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SPECIAL ISSUE

Comparison of the principal production methods for dealcoholised wine based on analytical parameters

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ABSTRACT

Production, demand, and brand awareness of dealcoholised wine (< 0.5 % *v/v*) are progressively increasing worldwide. This study aimed to evaluate the efficiency of membrane- and thermal-based dealcoholisation methods by examining changes in quality parameters associated with ethanol removal. A total of 600-litres of Spanish white wine (OW) was subjected to dealcoholisation using key techniques, including vacuum distillation (VD), conventional distillation (Dist), spinning cone column (SCC), osmotic distillation (OD), a combination of reverse osmosis with osmotic distillation (RO-OD), where a wine beverage obtained from reverse osmosis via diafiltration, is used as the strip solution(RO-Dia(R)), reverse osmosis where the permeate was paired with dialysis (RO-Dia(P)), and standalone dialysis (Dia). Total extract and total acidity were significantly higher in wines dealcoholised by thermal-based methods, whereas they decreased in wines processed by membrane-based methods. A similar trend was observed for mineral content: VD-treated wines showed the highest concentrations of Mg, Ca, and K (55–59 % higher compared to OW), while Dia-treated wines exhibited the greatest losses (around 90 % lower compared to OW). Total phenol concentration significantly increased in VD-treated wines and significantly decreased in wines processed by RO-OD, RO-Dia(R), RO-Dia(P), and Dia. Techniques such as Dist, SCC, and OD showed no significant changes in total phenol concentration compared to OW. Colour intensity was highest in Dist-treated wine (0.96) but decreased in wines treated by other dealcoholisation methods. Furthermore, redox potential and acetaldehyde concentrations varied depending on the dealcoholisation technique, with OD-treated wines exhibiting the highest values.

KEYWORDS: dealcoholised wine, dealcoholisation, chemical parameters, thermo and membrane technologies, Macrowine 2025

INTRODUCTION

The definition of wine dealcoholisation, according to the International Organisation of Vine and Wine (OIV), is provided in the International Code of Oenological Practices, Part II – Oenological Treatments and Practices, Section II.3.5.16. This section defines dealcoholisation as the process of reducing part or almost all of the ethanol content in wine to obtain viti-vinicultural products with reduced or low alcohol content (OIV, 2023).

The need for this process has become increasingly important due to two distinct factors: climate change, which increases the sugar concentration in grapes and results in higher alcohol levels in wine, and the changing behaviour of modern consumers, who are reducing alcohol consumption for reasons such as adopting healthier lifestyles (Kumar *et al.*, 2024b; Sam *et al.*, 2021). These factors have posed a significant challenge to scientists and engineers, prompting the development of methods to remove ethanol while minimising its impact on the sensory and chemical properties of wine.

The OIV permits the use of separation techniques or combinations of methods, such as partial vacuum evaporation, membrane technologies, and distillation, although the production conditions for these methods are still under investigation. Physical methods for ethanol removal can be categorised into thermal processes and membrane techniques (Ozturk & Anli, 2014; Saha *et al.*, 2013).

Thermal processes, including vacuum distillation, are among the most common methods used for dealcoholisation, as they allow ethanol removal at relatively low temperatures under vacuum conditions (Sam *et al.*, 2021). A system available on the market is the GoLo system, which combines multiple batch separation operations into a single, continuous, easy-to-use process (Veiga-del-Baño *et al.*, 2024). It features a thin film creation system that operates with high efficiency and no moving parts. Other techniques, such as counterflow distillation, have also been applied in this context. A famous variant of vacuum distillation is the Spinning Cone Column (SCC), developed in the 1930s in the USA (Zamora *et al.*, 2016). This method utilises a vertical column with alternating rotating and stationary metal cones to achieve separation (Belisario-Sánchez *et al.*, 2009; Margallo *et al.*, 2015). Membrane techniques include reverse osmosis, which uses a semipermeable membrane with pore sizes of 0.1–1 nm to separate ethanol and water from wine under high pressure. In this method, ethanol must be removed from the permeate, and the remaining solution recombined with the retentate. Nanofiltration operates similarly to reverse osmosis but allows a broader range of substances to pass through the membrane (Kumar *et al.*, 2025b; Kumar *et al.*, 2025c). This makes it less commonly used for ethanol removal but suitable for sugar separation in must to reduce potential ethanol production (Schmidtke *et al.*, 2012). Osmotic distillation employs a hydrophobic membrane, through which volatile compounds migrate and condense on the opposite side (Schmitt & Christmann, 2019). The technique does not decrease the water content in the processed wine, and the loss in product is only due to the alcohol removal (Akhtar *et al.*, 2025). Pervaporation is another membrane-based technique that uses selective diffusion and partial vaporisation to separate ethanol based on concentration and vapour pressure gradients (Takács *et al.*, 2007). Dialysis, on the other hand, relies on a semipermeable membrane to enable the transfer of ethanol and larger molecules between wine and a stripping solution via diffusion and convection (Calvo *et al.*, 2022; Italiano *et al.*, 2024).

