A.M., Holban, A.M. (Eds.), *Quality Control in the Beverage Industry*, Cambridge, pp. 385–417 (Chapter 11).
- Castro-Marín, A., Buglia, A.G., Riponi, C., Chinnici, F., 2018. Volatile and fixed composition of sulphite-free white wines obtained after fermentation in the presence of chitosan. *Lebensm. Wiss. Technol.* 93, 174–180.
- Castro-Marín, A., Culcasi, M., Cassien, M., Stocker, P., Thétiot-Laurent, S., Robillard, B., Chinnici, F., Pietri, S., 2019. Chitosan as an antioxidant alternative to sulphites in oenology: EPR investigation of inhibitory mechanisms. *Food Chem.* 285, 67–76.
- Castro Marin, A., Chinnici, F., 2020. Physico-chemical features of sangiovese wine as affected by a post-fermentative treatment with chitosan. *Appl. Sci.-Basel* 10 (19), 6877–6892.
- Catarino, M., Mendes, A., 2011. Dealcoholizing wine by membrane separation processes. *Innov. Food Sci. Emerg.* 12, 330–337.
- Cook, B.I., Wolkovich, E.M., 2016. Climate change decouples drought from early wine grape harvests in France. *Nat. Clim. Change* 6, 715.
- Diban, N., Athes, V., Bes, M., Souchon, I., 2008. Ethanol and aroma compounds transfer study for partial dealcoholization of wine using membrane contactor. *J. Membr. Sci.* 311, 136–146.
- Diban, N., Arruti, A., Barceló, A., Puxeu, M., Urriaga, A., Ortiz, I., 2013. Membrane dealcoholization of different wine varieties reducing aroma losses. Modeling and experimental validation. *Innov. Food Sci. Emerg.* 20, 259–268.
- Esteras-Saz, J., de la Iglesia, Ó., Kumakiri, I., Peña, C., Escudero, A., Téllez, C., Coronas, J., 2023. Pervaporation of the low ethanol content extracting stream generated from the dealcoholization of red wine by membrane osmotic distillation. *J. Ind. Eng. Chem.* 122, 231–240.
- EU regulation no. 606/09, 2009. Categories of Wine Products, Oenological Practices and Related Restrictions. dated July 10, 2009.
- Ferrari, R., Ciman, G.M., Camin, F., Bandini, S., Gostoli, C., 2016. Variation of oxygen isotopic ratio during wine dealcoholization by membrane contactors: experiments and modelling. *J. Membr. Sci.* 498, 385–394.
- Fia, G., Bucalossi, G., Proserpio, C., Vincenzi, S., 2022. Unripe grapes: an overview of the composition, traditional and innovative applications, and extraction methods of a promising waste of viticulture. *Aust. J. Grape Wine Res.* 28, 8–26.
- Hannah, L., Roehrdanz, P.R., Ikegami, M., Shepard, A.V., Shaw, M.R., Tabor, G., Hijmans, R.J., 2013. Climate change, wine, and conservation. *P. Natl. Acad. Sci. USA* 110, 6907–6912.
- Hogan, P.A., Canning, R.P., Peterson, P.A., Johnson, R.A., Michaels, A.S., 1998. A new option: osmotic distillation. *Chem. Eng. Prog.* 94, 49–61.
- ISO 3972, 2011. Sensory analysis – methodology. Method of investigating sensitivity of taste.
- ISO 8586, 2023. Sensory Analysis - Selection and Training of Sensory Assessors.
- Jones, G.V., White, M.A., Cooper, O.R., Storchmann, K., 2005. Climate change and global wine quality. *Climatic Change* 73, 319–343.
- Kaiser, H.F., 1958. The varimax criterion for analytic rotation in factor analysis. *Psychometrika* 23, 187–200.
- Kumar, Y., Ricci, A., Parpinello, G.P., Versari, A., 2024. Dealcoholized wine: a scoping review of volatile and non-volatile profiles, consumer perception, and health benefits. *Food Bioprocess Technol.* 1–21.
- Liguori, L., De Francesco, G., Russo, P., Albanese, D., Perretti, G., Di Matteo, M., 2015. Quality improvement of low craft beer produced by evaporative pertraction. *Chem. Engineer. Trans.* 43, 13–18.
