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Dealcoholization of wine by vacuum distillation: Volatile and non-volatile profile, and sensory analysis

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ABSTRACT

This study produced partially (PDW) and fully dealcoholized (DW) white, rosé, and red wines via vacuum distillation (VD), analyzing ethanol removal impacts on physicochemical, color, and volatile profiles, alongside sensory attributes. Ethanol reduction significantly increased density, total extract, glycerin, total acidity, and volatile acidity, while decreasing pH. Color shifts ($\Delta E \geq 3$) were perceptible in DW wines, with red DW exhibiting the highest ΔE (24.33). Total aroma compounds declined progressively (72–80 % loss in PDW; 89–94 % in DW). Sensory evaluation highlighted reductions in fresh floral (white/rosé), fresh fruity (red), sweetness (white/rosé), hotness, and body/fullness (rosé), while color intensity (red), cooked vegetable notes, and acidity (white/rosé) increased after ethanol removal. PDW and DW white/red wines retained original overall acceptability scores, whereas rosé acceptability decreased. Overall, VD efficiently produced DW adhering to regulatory alcohol limits, offering insights into ethanol removal's impact on wine properties, essential for optimizing dealcoholized product quality.

1. Introduction

The global market for non-alcoholic wine has exhibited significant growth, with an annual compound growth rate of 10.4 % projected between 2024 and 2034. The industry is expected to expand from USD 2.7 billion in 2024 to an estimated USD 6.97 billion by the end of 2034 (Fact.MR, 2024). This rapid growth is driven by evolving consumer preferences influenced by health consciousness, personal lifestyle choices, and religious considerations (Kumar, Cassano, et al., 2024; Kumar, Ricci, et al., 2024). The European Union (EU) and the International Organization of Vine and Wine (OIV) introduced legal definitions of *"dealcoholized wine"* and *"partially dealcoholized wine"* for products that have actual alcoholic strengths of "no more than 0.5% v/v ethanol" and "above 0.5% v/v ethanol and below the minimum actual alcoholic strength of the wine category," respectively (EU Regulation 2117/2021, p. 270, 2021; OIV, 2021). With the growing demand and consumption of dealcoholized wines, alongside the establishment of defined regulatory standards for these products, there is a crucial need to produce high-quality product by preserving their volatile and non-volatile profiles, as well as their sensory characteristics, throughout the dealcoholization process. Currently, to remove alcohol from wine post-fermentation, thermal methods (such as vacuum distillation (VD), spinning cone column (SCC), and traditional distillation), membrane techniques (such as nanofiltration (NF), reverse osmosis (RO), osmotic distillation (OD), and dialysis), and combinations of these methods (such as reverse osmosis followed by osmotic distillation of the permeate or reverse osmosis paired with dialysis) are widely used (Calvo et al., 2022; El Rayess et al., 2024; Kumar, Ricci, et al., 2024; Sam et al., 2023; Sam, Ma, Salifu, et al., 2021; Schmitt & Christmann, 2019, 2022). Each technique affects wine quality differently during ethanol removal, depending on the type of wine, operating conditions (such as time, temperature, pressure, membrane pore size etc.), and the physico-chemical properties of the aroma/volatile compounds and its interaction with other components during the process. Furthermore, recent studies have focused on various dealcoholization techniques, including the dealcoholization of white wine (San Crispino, a blend of Trebbiano, Pinot, Chardonnay and Malvasia Italian grapes) (Kumar et al., 2025) and red wine (a blend of Marzemino and Cabernet) (Montevecchi et al., 2024) using OD; the dealcoholization of white wines (Airén, Sauvignon, Chardonnay, Verdejo, Macabeo, Moscatel, Syrah), red wines (Merlot, Cabernet, Syrah, Tempranillo,

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Garnacha), and rosé wines (Garnacha, Tempranillo) using VD (VD-GoLo) (Veiga-del-Baño et al., 2024); the dealcoholization of white wine by dialysis (Italiano et al., 2024) and white (San Crispino) wine by NF and RO (Kumar, Cassano, et al., 2024); red wine (Shiraz Sangiovese) dealcoholization using SCC (Puglisi et al., 2022); and red wine (Cabernet Sauvignon) dealcoholization using a combination of RO and OD (RO-OD) (Pham et al., 2019).

Kim et al. (2021) produced dealcoholized red wine using VD at different boiling points (25 °C, 45 °C, and 65 °C). The results indicated that color intensity and hue increased with higher boiling points. However, sensory parameters such as sweetness, acidity, and astringency were not affected, while dealcoholized wine produced at 65 °C received poor scores for color, odor, and overall acceptability. Furthermore, Petrozziello et al. (2019) observed a complete loss (100 %) of isobutanol, n-butanol, n-hexanol, cis-3-hexenol, and phenylethyl acetate, along with reductions of 16–40 % for organic acids (such as octanoic acid, decanoic acid, isovaleric acid, and hexanoic acid), 24 % for ethyl lactate, 18 % for diethyl succinate, and 19 % for 4-ethylphenol in dealcoholized white wine (Chardonnay) produced using VD. In a comparative study, Sam, Ma, Liang, et al. (2021) evaluated the effects of reverse osmosis (RO) and vacuum distillation (VD) on the production of dealcoholized red (Merlot), rosé (Pinot Noir), and white (Chardonnay) wines, with an alcohol content reduced to 0.7 % *v*/v. The results revealed that total acidity significantly increased in all dealcoholized wines, with VD-treated wines exhibiting the highest increase. Volatile acidity decreased in all dealcoholized wines, with reductions of 5–14 % in VD-treated wines and 62–82 % in RO-treated wines compared to their respective original wines. Color analysis indicated that all dealcoholized wines exhibited a color difference ($\Delta E \geq 1$), perceivable by trained eyes. Notably, rosé and red wines produced via VD displayed $\Delta E \geq 3$, signifying that the color difference was perceptible even to untrained observers. A marked loss in ester concentrations was observed across all wines, with reductions of 92 %, 81 %, and 87 % in RO-treated white, rosé, and red wines, respectively, and even greater losses of 96 %, 98 %, and 96 % in VD-treated wines. This higher loss of esters in VD-treated wines is likely attributable to the evaporation and condensation processes inherent to vacuum distillation. The volatile alcohol reduction was more pronounced in VD-treated wines, with decrease rates of 84 %, 85 %, and 95 % for red, rosé, and white wines, respectively, compared to reductions of 75 %, 58 %, and 68 % in RO-treated wines. Total organic acid concentrations also decreased significantly, with losses of 91 %, 89 %, and 85 % in VD-treated red, rosé, and white wines, respectively, and 76 %, 91 %, and 73 % reduction in RO-treated wines. During sensory analysis, RO-treated dealcoholized wines achieved higher acceptance scores from panelists compared to VD-treated wines. However, in all the aforementioned studies, the alcohol content in the dealcoholized wine was reported to be >0.5 % v/v, which does not meet the regulatory requirement set for dealcoholized wine/alcohol-free wine. Therefore, the current study aimed to produce dealcoholized wines (≤0.5 % *v*/v) and partially dealcoholized wines (6 % v/v) using VD, in alignment with alcohol limits established by regulatory standards. In the present study, three different types of dealcoholized and partially dealcoholized wines (red, rosé, and white) were produced using VD, and the impact on the quality of the dealcoholized wines was studied. Specifically, in this study, the influence of ethanol removal on physicochemical parameters, color profiles, and volatile composition, as well as an assessment of sensory attributes for each dealcoholized wine, was evaluated.

2. Materials and methods

2.1. Wine samples

Three wines, referred to as original/control wines (OW), were used for dealcoholization: a Riesling white wine (produced in stainless steel: ethanol 13.13 % v/v), a Pinot Noir rosé wine (produced in stainless steel: ethanol 12.92 % v/v,), and a Merlot red wine (produced in 220 L oak barrels for 7 months: ethanol 13.15 % v/v), all of them were produced in Hochschule Geisenheim University winery (Rheingau/Germany) during the 2022 vintage.

2.2. Experimental setup and dealcoholization conditions

Hei-VAP Industrial Rotary Evaporator (Heidolph Instruments GmbH & Co. KG, Germany) was used to dealcoholize the wines. This system included a heating bath that could hold water with a temperature setting of up to 180 °C, a chilling system (Hei-CHILL 3000) for condensation, and a vacuum pump (Hei-Vac Valve Industrial) for evacuating, evaporating, and pumping out gases and vapors. The dealcoholization process was carried out at 50 mbar vacuum pressure, with a water bath temperature of 50 °C and a feed flask rotation speed of 70 rpm. The ethanol content of each wine was reduced to 6 % v/v (referred to as partially dealcoholized wine, PDW) and to ≤0.5 % v/v (referred to as dealcoholized wine, DW. Immediately after the dealcoholization, 30 mg/L of SO_2 solution (5 % v/v water solution) was added to original and reduced alcohol wines respectively. Furthermore, the wines were bottled using a heat exchanger at 62 °C for 10–15 s in 750 mL brown glass bottles (without headspace) under screw cap closures. Each dealcoholization process was performed in duplicate.

