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Membrane dialysis for partial dealcoholization of wine. Comparison between white and red wines

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Abstract

BACKGROUND: Membrane dialysis is a suitable technique for the partial dealcoholization of wines that preserves most of the aromas of the original wine. In this study it has been compared the use of this technique in white and red wines of the same vintage. The results of partial dealcoholization have been checked in terms of chemical and sensory properties. In addition, gas chromatography was carried out to determine whether the aromas are appreciably diminished in their final composition for filtered wines.

RESULTS: Membrane dialysis resulted in wines with a lower alcoholic strength than the starting one, 11.0 g/kg alcohol reduction was obtained for white wines and 13.4 g/kg for red wines after dialysis, and with acceptable chemical and sensory characteristics but with a lower concentration of some aromatic compounds.

CONCLUSION: This partial dealcoholization technique is slightly more effective for the treated red wines. However, the dialyzed red wines become also less acceptable for consumers than the corresponding white wines.

Keywords: Wine dealcoholization; Dialysis; White wine; Red wine; Aromas

INTRODUCTION

Wine is a natural product whose quality varies with grape conditions, but skilled oenologists can reduce this variability to meet the strict standards required by regional wine appellation organizations (for example Denominazione di Origine Controllata, DOC; Appellation d'Origine Contrôlée, AOC; or Denominazione di Origine Controllata e Garantita, DOCG) for labelling and marketing.

One key characteristic of wine is its alcohol content, which depends on the sugar concentration in grapes before fermentation. Since alcohol levels are difficult to alter without affecting taste, choosing the right harvest time is crucial. As grapes ripen, sugar increases, and winemakers must balance acidity, aroma, phenolic maturity, and potential alcohol. Harvesting too early can produce wines with “green” flavors, and limited aging potential due to insufficient aroma complexity and underdeveloped tannins.

In Spain, red wines are usually marketed with an alcohol content of between 97.7-118 g/kg (12-15º in units of alcohol degree, much more used in alcoholic beverages), while white wines, in general, have a slightly lower alcohol content (71-110 g/kg). However, higher alcoholic wines are becoming increasingly common.

Several factors can affect the rise in alcohol content, but one of the main ones is climate change, which causes grapes to ripen earlier and accumulate more sugar. To counter this, some Spanish and other European wine regions have begun harvesting in late summer instead of autumn. However, harvesting earlier can hinder grape development and ultimately reduce yield.[1]

Conversely, there is an increasing demand for wines with lower alcohol content, as they offer fewer calories and reduce health risks linked to excessive alcohol consumption. Additionally, producing lower-alcohol wines can bring notable tax benefits.[2]

While excessive alcohol consumption is harmful, moderate intake as part of a Mediterranean diet can benefit health.[3] In red wines, phenolic compounds like resveratrol have antioxidant, anti-inflammatory, and antithrombotic properties, offering cardioprotective, anti-osteoporotic, and antimutagenic effects.[4] Therefore, producing wines with lower alcohol content but similar phenolic levels is both appealing and advantageous.

However, wine is a product that is consumed for pleasure, and while lower-alcohol wines are increasingly sought after, the tasting qualities and sensory satisfaction of a good wine remain highly valued.[5]

In this situation, several options can be considered.

One option is to modify viticulture practices—such as irrigation or canopy management—to control photosynthesis and limit sugar accumulation in grapes.[6] However, these methods are complex, labor-intensive, and raise production costs.

Other chemical techniques involves adding of glucose oxidase or catalase enzyme directly in the must before alcoholic fermentation.[7]

A further method, used frequently by our research group, is to remove part of the sugar from the must through membrane processes such as nanofiltration (NF),[8,9] or combining NF with pervaporation (PV) to recover some lost aromas.[10-12] While effective—especially for white wines—NF can also remove essential components, negatively affecting the wine’s sensory and taste qualities.[12] Even blending NF-treated wine with the original cannot fully restore its aromatic and sensory profile.

Finally, alcohol content can be reduced after the wine is produced, using various separation techniques, as reviewed by Figueroa-Paredes *et* al.[13]

The most conventional techniques to achieve this would be heat treatment, operating under vacuum; for example, evaporation, distillation or vapour separation.[14] But also, other techniques such as osmotic distillation or rotating cone columns can be used with satisfactory results.[15-19]

In addition to these methods, membrane processes present an attractive alternative due to their high selectivity and gentle treatment of wine, a delicate product that can easily degrade at relatively high temperatures.

On the other hand, the International Organisation of Vine and Wine (OIV) allows alcohol reduction using membrane techniques only under strict conditions:[20,21] the wine must be free of organoleptic defects; the must's sugar content cannot be altered before fermentation; alcohol reduction cannot exceed 20% of the initial level; and the wine with a modification of alcoholic strength must be more than 67 g/kg. In fact, Spanish regulations only consider as wine those products having at least 71 g/kg (9 % v/v of alcohol) to fall within the definition of wine of the OIV. Moreover, the process must be supervised by an oenologist or specialised technician.

Figueroa-Paredes *et* al.[13] used PV to strongly reduce alcohol in red wines (from 117 to 84 g/kg), exceeding the OIV's 20% maximum reduction limit (up to 93 g/kg). However, they compare the results with those obtained after this strong dealcoholisation, if the dealcoholized wine is then blended with the starting wine, to achieve a final result of 107 g/kg.

In our case, previous studies with various possibilities (NF, PV, dialysis) led us to opt for membrane dialysis,[22] which allows reductions acceptable to the OIV, in a single stage and with fairly good organoleptic results for white wines.

Membrane dialysis is a separation process in which a semi-permeable membrane of controlled porosity separates two solutions with different concentrations (usually the product to be dialysed and an aqueous solution). The difference in concentration between the two sides of the membrane induces, by diffusion, the passage of components from the concentrated solution to the more dilute one. If the pore size is adjusted so that only certain components can pass through the membrane, these components are removed from the starting solution. Advantages include no need for cooling, pressure, increase the concentration or dilution, minimizing CO_2 loss.[4] Previous tests on white wines showed minimal chemical and sensory differences between treated and untreated wines, making them hard for consumers to distinguish.[22]

Figueroa-Paredes *et al*.[13], in their study, focused on the analysis of productivity and costs of the process but also on the changes in volatile compounds due to PV. Accordingly, sensorial and chemical analysis has complemented with an analysis of aromas, which is expected that can help to discriminate the organoleptic differences found.

On the other side, it remains open the question if dialysis of wines results in similar performances and organoleptic changes when applied to red wines, with distinct sensorial characteristics. Therefore, in the work presented here, a further step has been tried by studying the performance of dialysis for the dealcoholisation of red wines, comparing it with the results for white wines, all of them from the same vintage.

Differences in applying membrane dialysis to white versus red wines may be more noticeable in sensory analysis than in chemical tests. To strengthen the validity of the sensory evaluation, over a hundred consumers participated in this study.

Finally, the aim of the present study is to check if the membrane dialysis process designed in our previous study for the partial dealcoholisation process of white wines, can be similarly used for red wines. To the best of our knowledge such comparison has not been previously tested and could be useful to offer a competitive and reliable process to reduce the alcohol content in wines.

MATERIALS AND METHODS

Departing wines

The wines used in this study were elaborated at the Escuela Técnica Superior de Ingenierías Agrarias de Palencia-Spain (ETSIIAA) with grapes from the 2022 harvest. Red wine was made from 80% Tempranillo and 20% Garnacha, while white wine was 100% Verdejo. Both wines followed traditional winemaking methods and were stored for at least 6 months at 6.0 ± 0.5 ºC. Before dialysis, the wines were homogenized and filtered through a 2.5 μm cellulose plate to prevent sedimentation.

Membrane and dialysis equipment

Membrane

Since the main mechanism of separation of alcohol in membrane dialysis is not sieving, the pore size of the membrane (or alternatively, the MWCO) to be used in the process is not the key factor in the membrane selection. In fact, diffusion from a concentrated side to the diluted one, allows separating molecules smaller than pore sizes. Wine alcohols are quite small molecules (47 Da for ethanol or 92 Da for glycerol, much scarcer), therefore any membrane with a cut-off over some hundreds of Da will be adequate to allow ethanol passage. This cut-off should be in the NF range, nevertheless, previous experience showed that using NF membranes, the resulting wine not only losses alcohol but almost other aromas or sensory compounds. Then a tight UF membrane seems to be more adequate.

Previous studies on white wines,[22] showed that the PLGC Ultracel membrane achieved the best alcohol reduction in the shortest time,[22] so it was selected for this study. These membranes, made of regenerated cellulose, are hydrophilic with a dense microstructure and pores in the ultrafiltration range. They are sold as with a diameter of 150 mm flat discs, and the 10 kDa molecular weight cut-off version (Sigma Aldrich 2023 catalogue) was chosen for this work.

This cut-off is high enough to assure passage of all volatile molecules, including alcohol but also aromas or similar molecules.

Dialysis setup

The dialysis filtration experiments were carried out in the laboratories of the Surfaces and Porous Materials Group (SMAP) at the Faculty of Science, Valladolid.

The main elements of the dialysis equipment have been described previously.[22] Firstly, 2 L of wine and Milli-Q water are added respectively to each of the Erlenmeyer flasks, Parafilm®-capped to prevent loss of aroma. The wine and Milli-Q water were pumped in crossflow and counter-current mode on each side of the membrane using their respective peristaltic pumps. Since both pumps operated at the same recirculation speed, the pressure difference between both sides of the membrane remained nil. The active area of the dialysis cell is 4.4×10^{-3} m^2. After passing through the cell, the liquids are returned to their respective Erlenmeyer flasks.

Filtration procedure

Following OIV regulations (maximum 20% alcohol reduction), an 8-hour dialysis was used to ensure alcohol did not exceed ~158 g/kg. Wine bottles were refrigerated and properly sealed before dialysis to preserve aromatic compounds.

For each wine type (red and white), filtration was carried out in three consecutive sessions to have enough filtered wine for the subsequent chemical and sensory analyses. The three filtrations of each type of wine were carried out with the same membrane sample, which was rinsed with pure water after finishing each day session. Later, Milli-Q water was circulated on both sides of the membrane for about 10 minutes to clean the system.

Membrane sample was changed for a fresh one when wine tested changed from white to red wine. All dialysis sessions lasted 8 hours and, at the end of the 3 sessions for each type of wine, the resulting wine was homogenised (by mixing the filtered wine from all sessions), re-bottled and stored in fridge until being chemically, chromatographically and sensorially analysed.

Although parafilm was used to seal both flasks, some partial oxygenation occurred during the equipment priming needed for consistent filtration. Additionally, after 8 hours of red wine dialysis, the aqueous phase flask showed a slight pink/reddish tint, likely due to anthocyanins passing through the membrane—a phenomenon not observed with white wines.

Finally, during the whole process, no noticeable change in volume was observed in each of the containers, which leads us to consider that there is no significant transfer of water from the extracting solution to the wine.

Analytical methods

All the chemical analyses described below were carried out in duplicate, both on control white and red wines and on dialyzed wines (white and red). The analyses carried out on these wines were: pH (pH-meter), total acidity (potentiometric method), alcohol content (ebullometry), volatile acidity (García Tena method), free and total sulphur (simple Ripper method), total polyphenol index (TPI, ultraviolet index method) and colour (Glories method). All methods used are described by the OIV.[23]

Determination of volatile organic compounds (VOCs) by headspace-solid-phase microextraction-gas chromatography–mass spectrometry (HS-SPME-GC-MS)

Gas chromatography was carried out on control and dialyzed white and red wines at the Laboratory of Instrumental Techniques (LTI) of the University of Valladolid (UVa). A 7890A Equipment from Agilent Technologies (Santa Clara, CA, USA), equipped with an HP-INNOWAX column (J &W Scientific, Folsom, CA, USA) was used. Components were extracted previously to GC by HS-SPME with Supelco Fibers (StableFlex).

VOCs analysis was done in duplicate using HS-SPME-GC-MS. Identification of compounds was achieved by comparing their mass spectra with those of pure standards and/or spectral data from the NIST08 v. 2.4 and Wiley7 libraries. Quantification was carried out using the internal standard quantification method as equivalents of 2-octanol.[24]

Sensory analysis

A sensory analysis was conducted with 126 non-trained consumers (57 (44.88%) men, 69 (54.33%) women), prioritizing a large sample to enhance statistical reliability. Most participants were familiar with wine tasting and all were regular wine consumers. The sensory test were carried out in the tasting room of the ETSIIAA in individual sensorial booths, which complies with the standards of the International Organisation for Standardisation (ISO) 8589.[25]

Wine glasses used comply with the ISO 3591 standard,[26] which contained ~25 mL of liquid, were coded with three-digit random numbers, and were presented to the consumers in random order. The serving temperature of the red wine was 15 ± 1°C and the white wine was served at 12 ± 1°C. Mineral water at room temperature was provided to the participants for palate cleansing.

The data from the online tasting tests were collected using a Google Forms survey, the results of which being automatically exported to Excel format.

Triangular test

This test has been designed according to ISO 4120.[27] The method consists of providing the judges with three samples, two of which are the same and one of which is different, so that the judge must indicate which of the samples is different even if based on an unsure assumption (forced judgement test).

CATA (Check-All-That-Apply)

The Check-All-That-Apply (CATA) technique involves selecting the descriptors that best describe each sample from a given list, reducing biases from open-ended responses. It is an effective method for discriminating and characterizing products, and also includes a free comment option for judges to add additional descriptors if they wish. [28]

CATA questionnaire, for white wines, contained 16 terms related to the sensory characteristics of the Verdejo wines grouped in two visual terms (clean, rusty), eight olfactory terms (fruity, citric, tropical, herbaceous, balsamic, reduced, aniseed, aroma intensity), four terms related with the mouth (bitter, acid, mouth volume, persistence), and finally consumers were asked to give a general evaluation of the wine by setting if the wines were pleasant for them (like or unlike). The terms were selected based on published data,[29] considering the descriptors selected by trained assessors in preliminary studies, along with the typical characteristics of Verdejo wines.[22,28,30]

Similarly, descriptors used to characterise the red wine were also selected based on the literature,[28,30] resulting in similar descriptors, excepting some not very common in white wines, and including alcoholic and astringent, more likely to appear in red wines. Therefore, the terms included in the CATA questionnaire for red wines were 14, two in the visual phase (clean, intense colour), five in the olfactory phase (fruity, herbaceous, alcoholic, reduced, aroma intensity), five in the mouth (bitter, acid, astringent, mouth volume, persistence), and two related with the global perception (like or unlike).

