Techniques for Dealcoholization of Wines

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To adapt to the trends in wine styles, and the effect of climate change on wine alcohol content, different techniques have been used at the various stages of winemaking, among which the physical dealcoholization techniques, particularly membrane separation (nanofiltration, reverse osmosis, evaporative perstraction, and pervaporation) and thermal distillation (vacuum distillation and spinning cone column), have shown promising results and hence are being used for commercial production.

dealcoholization | reduced-alcohol wine | alcohol-free wine | non-alcoholic wine | phenolic composition | volatile composition | aroma compounds | sensory quality

1. Introduction

Wine is an alcoholic beverage popularly produced from fermented grape juice. Wines can be classified as red, rose (pink), or white based on their color, and they can also be classified as table (red, rose, or white), sparkling, or fortified based on their alcohol level or carbon dioxide content [1]. Table wines are wines that are neither fortified nor sparkling and are typically served with food [2]. Fortified wines are made by adding alcohol (usually between 16% and 23%) [1][2][3]. Wines can also be classified based on how much carbon dioxide they contain. Those that contain carbon dioxide (about 10 g/L CO_2) [4] are classified as sparkling wines, while those that do not contain carbon dioxide are classified as "still" wines [1]. The carbon dioxide can be produced naturally during fermentation or added artificially. Based on alcoholic content, wines can further be classified as alcohol-free (< 0.5% v/v), low-alcohol (0.5% to 1.2% v/v), reduced-alcohol (1.2% to 5.5% or 6.5% v/v), lower-alcohol (5.5% to 10.5% v/v), and alcoholic wines (> 10.5% v/v) [5][6]. In addition, wines are also classified according to their sugar content: dry (maximum of 4 g/L sugar), medium dry (between 4 g/L and 12 g/L sugar), semi-sweet (between 12 g/L and 45 g/L sugar), and sweet (minimum of 45 g/L sugar) [7]. However, these classifications are not explicit and may vary between most wine producing countries and the applicable legislations. In the UK, for example, wines with an alcohol content of 1.2% alcohol by volume (ABV) or less are classified as low alcohol wines, while wines with an alcohol content of less than 0.5% ABV are referred to as non-alcoholic wines. In contrast, China classifies low alcohol wines as wines with 1.0% to 7.0% ABV and non-alcoholic wines as wines with 0.5% to 1.0% ABV [8].

From several studies (in vitro and in vivo), there is a positive consent of the beneficial impact of wine consumption on neurological diseases, cardiovascular disease, osteoporosis, diabetes, and longevity [9][10][11][12][13][14]. When consumed in adequate amounts and together with a meal, wine plays a vital role in mitigating oxidative stress and vascular endothelial damage induced by a high-fat meal [15]. According to Boban et al. [15], red wine consumption may help prevent heart diseases as well as type two diabetes, allowing consumers to enjoy better health and an increased lifespan as they age. A Chinese study on alcohol and mortality in middle-aged men discovered a 19% reduction in deaths with no more than two drinks per day [16]. Furthermore, a study conducted by Buettner and Skemp [17] on blue zones revealed adequate wine intake as one of the nine lifestyle habits in populations around the world that are known for their long lifespan and healthy aging. Despite the benefits associated with wine consumption, some consumers perceive wine to be harmful to human health because it contains alcohol [18].

High concentrations of ethanol in wine increase the sensation of hotness and bitterness, while decreasing acidity and masking the sensitivity of certain essential aroma compounds such as esters, higher alcohols, and monoterpenes [19][20][21]. Furthermore, high alcohol wines are subject to higher import duties and taxes in some countries [22]. For example, in the United States, wine with 14% alcohol or less is taxed at USD 1.07 per gallon, while wine with 14.1% to 21% alcohol is taxed at USD 1.57 per gallon [23]. There is a common view all over the world that the consumption of alcoholic wine should lessen in favor of low or non-alcoholic wines [24][25][26]. This is currently being witnessed globally as there is a growing popularity of low- or non-alcoholic wines and beverages, particularly in Europe and North America (www.factmr.com/report/4532/non-alcoholic-wine-market, accessed on 1 September 2021). Consumer preferences are shifting with consumers in the non-alcoholic wine market wanting new product offerings and alternatives. There is also an increasing percentage of the adult population seeking lower alcohol wines and beverages more frequently, which has boosted non-alcoholic wine sales. This trend has prompted producers to introduce new non-alcoholic wine products with fruity and floral notes. Additionally, the global non-alcoholic wine market size is valued at USD 20 billion with a compound annual growth rate (CAGR) of over 45% in 2018 and is projected to increase at a remarkable CAGR of over 7% during the forecast period (2019–2027), reaching a value pool of over USD 30 billion [24]. According to another school of thought (www.factmr.com/report/4532/non-alcoholic-wine-market, accessed on 1 September 2021), the global market will continue to grow steadily, with a CAGR of 10.4% from 2021 to 2031, up from an 8.8% CAGR from 2016 to 2020. Therefore, for wine producers to meet consumers' demands and adapt to the rising non-alcoholic wine market, they need to produce high-quality alcohol-free or low-alcoholic wines (**Figure 1**).