2.3. Physico-chemical analysis

The basic oenological parameters, such as ethanol, density, total extract, reducing sugar, pH total acidity, volatile acidity, malic acid, lactic acid, tartaric acid, glycerin were determined using Fourier Transform Infrared (FTIR) by Winescan ™ SO_2 Foss instrument equipped with Foss Integrator software (Foss, Hillerød, Denmark).

2.4. Color profile

The color parameters, including absorbance at 420, 520 and 620 nm, intensity (420 + 520 + 620 nm), tone (420/520), chroma, hue, 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).

2.5. GC–MS analysis for volatile aroma compounds

The volatile profile of OW, PDW, and DW wines was analyzed using targeted headspace solid-phase microextraction gas chromatography–mass spectrometry (HS-SPME-GC–MS), as previously described by Badura et al. (2023). For sample preparation, 5 mL of wine was mixed with 1.7 g of NaCl, 10 µL of an internal standard (1-octanol (600 mg/L), and 10 µL of an internal control standard (cumene, 52 mg/L). The GC–MS used was a GC 7890 A, coupled with an MS 5975 B (Agilent, Santa Clara, CA, USA), with an MPS robotic autosampler and a CIS 4 (Gerstel, Mülheim an der Ruhr, Germany). A 65 µm polydimethylsiloxane/divinylbenzene coating fiber was selected for solid-phase microextraction (SPME) (Supelco, Merck, Darmstadt, Germany). The volatiles were separated using a 60 m × 0.25 mm × 1 µm gas chromatography column (Rxi®-5Si1 MS w/5 m Integra-Guard, Restek, Bad Homburg v. d. Höhe, Germany) with helium as the carrier gas. Split mode injection was applied (split 1:10, initial temperature 30 °C, hold for 1 min, 12 °C/s ramp to 240 °C, hold for 4 min). The initial temperature of the GC run was 40 °C, held for 4 min, then ramped at 5 °C/min to 210 °C, and subsequently increased again to 240 °C at 20 °C/min and held for 10.5 min. Mass spectral data were acquired in a range of mass-to-charge ratio (*m/z*) of 35 to 250 and used to determine the concentration values. A 5-point calibration curve was used for each volatile compound within a wine model solution of 3, 6 and 12 % *v*/v ethanol with 3 % tartaric acid at pH 3. The 23 volatile compounds analyzed in this study were selected based on previous trials with the same wine samples, which identified them as key contributors to wine aroma.

Calibration curves were established specifically for these compounds to ensure reliable quantification.

Furthermore, the Kovats retention index (RI) values were from a GC column Rxi-5Sil MS (60 m × 0.25 mm × 1 μm, Restek, Order No: 13697) and were calculated using Eq. 1.

$$RI = 100 \times \left[n + (N - n) \frac{\mathrm{RT(unknown)} - \mathrm{RT(n)}}{\mathrm{RT(N)} - \mathrm{RT(n)}} \right] \quad (1)$$

where:

RI = Kovats retention index.
n = Number of carbon atoms of the first n-alkane.
N = Number of carbon atoms of the second n-alkane.
RT = Retention time.

2.6. 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 evaluated in the different wine types were as follows:

White Wine: Visual parameters (color intensity), aroma parameters (include fresh floral, evolved floral, fresh fruity, apple, citrus, peach, evolved fruity, cooked vegetables), and gustatory parameters (include sweetness, acidity, bitterness, body/fullness, hotness).

Rosé Wine: Visual parameters (color intensity), aroma parameters (include fresh floral, evolved floral, fresh fruity, red fruits like cherries and raspberries, evolved fruity, cooked vegetables), and gustatory parameters (including sweetness, acidity, bitterness, astringency, body/fullness, hotness).

Red Wine: Visual parameters (color intensity), aroma parameters (fresh floral, evolved floral, fresh fruity, red fruits such as cherry and raspberry, black cherries and plum, evolved fruity, green notes, oak, and cooked vegetables), and gustatory parameters (include sweetness, acidity, bitterness, astringency, body/fullness, hotness).

For the assessment of *overall acceptability*, panelists were instructed to evaluate the suitability of each wine sample for consumption using a structured 10-point hedonic scale, where a score of 1 denoted "not acceptable" and a score of 10 represented "highly acceptable for consumption.

Sensory analysis was conducted in adherence to ISO recommendations. Approximately 40–45 mL each sample was poured immediately before the evaluation and presented in wine-glasses. White and rosé wines were served at 12–14 °C, while red wine was served at 18–20 °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, sensory attribute scores were averaged across panelists for each wine sample, and the resulting mean values were used to construct radar plots for comparative profiling. A one-way ANOVA was performed to assess statistically significant differences among the OW, PDW, and DW samples for each sensory attribute. Furthermore, Principal Component Analysis (PCA) was conducted to explore the relationship between sensory attributes and the corresponding volatile compound profiles across the different experimental scenarios.

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 provided. 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 partially dealcoholized (PDW, 6 % v/v ethanol) and dealcoholized/alcohol free (DW, ≤0.5 % v/v ethanol) white, rosé, and red 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.

2.7. Statistical 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 2024.3.01423). Spider plots of sensory profiles were also generated with XLSTAT.

3. Results and discussion

3.1. Oenological parameters of dealcoholized wine

The impact of ethanol removal on the physico-chemical characteristics of white, rosé, and red wines is reported in Table 1. Volume loss increased with increasing ethanol removal, with an average volume loss of around 15.4–19.9 % for PDW and 33–35.6 % for DW. Density increased significantly and progressively from OW to PDW and DW for all white, rosé, and red wines. This increase is likely due to the concentration effect caused by the removal of ethanol and water, leading to a higher concentration of non-volatile compounds. Total dry extract content increased significantly with ethanol removal in white (OW: 22.05 g/L → PDW: 27.23 g/L → DW: 37.00 g/L), rosé (OW: 17.30 g/L → PDW: 22.35 g/L → DW: 29.25 g/L), and red wine (OW: 24.60 g/L → PDW: 30.45 g/L → DW: 39.90 g/L). Similarly, reducing sugar content increased significantly, especially in white wines. However, rosé wine showed no change due to its initially low sugar concentration in OW, while in red wine lacked reducing sugars altogether. The lack of reducing sugars in red wine is due to winemaking protocol used during production to achieve dry wines to fit marketing target. Glycerol levels increased significantly in dealcoholized wines; furthermore, the overall increase in non-volatile components particularly total dry extract, including sugars, polysaccharides and other solutes can contribute more substantially to the enhanced viscosity and mouthfeel in dealcoholized wines, whereas the contribution of glycerol is relatively minimal (Neto et al., 2015; Nurgel & Pickering, 2005; Yanniotis et al., 2007). In a recent study, Italiano et al. (2025) observed an increase in glycerol content in dealcoholized white wine (DW) produced using VD, possibly due to the concentration effect. In contrast, DW produced using membrane-based technologies such as osmotic distillation (OD), reverse osmosis (RO), and dialysis showed a reduction in glycerol content, likely due to its passage through the membrane. Notably, DW obtained via dialysis showed a complete loss of glycerol, possibly due to the larger pore size of the membrane used in this process.

Total acidity (TA) showed a significant increase across all wine types (e.g., White: OW: 6.88 g/L → DW: 10.05 g/L), primarily driven by the concentration of organic acids post-distillation. Concurrently, pH values experienced slight but significant reductions (e.g., White: OW: 3.00 → DW: 2.70), consistent with elevated total acidity and potential shifts in acid equilibrium. Volatile acidity showed no significant change in PDW but increased significantly in DW (e.g., Red: OW: 0.6 g/L → DW: 0.9 g/L). Similarly, Padureanu (2018) produced partially dealcoholized Feteasca Regală white (5.61 % *v*/v) and Pinot Noir red wine (4.82 % v/v) using vacuum distillation. The results indicated that total acidity significantly increased in both partially dealcoholized white (5.4 to 8.25

Table 1
The physico-chemical parameters of original (OW), partially dealcoholized wine (PDW) and dealcoholized wine (DW).

