Food Bioscience 77 (2026) 108343

Contents lists available at ScienceDirect

Food Bioscience

journal homepage: www.elsevier.com/locate/fbio

Quality assessment of dealcoholized wines produced by dialysis, osmotic distillation, and hybrid membrane technologies

Yogesh Kumar [a,b,*], Lorenzo Italiano [b], Matthias Schmitt [b], Sayali Bhor [b], Florian Kiene [c], Arianna Ricci [a], Giuseppina Paola Parpinello [a,**], Andrea Versari [a]

[a] Department of Agricultural and Food Sciences, University of Bologna, Piazza Goidanich 60, 47521, Cesena, FC, Italy
[b] Department of Enology, Hochschule Geisenheim University, Von-Lade-Str. 1, 65366, Geisenheim, Germany
[c] Department of Microbiology and Biochemistry, Hochschule Geisenheim University, Von-Lade-Str. 1, 65366, Geisenheim, Germany

ARTICLE INFO

Keywords:
Alcohol removal
Riesling
Non-alcoholic wine
Sensory attributes
Volatile compounds

ABSTRACT

This study investigates dealcoholization approaches, including dialysis (Dia), osmotic distillation (OD), and a hybrid membrane system combining nanofiltration (NF) and OD (NF-OD), for producing dealcoholized white wines (≤0.5 % v/v ethanol) in compliance with regulatory standards. Physicochemical results showed an increase in density for all dealcoholized wines (DWs). OD showed no significant change in the total dry extract, and an increase in acidity and glycerol content compared to the original wine (OW). In contrast, Dia caused significant losses in acidity (−63 %), glycerol (−45 %), and dry extract (−32 %), while NF-OD showed intermediate effects. Minerals were best retained in OD and NF-OD, whereas Dia induced severe depletion (>80 % loss of K, Ca, Mg). Colour parameters for OD/NF-OD remained stable ($\Delta E < 1$), while Dia showed perceptible differences ($\Delta E = 1.30$). GC–MS analysis showed more than a 73 % reduction in volatile compounds in the produced DWs compared to OW, with esters and higher alcohols being the most affected. Sensory evaluation indicated reduced sweetness, hotness and body/fullness in all DWs, but NF-OD preserved acidity, bitterness, and overall acceptability comparable to OW, outperforming OD and Dia. NF-OD emerges as the optimal technique for quality preservation.

1. Introduction

Wine, an alcoholic beverage is produced through the fermentation of grapes, contains several health-promoting components despite the drawbacks associated with alcohol consumption. These components, including organic acids, phenols, and aromatic compounds, are valued for their antioxidant properties, support of lipid metabolism, and ability to help regulate blood sugar levels (Oro et al., 2025; Succi et al., 2025). With health considerations, other factors such as personal preference, religious adherence, and a desire to reduce ethanol consumption are driving increased demand for non-alcoholic wine (Akhtar et al., 2025; Kumar, Khalangre, et al., 2025; Kumar, Ricci, et al., 2024; Sam, Ma, Salifu, et al., 2021). Based on this growing trend, it is projected that the non-alcoholic wine market will reach USD 2.84 billion in 2025 and USD 7.64 billion in 2035 at the compound annual growth rate (CAGR) of 10.4 % (Fact.MR., 2025).

The increasing demand for and acceptance of reduced and non-alcoholic wines, along with evolving regulatory standards, have posed significant challenges for scientists and engineers. This has driven the development of methods to remove ethanol while minimizing its impact on the sensory and chemical properties of wine. Therefore, to reduce or completely remove ethanol from wine post fermentation, a variety of techniques have been employed such as thermal methods include vacuum distillation (VD), conventional distillation (Dist), and the spinning cone column (SCC) and membrane-based techniques comprise osmotic distillation (OD), dialysis (Dia), nanofiltration (NF), reverse osmosis (RO), and hybrid approaches that combine RO or NF with other methods (Italiano et al., 2025; Schmitt & Christmann, 2019, 2022). Although each dealcoholization technique has its own advantages and limitations, membrane-based methods are generally superior to thermal-based techniques, as they operate at low temperatures, thereby minimizing the loss of volatile aroma compounds, preserving phenolic stability, and

This article is part of a special issue entitled: Alcohol-free or Low-alcohol Beverages published in Food Bioscience.

* Corresponding author. Department of Agricultural and Food Sciences, University of Bologna, Piazza Goidanich 60, 47521, Cesena, FC, Italy.
** Corresponding author.
E-mail addresses: yogesh.kumar3@unibo.it (Y. Kumar), giusi.parpinello@unibo.it (G.P. Parpinello).

https://doi.org/10.1016/j.fbio.2026.108343
Received 24 September 2025; Received in revised form 2 January 2026; Accepted 20 January 2026
Available online 20 January 2026

reducing undesirable changes in color and sensory quality (Sam, Ma, Liang, et al., 2021).

In our previous studies, Kumar, Cassano, et al. (2024) investigated the performance of three NF membranes (TS 40, NF99, HL) and one RO membrane (RO-SE) in filtering Sancrispino white wine (10.5 % v/v). Low-alcohol beverages (1.28–4.15 % v/v) were produced using a diafiltration process with water. Among the membranes tested, the HL membrane exhibited the highest permeate flux, while both the HL and NF99 membranes were more effective in reducing the alcohol content in wine, achieving ethanol rejection rates of 5.14 % and 5.46 %, respectively. In contrast, the RO-SE membrane achieved the highest ethanol rejection rate (10.64 %). In addition, the HL and NF99 membranes demonstrated the highest rejection rates (>80 %) for reducing sugars, glucose, fructose, citric acid, and tartaric acid in dealcoholized wine. The RO process required a considerably longer duration (39 h) to concentrate the wine at a volume reduction factor (VRF) of 4, compared to the NF membranes, which achieved this concentration in 3.4 h. In a subsequent study, Kumar, Cassano et al. (2025a) evaluated the efficacy of an NF-DK membrane and an RO-SG membrane for ethanol reduction in Italian white wine. The RO-SG membrane required substantially more time (247 min) than the NF-DK membrane (40 min) to concentrate wine at a weight reduction factor (WRF) of 4. However, RO-SG achieved a higher ethanol rejection rate (16.3 %) compared to NF-DK (1.8 %). Using the diafiltration process, low-alcohol wines were produced with final ethanol concentrations of 3.07 % v/v for RO(B) and 2.50 % v/v for NF(B). Further extending this, Tsibranska et al. (2025) investigated single and sequential diaNF/RO processes, along with two-stage diafiltration to assess separation efficiency for ethanol and polyphenols in red Mavrud wine. However, in all the aforementioned studies, NF membranes demonstrated high efficiency in wine concentration, effectively separating the feed into a retentate that retained most of the wine's valuable components and a permeate enriched in water and ethanol. Compared to RO, NF membranes offered shorter processing times and lower ethanol rejection, making them suitable for partial dealcoholization. However, further ethanol reduction typically requires diafiltration, where the permeate is replaced with water to facilitate continued ethanol removal. Notably, under European Commission (EC) and International Organisation of Vine and Wine (OIV) regulations, beverages produced through water-based diafiltration cannot be legally labeled as "wine" due to restrictions on water addition during winemaking. This regulatory limitation underscores a critical research gap: the need for advancement in membrane-based processes that can reduce ethanol below ≤0.5 % v/v while maintaining wine quality and complying with regulatory standards. In previous studies, a water-based dia-nanofiltration approach was employed, which is incompatible with the regulatory definitions of wine established by the OIV and EU for dealcoholized wine. Therefore, combining techniques such as NF and OD can be an effective solution for producers seeking compliant alternatives. Furthermore, studies on wine dealcoholization using dialysis remain limited, and existing research has not fully explored the effects of this technique on the volatile and sensory profiles of wine (Calvo et al., 2022; Italiano et al., 2024).