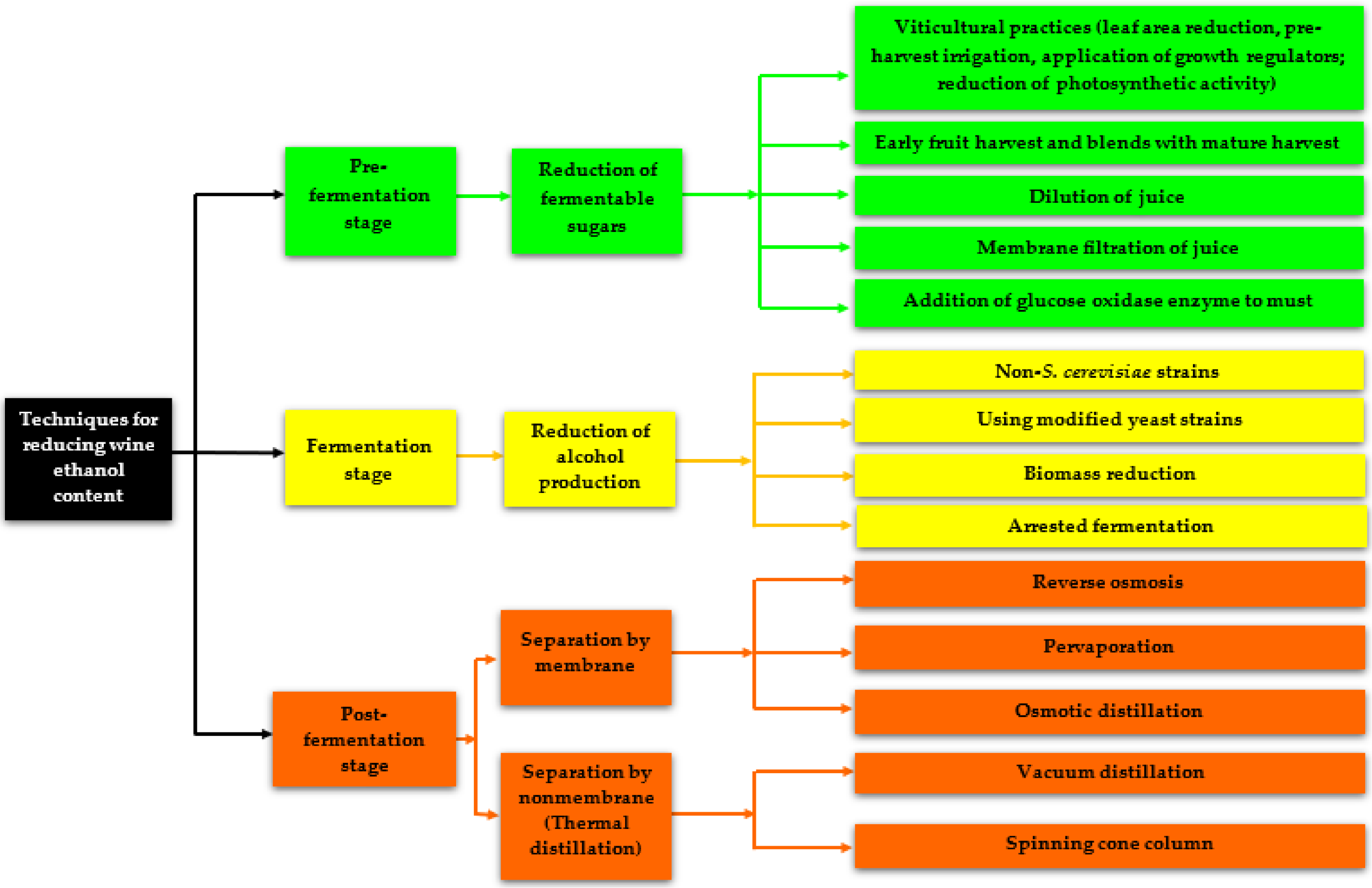

Figure 1. Techniques for alcohol reduction in wines and fermented beverages.