	White wine			Rosé wine			Red wine		
	OW	PDW	DW	OW	PDW	DW	OW	PDW	DW
Alcohol (% v/v)	11.93 ± 0.72^{a}	5.85 ± 0.06^{b}	0.49 ± 0.03^{c}	12.60 ± 0.12^{a}	5.88 ± 0.05^{b}	0.49 ± 0.10^{c}	12.75 ± 0.06^{a}	5.85 ± 0.06^{b}	0.50 ± 0.06^{c}
Volume loss (%)	–	16.06 ± 0.09	33.18 ± 4.50	–	19.85 ± 0.21	35.56 ± 0.60	–	15.42 ± 1.01	33.02 ± 4.27
Density (g/cm^3)	0.993 ± 0.000^{c}	1.002 ± 0.001^{b}	1.013 ± 0.001^{a}	0.990 ± 0.000^{c}	1.000 ± 0.000^{b}	1.010 ± 0.001^{a}	0.993 ± 0.001^{c}	1.004 ± 0.001^{b}	1.015 ± 0.001^{a}
Total dry extract (g/L)	22.05 ± 1.71^{c}	27.23 ± 2.29^{b}	37.00 ± 3.46^{a}	17.30 ± 0.24^{c}	22.35 ± 0.37^{b}	29.25 ± 0.93^{a}	24.60 ± 2.60^{c}	30.45 ± 3.35^{b}	39.90 ± 3.81^{a}
Reducing sugar (g/L)	1.93 ± 1.53^{a}	2.38 ± 2.02^{a}	3.08 ± 2.84^{a}	0.28 ± 0.17^{a}	0.28 ± 0.19^{a}	0.23 ± 0.33^{a}	0.00 ± 0.00	–	–
Glycerol (g/L)	5.93 ± 0.10^{b}	6.18 ± 0.10^{b}	7.78 ± 0.32^{a}	5.38 ± 0.10^{b}	5.48 ± 0.05^{b}	6.70 ± 0.29^{a}	8.40 ± 0.14^{c}	9.00 ± 0.12^{b}	11.20 ± 0.12^{a}
pH	3.00 ± 0.00^{a}	2.90 ± 0.12^{a}	2.70 ± 0.12^{b}	3.43 ± 0.05^{a}	3.40 ± 0.00^{ab}	3.35 ± 0.06^{b}	3.50 ± 0.12^{a}	3.45 ± 0.17^{a}	3.40 ± 0.23^{a}
Total acidity (g/L)	6.88 ± 0.49^{b}	7.83 ± 0.61^{b}	10.05 ± 0.87^{a}	4.40 ± 0.08^{c}	5.10 ± 0.00^{b}	6.20 ± 0.12^{a}	6.85 ± 2.37^{a}	7.70 ± 2.66^{a}	9.50 ± 3.46^{a}
Volatile acidity (g/L)	0.58 ± 0.21^{b}	0.70 ± 0.18^{b}	0.97 ± 0.20^{a}	0.32 ± 0.10^{b}	0.34 ± 0.07^{b}	0.51 ± 0.13^{a}	0.06 ± 0.06^{b}	0.07 ± 0.02^{b}	0.09 ± 0.03^{a}
Malic acid (g/L)	0.73 ± 0.51^{a}	0.80 ± 0.56^{a}	1.08 ± 0.77^{a}	0.80 ± 0.00^{b}	0.85 ± 0.06^{b}	1.05 ± 0.06^{a}	0.18 ± 0.05^{a}	0.25 ± 0.06^{a}	0.30 ± 0.23^{a}
Lactic acid (g/L)	1.38 ± 0.49^{b}	1.90 ± 0.50^{ab}	2.48 ± 0.63^{a}	1.00 ± 0.00^{c}	1.48 ± 0.05^{b}	1.88 ± 0.05^{a}	1.70 ± 0.23^{c}	2.23 ± 0.21^{b}	2.85 ± 0.29^{a}
Tartaric acid (g/L)	3.25 ± 0.10^{c}	3.78 ± 0.10^{b}	4.88 ± 0.10^{a}	1.95 ± 0.19^{c}	2.40 ± 0.00^{b}	2.95 ± 0.13^{a}	2.25 ± 0.96^{a}	1.98 ± 0.55^{a}	2.25 ± 0.75^{a}

Results are expressed as mean ± standard deviation (SD), and different superscript letters indicate significant differences (Tukey's test, $p < 0.05$).

g/L) and red (6.22 to 6.45 g/L) wines, while pH significantly decreased in partially dealcoholized white (3.15 to 3.06) and red wines (3.19 to 3.02). The increase in TA is likely due to the concentration effect.

Furthermore, organic acids such as tartaric, malic, and lactic acids exhibited significant variation in concentration across all wines following dealcoholization. Specifically, the concentration of malic acid was not significantly affected in white and red wines due to ethanol removal, while in DW rosé wine, it increased from 0.80 to 1.05 g/L compared to OW red wine. Lactic acid significantly increased with ethanol removal in white, rosé and red wines. Additionally, tartaric acid significantly increased in white and rosé wines after ethanol removal, whereas no significant change was detected in red wine. These increases may be explained with the concentration effect, where the loss of water and ethanol elevates the relative abundance of non-volatile organic acids. Uspalenko et al. (2024a) reported that production of dealcoholized (0.18 % *v*/v) white wine (Citronny Magaracha grape, initial ethanol content: 13.39 % v/v) using VD resulted in significant increases in several organic acids: tartaric acid by 10 %, acetic acid by 12 %, malic acid by 38 %, and citric acid by 27 %. These change affected the overall taste profile of the resulting DW, contributing to a perceived imbalance and disharmony in sensory attributes. The increased acidity influence not only the sour taste but also impact wine stability and microbiological safety. An increase in total acidity, with a reduction in pH, can inhibit microbial growth, and enhance the freshness and shelf life of the wine (Uspalenko et al., 2024b; Yang, 2021). Tartaric acid plays a crucial role in reinforcing the wine's structural integrity and enhancing its flavor complexity. In contrast, elevated malic acid levels may promote lactic acid formation through malolactic fermentation, which can compromise wine stability and introduce an unpleasant bitter taste (Uspalenko et al., 2024a). Similarly, acetic acid can impart undesirable sensory characteristics, such as a pronounced vinegar-like aroma (Corona et al., 2019; Uspalenko et al., 2024a).

3.2. Color profile of dealcoholized wine

The color profiles of white, rosé, and red wines exhibited significant changes following ethanol removal, as reported in Table 2. The browning index ($Abs_{420\ nm}$) increased substantially across all wine types, indicative of intensified yellow pigments, likely driven by concentration effects and oxidation occurring during the process. For white wines, the browning index rose from 0.10 AU in original wine (OW) to 0.17 AU in dealcoholized wine (DW). Similar trends were observed in rosé (0.17 to 0.29 AU) and red wines (2.88 to 4.24 AU). Abs at 520 nm (red pigments) and 620 nm (blue pigments) significantly increased in rosé and red wines following ethanol removal, while no notable changes were observed in white wines. This phenomenon may be attributed to distillation enhancing co-pigmentation in red and rosé wines through removal of ethanol, thereby intensifying absorbance at 520 nm and 620 nm, while white wines, lacking anthocyanins, remain unaffected. Color intensity followed an upward trend with ethanol removal: white wines increased from 0.13 to 0.15 and 0.22 AU; rosé from 0.27 to 0.36 and 0.50 AU; and red wines from 7.82 to 8.83and 10.61 AU (OW, PDW and DW, respectively). Similarly in previous findings Kumar et al. (2025) found that dealcoholized white wine (0.5 % *v*/v) exhibited higher levels of yellow pigments ($Abs_{420\ nm}$) and increased in color intensity compared to the original wine. This observed increase in color characteristics was primarily attributed to the concentration effects caused by the removal of alcohol and water during the distillation process, as well as oxidation effects occurring during processing. Furthermore, the increase in phenolic concentration also played a significant role in modifying the color characteristics. In our previous study Kumar, Italiano, et al. (2024), the total phenolic content (TPC) increased by 58.3 %, 46.9 %, and 56.3 % in DW white, rosé, and red wines, respectively, compared to their OW. Notably, the anthocyanin content was 38 % and 49 % higher in DW rosé and red wines, respectively, relative to OW, during dealcoholization of wine by VD (50 °C) and bottling (62 °C for 10–15 s).

The L^* values decreased significantly in PDW and DW across all wine types, contributing to a darker appearance. For white wines, the b^* value (yellowness) significantly increased, while the a^* value (red-green axis) decreased, indicating a shift towards a greener hue compared to the original wine. Conversely, rosé wines exhibited an increase in both a^* and b^* values, reflecting more intense red and yellow tones. Red wines, however, displayed a reduction in both a^* and b^* values.