Some of these methods can achieve ethanol removal in a single stage, while others require a combination of techniques to achieve optimal results. However, despite the availability of these technologies, few studies have directly compared the different physical methods for dealcoholising wine.

This study aimed to evaluate the efficiency of membrane- and thermal-based dealcoholisation methods by examining changes in quality parameters associated with ethanol removal. These differences are evaluated primarily through physicochemical parameters, analysed using techniques such as spectrophotometry, Fourier transform infrared spectroscopy (FTIR), Oxidation–Reduction Potential (ORP) sensor, and basic enzymatic wine analysis.

MATERIALS AND METHODS

1. Material

For this study, 600-litres of Airén wine (10 % *v/v*), a neutral white wine from the 2023 vintage produced in Spain, was used. The wine was supplied by the company Rotkäppchen-Mumm-Sektkellereien GmbH.

The dealcoholisation was carried out using eight different techniques, all processed in the Hochschule Geisenheim University, except for the Spinning Cone Column method, which was performed at the Rotkäppchen-Mumm facility in Eltville am Rhein, Germany.

After the dealcoholisation process, the wines (< 0.5 % *v/v*) were stabilised by the addition of liquid SO_2 to achieve 30 mg/L of free SO_2 and Nagardo®, a medium-chain fatty acid (Glycolipid), at a concentration of 20 mg/L. The stabilised wines were then bottled at the Department of Enology at Hochschule Geisenheim University in 750 mL brown glass bottles with crown caps. The bottles were stored at a temperature of 14 °C for one month. Afterwards, all experiments were conducted.

2. Dealcoholisation methodologies

The wine was dealcoholised using eight different techniques, categorised into thermal and membrane-based methods (Figure 1). Thermal methods included vacuum distillation (VD), conventional distillation (Dist), and Spinning Cone Column (SCC). Membrane-based techniques involved osmotic distillation (OD), dialysis (Dia), and hybrid approaches combining reverse osmosis (RO) with these methods. For the OD and Dia process, wine was used as the main solution and demineralised water as the strip solution. Reverse osmosis was coupled with osmotic distillation (RO-OD), where the permeate from the RO process underwent

dealcoholisation using OD, operating with demineralised water as the strip solution. The dealcoholised permeate was then reintroduced into the retentate. In a further approach, Dialysis was coupled with RO (RO-Dia(R)), where a beverage dealcoholised wine was first obtained through RO using the diafiltration technique. This dealcoholised wine was then used as the stripping solution in a dialysis membrane, with the wine serving as the main solution. Alternatively, in RO-Dia(P), the permeate from the RO process served as the main solution for dialysis, with demineralised water as the strip solution. The resulting solution was subsequently reintroduced into the retentate.

Demineralised water for all membrane-based processes was produced using the PureLab Option-R60 system, equipped with a reverse osmosis (RO) membrane model LC119 (ELGA LabWater, High Wycombe, HP14 3BY, UK). To minimise oxygen content, the water was deoxygenated using the CO_2 Membrane System 100 (KHTEC GmbH, D-75038 Oberderdingen, Germany). Water at 20 °C flowed at an average velocity of 1450 L/h on one side of the membrane contactor, while the other side was maintained under vacuum conditions (0 bar pressure). The system achieved a target dissolved oxygen concentration of 0.10 mg/L. All dealcoholised wines were immediately bottled following the respective processes and stored at a controlled temperature of 16–18 °C to preserve quality.

2.1. Spinning Cone Column

The Spinning Cone Column (SCC) is a technology widely used in the wine industry for applications such as aroma recovery, dealcoholisation, and the concentration of must or wine (Schmitt & Christmann, 2022). For this study, the SCC was operated at the Rotkäppchen-Mumm facility in Eltville am Rhein. It is a vacuum rectification device designed with alternating stationary and rotating conical inserts. The rotation of the cones forms a thin liquid film on their surface, less than 1 mm thick, while fins on the underside of the cones create turbulence in the rising vapours, enhancing the exchange between the liquid and vapour phases. A small amount of gas, typically a vaporised fraction of the product, is introduced at the base of the column to facilitate the process (Margallo *et al.*, 2015). The SCC operates as a two-stage system for wine dealcoholisation. In the first stage, aroma compounds are separated under high vacuum conditions (0.04 atm) at temperatures between 26 °C and 28 °C and are collected in a high-strength ethanol stream, representing approximately 1 % of the original wine volume. In the second stage, ethanol is removed from the base wine at approximately 38 °C. The aroma fraction is then reintroduced into the dealcoholised wine (Belisario-Sánchez *et al.*, 2009).