2. Techniques for Wine Alcohol Reduction

A summary of some techniques commonly used for the dealcoholization of wines at the various stages (pre-fermentation stage, fermentation stage, and post-fermentation stage) of wine production and their extent of ethanol removal is shown in **Table 1**.

Table 1. Different techniques to reduce wine alcohol content in the several stages of wine production.

Stage of Wine Production	Ethanol Removal Process	Technology	Alcohol Content Reduction	References
Pre-fermentation	Reduction of fermentable sugars	Viticultural practices (leaf area reduction, pre-harvest irrigation, application of growth regulators; reduction in photosynthetic activity)	Up to 2% v/v	[27][28][29][30][31][32][33][34][35][36][37][38][39][40][41][42][43][44][45]

Stage of Wine Production	Ethanol Removal Process	Technology	Alcohol Content Reduction	References
		Early fruit harvest and blends with mature harvest	Up to 3% v/v	[46][47][48][49][50][51][52][53][54][55][56]
		Dilution of grape must	Up to 7% v/v	[51][52][53][57][58][59][60][61][62][63]
		Filtration of must	Up to 5% v/v	[64][65][66][67][68][69][70][71][72][73]
		Addition of enzyme (glucose oxidase)	Up to 4% v/v	[5][74][75][76][77][78][79]
Fermentation	Reduction of alcohol production	Use of Non-*Saccharomyces cerevisiae* yeasts	Up to 2% v/v	[80][81][82][83][84][85][86][87][88][89][90][91][92][93][94][95][96][97][98][99][100][101][102][103][104][105][106][107][108][109][110]
		Use of modified yeast strains	Up to 3.6% v/v	[111][112][113][114][115][116][117][118][119][120][121][122]
		Biomass reduction	Up to 4% v/v	[123][124][125]
		Arrested fermentation	High reduction	[5][126]
Post-fermentation	Separation by membrane	Nanofiltration (NF)	Up to 4% v/v	[67][127][128][129][130][131][132]

Stage of Wine Production	Ethanol Removal Process	Technology	Alcohol Content Reduction	References
		Reverse osmosis (RO)	Up to 0.5% v/v or less	[22][133][134][130][135][136][137][138]
		Osmotic distillation (OD)	Up to 0.5% v/v or less	[133][139][140][138][141][142][143][144][145][146]
		Pervaporation (PV)	Up to 0.5% v/v or less	[147][148][149][150][151][152][153]
		Vacuum distillation (VD)	Up to 1% v/v or less	[154][155][156]
		Spinning cone column (SCC)	Up to 0.3% v/v	[157][158][159][160][161][162]
		Multi-stage membrane-based systems	Up to 0.5% v/v or less	[70][136][163][164][165][166]

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3. Impact of Dealcoholization Techniques on Wine Quality

3.1. Impact on phenolic composition

The phenolic composition of wine is made up of flavonoids and non-flavonoids [167]. Flavonoids include flavones, flavanols ((+)-catechin and (−)-epicatechin), flavonols (quercetin, myricetin, kaempferol, and rutin), anthocyanins, and proanthocyanidins while non-flavonoids are mainly resveratrol (3,4,5-trihydroxystilbene), hydroxybenzoic acids (p-hydroxybenzoic, vanillic, syringic, gallic, gentisic, salicylic, and protocatechuic acids), and hydroxycinnamic acids (caffeic, coumaric, and ferulic acids) [29][168][169][170][171][172]. Regarding wine quality, especially red wine, phenolic compounds play a vital role by contributing to organoleptic properties such as astringency and color [173]. Health-wise, phenolic compounds can be effective in the prevention of cardiovascular diseases [174][175][176].

Although changes in alcohol content do not generally affect basic wine parameters such as density, pH, titratable acidity, and volatile acidity [164][177], these changes have been reported to influence wine phenolic compounds [144]

[159][164][178] Important findings from some studies on the phenolic composition of wines dealcoholized by physical dealcoholization methods are summarized in **Table 2**.

Healthy People: A Randomized Crossover Trial. Oxidative Med. Cell Longev. 2014, 2014, 1–9.