Overall acceptability test

A 9-point hedonic scale was used to study the overall acceptability of the wines among consumers[31] with scale numbers from 1 (dislike extremely) to 9 (like extremely) as described by Stone *et al*.[32]

Statistical analysis

The statistical treatment of the chemical analyses and VOCs was carried out using analysis of variance (ANOVA), in addition to the Tukey test ($p < 0.05$), using the IBM SPSS Statistics 26.0 programme. Principal component analysis (PCA) was also performed on data of VOCs to characterize the four samples (control and dialyzed red and white wines) using Statgraphics Centurion 19.

The results of the triangular test were calculated according to ISO 4120.[27]

The CATA test was analysed by Cochran's Q test to check whether or not there are statistically significant differences between treated and untreated wine. In addition, a correspondence analysis (CA) with the four wines (control and dialyzed red and white wines) was also performed by considering the chi-square distance with the matrix containing the frequency of use of each term common for each sample. These analyses were performed with the statistical program IBM SPSS Statistics 26.0.

Finally, ANOVA and Tukey's test ($p < 0.05$), was performed on the overall acceptability test using Statgraphics Centurion 19.

RESULTS AND DISCUSSION

Chemical analysis

White wine

Table 1 shows the results of the statistical study of the chemical analysis of the control and dialysis-treated white wine sample. Firstly, the objective of the process is achieved with a reduction of 11.0 g/kg in the alcohol content of the wine (reduction corresponding to 10.60% of the original value, therefore acceptable according to OIV regulations). Also, it can be seen that there are significant differences in total acidity, alcohol content and colour intensity. In all these analytical parameters, the dialyzed wine shows significantly lower values.

Total acidity was significantly reduced after dialysis, it is likely that this loss of acidity is due to the diffusion of acidic components through the membrane, although this reduction did not translate into a similar pH drop. This could be due to the fact that, as can be seen in the table, the level of volatile acidity is relatively high, and it is this acidity that has accounted for most of the reduction in total acidity, without affecting the pH as much. The absence of significant changes in pH is related with the fact that wine is a buffer solution to a certain extent, even when small amounts of acids are added or removed.

There is also a significant drop in colour intensity (0.006 AU, corresponding to an 11% drop). This decrease could be due to the passage of brown (oxidised) polyphenols through the membrane, although this is not visible in the colour of the dialysed wine.[22]

If the analytical results obtained for the dialysis of white wines are compared with those presented in the previous work,[22] the major difference can be seen in a greater drop in alcoholic strength in this case (11 g/kg) reduction, compared to the previous work, 9.5 g/kg. Here it should be noted that, although in the 2022 work, the same methodology, equipment and filtration time were used, the starting product is different, as should be the case when using wines from the same grape but from different vintages. In the previous work, the starting alcohol content was significantly lower, 78.1 g/kg, which translates into a lower efficiency of the dialysis process and, consequently, a lower drop in alcohol content.

Table 1. Mean value ± standard deviation of the white wine analyses

Chemical Analysis	Control wine	Dialyzed wine
pH	3.30 ± 0.30^{a}	3.26 ± 0.00^{a}

Total acidity / $g \cdot L^{-1}$ (TH2)	4.9 ± 0.1^{b}	4.4 ± 0.0^{a}
Alcohol degree / $g \cdot kg^{-1}$	104 ± 2^{b}	93 ± 0^{a}
Volatile acidity / $g \cdot L^{-1}$ (acetic acid)	0.74 ± 0.14^{a}	0.69 ± 0.01^{a}
SO_2 L / $mg \cdot L^{-1}$	64 ± 0^{a}	61 ± 4^{a}
SO_2 T / $mg \cdot L^{-1}$	142 ± 9^{a}	113 ± 4^{a}
TPI	5 ± 0^{a}	5 ± 0^{a}
Colour intensity / AU	0.055 ± 0.000^{b}	0.049 ± 0.000^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test. AU: absorbance units.

Red wine

Table 2 shows the results of the chemical analyses of the control and dialysis-treated red wine sample. There are statistically significant differences in the alcohol content and TPI analyses.

Table 2. Mean value ± standard deviation of the red wine analyses

Chemical Analysis	Control wine	Dialyzed wine
pH	3.76 ± 0.02^{a}	3.77 ± 0.06^{a}
Total acidity / $g \cdot L^{-1}$ (TH2)	$3.7 \pm 0,0^{a}$	3.6 ± 0.1^{a}
Alcohol degree / $g \cdot kg^{-1}$	104 ± 0^{b}	91 ± 0^{a}
Volatile acidity / $g \cdot L^{-1}$ (acetic acid)	0.05 ± 0.00^{a}	0.04 ± 0.00^{a}
SO_2 L / $mg \cdot L^{-1}$	30 ± 4^{a}	26 ± 3^{a}
SO_2 T / $mg \cdot L^{-1}$	42 ± 1^{a}	45 ± 6^{a}
TPI	46 ± 1^{b}	42 ± 1^{a}
Colour intensity / AU	9.27 ± 0.06^{a}	9.06 ± 0.17^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test. AU: absorbance units.

The alcohol reduction has been of 13.4 g/kg after dialysis (then observed reduction corresponds to 12.90% of the original value, therefore equally acceptable according to OIV standards). This percentage is slightly higher than observed for white wines, which is consistent with previous comment of a higher efficiency of membrane dialysis for higher departing alcohol concentrations.

TPI of the partially dealcoholized wine in this study is significantly reduced, by 4 units. This may be due to the passage of polyphenols through the membrane, such as the anthocyanins. It would be necessary to study these TPI drops in other red wines to check whether with this membrane and these times the drop is always of the same order, although it seems clear that it is always higher than that observed with white wines, whose low initial TPI makes the reduction practically inappreciable.

VOCs comparison

Tables S1 and S2 (see Supporting information), show the concentrations (μg/L) of VOCs that show statistically significant differences between the control wines and the dialysed white and red wines, respectively.

The first three compounds in white wines (see Supporting information, Table S1), alcohols, are typically associated with undesirable, pungent odours. Notably, their concentrations decreased in the dialyzed wine, except for 2,4-ditert-butylphenol. This compound is a phenolic compound that usually provides notes that can vary from medicinal, smoky or plastic aromas, depending on its concentration. It is also commonly found in plastics and resins, likely increased due to leaching from the tubing used during dialysis. In other beverages such as Fu-brick tea, the 2,4-ditert-butylphenol was described as ‘phenolic’ and ‘herbal’ odors,[33] which was also detected as an odor-active compound in other Dark teas.[34,35] The subsequent nine compounds, primarily esters, known for their fruity and floral aromas, were observed at lower concentrations in the dialyzed wine. Similarly, 2-octanone, associated with apple aroma, also demonstrated a sensible reduction. Benzylamine, an amine, is often characterized by ammonia-like aromas.[36-39]

In red wines (see Supporting information, Table S2), the first twenty-four compounds, predominantly esters, associated with fruity and floral notes, were generally found at lower concentrations in the dialyzed red wine compared to the control. An exception was phenethyl acetate, which is associated to a honey aroma, and showed a clear increase. The following nine compounds were alcohols, typically linked to unpleasant, pungent odours. However, 1-hexanol (herbaceous), benzyl alcohol (fruity), and 2-phenylethanol and 1-nonanol (rose) are notable exceptions. All alcohols, except 2,4-ditert-butylphenol, decreased in the dialyzed wine. The increase in 2,4-ditert-butylphenol, common in plastic manufacturing, is likely attributable to leaching from the dialysis tubing, similarly to what happened for white wines. The subsequent three compounds, possessing aromatic rings, showed decreased concentrations in the dialyzed wine. These include naphthalene (unpleasant odour), toluene (bitter almond aroma), and 1,3-diacetylbenzene (no characteristic aroma). Similarly, two ketones, generally considered to have minimal impact on wine aroma, also decreased. Benzoic acid (odourless or slight acetaldehyde aroma) and butanedioic acid (no characteristic aroma) were also reduced. Diphenyl ether (geranium aroma) considered a defect in wines, and 4-nitrophthalamide (no characteristic aroma) were both found at lower concentrations in the dialyzed wine[36-39].

It can be concluded that those VOCs that underwent a change in their concentration after dialysis very mostly this change resulted in a significant reduction (typically between 30 and 70%), with some components being reduced by much larger amounts. Note for example a reduction of 90% in hexyl acetate (for white wine), 90% for ethyl nonanoate (in red wine) or 99.6% in ethyl palmitate (red wine).

When comparing the efficiency with respect to aromas of the membrane dialysis process applied to white or red wines, the problem arises because many of the VOCs that appear in white wines do not appear in red wines and vice versa. Therefore, it was decided to focus this comparison by selecting those aromas that, appearing simultaneously in both white and red wines, and in both the control sample and the filtered sample, have undergone a significant change during dialysis.

The values corresponding to those common aroma compounds are presented in Figure 1, after a PCA using VOCs as variables and the wines as samples.

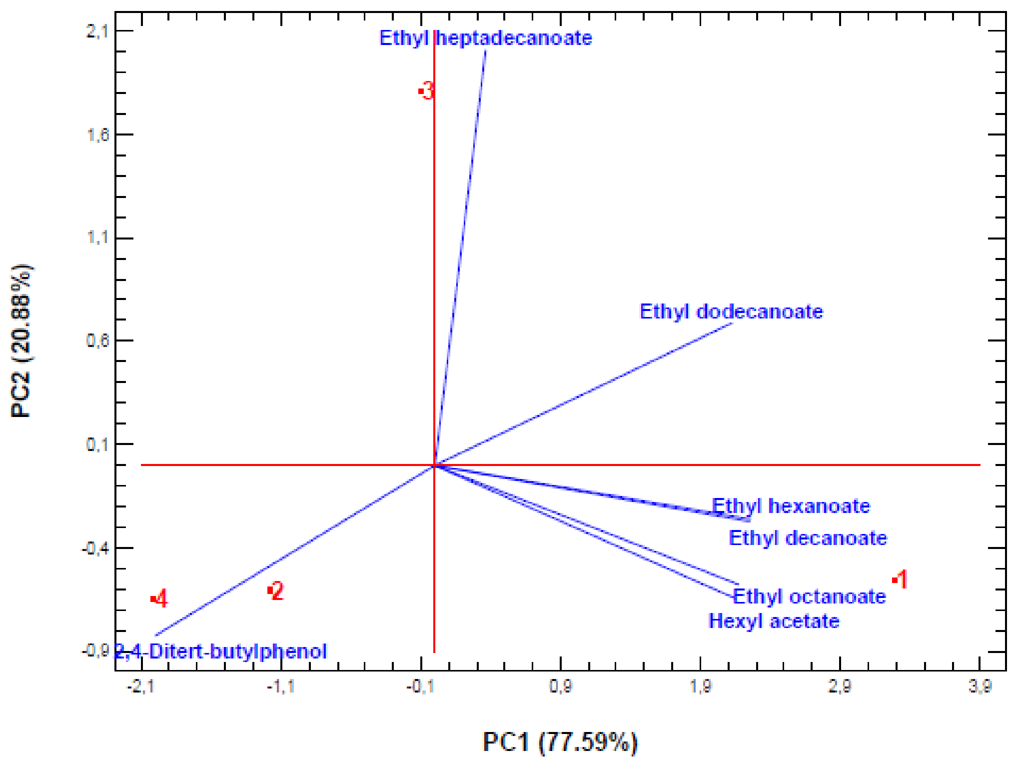

Fig. 1. Results of PCA analysis for VOCs present in both wines, before and after filtration (1-Control white wine, 2-Dialyzed white wine, 3-Control red wine, 4-Dialyzed red wine).

PC1 and PC2 explained 77.59% and 20.88% of the total variance, respectively (Figure 1). The wines were clearly differentiated into several groups. It was observed that the dialyzed wines (samples 2 and 4) were placed on the left side of the PC1, whereas the control white wine (sample 1) was positioned on the positive scale of the PC1, and the control red wine (sample 3) was located on the positive scale of PC2. This finding indicated that the aromatic features of the dialyzed wines was different from that observed control wines. It should be noted that ethyl hexanoate, ethyl decanoate, ethyl octanoate and hexyl acetate, were positively correlated with PC1, all of them associated with fruity notes, usually pleasant aroma descriptors in wines. Therefore, these volatile compounds play important roles in the aromatic feature of the control white wine (sample 1) indicating that these fruity aromatic compounds resulted in control white wine with different aromas than the other wine samples. In addition, ethyl heptadecanoate showed a similar correlation as seen for the control red wine (sample 3) to PC2, indicating that this fruity aromatic compound resulted in the control red wine with different aroma than the other wine samples. Finally, 2,4-diter-butylphenol appeared to be the major volatile compound that distinguish the aroma feature of the dialyzed wines (white and red) from the other wines. This compound, were identified for the first time in wines sealed with synthetic closures.[40] This compound has been routinely used as an intermediate for the preparation of antioxidants and ultraviolet stabilizers in the plastic industry and manufacturing of pharmaceuticals and fragrances.[41] However, their sensory impact on wine chemical and sensory properties are completely unknown.

Dimension 2 differentiated the control red wine (sample 3) from all other samples, notably without influence from Dimension 1. Conversely, Dimension 1 separated the control white wine (sample 1) from both dialyzed wines.

2,4-ditert-butylphenol and ethyl dodecanoate exhibited a negative correlation. Notably, dialyzed wines showed an increase in 2,4-ditert-butylphenol and a decrease in ethyl dodecanoate.

Sensory analysis comparison

Triangular test

According to the number of consumers, 126, and using ISO 4120,[36] the minimum number of judges necessary to consider both wines (dialyzed and control) as significantly different (with a significance level of 0.05) is 51. There were 76 people able to identify the different white wine and 85 were able to identify the different red wine. Accordingly, it should consider that dialyzed and control wines (in both white and red cases) are different attending to the triangular test results.

Moreover, from confidence intervals (95% significance level) it can be concluded that 52.09% for white and 64.06% for red wines would be the maximum proportion of people able to distinguish the sample (with a minimum proportion of 30.11% for the white and 38.14% for the red wine).