To address this limitation, the current study investigates alternative dealcoholization approaches including dialysis, osmotic distillation (OD), and hybrid membrane systems (combining NF and OD) for producing white wines with ≤0.5 % v/v ethanol while complying with regulatory standards. The performance of these technologies was systematically assessed through comprehensive physicochemical analysis, color profiling, volatile compound quantification, and sensory assessment.

The hypothesis of this study is that dialysis and OD, and combination OD with NF, can achieve ethanol reduction to legally compliant levels (≤0.5 % v/v) while maintaining the essential physicochemical composition and sensory characteristics of white wine.

This study is novel in that it provides a comparative assessment of dialysis, OD, and hybrid membrane systems as alternative dealcoholization strategies that avoid the use of water-based diafiltration. By side-stepping water-based diafiltration, this work advances membrane-based strategies for producing regulatory-compliant dealcoholized wines without compromising critical oenological quality parameters.

2. Material and methods

2.1. Chemicals and reagents

The pure water for stripping solution of the OD and dialysis process was prepared using a PureLab Option-R60 system, equipped with a reverse osmosis (RO) membrane model LC119 (ELGA LabWater, High Wycombe, HP14 3BY, UK). Sodium hydroxide (NaOH, >98 % p. a) was procured from Carl Roth GmbH + Co. KG, Karlsruhe, Germany. Reagents used during GC-MS, including suppliers and purity, are listed in the supplementary file (Section S1.1).

2.2. Wine

Riesling white wine (OW), produced in stainless steel with a final alcohol content of 13.13 % v/v at the Hochschule Geisenheim University winery (Rheingau, Germany) during the 2022 vintage, was used for dealcoholization.

2.3. Wine dealcoholization

Osmotic distillation: Dealcoholization was performed using an osmotic distillation system (CO_2 Membrane System 100, KH TEC GmbH, D-75038 Oberderdingen, Germany) equipped with two 3M™ Liqui-Cel™ membrane contactors (MF-PP Series, Type B65; surface area: 20 m^2 x 2 membranes). The system featured automated process control (SIMATIC HMI) for real-time feed and stripping flow regulation. For each trial, 30 L of wine was circulated on the feed side, while the stripping side contained deoxygenated distilled water (prepared by CO_2 sparging to minimize dissolved oxygen). The feed and stripping flow rates were maintained at 30 L/min and 45 L/min, respectively, with a constant process temperature of 21 °C. A total of 450 L of stripping water was used to produce the dealcoholized wine (<0.5 % v/v) and produced dealcoholized wine samples were labeled as OD.

Nanofiltration- Osmotic distillation: The dealcoholization process involved a two-step hybrid membrane approach: nanofiltration followed by osmotic distillation. Initially, wine was subjected to a spiral-wound nanofiltration membrane module (Vinopro30 D, Lenntech B.V., Distributieweg 3, 2645 EG Delfgauw, Netherlands) made of polyamide material with a molecular weight cut-off (MWCO) of 150–300 kDa, a surface area of 7.9 m^2, and a minimum rejection rate of 98 % for $MgSO_4$ (2000 ppm at 25 °C). The filtration was performed at 40 bar and 20 °C, achieving a weight reduction factor (WRF) of 4. The operating condition was determined based on previous trials to achieve optimal ethanol removal efficiency, flux, and retention of essential wine components. The resulting permeate was then dealcoholized via osmotic distillation (the process explained above). The dealcoholized permeate was subsequently reintroduced into the retentate (concentrated wine) in a diafiltration process. This cycle was repeated continuously until the desired alcohol content (<0.5 % v/v) was achieved. The final dealcoholized wine, labeled NF-OD, was obtained after sequential NF and OD treatments.

Dialysis: The process was performed using a dialysis membrane system equipped with a polyethersulfone (PES) membrane (4.6 m^2 surface area, 10–15 kDa MWCO; InnoSpire Technologies GmbH, Germany), following the protocol established in our laboratory and also reported in our previous work (Italiano et al., 2025). In this system, wine (feed solution) and demineralized water (draw solution) were circulated through the membrane at 1 bar, with pressure regulated by a manometer (MS 10160, WIKA, Germany). Flow rates at both inlets and outlets were

precisely controlled using flowmeters (DK 800, KROHNE Messtechnik GmbH, Germany), while interconnected tubing enabled real-time monitoring of osmotic pressure gradients across the membrane. System integrity was verified using four supplementary manometers (MS 10160) positioned at critical nodes. The process was carried out in cycles: the wine was repeatedly pumped back into the feed tank, while the water on the draw solution side was refreshed with new demineralized water each time. This process continued until dealcoholized wine was achieved and the final product labled as "Dia".

To stabilize all wines, immediately after dealcoholization, 30 mg/L of SO_2 (prepared as a 5 % v/v aqueous solution) was added to both the OW and dealcoholized wines (DW). The wines were then bottled using a heat exchanger at 62 °C for 10–15 s into 750 mL brown glass bottles (without headspace) under screw-cap closures. Each dealcoholization process was performed in duplicate.

2.4. Physicochemical parameters

pH was measured using a Brinkmann Metrohm 605 pH meter (Metrohm Herisau, Switzerland). Total acidity was determined by titration using an 848 Titrino Plus system (Metrohm Herisau, Switzerland), equipped with a Samplet autosampler capable of processing up to 12 samples per run. A 30 mL aliquot of each sample was titrated with 0.1N NaOH. Additional physicochemical parameters including dry extract, density, volatile acidity, malic acid, tartaric acid, citric acid, succinic acid, and glycerin, were quantified using Fourier-transform infrared (FTIR) spectroscopy (BACCHUS 3 Multispec model-TDI, Barcelona, Spain).

2.5. Color profile

The color parameters, including absorbance at 420 nm, color intensity (420 + 520+620 nm), chroma, as well as L* (perceptual lightness), a* (red/green value), and b* (yellow/blue value) values were measured using a photoLab® 7600 UV–VIS spectrophotometer (Xylem Analytics Germany) (Kumar, Italiano, et al., 2024).

2.6. Mineral analyses

Minerals such as potassium, calcium, and magnesium were analyzed using a ContrAA 300 instrument (Analytik Jena AG, Jena, Germany) following the SOP-0921 method (Italiano et al., 2025).