Chroma values, representing color saturation, increased in dealcoholized white and rosé wines, signifying more vivid color. In contrast, chroma decreased in red wines, potentially reflecting the disruptions in co-pigmentation. Hue angles significantly decreased in white and rosé wines, suggesting minor shifts in perceived color, while only marginal increases were noted in dealcoholized red wines. The total color difference (ΔE^*), a metric for perceivable color change, was markedly higher in dealcoholized wines: 4.08 for white, 7.60 for rosé, and 24.33 for red wines. Gonzalezmanzano et al. (2009) and Martínez et al. (2001) indicated that a non-trained human eye can distinguish two colors when $\Delta E^* \geqslant 3.0$, while Pérez-Magariño and González-Sanjosé (2003) mentioned that color differences are perceptible to trained human eye when $\Delta E^* \geqslant 1$. Since $\Delta E^* \geqslant 1$ for all samples, the color differences were

Table 2
The color profiles of original (OW), partially dealcoholized wine (PDW) and dealcoholized wine (DW).

	White wine			Rosé wine			Red wine		
	OW	PDW	DW	OW	PDW	DW	OW	PDW	DW
420 nm	0.10 ± 0.01^{c}	0.12 ± 0.00^{b}	0.17 ± 0.00^{a}	0.17 ± 0.01^{c}	0.21 ± 0.02^{b}	0.29 ± 0.01^{a}	2.88 ± 0.01^{b}	3.46 ± 0.01^{b}	4.24 ± 0.37^{a}
520 nm	0.02 ± 0.00^{a}	0.02 ± 0.01^{a}	0.03 ± 0.01^{a}	0.08 ± 0.01^{c}	0.12 ± 0.01^{b}	0.17 ± 0.01^{a}	3.88 ± 0.24^{a}	4.18 ± 0.45^{a}	4.32 ± 0.26^{a}
620 nm	0.01 ± 0.00^{a}	0.01 ± 0.01^{a}	0.01 ± 0.00^{a}	0.02 ± 0.00^{b}	0.03 ± 0.01^{b}	0.04 ± 0.01^{a}	1.06 ± 0.03^{c}	1.19 ± 0.01^{b}	2.06 ± 0.02^{a}
Color intensity	0.13 ± 0.00^{c}	0.15 ± 0.01^{b}	0.22 ± 0.01^{a}	0.27 ± 0.02^{c}	0.36 ± 0.04^{b}	0.50 ± 0.04^{a}	7.82 ± 0.20^{b}	8.83 ± 0.47^{b}	10.61 ± 0.65^{a}
L^*	98.63 ± 0.23^{a}	98.39 ± 0.52^{a}	97.44 ± 0.47^{b}	94.96 ± 0.39^{a}	93.06 ± 1.49^{b}	89.63 ± 1.33^{c}	14.64 ± 0.73^{a}	12.51 ± 0.19^{b}	1.72 ± 0.10^{c}
a^*	-1.24 ± 0.02^{a}	-1.34 ± 0.12^{ab}	-1.60 ± 0.28^{b}	2.56 ± 0.24^{c}	3.87 ± 0.96^{b}	6.13 ± 0.42^{a}	43.96 ± 0.98^{a}	42.51 ± 0.11^{a}	27.20 ± 0.32^{b}
b^*	6.53 ± 0.68^{c}	7.71 ± 0.21^{b}	10.41 ± 0.03^{a}	8.99 ± 0.09^{c}	10.42 ± 0.19^{b}	12.98 ± 0.59^{a}	34.01 ± 0.71^{b}	38.34 ± 0.69^{a}	21.99 ± 0.27^{c}
Chroma	6.65 ± 0.67^{c}	7.83 ± 0.22^{b}	10.54 ± 0.06^{a}	9.35 ± 0.14^{c}	11.14 ± 0.51^{b}	14.37 ± 0.50^{a}	55.58 ± 1.20^{a}	57.25 ± 0.54^{a}	34.99 ± 0.42^{b}
Hue	100.81 ± 1.02^{a}	99.83 ± 0.70^{ab}	98.73 ± 1.47^{b}	74.10 ± 1.27^{a}	69.76 ± 4.32^{a}	64.70 ± 2.06^{b}	37.73 ± 0.04^{c}	42.05 ± 0.45^{a}	38.95 ± 0.01^{b}
ΔE	–	1.20	4.08	–	2.71	7.60	–	5.03	24.33
Simulated color									

Results are expressed as mean ± standard deviation (SD), and different superscript letters indicate significant differences (Tukey's test, $p < 0.05$).

perceptible to the human eye, confirming visually discernible changes in appearance between original and dealcoholized wines. These differences can be further confirmed by the simulated color blocks presented in Table 2. The observed color changes during dealcoholization likely result not only from concentration effect produced due to ethanol reduction and water removal but also from disruptions in co-pigmentation and/or the formation of anthocyanin-derived pigments due to oxygen uptake and sulfur dioxide depletion, as well as a slight pH shift (Gambuti et al., 2011; Kumar, Italiano, et al., 2024; Sam, Ma, Liang, et al., 2021).

3.3. Volatile profile of dealcoholized wines

A total of 23 volatile compounds were analyzed to assess the impact of ethanol removal on the aromatic profile of white, rosé, and red wines. Table 3 summarizes the results of selected volatile compounds, while Fig. 1 illustrates the progressive increase in total aroma loss with decreasing ethanol content. In white wine, PDW retained only 27.9 % of the total aroma, corresponding to a 72.1 % loss, while DW retained 10.6 %, indicating an 89.4 % loss compared to the original wine (OW). Similarly, in rosé wine, PDW retained 23.0 % of the total aroma (77.3 % loss), and DW retained just 8.8 %, signifying a 91.2 % loss. For red wine, PDW retained 20.3 % of the total aroma (79.7 % loss), whereas DW retained only 6.3 %, reflecting a 93.7 % loss.

Briefly, across all wine types, the levels of higher alcohols decrease substantially with removal of ethanol. Isobutanol levels dropped by 80.4 %, 81.1 %, and 85.8 % in PDW for white, rosé, and red wines, respectively, and were undetectable in all DW samples. Similarly, 3-methylbutanol levels decreased by 78–79 % in PDW for all wine types and were also undetectable in DW. The concentrations of 2-methylbutanol and 1-hexanol declined by 83–88 % and 74–78 %, respectively, in PDW wines and were undetectable in DW. Notably, 2-phenylethanol was not significantly affected by ethanol removal. The varied behaviors of alcohol compounds can be linked to changes in vapor pressure values, volatilities, and ethanol affinity (Diban et al., 2008). Additionally, Esteras-Saz et al. (2021) noted that due to larger molar mass and low volatility, aromatic alcohols (such as 2-phenylethanol) behave differently from aliphatic alcohols (such as isobutanol and 1-hexanol). Similarly, Motta et al. (2017) observed no significant change in phenylethanol during the production of dealcoholized red and rosé wines with 5 % *v*/v ethanol using vacuum distillation, while a significant reduction was observed in isobutanol (72–75 %), isoamyl alcohol (67–73 %), and n-hexanol (66–70 %).

Esters, which are critical for fruity and floral aromas, showed significant declines. Ethyl acetate, the most abundant ester across all wine types, decreased by 81.4 % and 94.6 % in PDW for white and red wines, respectively, and was undetectable in DW. In rosé wine, ethyl acetate was completely lost in both PDW and DW. Other esters, including ethyl propionate (78–84 %), ethyl isobutyrate (84–87 %), ethyl butyrate (76–98 %), 2-methylbutyl acetate (79–87 %), ethyl hexanoate (93–95 %), and hexyl acetate (68–88 %), decreased significantly in PDW and were entirely absent in DW. Isoamyl acetate, ethyl octanoate, ethyl phenylacetate, and ethyl decanoate were completely lost in both PDW and DW. Conversely, ethyl 2-hydroxy-4-methylvalerate, diethyl succinate, and phenethyl acetate retained 20–40 % of their original levels in DW. Similarly, Sam, Ma, Liang, et al. (2021) observed a total ester loss of 96.3 %, 98.1 %, and 95.8 % in dealcoholized white (Chardonnay), rosé (Pinot Noir), and red (Merlot) wines, respectively, with a final ethanol content of 0.7 % *v*/v achieved through vacuum distillation. Specifically, losses in the concentrations of phenethyl acetate (77–100 %), ethyl 2-hexenoate (96–100 %), ethyl acetate (91–100 %), ethyl decanoate (99–100 %), ethyl hexanoate (99–100 %), ethyl nonanoate (97–100 %), and ethyl octanoate (99 %) were reported in the dealcoholized wines compared to the original wines. Moreover, there were complete losses (100 %) of ethyl dodecanoate, 4-methyl-1-pentanol, 3-ethoxy-1-propanol, and isoamyl octanoate. Generally, esters are predominantly

Table 3
Volatile compounds content (VOC) of original (OW), partially dealcoholized wine (PDW) and dealcoholized wine (DW).