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Table 2. Some reported changes in wine phenolic compounds using different dealcoholization processes.

Wine Type	Dealcoholization Process	Alcohol Reduction		Reported Effects on Phenolic Composition	Reference
		Co (% v/v)	Cf (% v/v)		
Red wine	NF	12.0	6.0–4.0	Reduction in wine alcohol volume by a factor of 4 leads to 2.5–3 times more anthocyanins and resveratrol in the wine concentrates	[128]
Cabernet Sauvignon–Merlot–Tempranillo red wine	RO	12.7	4.0–2.0	No significant differences were observed in total anthocyanins and phenolic compounds for both original and dealcoholized wines. Colour intensity increased by around 20% in dealcoholized wines (due to the concentration effect from the removal of ethanol as well as the retention of anthocyanins by the membrane), while the tonality diminished by around 15%	[179]
Cabernet Sauvignon red wine	RO	14.8	13.8–12.8	The total phenolic index, total proanthocyanidins, and percentages of procyanidins, prodelphinidins, and galloylation of partially dealcoholized wines and the control wine remains almost unchanged and did not differ. Control wine and partially dealcoholized wines have statistically similar total anthocyanin concentrations with no observed color differences between these wines	[22]
Grenache–Carignan red	RO	16.2	15.1–14.1	The total phenolic index and total proanthocyanidins of partially dealcoholized	[22]

Dealcoholization by Reverse Osmosis on Red Wine Composition and Sensory Characteristics. Eur. Food Res. Technol. 2013, 237, 481–488.

Wine Type	Dealcoholization Process	Alcohol Reduction		Reported Effects on Phenolic Composition	Reference
		Co (% v/v)	Cf (% v/v)		
wine				wines and the control wine remain almost unchanged and do not differ. Slight but statistically significant differences were observed in the percentages of procyanidins, prodelphinidins, and galloylation during alcohol reduction. Total anthocyanin concentrations of partially dealcoholized wines were statistically significantly higher than that of the control wine	
Montepulciano d'Abruzzo red wine	RO	13.2	9.0	Increase in total phenols and decrease in total anthocyanins during ethanol reduction in wine samples. Color intensity increases during ethanol removal	[138]
Aglianico red wine	OD/EP	12.8	4.9–0.4	Higher amount of total phenols in dealcoholized wine samples compared to the original wine. Color intensity decreased slightly at the end of dealcoholization	[180]
Aglianico red wine	OD/EP	15.4	13.5–10.8	The alcohol removal process did not affect the content of vanillin reactive flavans and total phenolics. A loss of 49% of total monomeric anthocyanins was observed after dealcoholization while total anthocyanins remained almost unchanged with no significant differences. Color parameters of dealcoholized wines were not significantly different compared to the original wine after alcohol removal	[144]

Limitations Induced by Trimming and Antitranspirants Canopy Sray on Grape Composition during Ripening in Vitis Vinifera Cv. Sangiovese Progr. Agric. Vitic. Hors Série Spec. 2011, 17, 259–262.

Wine Type	Dealcoholization Process	Alcohol Reduction		Reported Effects on Phenolic Composition	Reference
		Co (% v/v)	Cf (% v/v)		
Merlot red wine	OD/EP	13.8	11.1–8.9	The alcohol removal process did not affect the content of vanillin reactive flavans and total phenolics. A loss of 57% of total monomeric anthocyanins was observed after dealcoholization while total anthocyanins remained almost unchanged with no significant differences. Color parameters of dealcoholized wines were not significantly different compared to the original wine after alcohol removal	[144]
Piedirosso red wine	OD/EP	13.6	11.5–8.4	The alcohol removal process did not affect the content of vanillin reactive flavans and total phenolics. A loss of 52% of total monomeric anthocyanins was observed after dealcoholization while total anthocyanins remained almost unchanged with no significant differences. Color parameters of dealcoholized wines were not significantly different compared to the original wine after alcohol removal	[144]
Aglianico red wine	OD/EP	12.5	10.6	No significant differences between base wine and dealcoholized wine in terms of total polyphenols and color intensity	[146]
Barbera red wine	OD/EP	15.2	5.0	Higher contents of total anthocyanins and total flavonoids compared to the original wine. Color: the intensity increases and the hue	[155]