2.7. Volatile profile

The volatile compounds in OW and dealcoholized wine were analyzed using targeted headspace solid-phase microextraction coupled with gas chromatography–mass spectrometry (HS-SPME-GC-MS), following the methodology outlined by Badura et al. (2023). For sample preparation, each wine sample (5 mL) was mixed with 1.7 g of NaCl, 10 μL of internal standard (1-octanol, 551 mg/L), and 10 μL of internal control standard (cumene, 52 mg/L). Analysis was performed using an Agilent GC 7890 A system paired with an MS 5975 B detector (Agilent, Santa Clara, CA, USA), equipped with a Gerstel MPS robotic autosampler and a CIS 4 inlet system (Gerstel, Mülheim an der Ruhr, Germany). A 65 μm polydimethylsiloxane/divinylbenzene (PDMS/DVB) SPME fiber (Supelco, Merck, Darmstadt, Germany) was used for extraction. Volatile separation was achieved using a 60 m × 0.25 mm × 1 μm Rxi®-5Si1 MS column (Restek, Bad Homburg, Germany) with helium as the carrier gas (constant flow, 1.2 mL/min). The injection was performed in split mode (1:10 ratio) with an initial temperature of 30 °C (held for 1 min), followed by a rapid ramp at 12 °C/s to 240 °C (held for 4 min). The GC oven program began at 40 °C (4 min hold), increased at 5 °C/min to 210 °C, then ramped at 20 °C/min to 240 °C (held for 10.5 min). Mass spectral detection was performed in scan mode (m/z 35–250) using electron impact ionization (EI) at 70 eV. For quantification, a 5-point calibration curve was constructed four times for each target volatile using various wine model solutions (3 % tartaric acid, pH 3.0) with ethanol contents of 3.0 % or 12 % v/v. Calibration parameters and analytical performance data for the target wine aroma compounds analyzed by GC–MS using 3 % and 12 % (v/v) model wine matrices are reported in Tables S1 and S2.

2.8. Sensory analysis

Sensory evaluation was conducted by 21 judges, composed of 17 males and 4 females, who are all members of Assoenologi section Romagna (Italy). All panelists were enologists with significant experience in wine evaluation, regularly participating in national and regional wine tastings. Each judge was asked to give scores to descriptors on a 1 to 10 scale, where 1 indicates "Low Intensity" and 10 indicates "High Intensity". The parameters included were visual (color intensity), aroma (include fresh floral, evolved floral, fresh fruity, apple, citrus, peach, evolved fruity, cooked vegetables), and gustatory parameters (include sweetness, acidity, bitterness, body/fullness, hotness). In the last panelists were asked to assess the overall acceptability of each wine sample. In that they were instructed to evaluate the suitability of the wines for consumption using a structured 10-point hedonic scale, where a score of 1 indicated "not acceptable" and 10 represented "highly acceptable."

Sensory analysis was conducted in adherence to ISO recommendations. Approximately 40–45 ml each sample was poured immediately before the evaluation and presented in wineglasses and served at 12–14 °C. Preparation of the samples took place in a separate room and was put under randomized order within three digits as code. Natural water and bread were provided during each session to neutralize the effects of previous wines.

For data interpretation, the attribute scores representing each sensory response to a given wine sample were averaged over the panellists and the resulting average values were plotted in radar charts to compare the wines. A one-way ANOVA was carried out for statistically significant differences between OW and dealcoholized wine samples for each sensory attribute. Furthermore, Principal Component Analysis (PCA) was performed to analyse the correlation between sensory attributes and the corresponding volatile compound for the different samples.

Ethical compliance: All sensory procedures involving human participants were conducted in accordance with the Helsinki Declaration or comparable ethical standards. All participants provided informed written consent: *"I confirm that I have read and understood the information. I voluntarily agree to participate in this sensory evaluation and consent to the anonymous use of my responses for research and publication purposes"*. They were informed that the samples included dealcoholized/alcohol free (DW, ≤0.5 % v/v ethanol) white wines, which they had to taste. Participants were also made aware of the safety, confidentiality, and voluntary nature of their participation, including their right to withdraw at any time. A specific ethical approval to conduct a human sensory study was not a requirement at the institution where this study was conducted.

2.9. Statical analysis

Each dealcoholization process was performed in duplicate, and subsequently, each sample was analyzed in duplicate. Results were reported as averages ± standard deviations and analyzed by ANOVA. The Tukey test was used to find significant differences (p-level <0.05) between control and reduced alcohol wine samples using XLSTAT BASIC^{+} (Annual version 2024.3.0 1423). Spider plots of sensory profiles were also generated with XLSTAT.

3. Results and discussion

3.1. Physicochemical characteristics of dealcoholized wine

Table 1 presents the changes in physicochemical parameters

Table 1
Physicochemical characteristics of original wine and dealcoholized wines obtained using different dealcoholization techniques.

Parameters	OW	NF-OD	OD	Dia
Alcohol (% v/v)	13.13	0.43 ± 0.13	0.35 ± 0.06	0.48 ± 0.02
Density	0.993 ± 0.001^{d}	1.008 ± 0.002^{a}	1.006 ± 0.001^{b}	1.004 ± 0.002^{c}
Dry extract (g/L)	24.86 ± 0.06^{a}	21.29 ± 0.15^{b}	24.16 ± 0.15^{a}	16.84 ± 0.15^{c}
Total acidity (g/L)	7.53 ± 0.06^{b}	6.53 ± 0.06^{c}	7.86 ± 0.06^{a}	2.47 ± 0.21^{d}
pH	3.01 ± 0.02^{a}	2.93 ± 0.06^{b}	2.81 ± 0.01^{c}	2.80 ± 0.01^{c}
Volatile acidity (g/L)	0.71 ± 0.00^{a}	0.31 ± 0.01^{b}	0.31 ± 0.00^{b}	0.22 ± 0.01^{c}
Malic acid (g/L)	1.06 ± 0.01^{c}	1.56 ± 0.03^{b}	1.97 ± 0.01^{a}	0.36 ± 0.06^{d}
Tartaric acid (g/L)	4.17 ± 0.02^{bc}	4.46 ± 0.03^{b}	5.03 ± 0.04^{a}	2.22 ± 0.03^{c}
Citric acid (g/L)	0.33 ± 0.01^{c}	0.39 ± 0.02^{b}	0.50 ± 0.01^{a}	0.08 ± 0.01^{d}
Glycerol (g/L)	6.17 ± 0.05^{c}	6.55 ± 0.07^{b}	7.75 ± 0.10^{a}	3.37 ± 0.10^{d}

following ethanol removal using different dealcoholization techniques. The results demonstrate a significant increase in density across all DW samples, likely due to the reduction in ethanol content, which has a lower density than water, thereby increasing the relative proportion of dissolved solids. Total dry extract remained largely unaffected in OD wine, whereas a marked reduction was observed in NF-OD and Dia samples. This decline suggests substantial compound loss during alcohol removal, attributable to molecular size exclusion and selective diffusion across membranes. These processes not only eliminate ethanol but also selectively remove low molecular-weight compounds, including sugars, organic acids, and minerals, thereby altering the wine's compositional profile (Italiano et al., 2024).