Compounds	RT	RI	White wine					Rosé wine					Red wine				
			OW	PDW	Loss (%)	DW	Loss (%)	OW	PDW	Loss (%)	DW	Loss (%)	OW	PDW	Loss (%)	DW	Loss (%)
Isobutanol [mg/L]	10.98	616	41.28 ± 8.65^{a}	8.11 ± 2.02^{b}	80.4	nd	–	33.17 ± 2.6^{a}	6.26 ± 2.60^{b}	81.1	nd	–	139.87 ± 30.0^{a}	19.90 ± 1.22^{b}	85.8	nd	–
3-Methylbutanol [mg/L]	15.33	740	206.40 ± 19.16^{a}	44.68 ± 21.15^{b}	78.4	nd	–	206.17 ± 12.92^{a}	45.21 ± 21.10^{b}	78.1	nd	–	583.13 ± 30.14^{a}	121.08 ± 42.17^{b}	79.2	nd	–
2-Methylbutanol [mg/L]	15.50	752	40.41 ± 3.11^{a}	4.82 ± 3.42^{b}	88.1	nd	–	44.03 ± 4.08^{a}	6.50 ± 4.07^{b}	85.2	nd	–	147.08 ± 19.96^{a}	23.84 ± 8.95^{b}	83.8	nd	–
1-Hexanol [mg/L]	20.78	965	1.77 ± 0.50^{a}	0.40 ± 0.05 ^{b}	77.4	nd	–	1.32 ± 0.04^{a}	0.34 ± 0.11^{b}	74.2	nd	–	2.33 ± .041^{a}	0.52 ± 0.03^{b}	77.7	nd	–
2-Phenylethanol [mg/L]	30.25	1165	25.32 ± 2.70^{a}	22.47 ± 4.56^{a}	–	30.36 ± 8.14^{a}	–	20.67 ± 3.30^{a}	16.54 ± 2.59^{a}	–	21.46 ± 4.50^{a}	–	72.57 ± 8.97^{a}	65.28 ± 20.28^{a}	–	70.26 ± 15.74^{a}	–
Ethyl acetate [mg/L]	10.22	615	84.67 ± 6.09^{a}	15.71 ± 19.20^{b}	81.4	nd	–	92.39 ± 8.73^{a}	nd	–	nd	–	335.94 ± 189.19^{a}	18.10 ± 12.71^{b}	94.6	nd	–
Ethyl propionate [μg/L]	14.26	717	254.79 ± 19.58^{a}	54.98 ± 2.436^{b}	78.4	nd	–	295.59 ± 36.10^{a}	49.76 ± 6.23^{b}	83.2	nd	–	413.60 ± 46.64^{a}	66.80 ± 29.04^{b}	83.8	nd	–
Ethyl isobutyrate [μg/L]	16.26	757	179.98 ± 53.80^{a}	23.33 ± 0.25^{b}	87.0	nd	–	114.05 ± 22.15^{a}	17.64 ± 1.85^{b}	84.5	nd	–	229.30 ± 86.65^{a}	34.21 ± 15.93^{b}	85.1	nd	–
Ethyl butyrate [mg/L]	17.98	798	0.46 ± 0.091^{a}	0.01 ± 0.01^{b}	97.8	nd	–	0.65 ± 0.06^{a}	0.10 ± 0.02^{b}	84.6	nd	–	0.34 ± 0.07^{a}	0.08 ± 0.00^{b}	76.5	nd	–
Isoamyl acetate [mg/L]	21.06	972	0.33 ± 0.15^{a}	nd	–	nd	–	0.91 ± 0.03^{a}	nd	–	nd	–	0.50 ± 0.39^{a}	0.11 ± 0.00^{b}	78.0	nd	–
2-Methylbutyl acetate [μg/L]	21.14	974	28.42 ± 4.57^{a}	5.90 ± 0.60^{b}	79.2	nd	–	67.47 ± 11.27^{a}	9.03 ± 1.13^{b}	86.6	nd	–	137.88 ± 136.31^{a}	18.65 ± 25.15^{b}	86.5	nd	–
Ethyl hexanoate [mg/L]	25.65	1093	1.08 ± 0.22^{a}	0.06 ± 0.02^{b}	94.4	nd	–	1.73 ± 0.35^{a}	0.11 ± 0.01^{b}	93.6	nd	–	0.23 ± 0.11^{a}	nd	–	nd	–
Hexyl acetate [μg/L]	26.12	1103	21.68 ± 1.36^{a}	2.51 ± 0.09^{b}	88.4	nd	–	10.50 ± 0.99^{a}	3.37 ± 0.25^{b}	67.9	nd	–	nd	nd	–	nd	–
Ethyl 2-hydroxy-4-methylvalerate [μg/L]	27.89	1130	183.88 ± 6.23^{a}	104.46 ± 7.37^{b}	43.2	46.92 ± 1.64^{c}	74.5	161.39 ± 8.30^{a}	92.07 ± 3.56^{b}	43.0	44.87 ± 3.38^{c}	72.2	286.47 ± 75.93^{a}	146.94 ± 34.20^{b}	48.7	55.61 ± 2.54^{c}	80.6
Diethyl succinate [mg/L]	31.58	1185	8.96 ± 4.09^{a}	6.84 ± 0.95^{ab}	23.7	3.85 ± 0.35^{b}	57.0	7.28 ± 1.25^{a}	5.87 ± 0.83^{a}	19.4	3.55 ± 1.23^{b}	51.2	12.70 ± 0.31^{a}	8.35 ± 0.74^{ab}	34.3	5.25 ± 0.21^{b}	58.7
Ethyl octanoate [mg/L]	32.30	1196	2.37 ± 0.14^{a}	nd	–	nd	–	3.49 ± 0.94^{a}	0.04 ± 0.01^{b}	98.9	nd	–	0.26 ± 0.05^{a}	nd	–	nd	–
Ethyl phenylacetate [μg/L]	34.12	1352	27.63 ± 0.50^{a}	nd	–	nd	–	13.77 ± 0.11^{a}	nd	–	nd	–	17.66 ± 0.12^{a}	nd	–	nd	–
Phenethyl acetate [μg/L]	34.53	1365	89.66 ± 36.94^{a}	27.13 ± 14.75^{b}	69.7	14.62 ± 2.24^{b}	83.7	61.54 ± 0.74^{a}	15.04 ± 1.08^{b}	75.6	12.18 ± 0.11^{c}	80.2	66.35 ± 25.13^{a}	19.74 ± 16.12^{b}	70.2	26.60 ± 23.53^{ab}	59.9
Ethyl decanoate [mg/L]	38.11	1491	0.87 ± 0.45^{a}	nd	–	nd	–	1.35 ± 0.45^{a}	0.09 ± 0.01^{b}	93.3	nd	–	0.11 ± 0.04^{a}	nd	–	nd	–
Isovaleric acid [mg/L]	18.90	919	1.44 ± 0.07^{a}	1.28 ± 0.02^{a}	–	1.03 ± 0.03^{a}	–	1.39 ± 0.02^{a}	1.20 ± 0.01^{b}	–	0.95 ± 0.06^{a}	–	2.45 ± 0.46^{a}	1.91 ± 0.36^{a}	–	1.93 ± 0.25^{a}	–
Hexanoic acid [mg/L]	24.35	1058	7.91 ± 1.08^{a}	6.83 ± 1.22^{a}	–	6.72 ± 1.37^{a}	–	9.30 ± 1.32^{a}	8.14 ± 0.65^{a}	–	8.09 ± 1.67^{a}	–	6.02 ± 0.11^{a}	4.08 ± 0.02^{b}	32.2	3.24 ± 0.13^{c}	46.2
Octanoic acid [mg/L]	31.16	1179	7.08 ± 2.41^{a}	6.13 ± 1.46^{a}	–	3.77 ± 0.53^{a}	–	9.10 ± 1.33^{a}	7.35 ± 0.24^{a}	–	4.15 ± 0.95^{a}	–	3.33 ± 0.28^{a}	1.97 ± 0.06^{b}	40.8	1.18 ± 0.06^{c}	64.6
Decanoic acid [μg/L]	37.03	1452	2.26 ± 0.94^{a}	3.12 ± 0.61^{a}	–	0.31 ± 0.01^{b}	–	2.62 ± 0.48^{a}	2.28 ± 0.22^{a}	–	0.32 ± 0.02^{b}	87.8	nd	nd	–	nd	–

RT: Retention Time; RI: Calculated Kovats retention index. Results are expressed as mean ± standard deviation (SD), and different superscript letters indicate significant differences (Tukey's test, $p < 0.05$); nd: not detected.