In the previous work,[22] that employed white wines and a similar procedure, there were not shown significant differences, which can be related to the low number of consumers in that study (33 vs. 126 in the present work). According to ISO 4120,[36] the participation of a high number of judges increases the probability of detecting small differences between samples.

CATA test

The number of consumers that have been considered for CATA data processing was reduced to 116 for white wine and 115 consumers for red wine lower, once erroneous answers (incorrect naming of the samples) were eliminated.

Figure 2 presents the frequencies of mention of each of the terms for the control wine and the dialyzed white wine, as well as the results of Cochran's Q test.

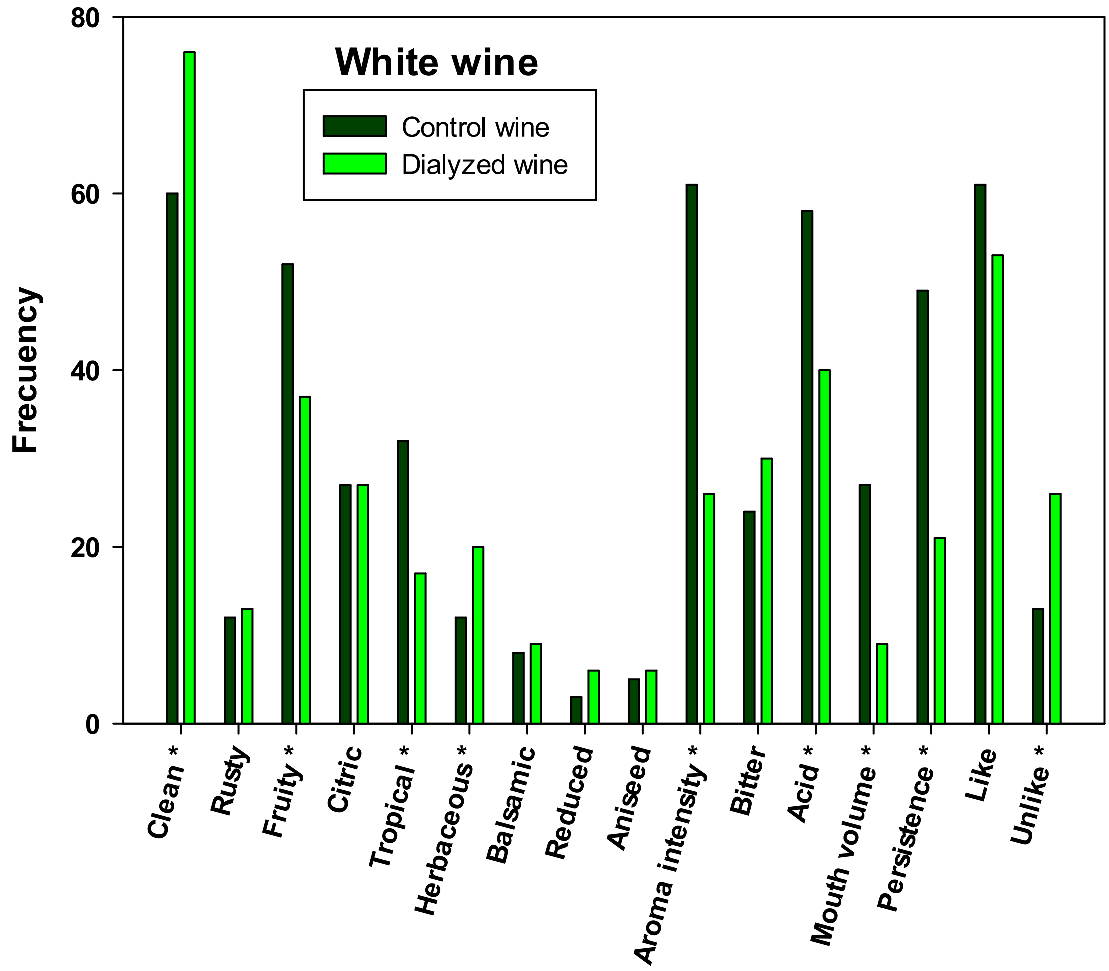

Fig. 2. Bar chart of the parameters of the CATA test of the white wine. An asterisk (*) marks the parameters that showed statistically significant differences

Nine of the sixteen parameters used to describe the white wines show significant differences (Figure 2). Consumers consider the dialyzed wine cleaner; with less volume in the mouth; less acidic, fruity and tropical; more herbaceous; less aromatic and persistent; and more consumers did not like it compared to the control white wine.

The decrease in acidity was also noted in the chemical analysis (Table 1) and the decrease in aromas was analytically noted in the almost general decrease in the concentration of aromatic compounds (Table 3 and Figure 1). The decrease in mouthfeel may be associated with the passage of certain alcohols such as glycerol through the membrane. Therefore, the fact that dialyzed wine shows a lower persistence may be due to a decrease in aroma and mouthfeel. It should be noted that the dialyzed white wine was liked by fewer people (53 compared to 61 for the control white wine), although there were no significant differences in this attribute. Several consumers added watery, flat and smooth as other attributes of the dialysed wine.

The bitter, citric, balsamic, reduced, aniseed, oxidised and "I like" parameters do not show statistically significant differences between the two wines.

It can be said that most of the parameters used to characterise the white wine show a certain reduction in their appreciation by the judges. This reduction is notably evident in the case of the aromatic and persistent attributes, which is undoubtedly consistent with the significant decrease in aromatic compounds mainly present in white wines.

Calvo et al.[22], who carried out a CATA test with the same attributes using 33 consumers, found that there were no significant differences for any of the parameters. Again, this different result may also be due to the low number of consumers who carried out the sensory analysis.

Figure 3 shows the frequencies obtained for all parameters tested and the results of Cochran's Q test for the red wines study.

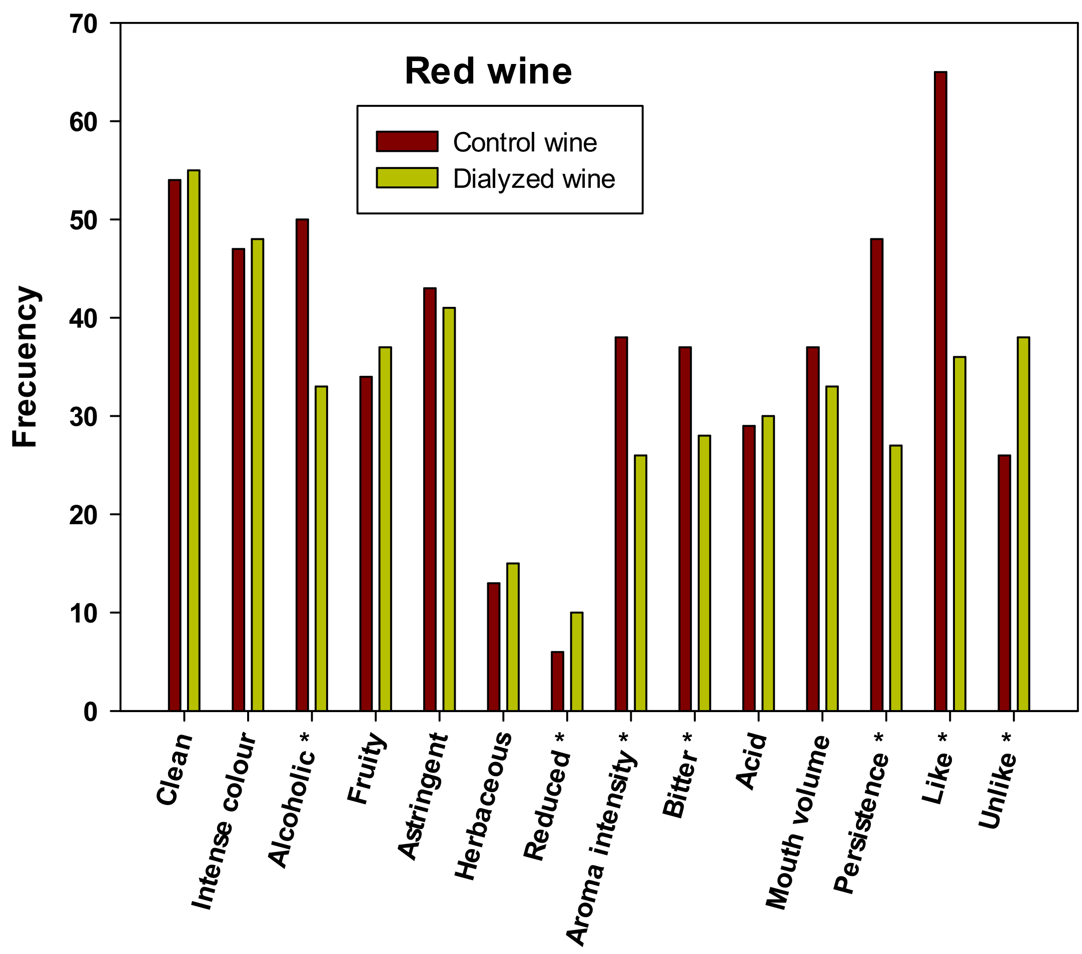

Fig. 3. Bar chart of the parameters of the red wine CATA test. With an asterisk (*) the parameters that presented statistically significant differences.

Seven of the fourteen parameters (alcoholic, reduced, aromatic, bitter, persistent, "like" and "unlike") used to describe the red wines in CATA methodology show significant differences. Although significant differences were also found in the reduced attribute, it was only selected by reduced number of consumers (6 out of 115 for control wine and 10 out of 115 in the case of the dialyzed red wine. It is likely that this low number could be due to the fact that consumers may not distinguish clearly what a reduced wine is.

The dialyzed wine, compared to the control, was considered less bitter, which could be due to the analytically proven decrease in phenols; less alcoholic, due to the 12.9% decrease in alcoholic strength; less aromatic, surely due to a lower concentration of VOCs; and less persistent, this may be because this wine is less aromatic and bitter. In addition, the dialyzed wine was liked by fewer consumers and disliked by more compared to the control.

The parameters clean, intense colour, fruity, astringent, herbaceous, acid and mouthfeel volume, showed no significant differences between the two wines.

These outcome can be summarised by indicating that significant attributes in red wines, such as alcoholic, aromatic or persistent, show a significant reduction in their appreciation by the judges. These results coincide with a significant drop in alcohol content, as well as a reduction in aromas (although less drastic than in the white wines, as shown by the chromatographic study). The conjunction of these changes influences the remarkable change in consumers with respect to the attributes “I like”, and “I don't like”.

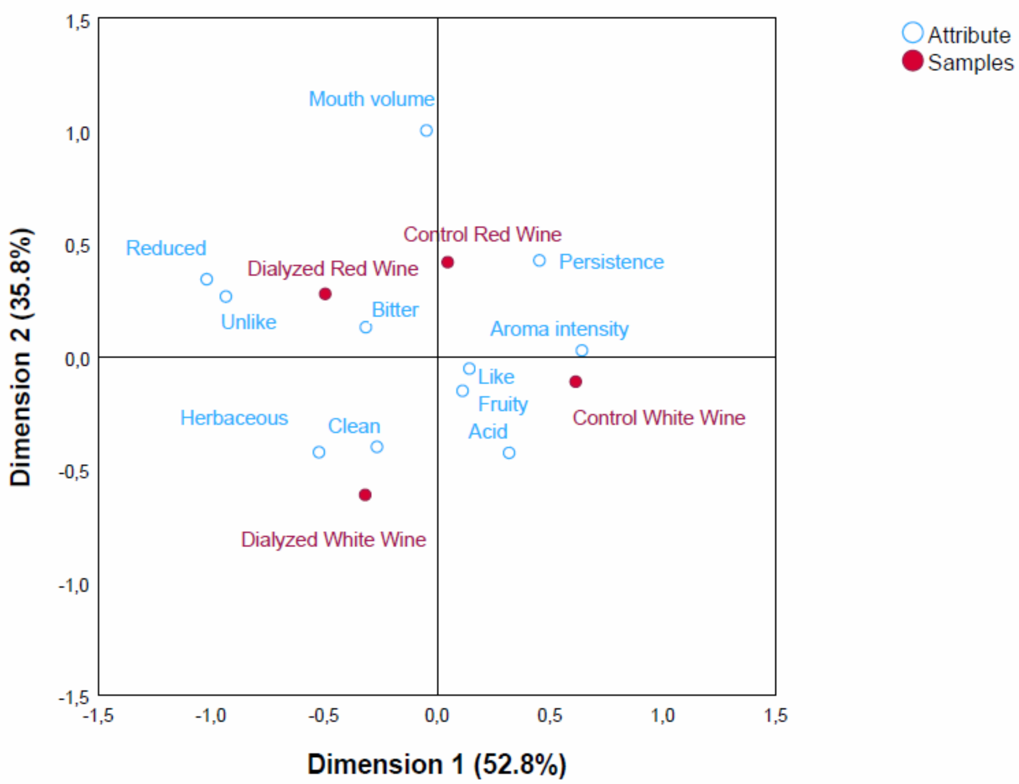

Fig. 4. Descriptive map of the four wines (control and dialyzed red and white wines) and sensory attributes used to describe them in two-dimensional maps of CA of CATA frequency.

Figure 4 shows the results from the CA with the 11 common sensory descriptors significant used in the CATA test (clean, fruity, herbaceous, reduced, aroma intensity, bitter, acid, mouth volume, persistence, like and unlike) of the four wines (control and dialyzed red and white wines). The first two dimensions accounted for 88.6% of the total experimental data, attesting to the robustness and relevance of the data.

Graph analysis revealed that most of the data explanation was on the Dimension 1, indicating that the differences between the wine samples were more pronounced on the horizontal axis rather than the vertical axis. The control samples differed clearly from the dialyzed samples (red and white wines). Plot also shows which descriptors or attributes were associated with each wine. Persistence, aroma intensity, like, fruity and acid attributes were identified in the control wines; while attributes bitter, unlike, reduced, clean and herbaceous were associated with the dialyzed wines. It should be noted that the attribute mouth volume, although it showed statistically significant differences among wine samples, did not have a great impact on the wines evaluated. More specifically, considering the quadrants in the graphic, the control red wine was characterized by the persistence and aroma intensity attributes while the control white wine by the like, fruity and acid attributes. On the other hand, the dialyzed red wine was differentiated by the attributes bitter, unlike and reduced; and the dialyzed white wine was associated with the attributes clean and herbaceous.

Dimension 2 effectively differentiates wine types, with red wines characterized by positive quadrant and white wines by negative quadrant. Dimension 1 distinguishes between dialyzed and control wines.