Total acidity exhibited a significant increase in the OD sample, likely due to the concentration of non-volatile acids as ethanol is removed. Furthermore, the absence of ethanol increased the sensory perception of acidity (Kucherenko et al., 2024). In contrast, NF-OD and Dia samples showed a reduction in total acidity, with Dia-treated wine displaying the lowest value (2.80 g/L). This decrease may result from the loss of acidic compounds through membrane permeation. The change in acidity plays a crucial role in wine quality, with low acidity leading to flat, tasteless wines, and high acidity resulting in overly sour wines (Darias-Martín et al., 2003; Kumar, Cassano, et al., 2025b). While pH decreased significantly in all the dealcoholized samples. Similarly, Calvo et al. (2022) observed decreases in both pH and total acidity during partial dealcoholization of Verdejo variety white wine, where ethanol was reduced from 9.90 % v/v to 8.70 % v/v using dialysis. Typically, a reduction in total acidity is accompanied by a pH increase, which did not occur with the dialysis process. This apparent contradiction can be explained by recognizing that pH and total acidity refer to different contributions. pH directly reflects the concentration of free hydrogen ions (H^{+}), while total acidity quantifies the combined concentration of all titratable acids, expressed as tartaric acid equivalents (g/L). Tartaric acid is a major component, alongside malic, citric, and lactic acids. Consequently, experimental results can show differing behaviors for pH and total acidity (Calvo et al., 2022). Volatile acidity decreased significantly in all dealcoholized wines, with the lowest value observed for Dia (0.22 g/L), suggesting effective removal of volatile acids such as acetic acid during membrane-based processes. Among organic acids, malic acid concentration increased in NF-OD and OD. Conversely, Dia treatment led to a sharp decline, likely due to diffusion across the membrane. Similar trends were observed for tartaric and citric acids, reinforcing the role of membrane selectivity in modulating acid retention. Organic acids are a pivotal class of wine constituents, with their concentration and composition critically influencing the physicochemical balance, microbiological stability, and sensory profile. The changes in these acids during ethanol removal can markedly affect the overall quality, stability, and consumer perception of the final product (Coelho et al., 2018; Uspalenko et al., 2024b).

Glycerol, a key contributor to wine mouthfeel, showed a slight increase in NF-OD and OD dealcoholized wines, possibly due to partial concentration effects. However, Dia treatment resulted in a substantial (45 %) depletion compared to OW, highlighting significant glycerol loss through dialysis, which may affect sensory properties. Similarly, an increase in glycerol content from 4.76 to 5.92 g/L was observed in dealcoholized wine (0.11 % v/v) compared to the original dry white table wine (Citronny Magaracha) (13.39 % v/v) produced using OD (Uspalenko et al., 2024a).

3.2. Effect of dealcoholisation on mineral content

The minerals like potassium (K), calcium (Ca), and magnesium (Mg) are important in wine and contribute to its stability, acidity balance, and influence sensory properties (Cabello-Pasini et al., 2013; Rogiers et al., 2017). Fig. 1 shows the variations in mineral composition of dealcoholized wines produced using different methods.

The findings demonstrate that there are differences in mineral retention in various dealcoholization processes. In the case of OD, the K level was increased (681.02 mg/L) with respect to the OW (641.16 mg/L). Contrastingly, the NF-OD process led to the decrease of K level (539.88 mg/L), which might be attributed to the selective membrane rejection, whereas the highest K depletion was found in Dia (115.38 mg/L). This trend reflected the variation in tartaric acid content of 5.03 g/L in OD to 2.22 g/L in Dia (Table 1). The tartrate stability equilibrium can be changed by any change in either of the components since potassium is readily dissolved when it is mixed with tartaric acid, which forms an insoluble potassium bitartrate (KHT). The decrease in the concentrations of K and tartaric acid in Dia wine indicates that membrane processing eliminated the high K and tartaric acid, which may have destabilized the natural tartrate balance of the wine and changed the buffering capacity of the wine. In contrast, OD led to an increase in K and tartaric acid, likely due to selective water removal and partial retention of ionic species, which may increase the risk of tartrate precipitation. Furthermore, NF-OD resulted in a reduction in K and an increase in tartaric acid

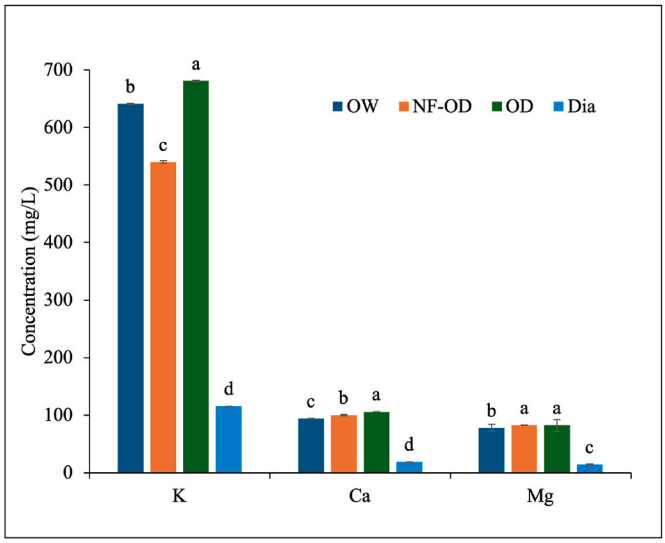

Fig. 1. Mineral content in dealcoholized wine obtained from different dealcoholisation techniques. Different letters indicate significant differences among samples produced from different techniques ($p < 0.05$, Tukey test).

compared to OW, suggesting that wine is likely to be more stable against tartrate precipitation due to the lower availability of potassium for KHT crystallization. Furthermore, Cui et al. (2024) mentioned that changes in pH and alcohol content also affect the stability of tartrates in wine. A higher pH increases tartrate ion concentration, elevating precipitation risk, while lower alcohol content, a direct result of dealcoholization, typically increases KHT solubility.

Ca concentrations were significantly higher in both OD (105.85 mg/L) and NF-OD (100.10 mg/L) wines than OW (94.17 mg/L), with Dia again showing minimal retention (18.88 mg/L). Magnesium (Mg) followed a similar pattern, with OD (82.45 mg/L) and NF-OD (82.71 mg/L) maintaining higher levels than OW (77.94 mg/L), whereas Dia treatment led to dramatic Mg reduction (14.31 mg/L). These findings demonstrate that OD most effectively preserves the mineral profile of dealcoholized wine, while NF-OD represents a suitable alternative with selective mineral retention. However, the Dia method substantially alters the wine's mineral composition, with significant depletion observed. This effect is primarily attributed to the compositional differences between the wine and the aqueous draw solution, which hinder equilibrium establishment and drive solute migration from the more concentrated to the less concentrated solution, and potential dilution effects caused by the use of water as the draw solution. Similarly, in a study on OD, reducing the ethanol content in Langhe Rosé wine from 13.2 % to 5 % v/v resulted in increased concentrations of K (773–982 mg/L), Ca (79.6–92.7 mg/L), and Mg (79.1–80.5 mg/L) (Motta et al., 2017).