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Wine Type	Dealcoholization Process	Alcohol Reduction		Reported Effects on Phenolic Composition	Reference
		Co (% v/v)	Cf (% v/v)		
				decreases (loss of orange notes) due to the increased content of total anthocyanins	
Langhe Rosè wine	OD/EP	13.2	5.0	Higher contents of total anthocyanins and total flavonoids compared to the original wine. Color: the intensity increases and the hue decreases (loss of orange notes) due to the increased content of total anthocyanins	[155]
Verduno Pelaverga red wine	OD/EP	14.6	5.0	Higher contents of total anthocyanins and total flavonoids compared to the original wine. Color: the intensity increases and the hue decreases (loss of orange notes) due to the increased content of total anthocyanins	[155]
Falanghina white wine	OD/EP	12.5	9.8–0.3	At different alcohol content levels of wines, the total phenols and flavonoids do not differ significantly as they remain almost unchanged during the alcohol removal process	[140]
Montepulciano d’Abruzzo red wine	OD/EP	13.2	8.3–5.4	Both total phenols and total anthocyanins decrease in dealcoholized wines with no significant differences compared to the original wine. The color intensity remains almost unchanged during ethanol removal	[138]
Montepulciano d’Abruzzo red wine	OD/EP	13.2	8.3–2.7	Flavonoids and phenolic compounds remain almost unchanged in all dealcoholized samples compared to the base wine with no significant differences. Color intensity (evaluated by flavonoids and phenolic	[139]

Manipulations on Cabernet Sauvignon Wine Sensory Characteristics. South African J. Enol. Vitic. 2013, 34, 86–99.

Wine Type	Dealcoholization Process	Alcohol Reduction		Reported Effects on Phenolic Composition	Reference
		Co (% v/v)	Cf (% v/v)		
				compounds) decrease slightly in all dealcoholized samples	
Langhe Rosè wine	VD	13.2	5.0	Higher contents of total anthocyanins and total flavonoids compared to the original wine. Color the intensity increases and the hue decreases (loss of orange notes) due to the increased content of total anthocyanins	[155]
Barbera red wine	VD	15.2	5.0	Higher contents of total anthocyanins and total flavonoids compared to the original wine. Color: the intensity increases and the hue decreases (loss of orange notes) due to the increased content of total anthocyanins	[155]
Verduno Pelaverga red wine	VD	14.6	5.0	Higher contents of total anthocyanins and total flavonoids compared to the original wine. Color the intensity increases and the hue decreases (loss of orange notes) due to the increased content of total anthocyanins	[155]
Red wine	SCC	14.0	< 0.3	Increase in phenolic compounds, total phenolic, flavonol, tartaric ester, and anthocyanin contents by approximately 24%. Higher content of resveratrol than the original wine	[159]
Rose wine	SCC	14.0	< 0.3	Increase in phenolic compounds, total phenolic, flavonol, tartaric ester, and anthocyanin contents by approximately 24%.	[159]

Flavored Low Alcohol White Wines. Food Bioprod. Process. 2017, 101, 11–21.

The composition of volatile compounds influences the overall aroma and flavor of wine [182][183][184][185][186]. Wine contains over 1000 volatile compounds of various chemical classes (alcohols, esters, fatty acids, aldehydes, terpenes, ketones, and sulfur compounds), and wine fermentation produces approximately 400 volatile compounds

Wine Type	Dealcoholization Process	Alcohol Reduction Co (% v/v)	Alcohol Reduction Cf (% v/v)	Reported Effects on Phenolic Composition	Reference
				Higher content of resveratrol than the original wine	[157]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction Co (% v/v)	Alcohol Reduction Cf (% v/v)	Volatile Composition: Volatile Compounds	Volatile Composition: Estimated Average Losses (%)	Sampling and Analytical Method	Reference
NF	White model wine	TORAY–UB70	Batch retentate–recycling mode T = 15 P = 10	12.0	8.4	Diethyl succinate 2–phenyl–ethanol *cis*–3–hexenol Isovaleric acid	2.4 2.9 12.6 11.7	HS/SPME–GC/MS	[130]
	Red Wine	Polyamide, NF9, Alfa Laval	T = 30 P = 16	12.0	9.1	Total volatile aroma**	30.0	GC–FID	[189]
RO	Model wine	Osmonics–SE	Batch retentate–recycling mode T = 15 P = 17–29	12.0	8.4	Diethyl succinate 2–phenyl–ethanol *cis*–3–hexenol	0.6–1.6 2.5–3.5 7.8–11	HS/SPME–GC/MS	[130]