- Liguori, L., Russo, P., Albanese, D., Di Matteo, M., 2018. Production of low-alcohol beverages: current status and perspectives (Chapter 12). In: Grumezescu, A.M., Holban, A.M. (Eds.), *Handbook of Food Bioengineering. Food Processing for Increased Quality and Consumption*. Academic Press, Cambridge, pp. 347–382.
- Longo, R., Blackman, J.W., Antalick, G., Torley, P.J., Rogiers, S.Y., Schmidtke, L.M., 2018. A comparative study of partial dealcoholisation versus early harvest: effects on wine volatile and sensory profiles. *Food Chem.* 261, 21–29.
- Masino, F., Montecchi, G., Calvini, R., Foca, G., Antonelli, A., 2022. Sensory evaluation and mixture design assessment of coffee-flavored liquor obtained from spent coffee grounds. *Food Qual. Prefer.* 96, 104427.
- Meillon, S., Urbano, C., Schlich, P., 2009. Contribution of the temporal dominance of sensations (TDS) method to the sensory description of subtle differences in partially dealcoholized red wines. *Food Qual. Prefer.* 20, 490–499.
- Meilgaard, M.C., Carr, B.T., Civille, G.V., 1999. Descriptive analysis technique. In: *Sensory Evaluation Techniques*, III Edition. CRC press, Boca Raton, FL, USA, pp. 161–225. and 353–375.
- Montecchi, G., Masino, F., Vasile Simone, G., Cerretti, E., Antonelli, A., 2015. Aromatic profile of white sweet semi-sparkling wine from Malvasia di Candia aromatica grapes. *S. Afr. J. Enol. Vitic.* 36, 267–276.
- Montecchi, G., Masino, F., Versari, A., Ricci, A., Nigro, G., Antonelli, A., 2021. Effect of kaolin/defoliation combined with dry ice on lambrusco red wine production to constrain the effects of climate change. *S. Afr. J. Enol. Vitic.* 42, 100–113.
- Mozell, M.R., Thach, L., 2014. The impact of climate change on the global wine industry: challenges & solutions. *Wine Econ. Policy* 3, 81–89.
- Noble, A.C., 1996. Taste-aroma interactions. *Trends Food Sci. Technol.* 7, 439–444.
- OIV-MA-AS315-01: R2009. Acetaldehyde. Compendium of international methods of wines and musts analysis. Annex A – methods of analysis of wine and must. Section 3- Chemical Analysis. Section 3.1 – Organic Compounds. Section 3.1.5-Other Organic compounds..
- OIV-MA-AS312-01B: R2009. Alcoholic strength by volume (type IV method) – Compendium of international methods of wines and musts analysis. Annex A – methods of analysis of wine and must. Section 3- Chemical Analysis. Section 3.1 – Organic Compounds. Section 3.1.2-Alcohols.
- OIV-MA-AS313-15: R2011. pH (Type I method). Compendium of international methods of wines and musts analysis. Annex A – methods of analysis of wine and must. Section 3- Chemical Analysis. Section 3.1 – Organic Compounds. Section 3.1.3-Acids..
- OIV-MA-AS313-01: R2015. Total acidity (type I method). Compendium of international methods of wines and musts analysis. Annex A – methods of analysis of wine and must. Section 3- chemical analysis. Section 3.1 – Organic Compounds. Section 3.1.3-Acids..
- OIV-MA-AS313-02: R2015. Volatile acidity (type I method). Compendium of international methods of wines and musts analysis. Annex A – methods of analysis of wine and must. Section 3- chemical analysis. Section 3.1 – Organic Compounds. Section 3.1.3-Acids..
- OIV-MA-AS323-04A: R2012. Sulphur dioxide (Type IV method). Compendium of international methods of wines and musts analysis. Annex A – methods of analysis of wine and must. Section 3- Chemical Analysis. Section 3.1 – Section 3.2 - Non-Organic Compound. Section 3.2.3 – Other non-Organic Compounds..
- OIV-MA-AS2-07B: R2009. Chromatic characteristics (Type IV method). Compendium of International Methods of Wine and Must Analysis. Annex A - Methods of Analysis of Wines and Musts. Section 1 – Definitions and General Principles..