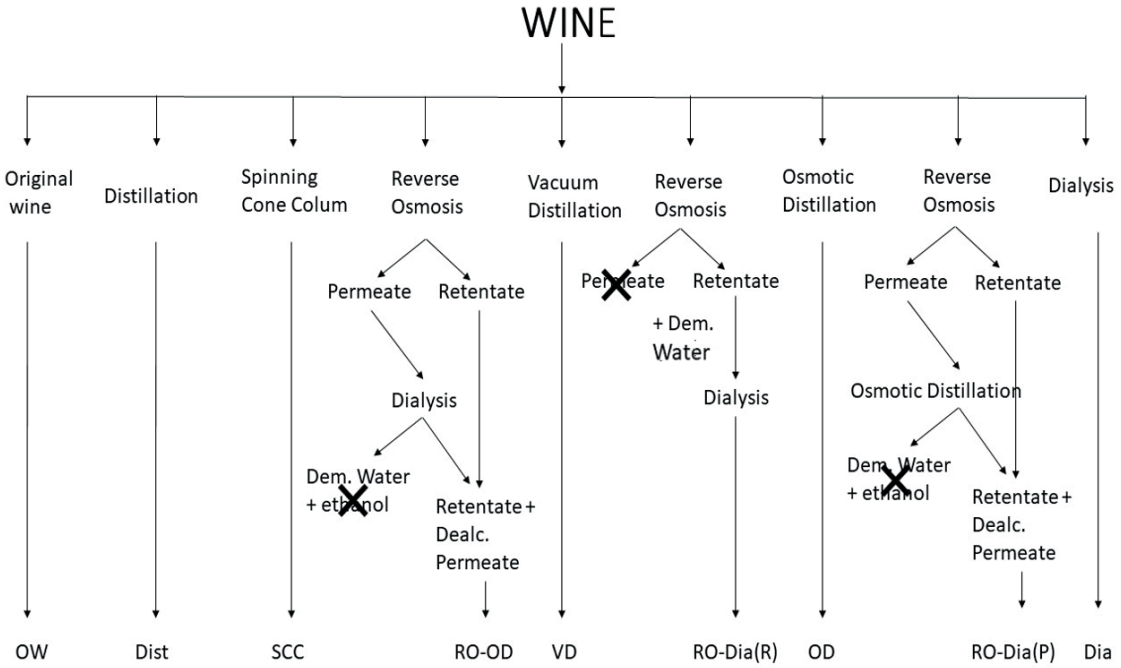


FIGURE 1. Different approaches for the production of dealcoholised wine. Dem. Wine: Demineralised Water

2.2. Vacuum Distillation

The dealcoholisation of the wines was conducted using Hei-VAP Industrial Rotary Evaporators (Heidolph Instruments GmbH & Co. KG, 91126 Schwabach, Germany). This system comprised a heating bath capable of water temperature settings up to 180 °C, a vacuum pump (Hei-Vac Valve Industrial) for evacuating, evaporating, and pumping out gases and vapours, and a chilling system (Hei-CHILL 3000) for condensation.

The dealcoholisation process was followed, as explained by Kumar *et al.* (2024d), with minor modifications, and the wine was distilled using an evaporating flask with a 20 L capacity. The vacuum pressure was maintained at 50 mbar, with a water bath temperature initially set at 30 °C and a feed flask rotation speed of 70 rpm. The condensation temperature was kept constant at 1.8 °C throughout the experiments. After separating approximately 1 % of the wine's aromatic

fraction, the water bath temperature was increased to 40 °C until the wine reached an alcohol content below 0.5 % *v/v*.

Following the initial distillation, the collected spirits were redistilled under the same vacuum and pressure conditions, but with the water bath temperature increased to 50 °C. The water obtained from the re-distillation of the spirits was blended with the dealcoholised wine to produce the final product.

2.3. Distillation

The distillation was conducted using a batch distillation system from Arnold Holstein (88677 Markdorf, Germany). The apparatus consists of a product container equipped with a mixer to ensure homogeneity of the solution. A pre-condenser is installed upstream of the rectification process to optimise initial vapour condensation and energy efficiency. The system includes a rectification column with four plates, designed to enhance separation efficiency. The column is equipped with two thermometers to monitor the temperature gradient along the column. Pressure is controlled and monitored via a manometer positioned at the top of the column. Downstream of the rectification process, a final condenser is installed to cool the distillate. A densimeter is integrated into the system to measure the alcohol content of the final product in real time, ensuring precise control over the distillation parameters and output quality.