Sensory 'unlike' ratings correlated with reduced and bitter notes, while 'like' ratings correlated with fruity and acidic notes. Notably, 'like' and 'unlike' ratings exhibited a negative correlation.

Overall acceptability test

The number of consumers considered for this test was 113 (for white wine) and 118 (for red wine), again after eliminating some errors in sample naming. Table 3 summarize the results of the overall acceptability test.

Table 3. Means and standard deviation of the overall acceptability of the samples for red and white wine

	Control wine	**Dialyzed wine**
White wine	6.16 ± 1.87^{a}	5.62 ± 1.88^{b}
Red wine	5.62 ± 1.90^{a}	5.22 ± 1.80^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test.

Both dialysed wines show a lower overall acceptability than the control wines, although only in the case of the white wine those differences present statistical significance.

For both wines the acceptance score is quite low, with values between 5 (neither like nor dislike) and 6 (like slightly), which was expected from young wines elaborated with no special grape selection.

Attending to the comparison of acceptability before and after dialysis, it can be seen that control wine has sensorial characteristics that are more pleasant to the consumer, but this difference is less than half a point in both cases. In any case, it is clear from this test and from results of CATA test, that global acceptance of the dialyzed wine is lower than that of the control wine for both white and red ones. It is well known that alcohol has an enhancing effect on the aromas of wine. Thus, the reduction of alcohol content leads to the loss of some aromas. But certainly, if the objective is to produce wines with low alcohol content, it is needed to sacrifice some of the aroma-enhancing effect of alcohol.

CONCLUSIONS

The study showed that alcohol content in both white and red wines was successfully reduced to levels meeting OIV standards through dialysis. Increasing the membrane area could further improve alcohol reduction, while extending dialysis time is less desirable due to higher costs and aroma loss.

Dialysis was found to be more effective in red wines, likely because their higher alcohol content enhances separation efficiency. However, sensory tests revealed that dialyzed wines were less intense and aromatic, a result confirmed by chromatographic analysis, which showed decreases in most aroma compounds. Using a membrane with a lower cut-off (<10 kDa) could help reduce these losses.

Overall, partial dealcoholization by dialysis produces wines with different but acceptable sensory characteristics, making it a viable option for consumers seeking lower-alcohol wines. Future work will aim to scale up the process using larger membranes and optimize filtration times to minimize sensory alterations. Additionally, techniques like barrel aging or aging on lees could help enhance the sensory quality of the final product.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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Membrane dialysis for partial dealcoholization of wine. Comparison between white and red wines

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Abstract

BACKGROUND: Membrane dialysis is a suitable technique for the partial dealcoholization of wines that preserves most of the aromas of the original wine. In this study it has been compared the use of this technique in white and red wines of the same vintage. The results of partial dealcoholization have been checked in terms of chemical and sensory properties. In addition, gas chromatography was carried out to determine whether the aromas are appreciably diminished in their final composition for filtered wines.

RESULTS: Membrane dialysis resulted in wines with a lower alcoholic strength than the starting one, 11.0 g/kg alcohol reduction was obtained for white wines and 13.4 g/kg for red wines after dialysis, and with acceptable chemical and sensory characteristics but with a lower concentration of some aromatic compounds.

CONCLUSION: This partial dealcoholization technique is slightly more effective for the treated red wines. However, the dialyzed red wines become also less acceptable for consumers than the corresponding white wines.

Keywords: Wine dealcoholization; Dialysis; White wine; Red wine; Aromas

INTRODUCTION

Wine is a natural product whose quality varies with grape conditions, but skilled oenologists can reduce this variability to meet the strict standards required by regional wine appellation organizations (for example Denominazione di Origine Controllata, DOC; Appellation d'Origine Contrôlée, AOC; or Denominazione di Origine Controllata e Garantita, DOCG) for labelling and marketing.

One key characteristic of wine is its alcohol content, which depends on the sugar concentration in grapes before fermentation. Since alcohol levels are difficult to alter without affecting taste, choosing the right harvest time is crucial. As grapes ripen, sugar increases, and winemakers must balance acidity, aroma, phenolic maturity, and potential alcohol. Harvesting too early can produce wines with “green” flavors, and limited aging potential due to insufficient aroma complexity and underdeveloped tannins.

In Spain, red wines are usually marketed with an alcohol content of between 97.7-118 g/kg (12-15º in units of alcohol degree, much more used in alcoholic beverages), while white wines, in general, have a slightly lower alcohol content (71-110 g/kg). However, higher alcoholic wines are becoming increasingly common.

Several factors can affect the rise in alcohol content, but one of the main ones is climate change, which causes grapes to ripen earlier and accumulate more sugar. To counter this, some Spanish and other European wine regions have begun harvesting in late summer instead of autumn. However, harvesting earlier can hinder grape development and ultimately reduce yield.[1]

Conversely, there is an increasing demand for wines with lower alcohol content, as they offer fewer calories and reduce health risks linked to excessive alcohol consumption. Additionally, producing lower-alcohol wines can bring notable tax benefits.[2]

While excessive alcohol consumption is harmful, moderate intake as part of a Mediterranean diet can benefit health.[3] In red wines, phenolic compounds like resveratrol have antioxidant, anti-inflammatory, and antithrombotic properties, offering cardioprotective, anti-osteoporotic, and antimutagenic effects.[4] Therefore, producing wines with lower alcohol content but similar phenolic levels is both appealing and advantageous.

However, wine is a product that is consumed for pleasure, and while lower-alcohol wines are increasingly sought after, the tasting qualities and sensory satisfaction of a good wine remain highly valued.[5]

In this situation, several options can be considered.

One option is to modify viticulture practices—such as irrigation or canopy management—to control photosynthesis and limit sugar accumulation in grapes.[6] However, these methods are complex, labor-intensive, and raise production costs.

Other chemical techniques involves adding of glucose oxidase or catalase enzyme directly in the must before alcoholic fermentation.[7]

A further method, used frequently by our research group, is to remove part of the sugar from the must through membrane processes such as nanofiltration (NF),[8,9] or combining NF with pervaporation (PV) to recover some lost aromas.[10-12] While effective—especially for white wines—NF can also remove essential components, negatively affecting the wine’s sensory and taste qualities.[12] Even blending NF-treated wine with the original cannot fully restore its aromatic and sensory profile.

Finally, alcohol content can be reduced after the wine is produced, using various separation techniques, as reviewed by Figueroa-Paredes *et* al.[13]

The most conventional techniques to achieve this would be heat treatment, operating under vacuum; for example, evaporation, distillation or vapour separation.[14] But also, other techniques such as osmotic distillation or rotating cone columns can be used with satisfactory results.[15-19]

In addition to these methods, membrane processes present an attractive alternative due to their high selectivity and gentle treatment of wine, a delicate product that can easily degrade at relatively high temperatures.

On the other hand, the International Organisation of Vine and Wine (OIV) allows alcohol reduction using membrane techniques only under strict conditions:[20,21] the wine must be free of organoleptic defects; the must's sugar content cannot be altered before fermentation; alcohol reduction cannot exceed 20% of the initial level; and the wine with a modification of alcoholic strength must be more than 67 g/kg. In fact, Spanish regulations only consider as wine those products having at least 71 g/kg (9 % v/v of alcohol) to fall within the definition of wine of the OIV. Moreover, the process must be supervised by an oenologist or specialised technician.

Figueroa-Paredes *et* al.[13] used PV to strongly reduce alcohol in red wines (from 117 to 84 g/kg), exceeding the OIV's 20% maximum reduction limit (up to 93 g/kg). However, they compare the results with those obtained after this strong dealcoholisation, if the dealcoholized wine is then blended with the starting wine, to achieve a final result of 107 g/kg.

In our case, previous studies with various possibilities (NF, PV, dialysis) led us to opt for membrane dialysis,[22] which allows reductions acceptable to the OIV, in a single stage and with fairly good organoleptic results for white wines.

Membrane dialysis is a separation process in which a semi-permeable membrane of controlled porosity separates two solutions with different concentrations (usually the product to be dialysed and an aqueous solution). The difference in concentration between the two sides of the membrane induces, by diffusion, the passage of components from the concentrated solution to the more dilute one. If the pore size is adjusted so that only certain components can pass through the membrane, these components are removed from the starting solution. Advantages include no need for cooling, pressure, increase the concentration or dilution, minimizing CO_2 loss.[4] Previous tests on white wines showed minimal chemical and sensory differences between treated and untreated wines, making them hard for consumers to distinguish.[22]

Figueroa-Paredes *et al*.[13], in their study, focused on the analysis of productivity and costs of the process but also on the changes in volatile compounds due to PV. Accordingly, sensorial and chemical analysis has complemented with an analysis of aromas, which is expected that can help to discriminate the organoleptic differences found.

On the other side, it remains open the question if dialysis of wines results in similar performances and organoleptic changes when applied to red wines, with distinct sensorial characteristics. Therefore, in the work presented here, a further step has been tried by studying the performance of dialysis for the dealcoholisation of red wines, comparing it with the results for white wines, all of them from the same vintage.

Differences in applying membrane dialysis to white versus red wines may be more noticeable in sensory analysis than in chemical tests. To strengthen the validity of the sensory evaluation, over a hundred consumers participated in this study.

Finally, the aim of the present study is to check if the membrane dialysis process designed in our previous study for the partial dealcoholisation process of white wines, can be similarly used for red wines. To the best of our knowledge such comparison has not been previously tested and could be useful to offer a competitive and reliable process to reduce the alcohol content in wines.

MATERIALS AND METHODS

Departing wines

The wines used in this study were elaborated at the Escuela Técnica Superior de Ingenierías Agrarias de Palencia-Spain (ETSIIAA) with grapes from the 2022 harvest. Red wine was made from 80% Tempranillo and 20% Garnacha, while white wine was 100% Verdejo. Both wines followed traditional winemaking methods and were stored for at least 6 months at 6.0 ± 0.5 ºC. Before dialysis, the wines were homogenized and filtered through a 2.5 µm cellulose plate to prevent sedimentation.

Membrane and dialysis equipment

Membrane

Since the main mechanism of separation of alcohol in membrane dialysis is not sieving, the pore size of the membrane (or alternatively, the MWCO) to be used in the process is not the key factor in the membrane selection. In fact, diffusion from a concentrated side to the diluted one, allows separating molecules smaller than pore sizes. Wine alcohols are quite small molecules (47 Da for ethanol or 92 Da for glycerol, much scarcer), therefore any membrane with a cut-off over some hundreds of Da will be adequate to allow ethanol passage. This cut-off should be in the NF range, nevertheless, previous experience showed that using NF membranes, the resulting wine not only losses alcohol but almost other aromas or sensory compounds. Then a tight UF membrane seems to be more adequate.

Previous studies on white wines,[22] showed that the PLGC Ultracel membrane achieved the best alcohol reduction in the shortest time,[22] so it was selected for this study. These membranes, made of regenerated cellulose, are hydrophilic with a dense microstructure and pores in the ultrafiltration range. They are sold as with a diameter of 150 mm flat discs, and the 10 kDa molecular weight cut-off version (Sigma Aldrich 2023 catalogue) was chosen for this work.

This cut-off is high enough to assure passage of all volatile molecules, including alcohol but also aromas or similar molecules.

Dialysis setup

The dialysis filtration experiments were carried out in the laboratories of the Surfaces and Porous Materials Group (SMAP) at the Faculty of Science, Valladolid.

The main elements of the dialysis equipment have been described previously.[22] Firstly, 2 L of wine and Milli-Q water are added respectively to each of the Erlenmeyer flasks, Parafilm®-capped to prevent loss of aroma. The wine and Milli-Q water were pumped in crossflow and counter-current mode on each side of the membrane using their respective peristaltic pumps. Since both pumps operated at the same recirculation speed, the pressure difference between both sides of the membrane remained nil. The active area of the dialysis cell is 4.4×10^{-3} m^2. After passing through the cell, the liquids are returned to their respective Erlenmeyer flasks.

Filtration procedure

Following OIV regulations (maximum 20% alcohol reduction), an 8-hour dialysis was used to ensure alcohol did not exceed ~158 g/kg. Wine bottles were refrigerated and properly sealed before dialysis to preserve aromatic compounds.

For each wine type (red and white), filtration was carried out in three consecutive sessions to have enough filtered wine for the subsequent chemical and sensory analyses. The three filtrations of each type of wine were carried out with the same membrane sample, which was rinsed with pure water after finishing each day session. Later, Milli-Q water was circulated on both sides of the membrane for about 10 minutes to clean the system.

Membrane sample was changed for a fresh one when wine tested changed from white to red wine. All dialysis sessions lasted 8 hours and, at the end of the 3 sessions for each type of wine, the resulting wine was homogenised (by mixing the filtered wine from all sessions), re-bottled and stored in fridge until being chemically, chromatographically and sensorially analysed.

Although parafilm was used to seal both flasks, some partial oxygenation occurred during the equipment priming needed for consistent filtration. Additionally, after 8 hours of red wine dialysis, the aqueous phase flask showed a slight pink/reddish tint, likely due to anthocyanins passing through the membrane—a phenomenon not observed with white wines.

Finally, during the whole process, no noticeable change in volume was observed in each of the containers, which leads us to consider that there is no significant transfer of water from the extracting solution to the wine.

Analytical methods

All the chemical analyses described below were carried out in duplicate, both on control white and red wines and on dialyzed wines (white and red). The analyses carried out on these wines were: pH (pH-meter), total acidity (potentiometric method), alcohol content (ebullometry), volatile acidity (García Tena method), free and total sulphur (simple Ripper method), total polyphenol index (TPI, ultraviolet index method) and colour (Glories method). All methods used are described by the OIV.[23]

Determination of volatile organic compounds (VOCs) by headspace-solid-phase microextraction-gas chromatography–mass spectrometry (HS-SPME-GC-MS)

Gas chromatography was carried out on control and dialyzed white and red wines at the Laboratory of Instrumental Techniques (LTI) of the University of Valladolid (UVa). A 7890A Equipment from Agilent Technologies (Santa Clara, CA, USA), equipped with an HP-INNOWAX column (J &W Scientific, Folsom, CA, USA) was used. Components were extracted previously to GC by HS-SPME with Supelco Fibers (StableFlex).