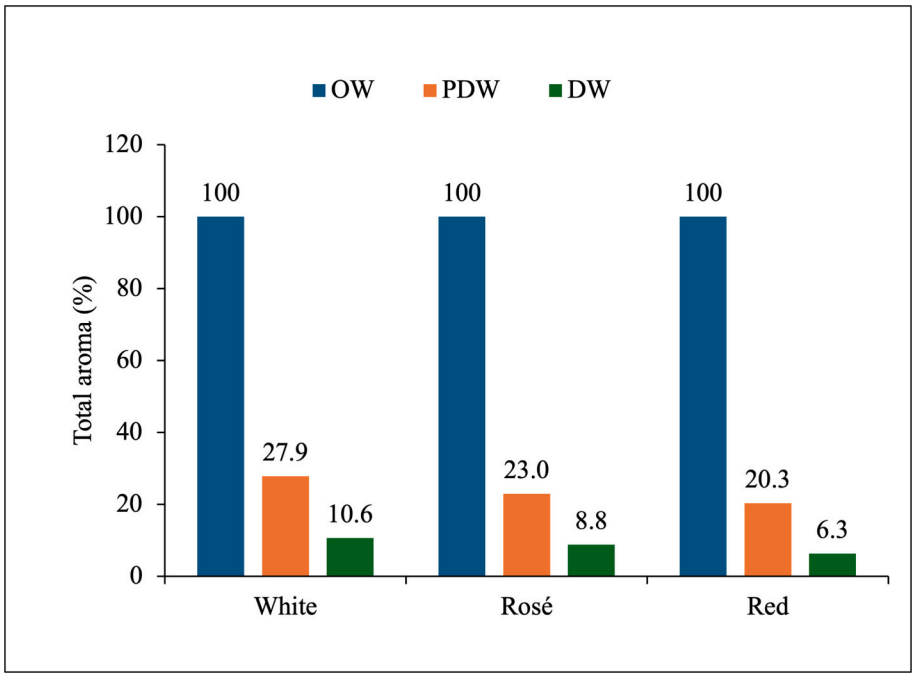

Fig. 1. Total aroma retained (%) in original wine (OW), partially dealcoholized wine (PDW), and dealcoholized wine (DW) for white, rosé, and red wines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hydrophobic in nature, making their loss during the dealcoholization process a predictable outcome (Diban et al., 2013; Kumar et al., 2025). In addition, the loss in ester concentration can be explained by the temperature used in vacuum distillation (50 °C), which might have contributed to a greater loss of esters, as high temperatures increase evaporation and promote the thermal degradation of volatiles and other wine components.

Volatile acids, which influence wine balance and mouthfeel, exhibited moderate reductions. In white wine, isovaleric acid, hexanoic acid, octanoic acid, and decanoic acid showed no significant changes during the production of PDW and DW. In rosé wine, isovaleric acid, hexanoic acid, and octanoic acid remained unaffected, while decanoic acid decreased significantly (87.8 %) in DW. For red wine, octanoic acid concentrations decreased by 40.8 % in PDW and 64.6 % in DW, while hexanoic acid dropped by 32.2 % in PDW and 46.2 % in DW. Isovaleric acid remained unaffected across all wine types during ethanol removal. The reduction in fatty acids can significantly alter the cheese and fat flavors often perceived in wine (Ma et al., 2022). Similarly, Sam, Ma, Salifu, et al. (2021) dealcoholized Chardonnay white, Pinot Noir rosé, and Merlot red wines (final alcohol content: 0.7 % *v*/v) using vacuum distillation. The process resulted in substantial reductions in key fatty acids, with hexanoic acid losses of 81.0 %, 78.0 %, and 89.7 % in white, rosé, and red wines, respectively. Octanoic acid exhibited even greater reductions, with losses of 86.9 % in white wine, 90.7 % in rosé, and 95.3 % in red wine. Similarly, decanoic acid decreased by 88.3 %, 88.0 %, and 91.4 % in white, rosé, and red wines, respectively. Petrozziello et al. (2019) observed a lower loss in the concentration of octanoic acid (40 %) and decanoic acid (39 %) in Chardonnay wine dealcoholized by vacuum distillation. According to these results, the mechanism of aroma loss is dependent on the interaction of the volatile compounds', physical and chemical characteristics (such as their hydrophobicity, water solubility, boiling point, vapor pressure, and chemical structure), as well as the process's operating temperature and duration. It is to be noted that the technology used did not allow a partial recovery of aroma. During continuous counter-flow distillation under vacuum aroma losses can be partly reduced by partial condensation within the process.

The odor activity values (OAV) were calculated for each individual compound, and the results were reported in Table 4. According to the results shown in Table 4, 15 of the 23 quantified volatile compounds presented concentrations above the odor threshold (OAV $>$ 1) in at least one sample or type of wine. Therefore, these are the volatiles that most likely contribute to the wine's overall scent and need to be considered when evaluating the impact of ethanol removal. Overall, in PDW, eight compounds retained an OAV $>$ 1, including 3-methylbutanol (fruity, floral, chemical), 2-phenylethanol (fruity, floral), ethyl acetate (fruity, balsamic), ethyl hexanoate (fruity, fatty), diethyl succinate (fruity, floral, creamy), isovaleric acid (cheesy, sweaty, rancid), hexanoic acid (cheesy, fatty), and octanoic acid (rancid, grassy, dusty). However, further dealcoholization had a pronounced impact, as DW retained only 2-phenylethanol, diethyl succinate, isovaleric acid, hexanoic acid, and octanoic acid with OAV $>$ 1. This significant reduction in volatile compounds, particularly esters and higher alcohols, suggests a loss of fruity and floral notes, which are essential for the overall aromatic complexity of wine. The persistence of fatty acids and diethyl succinate in DW indicates that certain aroma components are more resistant to ethanol removal.

3.4. Sensory profile of dealcoholized wine

The sensory assessment results of PDW and DW for white, rosé, and red wines, as shown in Fig. 2, indicate that the removal of ethanol significantly impacts various sensory attributes. For white wine (Fig. 2a), ethanol removal led to significant increases in color intensity, cooked vegetable, evolved floral notes, bitterness and acidity. Conversely, perceptions of sweetness, body/fullness and hotness decreased significantly. However, attributes such as fresh fruit, apple, citrus, peach, evolved fruity, and overall acceptability were not significantly affected by the ethanol removal. In the case of rosé wine (Fig. 2b), the sensory differences were more pronounced. The removal of ethanol significantly increased the scores for color intensity, evolved floral, evolved fruity, and cooked vegetable notes. On the other hand, perceptions of fresh floral, fresh fruity, body/fullness, hotness and overall acceptability decreased significantly. Interestingly, DW wine exhibited sensory scores similar to OW for parameters such as red fruit

Table 4
Odor descriptors, odor thresholds, and odor activity values (OAV) of volatile compounds corresponding to each wine sample.