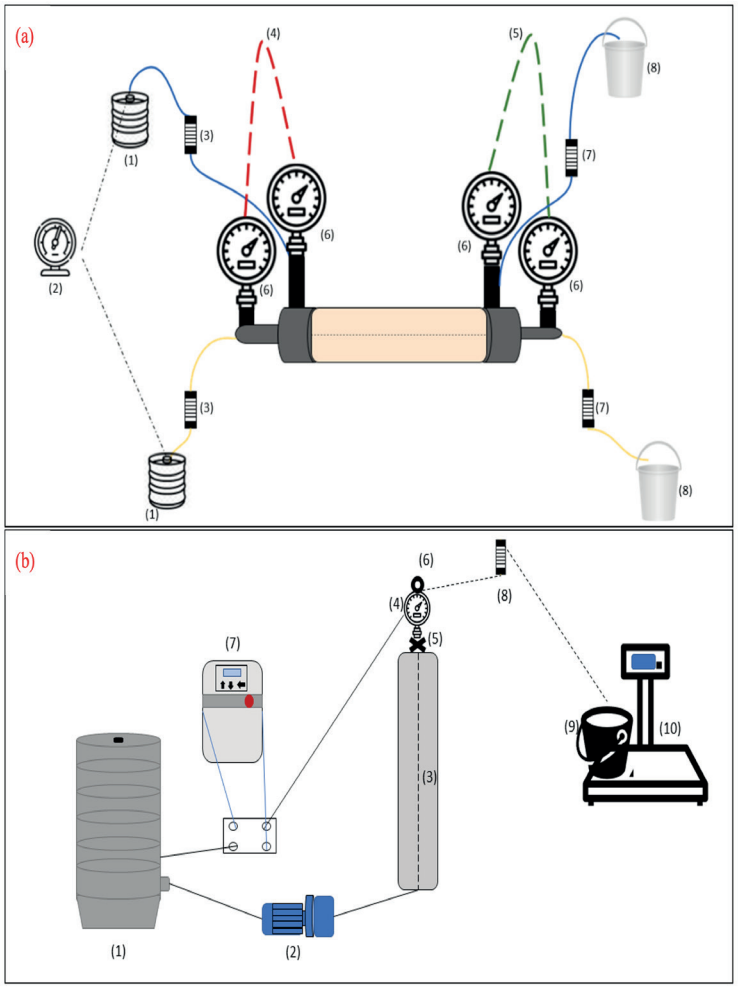


FIGURE 2. Different approaches for the production of dealcoholised wine. (a) Dialysis set-up. (b) RO set-up (Italiano *et al.*, 2024).

2.4. Osmotic Distillation

The Osmotic Distillation setup utilised a CO_2 Membrane System 100 (KH TEC GmbH, D-75038 Oberderdingen, Germany) equipped with two membrane contactors (3M™ Liqui-Flux™ membrane module, MF-PP Series, Type B65) with a surface area of 20 m^2 × two membranes. The system featured automated process control (SIMATIC HMI) for operational monitoring and flow control, as well as an integrated vacuum pump to support the process.

2.5. Dialysis

The dialysis membrane (InnoSpire Technologies GmbH, D-65510 Idstein, Germany) characteristics are reported in Table 1, along with the plant setup illustrated in Figure 2a, describe a system in which both the main solution and the draw solution are pumped through a dialysis membrane (9) in the same flow direction. These solutions originate from two separate kegs (one for the feed solution and one for the draw solution) and are maintained at a pressure of 1 bar, regulated by a manometer. The flow rates of the two liquids

are monitored and adjusted using flowmeters (3) (DK 800, KROHNE Messtechnik GmbH, 47058 Duisburg, Germany) at their respective inlets. Tubing connects the inlet (4) and outlet (5) of both the main and draw solutions, enabling the measurement of osmotic pressure differences before and after passing through the membrane.

The setup is equipped with four additional manometers (6) (MS 10160, WIKA Alexander Wiegand SE & Co. KG, 63911 Klingenberg, Germany) for verifying system pressure. Two additional flowmeters (7) (DK 800) are positioned at the outlets to control the outflow of the liquids and further regulate their osmotic pressure. The processed liquids are collected in two separate buckets (8). The process operates discontinuously: the main solution is recirculated into the feed keg, while a fresh keg of demineralised water is introduced during each step. This cycle continues until the main solution (wine or permeate) is fully dealcoholised.

2.6. Reverse Osmosis

The reverse osmosis (UNISOL Membrane Technology, 99867 Gotha, Germany) characteristics reported in Table 1, along with the plant setup illustrated in Figure 2b, consist of a 100-litre tank (1) that supplies wine to a high-pressure pump (2) (5CP5120, 55449 Minneapolis, USA). This pump directs the wine into a still module (3) equipped with a reverse osmosis (RO) membrane. Pressure monitoring is facilitated by a manometer (4) installed on top of the module, along with two valves: a handle-operated valve (5) serving as a potential bypass and a rotary-knob valve (6) for precise adjustments. The retentate flows through a heat exchanger (7) (FL4003, JULABO GmbH, 77960 Seelbach, Germany), which is maintained at 20 °C, before returning to the tank. Simultaneously, the permeate is routed through a flowmeter (8) and collected in a bucket (9) placed on a scale (10) for weight measurement.

TABLE 1. Properties of the membranes used for removing alcohol from wine.