VOCs analysis was done in duplicate using HS-SPME-GC-MS. Identification of compounds was achieved by comparing their mass spectra with those of pure standards and/or spectral data from the NIST08 v. 2.4 and Wiley7 libraries. Quantification was carried out using the internal standard quantification method as equivalents of 2-octanol.[24]

Sensory analysis

A sensory analysis was conducted with 126 non-trained consumers (57 (44.88%) men, 69 (54.33%) women), prioritizing a large sample to enhance statistical reliability. Most participants were familiar with wine tasting and all were regular wine consumers. The sensory test were carried out in the tasting room of the ETSIIAA in individual sensorial booths, which complies with the standards of the International Organisation for Standardisation (ISO) 8589.[25]

Wine glasses used comply with the ISO 3591 standard,[26] which contained ~25 mL of liquid, were coded with three-digit random numbers, and were presented to the consumers in random order. The serving temperature of the red wine was 15 ± 1°C and the white wine was served at 12 ± 1°C. Mineral water at room temperature was provided to the participants for palate cleansing.

The data from the online tasting tests were collected using a Google Forms survey, the results of which being automatically exported to Excel format.

Triangular test

This test has been designed according to ISO 4120.[27] The method consists of providing the judges with three samples, two of which are the same and one of which is different, so that the judge must indicate which of the samples is different even if based on an unsure assumption (forced judgement test).

CATA (Check-All-That-Apply)

The Check-All-That-Apply (CATA) technique involves selecting the descriptors that best describe each sample from a given list, reducing biases from open-ended responses. It is an effective method for discriminating and characterizing products, and also includes a free comment option for judges to add additional descriptors if they wish. [28]

CATA questionnaire, for white wines, contained 16 terms related to the sensory characteristics of the Verdejo wines grouped in two visual terms (clean, rusty), eight olfactory terms (fruity, citric, tropical, herbaceous, balsamic, reduced, aniseed, aroma intensity), four terms related with the mouth (bitter, acid, mouth volume, persistence), and finally consumers were asked to give a general evaluation of the wine by setting if the wines were pleasant for them (like or unlike). The terms were selected based on published data,[29] considering the descriptors selected by trained assessors in preliminary studies, along with the typical characteristics of Verdejo wines.[22,28,30]

Similarly, descriptors used to characterise the red wine were also selected based on the literature,[28,30] resulting in similar descriptors, excepting some not very common in white wines, and including alcoholic and astringent, more likely to appear in red wines. Therefore, the terms included in the CATA questionnaire for red wines were 14, two in the visual phase (clean, intense colour), five in the olfactory phase (fruity, herbaceous, alcoholic, reduced, aroma intensity), five in the mouth (bitter, acid, astringent, mouth volume, persistence), and two related with the global perception (like or unlike).

Overall acceptability test

A 9-point hedonic scale was used to study the overall acceptability of the wines among consumers[31] with scale numbers from 1 (dislike extremely) to 9 (like extremely) as described by Stone *et al*.[32]

Statistical analysis

The statistical treatment of the chemical analyses and VOCs was carried out using analysis of variance (ANOVA), in addition to the Tukey test ($p < 0.05$), using the IBM SPSS Statistics 26.0 programme. Principal component analysis (PCA) was also performed on data of VOCs to characterize the four samples (control and dialyzed red and white wines) using Statgraphics Centurion 19.

The results of the triangular test were calculated according to ISO 4120.[27]

The CATA test was analysed by Cochran's Q test to check whether or not there are statistically significant differences between treated and untreated wine. In addition, a correspondence analysis (CA) with the four wines (control and dialyzed red and white wines) was also performed by considering the chi-square distance with the matrix containing the frequency of use of each term common for each sample. These analyses were performed with the statistical program IBM SPSS Statistics 26.0.

Finally, ANOVA and Tukey's test ($p < 0.05$), was performed on the overall acceptability test using Statgraphics Centurion 19.

RESULTS AND DISCUSSION

Chemical analysis

White wine

Table 1 shows the results of the statistical study of the chemical analysis of the control and dialysis-treated white wine sample. Firstly, the objective of the process is achieved with a reduction of 11.0 g/kg in the alcohol content of the wine (reduction corresponding to 10.60% of the original value, therefore acceptable according to OIV regulations). Also, it can be seen that there are significant differences in total acidity, alcohol content and colour intensity. In all these analytical parameters, the dialyzed wine shows significantly lower values.

Total acidity was significantly reduced after dialysis, it is likely that this loss of acidity is due to the diffusion of acidic components through the membrane, although this reduction did not translate into a similar pH drop. This could be due to the fact that, as can be seen in the table, the level of volatile acidity is relatively high, and it is this acidity that has accounted for most of the reduction in total acidity, without affecting the pH as much. The absence of significant changes in pH is related with the fact that wine is a buffer solution to a certain extent, even when small amounts of acids are added or removed.

There is also a significant drop in colour intensity (0.006 AU, corresponding to an 11% drop). This decrease could be due to the passage of brown (oxidised) polyphenols through the membrane, although this is not visible in the colour of the dialysed wine.[22]

If the analytical results obtained for the dialysis of white wines are compared with those presented in the previous work,[22] the major difference can be seen in a greater drop in alcoholic strength in this case (11 g/kg) reduction, compared to the previous work, 9.5 g/kg. Here it should be noted that, although in the 2022 work, the same methodology, equipment and filtration time were used, the starting product is different, as should be the case when using wines from the same grape but from different vintages. In the previous work, the starting alcohol content was significantly lower, 78.1 g/kg, which translates into a lower efficiency of the dialysis process and, consequently, a lower drop in alcohol content.

Table 1. Mean value ± standard deviation of the white wine analyses

Chemical Analysis	Control wine	Dialyzed wine
pH	3.30 ± 0.30[a]	3.26 ± 0.00[a]

Total acidity / g·L^{-1} (TH2)	4.9 ± 0.1^{b}	4.4 ± 0.0^{a}
Alcohol degree / g·kg^{-1}	104 ± 2^{b}	93 ± 0^{a}
Volatile acidity / g·L^{-1} (acetic acid)	0.74 ± 0.14^{a}	0.69 ± 0.01^{a}
SO_2 L / mg·L^{-1}	64 ± 0^{a}	61 ± 4^{a}
SO_2 T / mg·L^{-1}	142 ± 9^{a}	113 ± 4^{a}
TPI	5 ± 0^{a}	5 ± 0^{a}
Colour intensity / AU	0.055 ± 0.000^{b}	0.049 ± 0.000^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test. AU: absorbance units.

Red wine

Table 2 shows the results of the chemical analyses of the control and dialysis-treated red wine sample. There are statistically significant differences in the alcohol content and TPI analyses.

Table 2. Mean value ± standard deviation of the red wine analyses

Chemical Analysis	Control wine	Dialyzed wine
pH	3.76 ± 0.02^{a}	3.77 ± 0.06^{a}
Total acidity / g·L^{-1} (TH2)	3.7 ± 0,0^{a}	3.6 ± 0.1^{a}
Alcohol degree / g·kg^{-1}	104 ± 0^{b}	91 ± 0^{a}
Volatile acidity / g·L^{-1} (acetic acid)	0.05 ± 0.00^{a}	0.04 ± 0.00^{a}
SO_2 L / mg·L^{-1}	30 ± 4^{a}	26 ± 3^{a}
SO_2 T / mg·L^{-1}	42 ± 1^{a}	45 ± 6^{a}
TPI	46 ± 1^{b}	42 ± 1^{a}
Colour intensity / AU	9.27 ± 0.06^{a}	9.06 ± 0.17^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test. AU: absorbance units.

The alcohol reduction has been of 13.4 g/kg after dialysis (then observed reduction corresponds to 12.90% of the original value, therefore equally acceptable according to OIV standards). This percentage is slightly higher than observed for white wines, which is consistent with previous comment of a higher efficiency of membrane dialysis for higher departing alcohol concentrations.

TPI of the partially dealcoholized wine in this study is significantly reduced, by 4 units. This may be due to the passage of polyphenols through the membrane, such as the anthocyanins. It would be necessary to study these TPI drops in other red wines to check whether with this membrane and these times the drop is always of the same order, although it seems clear that it is always higher than that observed with white wines, whose low initial TPI makes the reduction practically inappreciable.

VOCs comparison

Tables S1 and S2 (see Supporting information), show the concentrations (µg/L) of VOCs that show statistically significant differences between the control wines and the dialysed white and red wines, respectively.

The first three compounds in white wines (see Supporting information, Table S1), alcohols, are typically associated with undesirable, pungent odours. Notably, their concentrations decreased in the dialyzed wine, except for 2,4-ditert-butylphenol. This compound is a phenolic compound that usually provides notes that can vary from medicinal, smoky or plastic aromas, depending on its concentration. It is also commonly found in plastics and resins, likely increased due to leaching from the tubing used during dialysis. In other beverages such as Fu-brick tea, the 2,4-ditert-butylphenol was described as 'phenolic' and 'herbal' odors,[33] which was also detected as an odor-active compound in other Dark teas.[34,35] The subsequent nine compounds, primarily esters, known for their fruity and floral aromas, were observed at lower concentrations in the dialyzed wine. Similarly, 2-octanone, associated with apple aroma, also demonstrated a sensible reduction. Benzylamine, an amine, is often characterized by ammonia-like aromas.[36-39]

In red wines (see Supporting information, Table S2), the first twenty-four compounds, predominantly esters, associated with fruity and floral notes, were generally found at lower concentrations in the dialyzed red wine compared to the control. An exception was phenethyl acetate, which is associated to a honey aroma, and showed a clear increase. The following nine compounds were alcohols, typically linked to unpleasant, pungent odours. However, 1-hexanol (herbaceous), benzyl alcohol (fruity), and 2-phenylethanol and 1-nonanol (rose) are notable exceptions. All alcohols, except 2,4-ditert-butylphenol, decreased in the dialyzed wine. The increase in 2,4-ditert-butylphenol, common in plastic manufacturing, is likely attributable to leaching from the dialysis tubing, similarly to what happened for white wines. The subsequent three compounds, possessing aromatic rings, showed decreased concentrations in the dialyzed wine. These include naphthalene (unpleasant odour), toluene (bitter almond aroma), and 1,3-diacetylbenzene (no characteristic aroma). Similarly, two ketones, generally considered to have minimal impact on wine aroma, also decreased. Benzoic acid (odourless or slight acetaldehyde aroma) and butanedioic acid (no characteristic aroma) were also reduced. Diphenyl ether (geranium aroma) considered a defect in wines, and 4-nitrophthalamide (no characteristic aroma) were both found at lower concentrations in the dialyzed wine[36-39].

It can be concluded that those VOCs that underwent a change in their concentration after dialysis very mostly this change resulted in a significant reduction (typically between 30 and 70%), with some components being reduced by much larger amounts. Note for example a reduction of 90% in hexyl acetate (for white wine), 90% for ethyl nonanoate (in red wine) or 99.6% in ethyl palmitate (red wine).

When comparing the efficiency with respect to aromas of the membrane dialysis process applied to white or red wines, the problem arises because many of the VOCs that appear in white wines do not appear in red wines and vice versa. Therefore, it was decided to focus this comparison by selecting those aromas that, appearing simultaneously in both white and red wines, and in both the control sample and the filtered sample, have undergone a significant change during dialysis.

The values corresponding to those common aroma compounds are presented in Figure 1, after a PCA using VOCs as variables and the wines as samples.

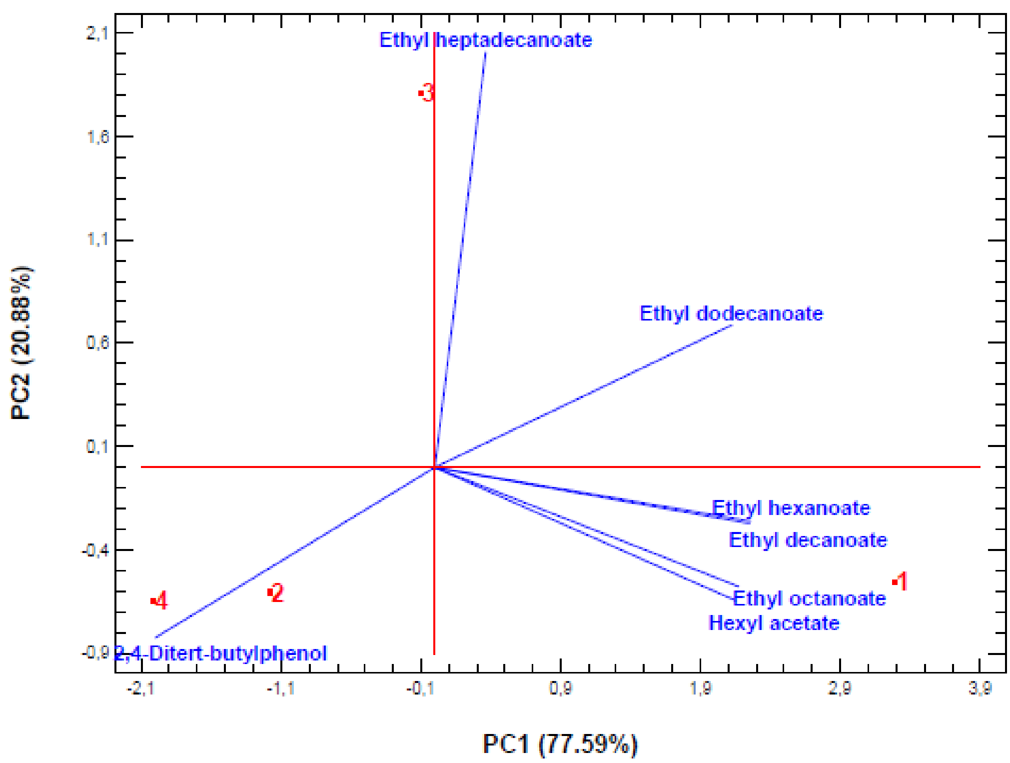

Fig. 1. Results of PCA analysis for VOCs present in both wines, before and after filtration (1-Control white wine, 2-Dialyzed white wine, 3-Control red wine, 4-Dialyzed red wine).