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
						Isovaleric acid	11.9–18.1		
	Red Wine	Cellulose acetate, CA995PE	T = 30◦C P = 16	12.0	8.4	Total aroma**	90.0	GC–FID	[189]
	Montepulciano d'Abruzzo red wine	RO membrane (100 DA)	T = 10 P = ns Time = 40	13.2	9.0	Alcohols Acids Esters Phenols Lactones	30.0 22.0 8.0 13.0 14.0	SPME–GC/MS	[138]
OD/EP	Model wine	Polyvinylidene fluoride (PVDF) Memcor	Qf = 0.053 Qs = 0.093 T = 30 Time = 60	13.0	8.1	Isoamyl alcohol Ethyl acetate	44.0 70.0	GC–FID	[190]
	Falanghina white wine	Liqui–Cel 0.5 × 1, PP hollow fiber	Qf = 0.07 Qs = 0.14 T = 10	12.5	9.8–0.3	Higher alcohols Acids Esters	49.5–98.9 60.5–98.7	LE–GC/MS, LE–GC/FID	[140]

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
			Time = 240			Ketones lactones	71.5–99.0 67.1–99.9 73.6–98.2		
	Xarelo white wine	Liqui–Cel ExtraFlow	Qf = 10 Qs = 10 T = room temperature Time = 20	11.5	10.1	Isoamyl acetate Ethyl hexanoate Ethyl octanoate Ethyl decanoate	27.0 37.0 28.0 24.0	SBSE–GC/MS	[142]
	Soave white wine	PTFE hollow fiber (Teflon, Verona, Italy)	Qf = 0.2 Qs = 0.2 T = 20 Time = ns	ns	*	Alcohols Acids Esters Terpenes	12.6–32.2 5.6–16.4 34.0–58.4 22.0–26.0	SPE–GC/MS	[191]

Spoilage Caused by Zygosaccharomyces Species on Sweet Wines and Concentrated Grape Musts. Food Control 2015, 51, 129–134.

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
	Verdicchio white wine	PTFE hollow fiber (Teflon, Verona, Italy)	Qf = 0.2 Qs = 0.2 T = 20 Time = ns	ns	*	Alcohols Acids Esters Terpenes	8.9–25.8 8.0–15.8 40.0–54.1 21.0–28.0	SPE–GC/MS	[191]
	Aglianico red wine	Liqui–Cel Extra–flow, PP hollow fiber	Qf = 0.583 Qs = 0.183 T = 20 Time = 283	13.8	11.6–8.8	Alcohols Esters Acids Terpenes *Others:* Benzaldehyde ?–Butyrolactone	8.4–31.8 42.9–60.9 12.5–17.1 13.8–32.3 55.3–65.9 4.5–13.6	SPE–GC/MS	[133]

...east That Exhibits Reduced Ethanol Production during Fermentation under Controlled Microoxygenation Conditions. Appl. Environ. Microbiol. 2006, 72, 5822–5828.

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
	Aglianico red wine	Liqui–Cel Extra–flow, PP hollow fiber	Qf = 0.583 Qs = 0.183 T = 20 Time = 283	15.5	13.5–10.8	Alcohols Esters Acids Terpenes *Others:* Benzaldehyde ?–Butyrolactone Vitispirane	9.2–13.7 33.8–50.6 11–18.5 3.6–14.5 nf 12.9 Unc	SPE–GC/MS	[133]
	Aglianico red wine	Liqui–Cel 0.5×1, PP hollow fiber	Qf = 0.07 Qs = 0.14 T = 20 Time = 255	13.0	6.5–0.2	Alcohols Acids Esters Sulfur compounds Phenols Ketones and lactones Aldehydes	57.9–99.9 23.6–78.9 12.8–89.9 2.1–78.7 66.7–100	LE–GC/MS, LE–GC/FID	[145]

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
							23.6–97.9 unc–100		
	Merlot red wine	Liqui–Cel Extra–flow, PP hollow fiber	Qf = 5.8 Qs = 8.1 T = 20 Time = 60	13.4	11.3	Ethyl acetate Isoamyl acetate Isoamyl alcohol Ethyl hexanoate Ethyl octanoate Linalool 2–Phenylethyl acetate	37.4 34.9 13.7 33.0 67.8 14.5 13.6	HS/SPME–GC/MS	[141]
	Barbera red wine	Polypropylene hollow fibers (JU.CLA.S. LTD, Verona, Italy)	Qf = 1.6 Qs = 0.8 T = 10 Time = 360	14.6	5.0	Alcohols Acids Esters	63.9 17.4 23.8	SPE–GC/FID	[155]