Membrane	Type	Outer wrap	Membrane area (m²)	MWCO (kDa)	RNaCl/RMgSO4 (ppm)	P (bar)	T (°C)	pH
Dialysis	Polyether sulfone	–	4.6	10–15	–	6	40	3–11
RO (BW3022)	Polyamide	Net wrap	7.4	80	32,000 (55 bar, 25 °C, pH 6.5–7)	55	50	2–10

2.7. Analysis

The original and dealcoholised wines were analysed one month after bottle storage following the dealcoholisation process. Colour parameter was determined using a photoLab® 7600 UV-VIS spectrophotometer (Xylem Analytics Germany Sales GmbH & Co. KG, 82362 Weilheim, Germany) in the Department of Enology laboratory at Hochschule Geisenheim University. The analyses were also conducted on redox potential using an ORP sensor (Hamilton Medical Germany GmbH, DE-82166 Gräfelfing, Germany), acetaldehyde levels determined by the UV-enzymatic method (R-Biopharm AG, D-64297 Darmstadt), and total phenols quantified using the Folin-Ciocalteu reagent (FCR) and measurement at 780 nm.

Mineral content analyses were performed using the SOP-092-1 method with a ContrAA 300 instrument (Analytik Jena AG, 007745 Jena, Germany). Furthermore, oenological parameters including density, extract, total acidity, pH, tartaric acid, malic acid, lactic acid, volatile acidity, and glycerol were measured using Fourier Transform Infrared (FTIR) spectroscopy with a Winescan™ SO2 instrument equipped with Foss Integrator software (Foss, 3400 Hillerød, Denmark).

2.8. Statistics

All measurements were conducted in triplicate, with the results expressed as mean values alongside their respective standard deviations. The Tukey test was used to find significant differences (p-level < 0.05) between control and de-alcoholised wine samples. The analyses were performed using XLSTAT (Addinsoft, 75018 Paris, France).

RESULTS AND DISCUSSION

1. Effect of dealcoholisation on physico-chemical parameters

The physicochemical parameters of dealcoholised wines (DW) obtained from different dealcoholisation techniques are presented in Table 2. The results revealed significant variations compared to the original wine (OW), reflecting the distinct mechanisms and selectivity of each method. Density significantly increased in all DW compared to OW (0.994 g/mL), with VD-treated wine showing the highest density (1.011 g/mL) ($p < 0.05$). This increase is likely due to the concentration effect caused by ethanol removal (Kumar *et al.*, 2025a). Total extract, which indicates the concentration of non-volatile solids, increased significantly in DW produced using VD (31.70 g/L), SCC (25.10 g/L), Dist (23.95 g/L), and OD (22.45 g/L) compared to OW (19.73 g/L) ($p < 0.05$). In contrast, wines dealcoholised using RO-OD, RO-Dia(P), and RO-Dia(R) maintained moderate extract values.

Conversely, DW produced using Dia exhibited a drastic reduction (3.80 g/L), suggesting significant compound loss during alcohol removal. This reduction is likely attributed to molecular size exclusion and selective diffusion across the membrane, which not only removes ethanol but also low-molecular-weight compounds, including sugars, acids, and minerals (Italiano *et al.*, 2024; Kumar *et al.,* 2024a).

Total acidity significantly increased in wines dealcoholised using thermal techniques such as VD, Dist, and SCC, due to the concentration effect, whereas it decreased in DW

TABLE 2. Physicochemical parameters in dealcoholised wine obtained from different dealcoholisation techniques.

Samples	OW	VD	Dist	SCC	OD	RO-OD	RO-Dia(R)	RO- Dia(P)	Dia
Density	0.994 ± 0.000^{g}	1.011 ± 0.001^{a}	1.009 ± 0.000^{b}	1.009 ± 0.000^{bc}	1.008 ± 0.000^{c}	1.006 ± 0.000^{d}	1.004 ± 0.001^{e}	1.004 ± 0.001^{e}	1.000 ± 0.000^{f}
Extract (g/L)	19.73 ± 0.50^{d}	31.70 ± 2.40^{a}	25.10 ± 0.14^{b}	23.95 ± 0.21^{bc}	22.45 ± 0.07^{c}	17.20 ± 0.00^{e}	15.15 ± 1.91^{ef}	13.50 ± 1.13^{f}	3.80 ± 0.14^{g}
Total acidity (g/L)	5.30 ± 0.00^{c}	7.40 ± 0.57^{a}	6.30 ± 0.00^{b}	5.50 ± 0.00^{c}	5.30 ± 0.00^{c}	3.85 ± 0.07^{d}	3.30 ± 0.42^{e}	2.90 ± 0.28^{e}	0.75 ± 0.07^{f}
pH value (g/L)	3.10 ± 0.00^{b}	2.90 ± 0.00^{d}	2.90 ± 0.00^{d}	3.00 ± 0.00^{c}	3.00 ± 0.00^{c}	3.00 ± 0.00^{c}	3.10 ± 0.00^{b}	3.10 ± 0.00^{b}	3.20 ± 0.00^{a}
Tartaric acid (g/L)	2.93 ± 0.06^{b}	3.85 ± 0.07^{a}	2.80 ± 0.00^{b}	3.00 ± 0.00^{b}	2.85 ± 0.07^{b}	1.40 ± 0.00^{d}	1.75 ± 0.21^{c}	1.25 ± 0.21^{d}	0.30 ± 0.00^{e}
Malic acid (g/L)	1.03 ± 0.06^{b}	1.55 ± 0.21^{a}	1.70 ± 0.00^{a}	0.85 ± 0.07^{c}	0.90 ± 0.00^{bc}	0.75 ± 0.07^{c}	0.35 ± 0.07^{d}	0.45 ± 0.07^{d}	0.00 ± 0.00^{e}
Lactic acid (g/L)	0.37 ± 0.06^{d}	0.75 ± 0.07^{a}	0.50 ± 0.00^{c}	0.60 ± 0.00^{b}	0.50 ± 0.00^{c}	0.30 ± 0.00^{de}	0.30 ± 0.00^{de}	0.25 ± 0.07^{e}	0.10 ± 0.00^{f}
Volatile acidity (g/L)	0.30 ± 0.00^{b}	0.40 ± 0.00^{a}	0.40 ± 0.00^{a}	0.40 ± 0.00^{a}	0.30 ± 0.00^{b}	0.30 ± 0.00^{b}	0.20 ± 0.00^{c}	0.20 ± 0.00^{c}	0.10 ± 0.00^{d}
Glycerol (g/L)	4.20 ± 0.10^{b}	5.30 ± 0.71^{a}	4.10 ± 0.00^{b}	3.80 ± 0.00^{bc}	3.50 ± 0.00^{cd}	3.20 ± 0.00^{d}	1.85 ± 0.35^{e}	1.95 ± 0.07^{e}	0.00 ± 0.00^{f}