PC1 and PC2 explained 77.59% and 20.88% of the total variance, respectively (Figure 1). The wines were clearly differentiated into several groups. It was observed that the dialyzed wines (samples 2 and 4) were placed on the left side of the PC1, whereas the control white wine (sample 1) was positioned on the positive scale of the PC1, and the control red wine (sample 3) was located on the positive scale of PC2. This finding indicated that the aromatic features of the dialyzed wines was different from that observed control wines. It should be noted that ethyl hexanoate, ethyl decanoate, ethyl octanoate and hexyl acetate, were positively correlated with PC1, all of them associated with fruity notes, usually pleasant aroma descriptors in wines. Therefore, these volatile compounds play important roles in the aromatic feature of the control white wine (sample 1) indicating that these fruity aromatic compounds resulted in control white wine with different aromas than the other wine samples. In addition, ethyl heptadecanoate showed a similar correlation as seen for the control red wine (sample 3) to PC2, indicating that this fruity aromatic compound resulted in the control red wine with different aroma than the other wine samples. Finally, 2,4-diter-butylphenol appeared to be the major volatile compound that distinguish the aroma feature of the dialyzed wines (white and red) from the other wines. This compound, were identified for the first time in wines sealed with synthetic closures.[40] This compound has been routinely used as an intermediate for the preparation of antioxidants and ultraviolet stabilizers in the plastic industry and manufacturing of pharmaceuticals and fragrances.[41] However, their sensory impact on wine chemical and sensory properties are completely unknown.

Dimension 2 differentiated the control red wine (sample 3) from all other samples, notably without influence from Dimension 1. Conversely, Dimension 1 separated the control white wine (sample 1) from both dialyzed wines.

2,4-ditert-butylphenol and ethyl dodecanoate exhibited a negative correlation. Notably, dialyzed wines showed an increase in 2,4-ditert-butylphenol and a decrease in ethyl dodecanoate.

Sensory analysis comparison

Triangular test

According to the number of consumers, 126, and using ISO 4120,[36] the minimum number of judges necessary to consider both wines (dialyzed and control) as significantly different (with a significance level of 0.05) is 51. There were 76 people able to identify the different white wine and 85 were able to identify the different red wine. Accordingly, it should consider that dialyzed and control wines (in both white and red cases) are different attending to the triangular test results.

Moreover, from confidence intervals (95% significance level) it can be concluded that 52.09% for white and 64.06% for red wines would be the maximum proportion of people able to distinguish the sample (with a minimum proportion of 30.11% for the white and 38.14% for the red wine).

In the previous work,[22] that employed white wines and a similar procedure, there were not shown significant differences, which can be related to the low number of consumers in that study (33 vs. 126 in the present work). According to ISO 4120,[36] the participation of a high number of judges increases the probability of detecting small differences between samples.

CATA test

The number of consumers that have been considered for CATA data processing was reduced to 116 for white wine and 115 consumers for red wine lower, once erroneous answers (incorrect naming of the samples) were eliminated.

Figure 2 presents the frequencies of mention of each of the terms for the control wine and the dialyzed white wine, as well as the results of Cochran's Q test.

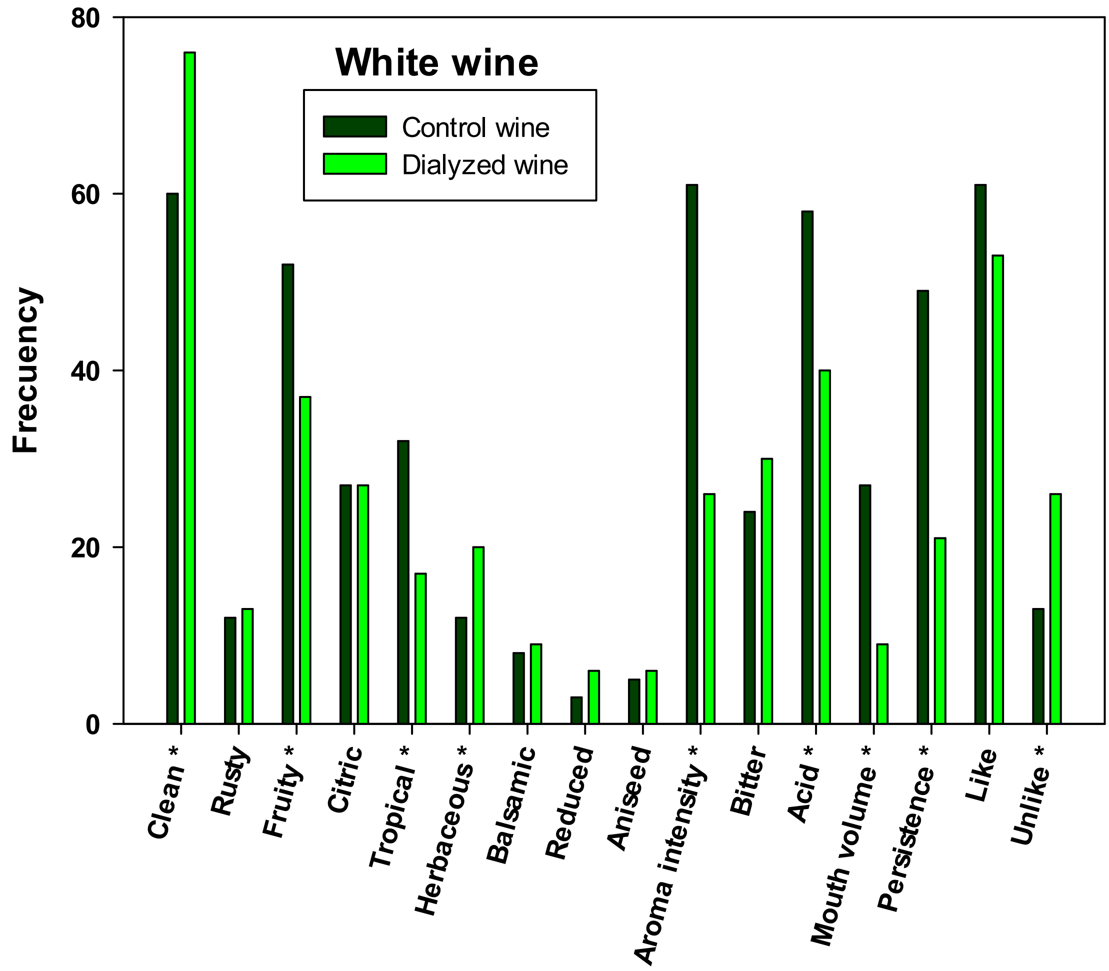

Fig. 2. Bar chart of the parameters of the CATA test of the white wine. An asterisk (*) marks the parameters that showed statistically significant differences

Nine of the sixteen parameters used to describe the white wines show significant differences (Figure 2). Consumers consider the dialyzed wine cleaner; with less volume in the mouth; less acidic, fruity and tropical; more herbaceous; less aromatic and persistent; and more consumers did not like it compared to the control white wine.

The decrease in acidity was also noted in the chemical analysis (Table 1) and the decrease in aromas was analytically noted in the almost general decrease in the concentration of aromatic compounds (Table 3 and Figure 1). The decrease in mouthfeel may be associated with the passage of certain alcohols such as glycerol through the membrane. Therefore, the fact that dialyzed wine shows a lower persistence may be due to a decrease in aroma and mouthfeel. It should be noted that the dialyzed white wine was liked by fewer people (53 compared to 61 for the control white wine), although there were no significant differences in this attribute. Several consumers added watery, flat and smooth as other attributes of the dialysed wine.

The bitter, citric, balsamic, reduced, aniseed, oxidised and “I like” parameters do not show statistically significant differences between the two wines.

It can be said that most of the parameters used to characterise the white wine show a certain reduction in their appreciation by the judges. This reduction is notably evident in the case of the aromatic and persistent attributes, which is undoubtedly consistent with the significant decrease in aromatic compounds mainly present in white wines.

Calvo et al.[22], who carried out a CATA test with the same attributes using 33 consumers, found that there were no significant differences for any of the parameters. Again, this different result may also be due to the low number of consumers who carried out the sensory analysis.

Figure 3 shows the frequencies obtained for all parameters tested and the results of Cochran's Q test for the red wines study.

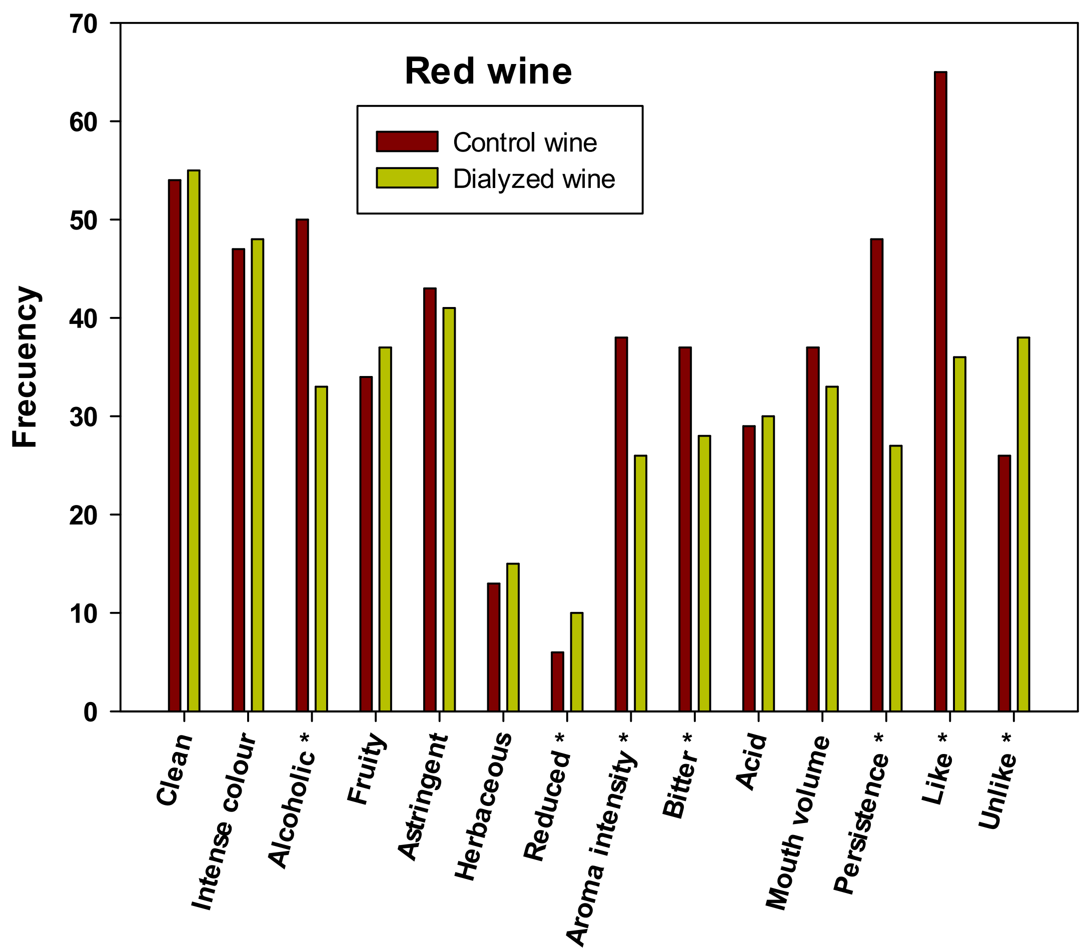

Fig. 3. Bar chart of the parameters of the red wine CATA test. With an asterisk (*) the parameters that presented statistically significant differences.

Seven of the fourteen parameters (alcoholic, reduced, aromatic, bitter, persistent, “like” and “unlike”) used to describe the red wines in CATA methodology show significant differences. Although significant differences were also found in the reduced attribute, it was only selected by reduced number of consumers (6 out of 115 for control wine and 10 out of 115 in the case of the dialyzed red wine. It is likely that this low number could be due to the fact that consumers may not distinguish clearly what a reduced wine is.

The dialyzed wine, compared to the control, was considered less bitter, which could be due to the analytically proven decrease in phenols; less alcoholic, due to the 12.9% decrease in alcoholic strength; less aromatic, surely due to a lower concentration of VOCs; and less persistent, this may be because this wine is less aromatic and bitter. In addition, the dialyzed wine was liked by fewer consumers and disliked by more compared to the control.

The parameters clean, intense colour, fruity, astringent, herbaceous, acid and mouthfeel volume, showed no significant differences between the two wines.

These outcome can be summarised by indicating that significant attributes in red wines, such as alcoholic, aromatic or persistent, show a significant reduction in their appreciation by the judges. These results coincide with a significant drop in alcohol content, as well as a reduction in aromas (although less drastic than in the white wines, as shown by the chromatographic study). The conjunction of these changes influences the remarkable change in consumers with respect to the attributes “I like”, and “I don't like”.

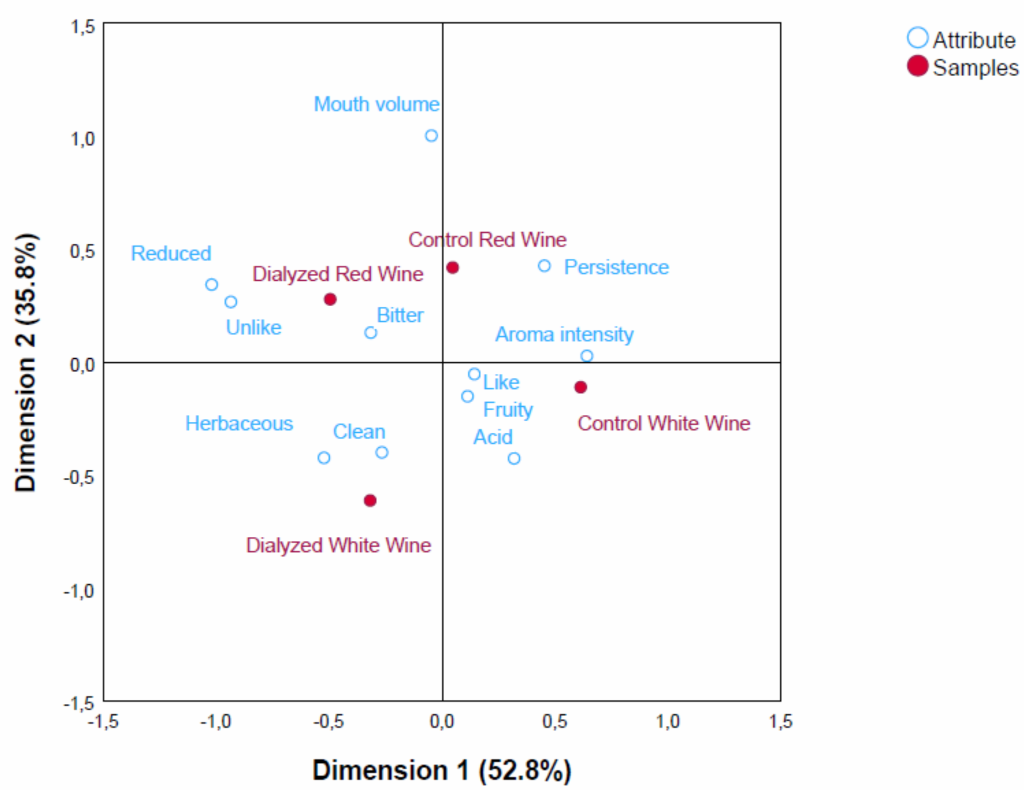

Fig. 4. Descriptive map of the four wines (control and dialyzed red and white wines) and sensory attributes used to describe them in two-dimensional maps of CA of CATA frequency.