3.3. Color profile of dealcoholized wine

The color parameters, including absorbance at 420 nm (Abs_{420}), color intensity, chroma, hue, and the CIELAB coordinates (L*, a*, and b*), were measured for the OW and DW produced using different techniques, and the results are presented in Table 2. The browning index (Abs_{420}nm) and color intensity exhibited slightly higher values in the dealcoholized wines compared to OW; however, these differences were not statistically significant. It is to be noted that oxygen uptake was not measured during the trials but, in this regards, further analysis could help to better judge the aging kinetics after dealcoholisation. Similarly, no significant differences were observed in L*, a*, b*, or chroma values between OW and DW obtained using the various dealcoholization techniques. The total color difference (ΔE*) values were <1 for NF–OD and OD, indicating that these differences are imperceptible to the human eye. In contrast, the Dia-treated wine showed a ΔE value of 1.30, suggesting that trained human eyes could distinguish the color difference (Pérez-Magariño & González-Sanjosé, 2003) between OW and DW.

3.4. Volatile profile of dealcoholized wine

The volatile profiles of original and dealcoholized wines were analyzed to evaluate the impact of different dealcoholization techniques on the aromatic composition of white wines. Table 3 and Table S3 summarise the percentage loss and the concentrations of selected volatile compounds, respectively. Due to method-specific limits of detection (LODs), several volatile compounds in dealcoholized wines were detected below their respective LODs; therefore, losses are reported as threshold values. Overall, a pronounced reduction of volatile compounds was observed in all dealcoholized wines. Based on the observed results, total aroma retention in DW was low across all treatments: NF-OD retained less than 25.5 % of the original aroma, OD less than 26.6 %, and Dia less than 23.8 %.

Briefly, higher alcohols decreased substantially across all dealcoholization techniques. Isobutanol losses exceeded 88.5 % in all dealcoholized wines, while 3-methylbutanol and 2-methylbutanol exhibited losses greater than 79.7 % and 65.9 %, respectively, in all dealcoholized wines. Moreover, 2-phenylethanol showed a lower apparent loss in NF-OD and OD (53.0 % and 35.7 %, respectively), whereas in Dia the loss exceeded 85.8 %. However, because LODs differ between analytes, these values interpreted only as minimum loss thresholds rather than as absolute or directly comparable retention levels. Such variation in higher alcohol retention has been linked to differences in vapor pressure, volatility, and ethanol affinity (Diban et al., 2008). Additionally, aromatic alcohols like 2-phenylethanol, with higher molar mass and lower volatility, tend to be more stable than aliphatic alcohols such as isobutanol and 1-hexanol (Esteras-Saz et al., 2021). 2-Phenylethanol was found to be stable, showing only a 2.9 % loss during the reduction of ethanol from 12 % v/v to 8.4 % in model white wine using NF (Labanda et al., 2009).

Esters, which are essential for fruity and floral aromas, were highly affected by dealcoholization. Ethyl acetate, ethyl propionate, ethyl isobutyrate, ethyl butyrate, diethyl succinate, phenethyl acetate, and ethyl decanoate exhibited losses exceeding 80 % in all dealcoholized wine samples. In addition, 2-methylbutyl acetate and ethyl phenylacetate showed losses greater than 70.5 % and 77.8 %, respectively, compared to the original wine.

Isoamyl acetate and ethyl hexanoate showed a minimal loss of 46.3 % and 37.1 %, respectively. Given their predominantly hydrophobic nature, making their loss during the dealcoholization process a predictable outcome (Diban et al., 2013; Kumar, Cassano, et al., 2025b). Additionally, this expected loss in ester concentrations is consistent with previous studies on dealcoholized white, rosé, and red wine (Gambuti et al., 2011; Ivić, Kopjar, Jukić, et al., 2021; Ivić, Kopjar, Obhođaš, et al.,

Table 2
Color profile of original wine and dealcoholized wines obtained using different dealcoholization techniques.

Color parameters	OW	NF-OD	OD	Dia
420 nm	0.09 ± 0.01^{ab}	0.10 ± 0.01^{a}	0.10 ± 0.01^{a}	0.11 ± 0.01^{a}
Color intensity	0.11 ± 0.01^{b}	0.14 ± 0.01^{ab}	0.14 ± 0.04^{ab}	0.16 ± 0.01^{a}
L*	98.74 ± 0.07^{a}	98.23 ± 0.11^{ab}	97.98 ± 1.04^{ab}	97.46 ± 0.14^{b}
a*	−0.94 ± 0.04^{a}	−1.00 ± 0.02^{a}	−0.96 ± 0.15^{a}	−1.06 ± 0.09^{a}
b*	6.24 ± 0.05^{a}	6.59 ± 0.01^{a}	6.45 ± 0.67^{a}	6.08 ± 0.03^{a}
Chroma	6.31 ± 0.04^{a}	6.67 ± 0.01^{a}	6.52 ± 0.69^{a}	6.17 ± 0.02^{a}
ΔE	–	0.62	0.79	1.30

Table 3
Volatile compounds loss (%) in dealcoholized wines obtained using different dealcoholization techniques compared to the original wine.

Volatile compounds	RT	RI	NF-OD	OD	Dia
Isobutanol	10.98	616	88.5	>91.4	85.7
3-Methylbutanol	15.33	740	>79.7	>79.7	>79.7
2-Methylbutanol	15.50	752	>65.9	>65.9	>65.9
1-Hexanol	20.78	965	>84.5	>84.5	>84.5
2-Phenylethanol	30.25	1165	53	35.7	>85.8
Ethyl acetate	10.22	615	>79.9	>79.9	>79.9
Ethyl propionate	14.26	717	>82.6	>82.6	>82.6
Ethyl isobutyrate	16.26	757	>83.4	>83.4	>83.4
Ethyl butyrate	17.98	798	>84.1	>84.1	>84.1
Isoamyl acetate	21.06	972	>46.3	>46.3	>46.3
2-Methylbutyl acetate	21.14	974	>70.5	>70.5	>70.5
Ethyl hexanoate	25.65	1093	>37.1	>37.1	>37.1
Diethyl succinate	31.58	1185	85.2	83.3	82.4
Ethyl phenylacetate	34.12	1352	>77.8	>77.8	>77.8
Phenethyl acetate	34.53	1365	>83.8	>83.8	>83.8
Ethyl decanoate	38.11	1491	>89.1	>89.1	>89.1

RT: Retention time, RI: Retention index.

2021; Ma et al., 2022; Russo, LoredanaCorona & DonatellaMarisaLuciano, 2019).

The results prove that selective aroma recovery during dealcoholization is essential in order to improve the potential aromatic quality of dealcoholized wines.