- Pallioti, A., Tombesi, S., Silvestroni, O., Lanari, V., Gatti, M., Poni, S., 2014. Changes in vineyard establishment and canopy management urged by earlier climate-related grape ripening: a review. *Sci. Hortic.-Amsterdam* 178, 43–54.
- Panceri, C.P., Burin, V.M., Caliarì, V., Amboni, R.D., Bordignon-Luiz, M.T., 2017. Aromatic character of Cabernet Sauvignon and Merlot wines produced with grapes dried under controlled conditions. *Eur. Food Res. Technol.* 243, 609–618.
- Rapp, A., Versini, G., 1996. Flüchtige phenolische Verbindungen in Wein (Volatile phenolic compounds of wine). *Deut. Lebens.-Rundsch.* 92, 42–48.
- Rehn, N., Room, R., Edwards, G., World Health Organization, 2001. Alcohol in the European Region: Consumption, Harm and Policies/by Nina Rehn, with Robin Room and Griffith Edwards. WHO Regional Office for Europe, Copenhagen.
- Ross, C.F., Hinken, C., Weller, K., 2007. Efficacy of palate cleansers for reduction of astringency carryover during repeated ingestions of red wine. *J. Sensory Stud.* 22, 243–266.
- Sam, F.E., Ma, T.Z., Salifu, R., Wang, J., Jiang, Y.M., Zhang, B., Han, S.Y., 2021. Techniques for dealcoholization of wines: their impact on wine phenolic composition, volatile composition, and sensory characteristics. *Foods* 10, 2498–2536.
- Saenz-Navajas, M.P., Campo, E., Cullere, L., Fernandez-Zurbano, P., Valentin, D., Ferreira, V., 2010. Effects of the nonvolatile matrix on the aroma perception of wine. *J. Agric. Food Chem.* 58, 5574–5585.
- Sáenz-Navajas, M.P., Campo, E., Fernández-Zurbano, P., Valentin, D., Ferreira, V., 2010. An assessment of the effects of wine volatiles on the perception of taste and astringency in wine. *Food Chem.* 121, 1139–1149.
- Sorbini, M., Aragrande, M., 2013. Evoluzione dei consumi di vino e prospettive per le Malvasie. In: 4th Symposium Malvasia of the Mediterranean. 24-28 June 2013, Monemvasia, Greece.
- Smith, C.R., 1996. Apparatus and Method for Removing Compounds from a Solution. Patent No. 5480665. United States of America.
- Teslić, N., Patrignani, F., Ghidotti, M., Parpinello, G.P., Ricci, A., Tofalo, R., Lanciotti, R., Versari, A., 2018. Utilization of 'early green harvest' and non-*Saccharomyces cerevisiae* yeasts as a combined approach to face climate change in winemaking. *Eur. Food Res. Technol.* 244, 1301–1311.
- Teslić, N., Vujadinović, M., Ruml, M., Ricci, A., Vuković, A., Parpinello, G.P., Versari, A., 2019. Future climatic suitability of the Emilia-Romagna (Italy) region for grape production. *Reg. Environ. Change* 19, 599–614.
- UNI-ISO 8589, 1990. Sensory Analysis - General Guidance for the Design of Test Rooms.
- Varavuth, S., Jiratananon, R., Atcharyawut, S., 2009. Experimental study on dealcoholization of wine by osmotic distillation process. *Sep. Purif. Technol.* 66, 313–321.
- Vasile Simone, G., Montecchi, G., Masino, F., Matrella, V., Imazio, S.A., Antonelli, A., Bignami, C., 2013. Ampelographic and chemical characterization of Reggio Emilia and Modena (northern Italy) grapes for two traditional seasonings: 'saba' and 'agresto'. *J. Sci. Food Agric.* 93, 3502–3511.
- Wollan, D., 2010. In: Reynolds, A.G. (Ed.), *Membrane and Other Techniques for the Management of Wine Composition* (Chapter 5). Woodhead Publishing Series in Food Science, Technology and Nutrition. Managing Wine Quality. Woodhead Publishing, Cambridge, pp. 133–163.