Figure 4 shows the results from the CA with the 11 common sensory descriptors significant used in the CATA test (clean, fruity, herbaceous, reduced, aroma intensity, bitter, acid, mouth volume, persistence, like and unlike) of the four wines (control and dialyzed red and white wines). The first two dimensions accounted for 88.6% of the total experimental data, attesting to the robustness and relevance of the data.

Graph analysis revealed that most of the data explanation was on the Dimension 1, indicating that the differences between the wine samples were more pronounced on the horizontal axis rather than the vertical axis. The control samples differed clearly from the dialyzed samples (red and white wines). Plot also shows which descriptors or attributes were associated with each wine. Persistence, aroma intensity, like, fruity and acid attributes were identified in the control wines; while attributes bitter, unlike, reduced, clean and herbaceous were associated with the dialyzed wines. It should be noted that the attribute mouth volume, although it showed statistically significant differences among wine samples, did not have a great impact on the wines evaluated. More specifically, considering the quadrants in the graphic, the control red wine was characterized by the persistence and aroma intensity attributes while the control white wine by the like, fruity and acid attributes. On the other hand, the dialyzed red wine was differentiated by the attributes bitter, unlike and reduced; and the dialyzed white wine was associated with the attributes clean and herbaceous.

Dimension 2 effectively differentiates wine types, with red wines characterized by positive quadrant and white wines by negative quadrant. Dimension 1 distinguishes between dialyzed and control wines.

Sensory 'unlike' ratings correlated with reduced and bitter notes, while 'like' ratings correlated with fruity and acidic notes. Notably, 'like' and 'unlike' ratings exhibited a negative correlation.

Overall acceptability test

The number of consumers considered for this test was 113 (for white wine) and 118 (for red wine), again after eliminating some errors in sample naming. Table 3 summarize the results of the overall acceptability test.

Table 3. Means and standard deviation of the overall acceptability of the samples for red and white wine

	Control wine	**Dialyzed wine**
White wine	6.16 ± 1.87^{a}	5.62 ± 1.88^{b}
Red wine	5.62 ± 1.90^{a}	5.22 ± 1.80^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test.

Both dialysed wines show a lower overall acceptability than the control wines, although only in the case of the white wine those differences present statistical significance.

For both wines the acceptance score is quite low, with values between 5 (neither like nor dislike) and 6 (like slightly), which was expected from young wines elaborated with no special grape selection.

Attending to the comparison of acceptability before and after dialysis, it can be seen that control wine has sensorial characteristics that are more pleasant to the consumer, but this difference is less than half a point in both cases. In any case, it is clear from this test and from results of CATA test, that global acceptance of the dialyzed wine is lower than that of the control wine for both white and red ones. It is well known that alcohol has an enhancing effect on the aromas of wine. Thus, the reduction of alcohol content leads to the loss of some aromas. But certainly, if the objective is to produce wines with low alcohol content, it is needed to sacrifice some of the aroma-enhancing effect of alcohol.

CONCLUSIONS

The study showed that alcohol content in both white and red wines was successfully reduced to levels meeting OIV standards through dialysis. Increasing the membrane area could further improve alcohol reduction, while extending dialysis time is less desirable due to higher costs and aroma loss.

Dialysis was found to be more effective in red wines, likely because their higher alcohol content enhances separation efficiency. However, sensory tests revealed that dialyzed wines were less intense and aromatic, a result confirmed by chromatographic analysis, which showed decreases in most aroma compounds. Using a membrane with a lower cut-off (<10 kDa) could help reduce these losses.

Overall, partial dealcoholization by dialysis produces wines with different but acceptable sensory characteristics, making it a viable option for consumers seeking lower-alcohol wines. Future work will aim to scale up the process using larger membranes and optimize filtration times to minimize sensory alterations. Additionally, techniques like barrel aging or aging on lees could help enhance the sensory quality of the final product.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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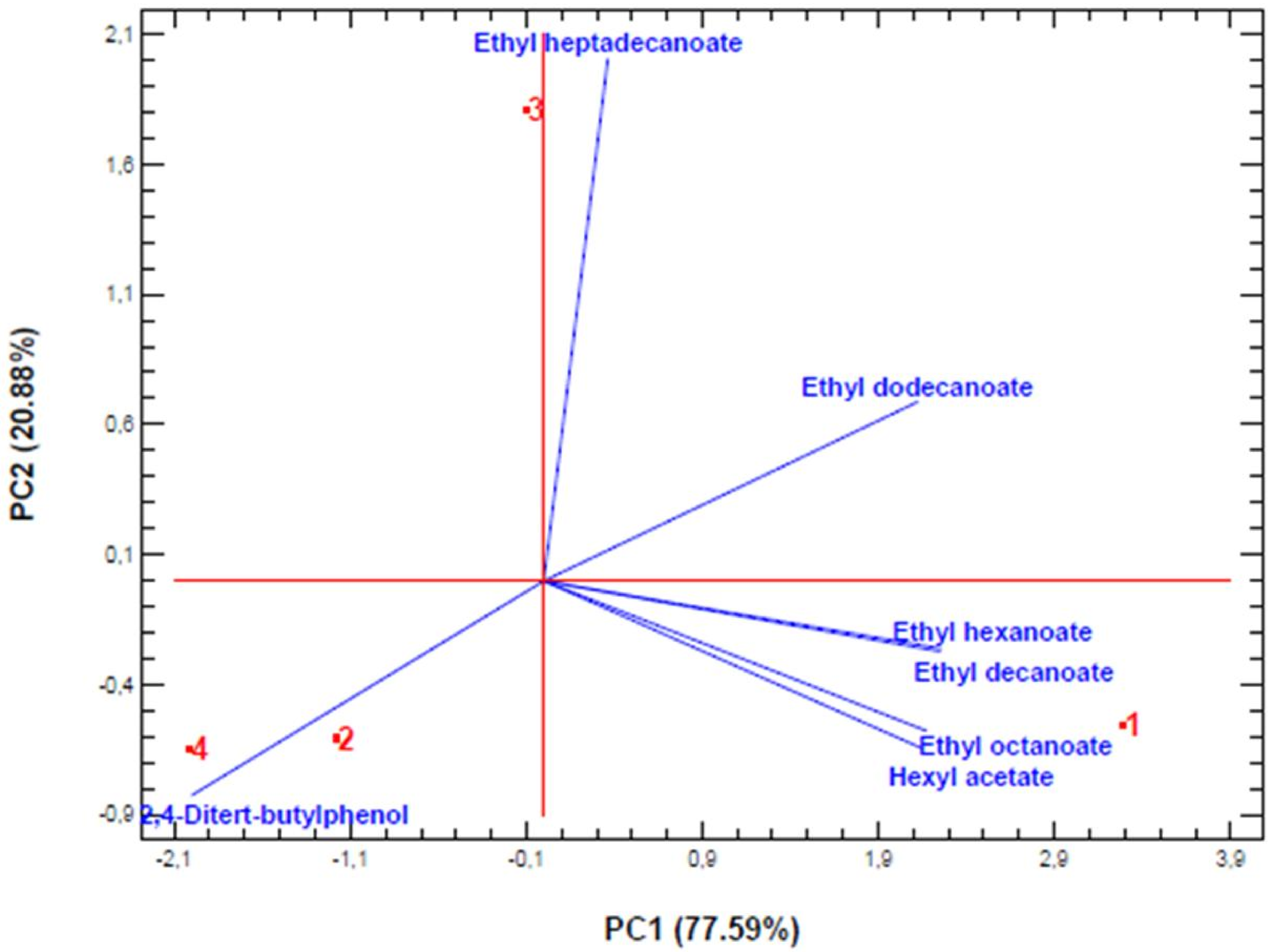
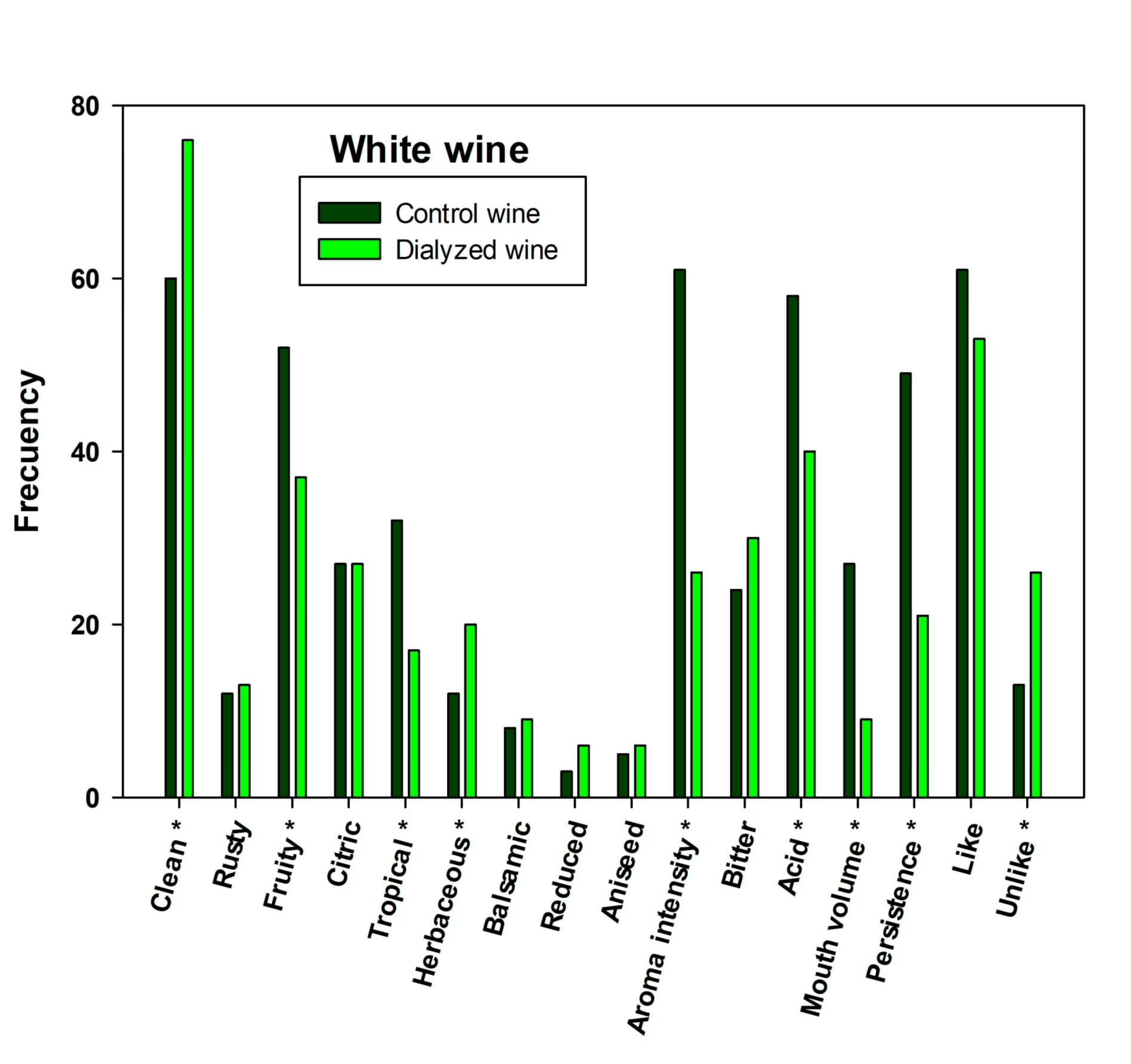
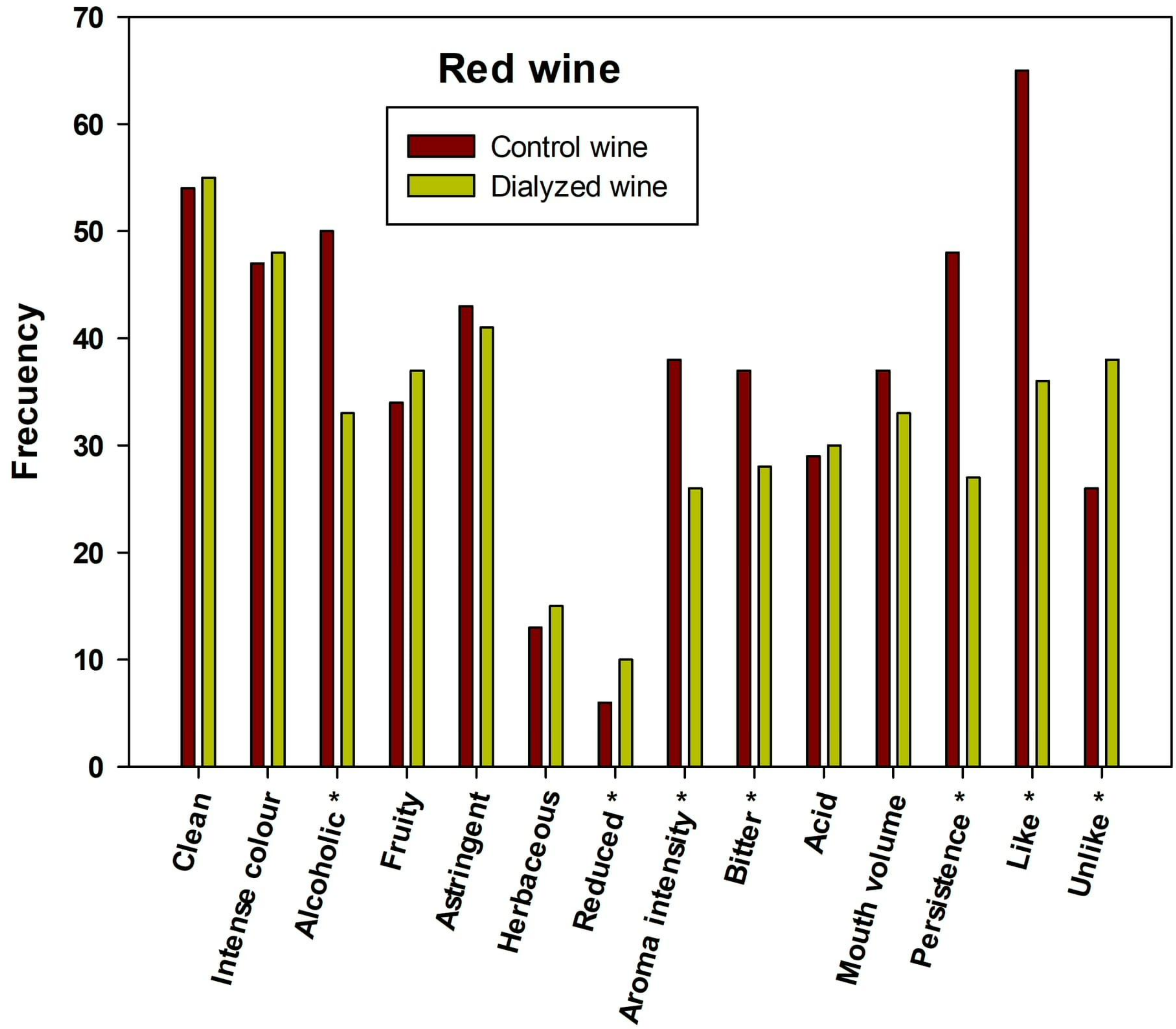
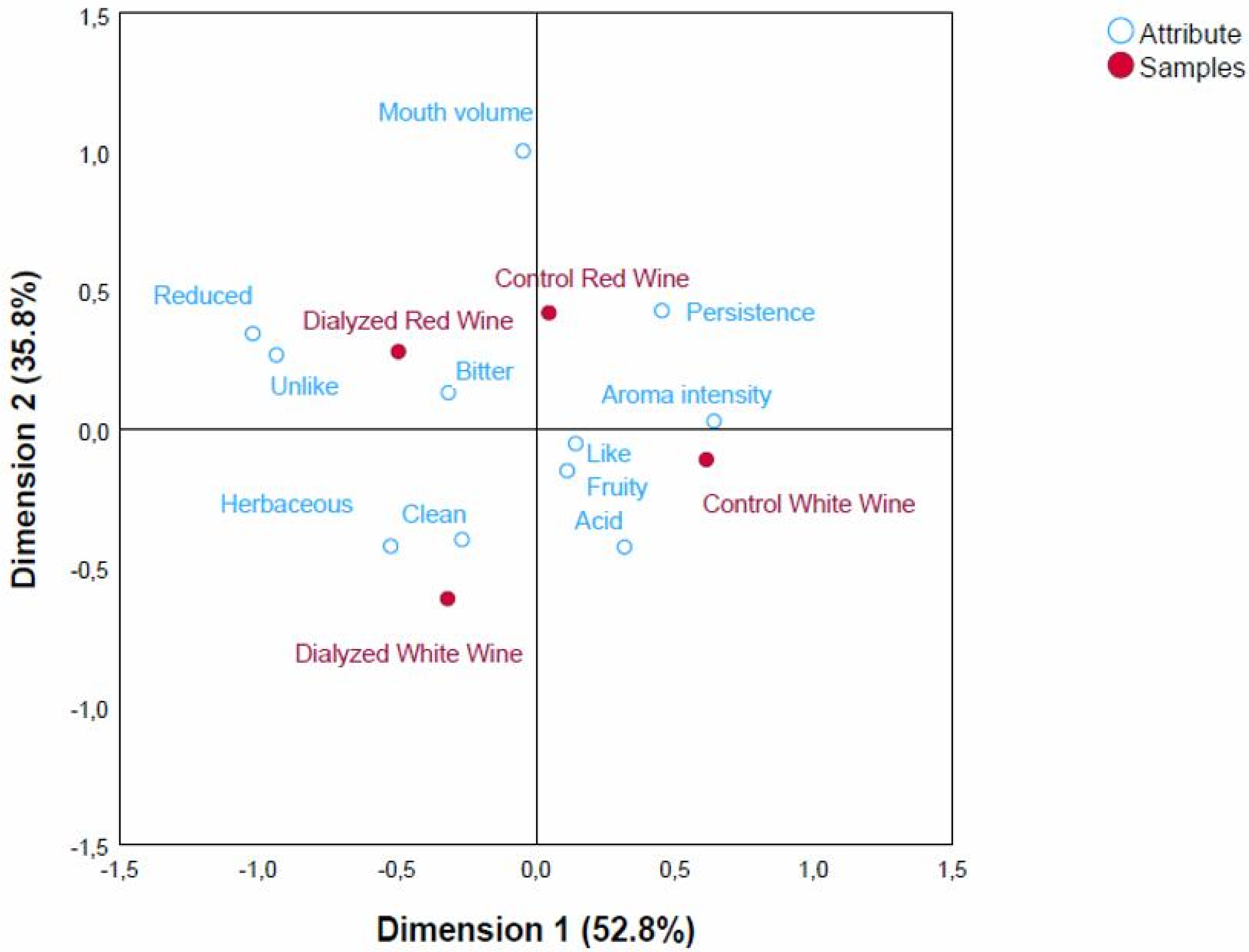