3.5. Sensory profile of dealcoholized wine

The sensory profiling of DW produced via different techniques revealed that the choice of dealcoholization method significantly influenced multiple sensory attributes (Fig. 2). No significant differences were observed among treatments for *evolved floral*, *apple*, *evolved fruity*, *cooked vegetables*, and *color intensity*. The *color intensity* observation aligns with the instrumental color analysis, where total color difference (ΔE) values were <1, confirming that these variations are imperceptible to the human eye. For *fresh fruity* and *peach*, Dia and NF-OD had similar scores to OW, whereas OD resulted in perceptibly lower scores. In contrast, *citrus* perception remained unchanged for NF-OD compared to OW but reduced in OD and Dia. However, the sensory perception of fruity and floral aromas does not decrease proportionally despite a higher loss of esters during wine dealcoholization. This can be explained by the fact that ester concentrations in wines are generally well above their odor activity value (OAV), which allows their aromatic impact to be maintained despite quantitative losses. Additionally, the aroma volatility and release dynamics are influenced by the reduction in alcohol content, which may help to maintain the perceived fruitiness. Thus, even with marked ester reduction, fruity and floral sensory attributes remain noticeable due to higher relative aroma volatility and ester concentrations still above sensory thresholds. For instance, a recent study by Alises et al. (2025) on Chardonnay white wine dealcoholized from 13.4 % to 0.55 % v/v using spinning cone column reported approximately a 95 % reduction in total esters. Despite this significant loss, sensory analysis revealed that panelists continued to perceive fruity and floral notes such as banana, apricot, apple, pineapple, floral, green, and fresh aromas, although with lower intensity scores compared to the original wine.

Furthermore, sweetness was significantly reduced in all DW samples. This is consistent with the expected sensory effect of ethanol removal, which adds sweetness to wine (Nurgel & Pickering, 2006). Acidity perception increased in OD and NF-OD relative to OW, whereas Dia showed a reduction, consistent with the corresponding changes in titratable acidity measurements. Additionally, ethanol exerts a masking effect on acidity and astringency due to its sweet, soft, and harmonizing characteristics (Lisanti et al., 2013). Bitterness perception was retained in NF-OD and OD but decreased in Dia. Attributes associated with *body/fullness* and *hotness* were markedly diminished across all DW compared to OW, reflecting the structural and trigeminal impact of ethanol removal. Despite these sensory shifts resulting from ethanol removal, the assessment of overall acceptability, reflecting the suitability of the product for consumption, revealed that NF-OD wines were rated similar to the OW, whereas OD and Dia received lower scores, with Dia obtaining the poorest rating. These findings suggest that NF-OD better preserves the sensory integrity and consumer acceptability. In a recent study, De-la-Fuente-Blanco et al. (2024) studied about relevance and complex role of ethanol in the sensory properties of model wines. Their approach employed seven white and seven red variants with identical non-volatile matrices and aroma profiles, differing only in ethanol concentration (0.5–15 % v/v). Analysis revealed that ethanol depletion induces significant perceptual shifts: sourness perception intensifies progressively below 10 % v/v ethanol, while attributes including body, alcoholic sensation, and most notably bitterness diminish substantially. The relationship between ethanol concentration and sensory attributes proved non-linear and attribute specific. Bitterness perception exhibited a strong positive correlation with ethanol levels exclusively above 5 % v/v, contrasting sharply with the steady sourness enhancement observed below the 10 %v/v threshold. Furthermore, reducing ethanol below 10 % v/v in red model wines caused significantly greater sensory imbalance (notably excessive sourness) than reduction below 7.5 % v/v in white model wines. These findings showed ethanol not merely as a solvent, but as a critical structural component governing taste balance and mouthfeel.

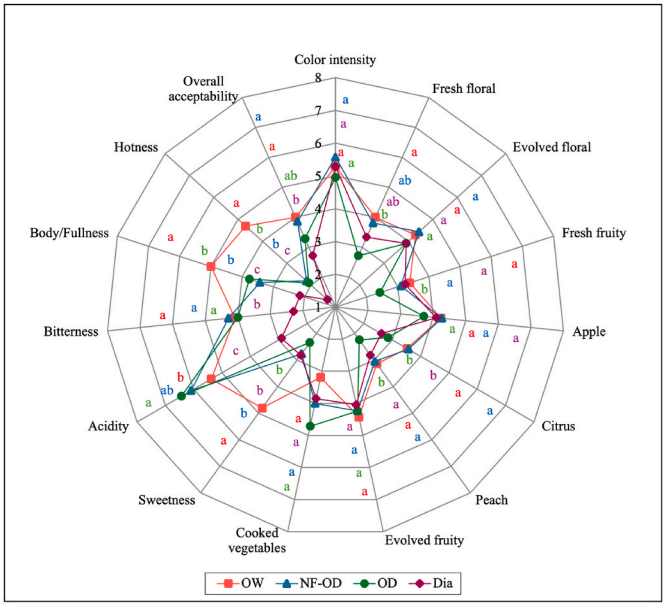

Fig. 2. Sensory profile of original wine and dealcoholized wines obtained using different dealcoholization techniques.

Moreover, in order to better understand the loss of volatile compounds and the changes in sensory characteristics upon ethanol removal with different dealcoholization processes, a Principal Component Analysis (PCA) was carried out on the quantitative data. The first two principal components, PC1 and PC2, accounted for 72.48 % and 15.02 % of the total variance (Fig. 3), respectively. In the biplot, there is a clear discrimination between OW and the DW variants obtained by OD, NF-OD, and Dia. OW located in the positive region of PC1 and is greatly correlated with most of the aroma compounds, especially esters (e.g., ethyl butyrate, ethyl hexanoate, isoamyl acetate) and higher alcohols, as well as positive sensory descriptors such as body/fullness, hotness, sweetness, higher fruitiness, and overall acceptability. Conversely, all DW samples clustered in the negative side of PC1, signifying depletion of volatile compounds and poor sensory performance after ethanol removal. PC2 facilitated further distinction across the DW samples, with Dia and NF-OD tying together in the positive PC2 area and OD appearing in the negative quadrant.

4. Conclusion

This study provides a comparative assessment of Dia, OD, and a hybrid combination of NF-OD system for producing dealcoholized white wines (≤0.5 % v/v ethanol). The findings revealed technique-dependent changes in physicochemical, mineral, aromatic, and sensory profiles, with significant implications for final product quality. The results showed that all DWs exhibited increased density due to ethanol removal. OD demonstrated superior retention of total dry extract and organic acids (malic, tartaric), alongside increased glycerol and titratable acidity. Conversely, Dia induced substantial losses in acidity, glycerol, and dry extract, attributable to molecular diffusion across the membrane and dilution. NF-OD exhibited intermediate performance, mitigating extreme losses. Mineral retention was critically technique-dependent: OD and NF-OD effectively preserved K, Ca, and Mg, while Dia caused more than 80 % loss of K and Mg, fundamentally altering the wine's composition due to solute migration driven by disequilibrium and

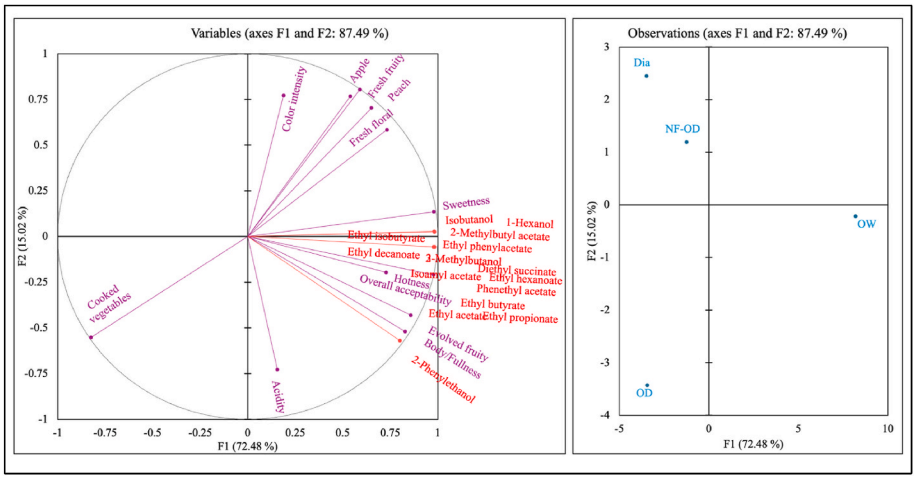

Fig. 3. PCA biplot of cases and variables based on total volatile compounds and sensory attributes characterizing original (OW) and dealcoholized wines (DW).

dilution. Color stability was largely maintained in OD and NF-OD (ΔE* <1, imperceptible change), whereas Dia-treated wine showed perceptible differences (ΔE* = 1.30).