Compounds	Odor Descriptor*	Odor threshold* (mg/L)	OAV White wine			OAV Rosé wine			OAV Red wine		
			OW	PDW	DW	OW	PDW	DW	OW	PDW	DW
Isobutanol	Apple, bitter, green	40	1.03	0.20	–	0.83	0.16	–	3.50	0.50	–
3-Methylbutanol	Fruity, floral, chemical	30	6.88	1.49	–	6.87	1.51	–	19.44	4.04	–
2-Methylbutanol	Nail polish, solvent	64	0.63	0.08	–	0.69	0.10	–	2.30	0.37	–
1-Hexanol	toasty, green, dry herb	8	0.22	0.05	–	0.17	0.04	–	0.29	0.07	–
2-Phenylethanol	Fruity, floral	10	2.53	2.25	3.04	2.07	1.65	2.15	7.26	6.53	7.03
Ethyl acetate	Fruity, balsamic	7.5	11.29	2.09	–	12.32	–	–	44.79	2.41	–
Ethyl propionate	fruity	3.5	0.07	0.02	–	0.08	0.01	–	0.12	0.02	–
Ethyl isobutyrate	fruity, apple, and pineapple-like aromas	0.03	6.00	0.78	–	3.80	0.59	–	7.64	1.14	–
Ethyl butyrate	pineapple, tropical fruit, and apple-like	0.02	23.00	0.50	–	32.50	5.00	–	17.00	4.00	–
Isoamyl acetate	fruity (apple, pear, and banana)	0.03	11.00	–	–	30.33	–	–	16.67	3.67	–
2-Methylbutyl acetate	Fruity, banana-like, pear, apple	0.02	1.42	0.30	–	3.37	0.45	–	6.89	0.93	–
Ethyl hexanoate	Fruity, fatty	0.014	77.14	4.29	–	123.57	7.86	–	16.43	0.0	–
Hexyl acetate	Fruity, green, herb	7.5	0.00	–	–	0.00	0.00	–	0.00	0.0	–
Ethyl 2-hydroxy-4-methylvalerate	fresh blackberry aroma	0.4	0.46	0.26	0.12	0.40	0.23	0.11	0.72	0.37	0.14
Diethyl succinate	Fruity, floral, cream	0.041	218.54	166.83	93.90	177.56	143.17	86.59	309.76	203.66	128.05
Ethyl octanoate	fruity, floral, green	0.24	9.88	–	–	14.54	0.17	–	1.08	–	–
Ethyl phenylacetate	sweet, floral, honey-like	0.1	0.28	–	–	0.14	–	–	0.18	–	–
Phenethyl acetate	floral, lilac	0.25	0.36	0.11	0.06	0.25	0.06	0.05	0.27	0.08	0.11
Ethyl decanoate	Fruity	0.2	4.35	0.00	–	6.75	0.45	–	0.55	–	–
Isovaleric acid	cheesy, sweaty, and rancid notes	1.0	1.44	1.28	1.03	1.39	1.20	0.95	2.45	1.91	1.93
Hexanoic acid	cheese/fatty	0.42	18.83	16.26	16.00	22.14	19.38	19.26	14.33	9.71	7.71
Octanoic acid	Rancid, grass, dust	0.5	14.16	12.26	7.54	18.20	14.70	8.30	6.66	3.94	2.36
Decanoic acid	Sour, vinegar	15	0.15	0.21	0.02	0.17	0.15	0.02	–	–	–

* Odor descriptions and odor threshold are mainly obtained from the following literature: Sam et al. (2023) and https://wineserver.ucdavis.edu/industry-info/enology/fermentation-management-guides/wine-fermentation

notes (e.g., cherry and raspberry), acidity, bitterness, and astringency, while these parameters scored lower for PDW. For red wine (Fig. 2c), OW and the ethanol-reduced wines (PDW and DW) displayed similar scores for overall acceptability, color intensity, sweetness, acidity, fresh floral, greenness notes, bitterness, astringency, and body/fullness. The lack of significant difference in astringency and bitterness, despite ethanol reduction, may be related to complex matrix effects, including pH, residual sugars, and phenolic composition, which can strongly influence sensory perception and potentially mask ethanol's effect (Fontoin et al., 2008; Kuhlman et al., 2024). Moreover, ethanol concentration affects tannin solubility and aggregation, with lower ethanol potentially favoring precipitation of larger tannins, which are often associated with stronger astringency (Pascotto et al., 2020; Poncet-Legrand et al., 2003; Villamor et al., 2013). Since tannin concentration was not measured in this study, its role in astringency remains unclear and should be examined in future work. However, evolved floral notes, red fruit notes (e.g., cherry and raspberry), cooked vegetables and oak-related attributes significantly increased with ethanol removal. Furthermore, PDW maintained sensory parameters similar to OW in terms of black cherry, plum, and evolved fruity notes. However, DW showed higher scores for these parameters compared to OW. In line with the comparable overall acceptability scores observed for PDW and DW white and red wines relative to their respective OW samples, panelists indicated that both PDW and DW wines remained suitable for consumption, despite the loss of specific volatile compounds during the dealcoholization process.

These variations are primarily attributed to ethanol reduction, the removal of volatiles, and the type of wine. Ethanol, being the most abundant volatile compound in wines, significantly influences the perception of wine aroma, taste, and various mouthfeel attributes (Diban et al., 2008; Fontoin et al., 2008; Pickering et al., 1998). Higher ethanol levels in wine enhance perceptions of bitterness, body, astringency, and hotness, while lower ethanol levels reduce mouthfeel persistence, aroma intensity, and flavor (Sam, Ma, Liang, et al., 2021). Additionally, ethanol exerts a masking effect on acidity and astringency due to its sweet, soft, and harmonizing characteristics (Lisanti et al., 2013). Furthermore, the observed increase in acidity can also be explained by the rise in total acidity in PDW and DW wines due to the concentration effect. Moreover, the higher perception of evolved and cooked aromas is likely attributed to the processing temperature (50 °C) during the dealcoholization process. In addition to the processing time, it is noted that modern continuous systems can significantly lower both processing time and temperature, ensuring that no thermal damage (detectable by HMF) occurs (Schmitt & Christmann, 2019). According to some recent studies (Fox & Harbertson, 2024; Liguori et al., 2019; Ma et al., 2022; Montevecchi et al., 2024; Schmitt et al., 2023), dealcoholization of wine can increase color intensity, acidity, and astringency while considerably lowering volatile scent components, hotness, bitterness, and sweetness. Based on the sensory results, PDW maintained better sensory characteristics than DW but still showed significant declines in critical parameters.

Furthermore, to better understand the loss of volatile compounds and the changes in sensory attributes upon ethanol removal at different concentrations in white, rosé, and red wines, Principal Component Analysis (PCA) of the quantitative data was performed. The first two principal components, PC1 and PC2, accounted for 40.41 % and 33.19 % of the total variance, respectively (Fig. 3). OW wines are closely associated with most of the aroma compounds and sensory attributes (such as body/fullness, hotness, sweetness, fresh floral, and fresh fruity notes) and are located on the positive side of PC1. In contrast, PDW and DW wines cluster on the negative side of PC1, indicating substantial shifts in their volatile composition and sensory profiles following ethanol reduction. Specifically, OW-Red wines were distinctly separated on the positive side of PC1, characterized by high levels of key esters (ethyl acetate, isoamyl acetate, ethyl isobutyrate, ethyl butyrate, and ethyl hexanoate) and fatty acids (octanoic and decanoic acids), which are strongly correlated with fresh fruity, fresh floral, sweetness, hotness, and body/fullness attributes. In contrast, PDW-Red and DW-Red wines