Different letters indicate significant differences among DW produced from different methods ($p < 0.05$, Tukey test).

produced using membrane techniques, including Dia, and combinations such as RO-OD, RO-Dia(P), and RO-Dia(R). This is due to retention factors in the membranes. OD-treated wine showed no significant change.

Similarly, volatile acidity significantly increased with thermal techniques (VD, Dist, and SCC) but decreased in DW produced by Dia and the combinations RO-Dia(P) and RO-Dia(R). RO-OD and OD treatments resulted in no significant changes in volatile acidity.

pH values exhibited minor variations across techniques. In particular, VD (2.90) and SCC (2.90) showed slightly lower values compared to OW (3.10), whereas Dia demonstrated a marginally higher pH (3.20), due to acidity depletion.

Among organic acids, tartaric acid concentration was significantly similar in OD, SCC, and Dist, but it significantly increased in VD (3.85 g/L) compared to OW (2.93 g/L). In contrast, Dia showed a sharp decrease (0.30 g/L). Similar trends were observed for lactic acid and malic acid, with the completely depleted in Dia (lactic acid 0.10 g/L and malic acid 0.00 g/L). Glycerol, a key compound contributing to wine mouthfeel, significantly increased in VD (5.30 g/L) and SCC (4.10 g/L) but was entirely depleted in Dia (0.00 g/L).

2. Effect of dealcoholisation on mineral content

The change in mineral content of dealcoholised wines (DW) obtained from different dealcoholisation techniques is presented in Figure 3. The concentration of minerals, including magnesium, calcium, and potassium, significantly increased in DW produced using VD, SCC, Dist, and OD, but significantly decreased in wines treated with RO-OD, RO-Dia(R), RO-Dia(P), and Dia. Specifically, VD exhibited the highest levels of magnesium (102.50 mg/L), calcium (136.0 mg/L), and potassium (1506.0 mg/L) among all samples, while Dia recorded the lowest values (magnesium: 6.00 mg/L; calcium: 9.50 mg/L; potassium: 92.0 mg/L). This significant mineral depletion in Dia is likely due to differences in the composition of the main wine solution and the draw solution (water), which hinder equilibrium between the two liquids and promote migration of components from a more concentrated to a less concentrated solution. Additionally, dilution effects might have played a role (Italiano *et al.*, 2024).

These results demonstrate that thermal techniques such as VD, Dist, and SCC are more effective in retaining key physicochemical and mineral parameters, often resulting in values surpassing those of the original wine due to concentration effects. In contrast, Dia, while effective at alcohol removal, led to substantial losses in critical parameters, potentially compromising wine quality. Membrane-based techniques such as OD and RO-OD provided a balanced profile, preserving key attributes without excessive alterations.