The most impact of ethanol removal was observed in the volatile profile, where all techniques incurred substantial losses (>73 % total aroma). Esters and most higher alcohols were largely affected, consistent with their volatility and ethanol affinity. Hydrophobic compounds (e.g., ethyl hexanoate) showed higher relative retention. Sensory evaluation corroborated these losses: all DWs exhibited significantly reduced sweetness, body/fullness, and hotness (direct ethanol effects). However, NF-OD uniquely preserved key attributes like acidity and bitterness, and achieved overall acceptability scores statistically comparable to the OW. In contrast, OD scored lower in fresh fruit and citrus notes, while Dia performed the poorest overall, reflecting its significant compositional degradation. In addition, PCA confirmed NF-OD's superior ability to maintain the volatile-sensory nexus closest to OW, despite losses. Overall, these results support the research hypothesis that dialysis, OD, and combination OD with NF can achieve ethanol reduction to regulatory-compliant levels while preserving essential physicochemical and sensory characteristics of white wine.

This study is limited to a single white wine and focused on changes in volatile and non-volatile and sensory profile of wine just after the production, without studying long-term stability or consumer perception. Additionally, the current optimized process showed a higher loss in the volatile profile. Therefore, future research should focus on long-term stability or consumer perception, with the aim of optimising the process to enhance further volatile retention and scaling the process for industrial viability.

CRediT authorship contribution statement

Yogesh Kumar: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lorenzo Italiano:** Writing – review & editing, Methodology, Investigation, Data curation. **Matthias Schmitt:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Sayali Bhor:** Investigation, Data curation. **Florian Kiene:** Writing – review & editing, Methodology, Investigation. **Arianna Ricci:** Writing – review & editing, Investigation. **Giuseppina Paola Parpinello:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Andrea Versari:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Conceptualization.

Funding

No funding was received for this research.

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 article.

Acknowledgment

Y.K. thanks the receipt of the Bologna University PhD scholarship and Marco Polo grant for the exchange stay at Hochschule Geisenheim University (Germany). Additionally, we would like to thank Prof. Doris Rauhut and Mrs. Silvia Brezina (both from the Department of Microbiology and Biochemistry, Hochschule Geisenheim University, Von-Lade-Str. 1, 65366 Geisenheim, Germany) for their support during the investigations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fbio.2026.108343.

Data availability

Metadata will be made available and searchable on AMS Acta repository (https://amsacta.unibo.it/) by recording the DOI of the article soon after publishing.

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Quality assessment of dealcoholized wines produced by dialysis, osmotic distillation, and hybrid membrane technologies

Yogesh Kumar[1,2*], Lorenzo Italiano[2], Matthias Schmitt[2], Sayali Bhor[2], Florian Kiene[3], Arianna Ricci[1], Giuseppina Paola Parpinello[1*], Andrea Versari[1]

[1]Department of Agricultural and Food Sciences, University of Bologna, Piazza Goidanich 60, 47521, Cesena, FC, Italy

[2]Department of Enology, Hochschule Geisenheim University, Von-Lade-Str. 1, 65366 Geisenheim, Germany

[3]Department of Microbiology and Biochemistry, Hochschule Geisenheim University, Von-Lade-Str. 1, 65366 Geisenheim, Germany

***Corresponding authors**

Yogesh Kumar and Giuseppina Paola Parpinello

Email: yogesh.kumar3@unibo.it; giusi.parpinello@unibo.it

Tel: +39 0547 338118. Fax: +39 0547 382348

S1.1 Chemicals and reagents used during GC-MS:

Ethyl acetate (≥99.8%, catalog number: 83963.320, CAS: 141-78-6) was ordered from Avantor Inc. (Radnor, PA, USA), sodium chloride (≥99.5%, catalog number: 3957.2, CAS: 7647-14-5) was bought from Carl Roth GmbH + Co. KG (Karlsruhe, Germany) and the following chemicals were purchased from Merck KGaA (Darmstadt, Germany): cumene (analytical standard, catalog number: 28220-5ML, CAS: 98-82-8), diethyl succinate (≥99.5%, catalog number: 07429-5ML-F, CAS: 123-25-1), ethyl butyrate (99%, catalog number: E15701-25ML, CAS: 105-54-4), ethyl decanoate (≥99.0%, catalog number: 00733-1ML, CAS: 110-38-3), ethyl hexanoate (≥99%, catalog number: 148962-5ML, CAS: 123-66-0), ethyl isobutyrate (analytical standard, catalog number: 19536-1ML, CAS: 97-62-1), ethyl phenylacetate (≥98.5%, catalog number: 91224-1ML, CAS: 101-97-3), ethyl propionate (99%, catalog number: 112305-25ML, CAS: 105-37-3), 1-hexanol (≥99.9%, catalog number: 73117-1ML-F, CAS: 111-27-3), isopentyl acetate (analytical standard, catalog number: 79857-1ML, CAS: 123-92-2), 2-methyl-1-butanol (≥99%, catalog number: 133051-100ML, CAS: 137-32-6), 3-methyl-1-butanol (≥99%, catalog number: 309435-100ML, CAS: 123-51-3), 2-methylbutyl acetate (>95%, catalog number: W364428-100G-K, CAS: 624-41-9), 2-methyl-1-propanol (analytical standard, catalog number: 82059-5ML-F, CAS: 78-83-1), 1-octanol (analytical standard, catalog number: 95446-5ML-F, CAS: 111-87-5), 2-phenethyl acetate (99%, catalog number: 290580-5ML, CAS: 103-45-7), 2-phenylethanol (≥99%, catalog number: 309435-100ML, CAS: 123-51-3).

Table S1: Calibration parameters and analytical performance data of target wine aroma compounds analyzed by GC–MS using a 3% EtOH model wine matrix.