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
	Tempranillo red wine	Liqui–Cel ExtraFlow	Qf = 5.8 Qs = 5.8 T = room temperature Time = 60	13.3	9.0	Isoamyl alcohol Ethyl hexanoate	21.0 20.0	SBSE–GC/MS	[142]
	Garnacha red wine	Liqui–Cel ExtraFlow	Qf = 5 Qs = 5 T = room temperature Time = 60	13.9	9.3	Isoamyl acetate Ethyl hexanoate	24.0 36.0	SBSE–GC/MS	[142]
	Verduno Pelaverga red wine	Polypropylene hollow fibers (JU.CLA.S. LTD, Verona, Italy)	Qf = 1.6 Qs = 0.8 T = 10 Time = 360	14.6	5.0	Alcohols Acids Esters	59.9 23.6 45.2	SPE–GC/FID	[155]
	Montepulciano d'Abruzzo red wine	Liqui–Cel 0.5×1, PP hollow fiber	Recycling mode Qf = 1.5	13.2	8.3–2.7	Alcohols Acids	56.0–84.0	SPE– LE–GC/MS/FID	[139]

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
			Qs = 0.5 T = 10 Time = 240			Esters Lactones Phenols *Others:* Benzaldehyde α–Terpineol	18.0–23.0 64.0–85.0 11.0–37.0 11.0–37.0 2.0–26.0 5.0–49.0		
	Montepulciano d'Abruzzo red wine	Liqui–Cel mini module 1.7x5.5 Membrana	Recycling mode Qf = 1.5 Qs = 0.5 T = 10 Time = 120	13.2	8.3–5.4	Alcohols Acids Esters Phenols Lactones	2.0–3.0 18.0–25.0 15.0–19.0 5.0–10.0	SPME–GC/MS	[138]

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
							7.0–25.0		
	Langhe Rosè wine	Polypropylene hollow fibers (JU.CLA.S. LTD, Verona, Italy)	Qf = 1.6 Qs = 0.8 T = 10 Time = 360	13.2	5.0	Alcohols Acids Esters	60.4 30.9 47.8	SPE–GC/FID	[155]
PV	Tokaji Hárslevelű white wine	PERVAP.Sulzer 1060 PDMS	"Carrier gas mode" under atmospheric pressure T = 40–70	13.1	0.1	Total volatile aroma**	70.0	Distillation/LE–GC/MS	[147]
	Cabernet Sauvignon red wine	PDMS JS–WSM–8040 (JiuSi High–Tech, Nanjing, China)	Batch operation T = 45 VP = 0.05	12.5	0.5	Alcohols Acids Esters	19.7–39.5 12.7–28.2 48.0–99.9	GC/MS	[192]
VD	Barbera red wine	–	T = 15	15.2	5.0	Alcohols Acids	50.4 13.7	SPE–GC/FID	[155]

compound losses were provided; SPE = solid phase extraction; GC = gas chromatography; MS = mass spectrometry; LE = liquid extraction; FID = flame ionization detector; SBSE = stir bar sorptive extraction; HS = headspace; SPME = solid phase micro-extraction; – means not applicable. Units: Concentration = (%v/v); Vacuum pressure/Pressure = bar; Rejection = %; T = °C; Flowrate = L/min; Time = min.

Several studies have reported on the use of membrane techniques in wine dealcoholization and their subsequent effect on the dealcoholized wine volatile compositions [147][133][139][140][130][135][138][145][155][190]. A low alcohol content apple cider was produced by RO with a polyamide membrane AFC99 in both batch and diafiltration configurations [135]. The process was operated at 15 °C and 45 bar with a feed flow of 200 L h^{-1}. During the batch configuration process, 60% of ethanol was removed with an estimated loss of 77% of total higher alcohols, 20% of total aldehydes, 25% of total acids, and 25% of total esters. In the diafiltration configuration, estimated losses of 96%

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds	Estimated Average Losses (%)		
						Esters	19.8		[141]
	Verduno Pelaverga red wine	–	T = 15	14.6	5.0	Alcohols Acids Esters	53.6 2.3 19.5	SPE–GC/FID	[155]
	Langhe Rosè wine	–	T = 15	13.2	5.0	Alcohols Acids Esters	51.4 2.5 22.9	SPE–GC/FID	[155]
SCC	White wine	–	T = 25 VP = 0.08 Time = 60	10.6	0.3	Aliphatic alcohols Aromatic alcohols Acids Esters Ketones	98.0 3.0 20.0 53.0 71.0	LE–GC/FID	[160]
	Chardonnay white wine	–	T = 30 VP = 0.04 Time = 60	ns	ns	Total aroma**	1.0–9.0	HS/SPME–GC/MS	[158]

... it is evident that the physical technologies used in the dealcoholization of wines can result in significant losses of volatile compounds due to the reduction in alcohol levels. However, the significance and extent of the changes can also depend on the operating conditions applied, the type of membrane used, and the non-volatile matrix of the wine.