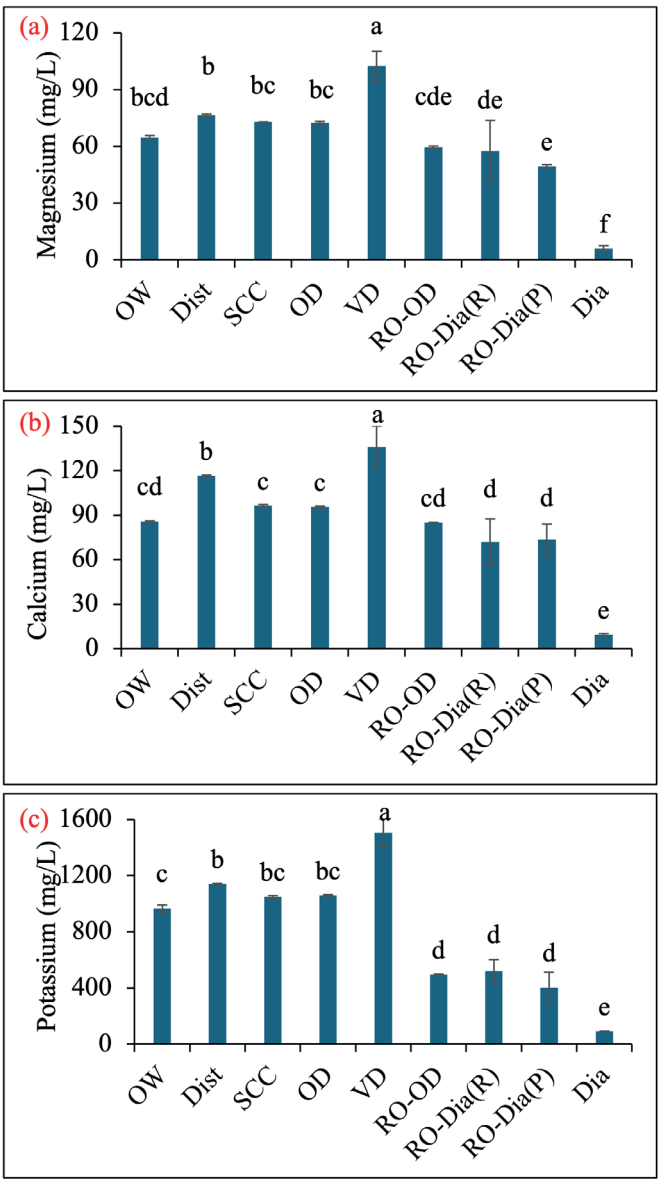


FIGURE 3. Mineral content in dealcoholised wine obtained from different dealcoholisation techniques: a) Magnesium, b) Calcium, c) Potassium. Different letters indicate significant differences among DW produced from different methods ($p < 0.05$, Tukey test)

3. Effect of dealcoholisation on acetaldehyde concentration, total phenolic content, redox potential, and colour intensity

Figure 4 shows the acetaldehyde concentration, total phenolic content, redox potential, and colour intensity of dealcoholised wines (DW) produced using different dealcoholisation techniques. The results indicate significant variations in these parameters depending on the method used, particularly in comparison to the OW. Among the DW samples, those produced using OD and VD retain higher acetaldehyde concentrations (57.8 mg/L and 56.6 mg/L, respectively), with OD resulting in the highest redox potential (102.9 mV). In contrast, wines dealcoholised via Dist and Dia exhibit drastically reduced acetaldehyde concentrations, with Dia showing the lowest value (3.8 mg/L) alongside a marked increase in redox potential (92.8 mV). The high levels of acetaldehyde in the DW produced using the OD and VD methods are attributed to oxidation during processing (Kumar *et al.*, 2025a), which also causes an increase in redox potential.

A high concentration of acetaldehyde gives undesired pungent and irritating organoleptic properties to wines, such as green apple, freshly cut grass, and nutty aromas (Guittin, 2023). However, the sensory perception threshold is reported around 100 to 125 mg/L (Guittin, 2023), so that is not the case. In the Dist method, acetaldehyde evaporates at its boiling point (20.2 °C at atmospheric pressure, 1 atm) (Yamazaki *et al.*, 2015), leading to minimal levels in the final product.

The removal of both ethanol and acetaldehyde, which contribute to redox potential, explains the observed decrease in this parameter (Berovic, 2024). In the case of Dia, the significant loss of acetaldehyde can be explained by its