Analyte	Calibration range	Calibration equation	R^2	Quantifier ion (m/z)	Qualifier ions (m/z)	LOD	LOQ
Isobutanol	9.5 – 78.7 mg/L	y = 2.4180 x - 0.0020	0.9971	41	74	2.5 mg/L	7.5 mg/L
3-Methyl-1-butanol	29.0 – 203.0 mg/L	y = 11.2849 x + 0.2071	0.9982	55	70, 42	34.2 mg/L	103.7 mg/L
2-Methyl-1-butanol	9.8 – 119.5 mg/L	y = 16.0709 x + 0.1106	0.9949	57	41, 70, 56	11.9 mg/L	36.0 mg/L
1-Hexanol	223.4 – 3575.1 µg/L	y = 0.1415 x + 0.0025	0.9935	56	69, 55, 84	152.5 µg/L	462.1 µg/L
2-Phenylethanol	5.0 – 64.9 mg/L	y = 52.6056 x + 0.1073	0.9960	91	92, 122	3.6 mg/L	10.9 mg/L
Ethyl acetate	24.0 – 206.0 mg/L	y = 1.6901 x + 0.0185	0.9964	88	43	20.0 mg/L	60.7 mg/L
Ethyl propionate	50.5 – 505.0 µg/L	y = 0.0695 x + 0.0016	0.9938	57	102, 75	45.5 µg/L	137.9 µg/L
Ethyl isobutyrate	24.7 – 306.3 µg/L	y = 0.1160 x + 0.0011	0.9986	43	71, 116	16.4 µg/L	49.6 µg/L
Ethyl butyrate	88.6 – 708.7 µg/L	y = 0.2151 x + 0.0059	0.9954	71	43, 88	58.9 µg/L	178.4 µg/L
Isoamyl acetate	334.0 – 2504.9 µg/L	y = 0.4748 x + 0.0882	0.9743	43	70, 61, 87	399.3 µg/L	1210.1 µg/L
2-Methylbutyl acetate	25.9 – 258.7 µg/L	y = 0.7719 x + 0.0099	0.9671	43	70, 55, 73	35.1 µg/L	106.4 µg/L
Ethyl hexanoate	168.9 – 1688.5 µg/L	y = 1.4362 x + 0.2977	0.9981	88	99, 43	490.1 µg/L	1485.3 µg/L
Diethyl succinate	543.1 – 5431.1 µg/L	y = 0.1701 x - 0.0144	0.9990	129	128, 101, 174	153.6 µg/L	465.5 µg/L
Ethyl phenylacetate	9.8 – 98.3 µg/L	y = 1.5150 x - 0.0063	0.9979	164	91, 92, 65	8.3 µg/L	25.2 µg/L
Phenethyl acetate	19.7 – 393.6 µg/L	y = 2.7750 x - 0.0286	0.9958	104	43	22.5 µg/L	68.3 µg/L
Ethyl decanoate	49.5 – 493.3 µg/L	y = 4.1574 x + 0.0863	0.9977	88	101, 73, 155	42.8 µg/L	129.6 µg/L

Table S2: Calibration parameters and analytical performance data of target wine aroma compounds analyzed by GC–MS using a 12% EtOH model wine matrix.

Analyte	Calibration range	Calibration equation	R^2	Quantifier ion (m/z)	Qualifier ions (m/z)	LOD	LOQ
Isobutanol	8.9 – 80.2 mg/L	y = 5.5858 x - 0.0162	0.9646	41	74	8.3 mg/L	25.2 mg/L
3-Methyl-1-butanol	29.0 – 203.0 mg/L	y = 22.5967 x + 0.0903	0.9875	55	70, 42	13.3 mg/L	40.4 mg/L
2-Methyl-1-butanol	9.8 – 95.8 mg/L	y = 32.3642 x - 0.0349	0.9887	57	41, 70, 56	5.1 mg/L	15.6 mg/L
1-Hexanol	223.4 – 3575.1 µg/L	y = 0.1707 x - 0.0435	0.9796	56	69, 55, 84	500.5 µg/L	1516.6 µg/L
2-Phenylethanol	5.0 – 64.9 mg/L	y = 81.0233 x - 0.3225	0.9827	91	92, 122	6.7 mg/L	20.4 mg/L
Ethyl acetate	25.5 – 199.2 mg/L	y = 2.2490 x - 0.0039	0.9967	88	43	5.3 mg/L	15.9 mg/L
Ethyl propionate	50.5 – 505.0 µg/L	y = 0.0875 x - 0.0016	0.9916	57	102, 75	38.4 µg/L	116.5 µg/L
Ethyl isobutyrate	24.7 – 306.3 µg/L	y = 0.1406 x - 0.0008	0.9878	43	71, 116	15.9 µg/L	48.3 µg/L
Ethyl butyrate	88.6 – 664.4 µg/L	y = 0.2617 x - 0.0140	0.9905	71	43, 88	104.8 µg/L	317.5 µg/L
Isoamyl acetate	334.0 – 2504.9 µg/L	y = 0.7009 x + 0.0041	0.9935	43	70, 61, 87	89.7 µg/L	271.7 µg/L
2-Methylbutyl acetate	28.3 – 242.5 µg/L	y = 0.9291 x + 0.0123	0.9886	43	70, 55, 73	28.7 µg/L	87.1 µg/L
Ethyl hexanoate	168.9 – 1519.7 µg/L	y = 2.2083 x + 0.4162	0.9720	88	99, 43	394.1 µg/L	1194.3 µg/L
Diethyl succinate	543.1 – 5431.1 µg/L	y = 0.1406 x - 0.0604	0.9887	129	128, 101, 174	712.9 µg/L	2160.2 µg/L
Ethyl phenylacetate	9.8 – 98.3 µg/L	y = 0.8751 x - 0.0108	0.9558	164	91, 92, 65	25.2 µg/L	76.4 µg/L
Phenethyl acetate	19.7 – 393.6 µg/L	y = 2.2726 x - 0.0683	0.9825	104	43	56.7 µg/L	171.9 µg/L
Ethyl decanoate	49.5 – 493.3 µg/L	y = 12.4868 x + 0.5521	0.9508	88	101, 73, 155	91.3 µg/L	276.7 µg/L

Table S3: Concentration of volatile compounds quantified by GC-MS in original wine (OW) and in dealcoholized wines produced using different techniques.

VC	OW	NF-OD	OD	Dia
Isobutanol [mg/L]	29	3	<2.5	4
3-Methylbutanol [mg/L]	169	<34.2	<34.2	<34.2
2-Methylbutanol [mg/L]	35	<11.9	<11.9	<11.9
1-Hexanol [µg/L]	982	<152.5	<152.5	<152.5
2-Phenylethanol [mg/L]	25	12	16	<3.6
Ethyl acetate [mg/L]	99	<20	<20	<20
Ethyl propionate [µg/L]	261	<45.5	<45.5	<45.5
Ethyl isobutyrate [µg/L]	99	<16.4	<16.4	<16.4
Ethyl butyrate [µg/L]	371	<58.9	<58.9	<58.9
Isoamyl acetate [µg/L]	743	<399.3	<399.3	<399.3
2-Methylbutyl acetate [µg/L]	119	<35.1	<35.1	<35.1
Ethyl hexanoate [µg/L]	779	<490.1	<490.1	<490.1
Diethyl succinate [µg/L]	1747	258	292	307
Ethyl phenylacetate [µg/L]	37	<8.3	<8.3	<8.3
Phenethyl acetate [µg/L]	139	<22.5	<22.5	<22.5
Ethyl decanoate [µg/L]	391	<42.8	<42.8	<42.8