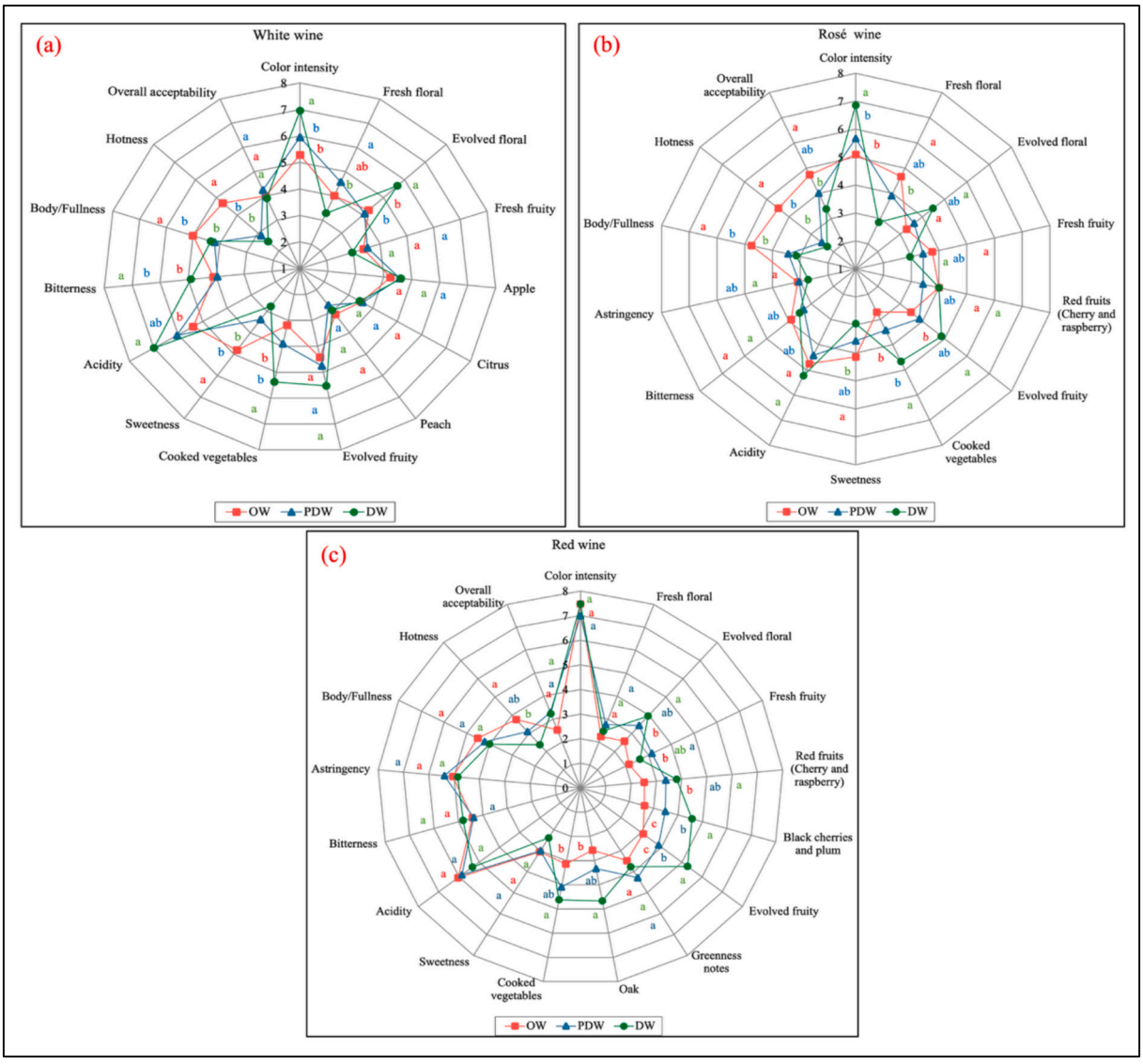

Fig. 2. Sensory profile of original wine (OW), partially dealcoholized wine (PDW) and dealcoholized wine (DW); (a): for white wine; (b): for rosé wine; (c): for red wine. The different superscript letters indicate significant differences (Tukey's test, $p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shifted towards the negative side of PC1 and the positive side of PC2, indicating a marked reduction in ester-derived fruity notes and a relative increase in less desirable attributes, such as greenness, cooked vegetable nuances, and astringency. For white and rosé wines, OW samples are located on the positive side of PC1 and the negative side of PC2, characterized by high concentrations of esters (ethyl butyrate, ethyl hexanoate, hexyl acetate, and ethyl decanoate) and fatty acids (hexanoic and decanoic acids), associated with sensory attributes such as fresh fruity, fresh floral, sweetness, and body/fullness. In contrast, PDW and DW samples for white and rosé wines cluster on the negative side of PC1, showing a loss of volatile esters and a shift towards sensory descriptors such as evolved floral and evolved fruity, indicating a reduction in freshness following ethanol removal.

4. Conclusion

Vacuum distillation has proven to be an efficient and promising technique for producing PDW (6 % v/v ethanol) and DW (0.5 % v/v ethanol). The dealcoholized wines exhibited significant differences ($p \leq 0.05$) in physico-chemical parameters compared to OW, including increased density, total extract, glycerin, total acidity, and volatile acidity, alongside a significant decrease in pH. Additionally, PDW and DW wines displayed higher AU_{420nm} values, increased intensity, and lower L* values compared to OW. For chromatic attributes, chroma and b* values increased in PDW and DW white and rosé wines but decreased in red wines. The total color difference (ΔE*), indicating perceivable color changes, was markedly higher in DW: 4.08 for white, 7.60 for rosé, and 24.33 for red wines. Ethanol removal significantly reduced volatile compound levels, with higher losses observed as ethanol content decreased, particularly with reductions of 89.4 %, 91.2 %, and 93.7 % in DW white, rosé, and red wines, respectively. Sensory evaluation revealed decreased intensity scores for fresh floral (white and rosé), fresh fruity (red), sweetness (white and rosé), hotness, and body/fullness (rosé) following ethanol removal. Conversely, color intensity (red), cooked vegetable notes (white and rosé), and acidity (white and rosé) increased. Overall acceptability scores for PDW and DW white and red wines were comparable to OW, while the overall acceptability of DW rosé wine significantly decreased with ethanol removal. This indicates that both PDW and DW white and red wines remained suitable for consumption, despite the loss of specific volatile compounds during the

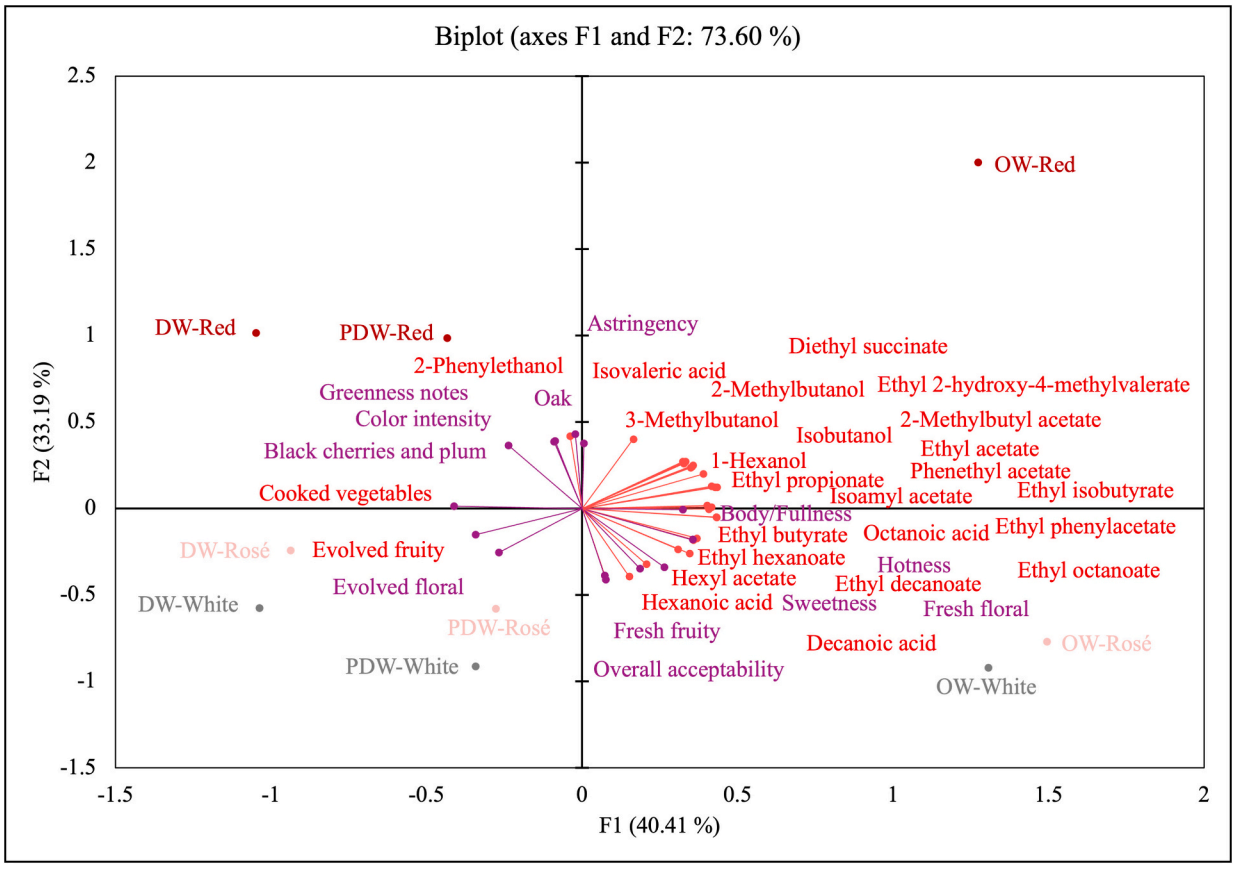

Fig. 3. PCA biplot of cases and variables based on total volatile compounds and sensory attributes characterizing original (OW), partially dealcoholized (PDW), and dealcoholized (DW) white, rosé, and red wines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dealcoholization process.

Currently, the main challenge is preserving volatile compounds during ethanol removal, so future research should explore strategies to mitigate the loss of these compounds during dealcoholization, such as the integration of complementary techniques like aroma recovery and reconstitution. Additionally, future work should include the determination or application of ethanol-adjusted threshold values to improve the accuracy of OAV calculations across wines with varying alcohol contents.

Metadata availability

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

CRediT authorship contribution statement

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

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

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