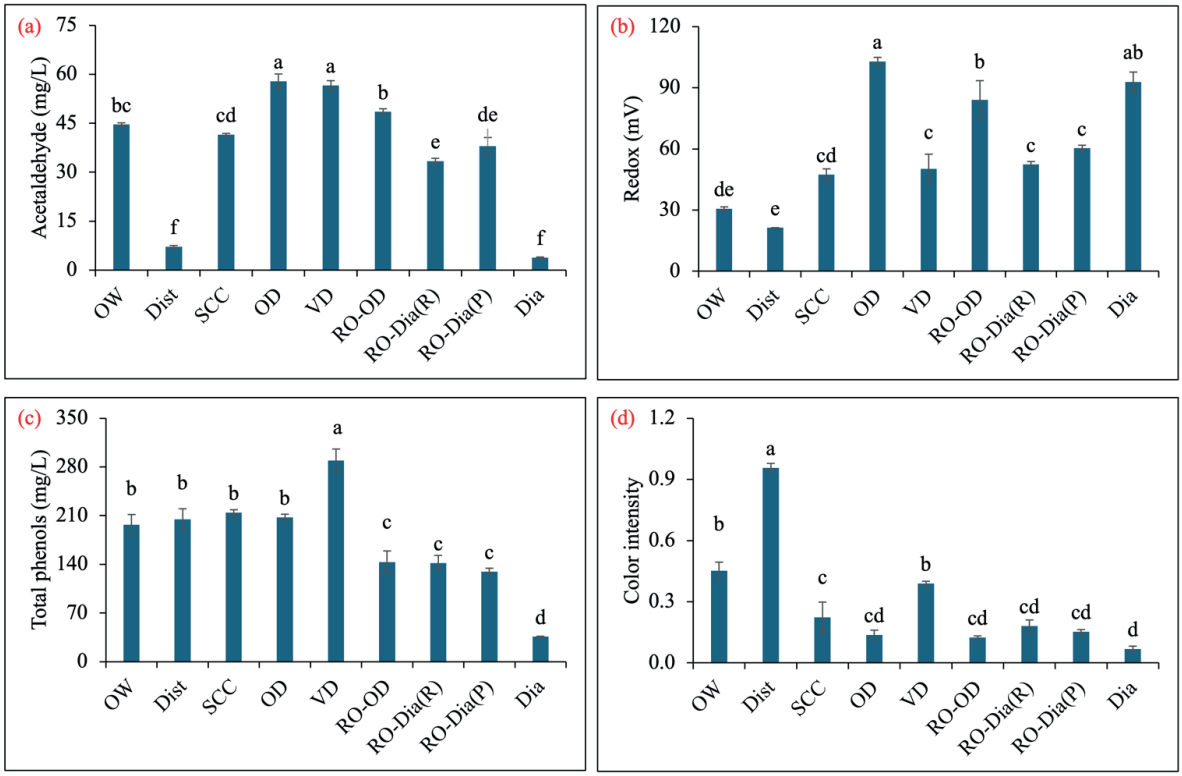


FIGURE 4. Parameters content in dealcoholised wine obtained from different dealcoholisation techniques: a) Acetaldehyde (mg/L), b) Redox (mV), c) Total phenols (mg/L), d) Colour intensity. Different letters indicate significant differences among DW produced from different methods ($p < 0.05$, Tukey test).

passage through the membrane and the dilution effect, while the high redox potential indicates severe oxidation.

Regarding total phenolic content, VD demonstrates superior retention (289.2 mg/L), whereas Dia leads to the most substantial losses (35.9 mg/L). The increase in total phenol concentration observed in dealcoholised wine produced using VD can be attributed to the concentration effect that occurs during the removal of ethanol. As ethanol is evaporated, the remaining compounds, including phenolic substances, become more concentrated, leading to a higher total phenol content (Kumar *et al.*, 2024d; Tomaskova *et al.*, 2017). A high concentration of total phenolics can influence the wine´s taste quality, increasing its astringency and bitterness sensations (Gutiérrez-Escobar *et al.,* 2021). However, polymerisation due to high temperatures reduces the overall phenol content and contributes to browning, which explains the higher colour intensity observed in the wine (Kumar *et al.*, 2024c; Wang & Kumar, 2024).

In contrast, methods such as RO, RO combined with OD and Dia, and dialysis tend to dilute the wine's components or result in the selective removal of phenolic compounds alongside ethanol, which can lead to a decrease in their overall concentration. Leading to sensations of a lack of body in the wine.

Colour intensity declines across most techniques, with Dia retaining the lowest values (0.07), while Dist achieves relatively higher values (0.96). These high values of colour intensity show a strong oxidation, caused by the formation of brown polymers (Eftihia *et al.*, 2023). Dia effectively removes phenols through the membrane, and dilution effects further reduce their levels. The lower value of colour intensity in Dia-treated wines results from near-complete pigment removal, making the final product resemble water more than wine. Based on these results, VD proves to be the most effective method for preserving phenolic content, whereas Dia causes the greatest deterioration in key quality attributes.

CONCLUSION

This study evaluates the effects of various dealcoholisation techniques on wine quality parameters, such as physicochemical properties, mineral content, total phenols, and colour intensity. Thermal methods like VD and SCC effectively concentrate key compounds such as total phenols and minerals due to ethanol removal and concentration effects. However, these techniques also promote oxidation, as indicated by elevated acetaldehyde levels and redox potential, leading to browning and altered wine balance. The Dist was included as a reference to demonstrate the severe impact of high-temperature processes on wine characteristics.

Membrane-based techniques, including RO and OD, offered a soft approach, preserving essential wine parameters. Coupled methods like reverse osmosis–dialysis (RO-Dia(R) and RO-Dia(P)) successfully reduced acetaldehyde, suggesting their potential for producing high-quality dealcoholised wines. However, these methods also showed increased redox

values and possible reductions in total phenols, which could influence wine texture.

In contrast, the Dia method caused significant dilution, removing low-molecular-weight compounds such as phenols, organic acids, and pigments. This resulted in a final product resembling water more than wine.

The findings underscore the need to carefully select dealcoholisation methods, with membrane-based techniques offering a promising pathway for producing high-quality alcohol-free wines while balancing preservation and oxidation challenges. Nevertheless, it is important to note that small batch scales can lead to an increase in oxygen uptake. Developing technical optimisations of the processing units can help reduce O_2 uptake.

Further research could aim to explore the differences in the aromatic characterisation of the products, as well as from an organoleptic sensory perspective, across various production methodologies.

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