Ethyl heptadecanoate
Ethyl dodecanoate
Ethyl hexanoate
Ethyl decanoate
Ethyl octanoate
Hexyl acetate
2,4-Ditert-butylphenol
1
2
3
4
2,1
1,6
1,1
0,6
0,1
-0,4
-0,9
-2,1
-1,1
-0,1
0,9
1,9
2,9
3,9
PC2 (20.88%)
PC1 (77.59%)


White wine
Control wine
Dialyzed wine
Frecuency
0
20
40
60
80
Clean *
Rusty
Fruity *
Citric
Tropical *
Herbaceous *
Balsamic
Reduced
Aniseed
Aroma intensity *
Bitter
Acid *
Mouth volume *
Persistence *
Like
Unlike *


Red wine
Control wine
Dialyzed wine
Frecuency
70
60
50
40
30
20
10
0
Clean
Intense colour
Alcoholic *
Fruity
Astringent
Herbaceous
Reduced *
Aroma intensity *
Bitter *
Acid
Mouth volume
Persistence *
Like *
Unlike *


Attribute
Samples
Mouth volume
Control Red Wine
Reduced
Dialyzed Red Wine
Persistence
Bitter
Unlike
Aroma intensity
Like
Fruity
Herbaceous
Clean
Acid
Control White Wine
Dialyzed White Wine
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
Dimension 2 (35.8%)
Dimension 1 (52.8%)

APPENDIX

Table S1. Mean value ± standard deviation of VOCs showing statistically significant differences for white wine (control and dialyzed)

Chemical compound	Control white wine (μg/L)	Dialyzed white wine (μg/L)
3-methyl-1-pentanol	2.9^{b}	1.4 ± 0.1^{a}
Trans-3-Hexen-1-ol	3.8^{b}	$2,4 \pm 0.0^{a}$
2,4-Ditert-butylphenol	2.9 ± 1.1^{a}	7.1 ± 0.7^{b}
Ethyl octanoate	$7,618.4 \pm 1,465.3^{b}$	$2,825.8 \pm 211.8^{a}$
Ethyl dodecanoate	344.6 ± 52.0^{b}	83.1 ± 26.5^{a}
Isopropyl myristate	5.3^{b}	2.6^{a}
Ethyl decanoate	$3,976.8 \pm 780.2^{b}$	985.1 ± 157.6^{a}
Ethyl hexanoate	$1,687.6 \pm 418.9^{b}$	263.5 ± 2.4^{a}
Ethyl heptadecanoate	4.0^{b}	2.3 ± 0.4^{a}
Hexyl acetate	444.5 ± 123.0^{b}	41.7 ± 3.8^{a}
Isoamyl decanoate	12.9 ± 1.7^{b}	4.0 ± 0.7^{a}
Ethyl benzoate	3.7 ± 0.2^{b}	2.2 ± 0.1^{a}
2-Octanone	2.4 ± 0.1^{b}	1.9 ± 0.1^{a}
Benzylimine	12.1 ± 1.9^{b}	5.1^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test.

Table S2. Mean value ± standard deviation of VOCs showing statistically significant differences for red wine (control and dialyzed)

Chemical compound	Control red wine (µg·L^{-1})	Dialyzed red wine (µg·L^{-1})
3-Methylpentanoic acid isopentyl ester	13.7^{b}	3.4^{a}
Phenethyl acetate	35.5 ± 0.1^{a}	60.2 ± 6.6^{b}
Ethyl butyrate	16.3 ± 1.5^{b}	3.2 ± 3.2^{a}
Ethyl heptanoate	6.4 ± 0.3^{b}	3.8^{a}
Ethyl octanoate	2,098.2 ± 70.2^{b}	1,204.0 ± 111.4^{a}
Ethyl dodecanoate	250.2 ± 27.5^{b}	77.9 ± 42.5^{a}
Isobutyl acetate	2.2 ± 0.1^{b}	1.1 ± 0.1^{a}
Ethyl decanoate	1,380.1 ± 52.1^{b}	608.0 ± 157.7^{a}
Diethyl succinate	580.1 ± 29.2^{b}	407.9 ± 23.9^{a}
Ethyl nonanoate	268.6 ± 33.4^{b}	26.8 ± 8.7^{a}
Ethyl hexanoate	72.1 ± 17.0^{b}	150.9 ± 6.1^{a}
Isoamyl acetate	311.3 ± 10.0^{b}	102.4 ± 0.2^{a}
Ethyl tetradecanoate	147.5 ± 21.5^{b}	61.4 ± 17.6^{a}
Ethyl heptadecanoate	10.3 ± 0.6^{b}	2.6^{a}
Ethyl acetate	189.1 ± 7.3^{b}	114.0 ± 3.0^{a}
Hexyl acetate	20.9 ± 2.0^{b}	9.8 ± 0.4^{a}
3-Methylbutyl octanoate	20.8 ± 1.4^{b}	8.2 ± 2.2^{a}
2-Methylbutyl hexanoate	14.0^{b}	2.5^{a}
2-Ethylhexyl propionate	1.4^{b}	0.6^{a}
Ethyl pentadecanoate	19.4 ± 0.7^{b}	6.0 ± 1.9^{a}
Ethyl 9-hexadecenoate	20.7 ± 1.2^{b}	4.9 ± 2.5^{a}
Ethyl undecanoate	15.9 ± 2.9^{b}	6.3 ± 0.5^{a}
Ethyl palmitate	663.0 ± 147.7^{b}	2.5 ± 0.6^{a}
Ethyl undecanoate	2.9 ± 0.1^{b}	1.5 ± 0.3^{a}
Benzyl alcohol	7.5 ± 0.2^{b}	4.9 ± 0.3^{a}
Isoamyl alcohol	1,711 ± 60^{b}	1,243 ± 28^{a}
Phenol	4.4 ± 0.5^{b}	2.8 ± 0.2^{a}
1-Hexanol	157.7 ± 3.3^{b}	123.6 ± 1.4^{a}
1-Heptanol	8.0 ± 0.0^{b}	5.3 ± 0.6^{a}
1-Nonanol	24.7 ± 1.7^{b}	6.7 ± 0.2^{a}
2-(2-(2-phenylethynyl)hexadecane-1,2-diol	5.8^{b}	2.7^{a}
2,4-Ditert-butylphenol	4.3 ± 1.5^{a}	10.1 ± 0.6^{b}
2-Phenylethanol	1,164.9 ± 111.3^{b}	770.0 ± 56.3^{a}
Naphthalene	2.4 ± 0.2^{b}	1.0 ± 0.1^{a}
1,3-Diacetylbenzene	5.9^{b}	2.4 ± 0.2^{a}
Toluene	12.3 ± 0.5^{b}	7.6 ± 0.8^{a}
Damascenone	5.2 ± 0.7^{b}	2.2 ± 0.5^{a}
1-(3,4-Dimethylphenyl)2thenone	2.9^{b}	1.4^{a}
Benzoic acid	4,711.9 ± 303.3^{b}	2,592.1 ± 46^{a}
Butanedioic acid	48.6 ± 0.4^{b}	29.3 ± 4.4^{a}
Diphenyl ether	4.9^{b}	1.9 ± 0.2^{a}
4-Nitrophthalamide	57.6 ± 5.4^{b}	34.4 ± 2.4^{a}

Different letters indicate statistically significant differences between samples with a $p < 0.05$ according to Tukey's test.

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Palencia, October 15th, 2025

Dr Angelita Gambuti
Associate Editor
Journal of the Science of Food and Agriculture

Dear Dr. Gamburi,

Attached you will find the revised version of the manuscript of our work entitled:

Membrane Dialysis for partial dealcoholization of wine. Comparison between white and red wines

whose authors are:

José I. Calvo, David Rodríguez, Encarnación Fernández-Fernández, Pedro Prádanos, Laura Palacio and Antonio Hernández

We have shortened considerably the previous version to meet journal requirements, while maintaining those changes required by referees in previous revision round and also avoiding loss of substantial information. Some of the tables are now considered as appendix while main points of them are still discussed in text.

We have also structured abstract according to your comments and finally we have revised carefully references, including format and superscript use to be sure they are now in line with usual JSFA presentation.

Hope now this manuscript will be now considered worthy to be published in J. Sci. Food &Agriculture.

With our very best wishes,

José Ignacio Calvo

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List of proposed referees:

- Volkmar Thom (volkmar.thom@sartorius-stedim.com), Sartorius-Stedim Biotech, GmbH (Germany): reputed researcher in both university and industry.

- José Ramón Alvarez (jras@uniovi.es) Universidad de Oviedo (Spain). Long experience in membrane processes, including treatment of alimentary fluids.

- José Espinosa (destila@santafe-conicet.gob.ar), INGAR (CONICET-UTN), Santa Fe, Argentina. Published studies on wine dealcoholization by membrane processes.