3.3. Impact on Sensory Characteristics

Ethanol is the most abundant of the volatile compounds in wine and its concentration can influence the perception of wine aroma and flavor as well as several mouthfeel and taste sensations [141][177][194][195]. Higher ethanol concentrations in wine typically enhance sensitivity to body, bitterness, and hotness, whereas lower concentrations can reduce the perception to aroma, flavor, acidity, and astringency [19][20][196][197][198]. Some studies have been

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[144][159][160][178][190][180]

[147][130][141]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Volatile Composition		Sampling and Analytical Method	Reference
				Co (% v/v)	Cf (% v/v)	Volatile Compounds [157][191][199][200]	Estimated Average Losses (%)		
			T = 30						

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
NF	Red Wine	Polyamide, NF97, NF99 HF Alfa Laval	T = 30 P = 16	12.0	9.1	Increase in astringency and unbalanced aroma and taste due to alcohol reduction	[189]
RO	Syrah red wine	ns	T = ns P = ns	12.7	11.1–9.6	Decrease in wine length in the mouth and increase in red fruits and then woody and blackcurrant perceptions (using TDS and attributed to alcohol reduction). Decrease in heat and sweetness	[178]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
						intensity (attributed to alcohol reduction) and red fruit intensity (attributed to RO)	
	Merlot red wine	ns	T = ns P = ns	13.4	11.8–10.2	Decrease om wine length in the mouth and increase in astringent and then of fruity perceptions (using TDS and attributed to alcohol reduction). Decrease in heat and texture intensity (attributed to alcohol reduction) and increase in acid intensity (attributed to RO)	[178]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
	Syrah red wine	ns	T = ns P = ns	13.4	11.4–7.9	Decrease in persistence, complexity, number of aromas and increase in balance, harmony, and familiarity. Decrease in familiarity and harmony after 4% v/v reduction	[201]
OD/EP	white wine	PTFE hollow fiber (Teflon, Verona, Italy)	Qf = 0.2 Qs = 0.2 T = 20 Time = ns	ns	*	Floral, fruity, and vegetable notes, as well as acidity, saltiness, and bitterness, were not significantly influenced. Decrease in wine body, persistence, and honey note.	[191]
	Falanghina white wine	Liqui-Cel 0.5x1, PP	Qf = 0.07	12.5	9.8–0.3	Decrease in odor,	[140]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
		hollow fiber	Qs = 0.14 T = 10 Time = 240			sweetness, and body, resulting in unbalanced taste and overall unacceptable, with an unpleasant aftertaste	
	Aglianico red wine	Liqui-Cel Extra-flow, PP hollow fiber	Qf = 0.583 Qs = 0.183 T = 20 Time = 283	13.8	11.6–8.8	Decrease in cherry, red fruits, and sweet notes. Increase in flowers notes only within 2% v/v reduction. Increase in grass and cooked notes and increase in astringency within 5% v/v reduction. Increase in bitterness and acid sensations within 3% v/v reduction	[133]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
	Aglianico red wine	Liqui-Cel Extra-flow	Qf = ns Qs = ns T = ns Time = 180	12.8	4.9–0.4	Decrease in sweet and solvent aroma series (due to alcohol reduction) which characterize the wine	[180]
	Aglianico red wine	Liqui-Cel Extra-flow, PP hollow fiber	Qf = 0.583 Qs = 0.183 T = 20 Time = 283	15.5	13.5–10.8	Decrease in cherry, red fruits, flowers, and grass notes. Increase in acid and astringent sensations	[133]
	Montepulciano d'Abruzzo red wine	Liqui-Cel 0.5×1, PP hollow fiber	Recycling mode Qf = 1.5 Qs = 0.5 T = 10 Time = 240	13.2	8.3–2.7	Increase in acidity, a decrease in red fruits and spices notes, astringency, bitterness, and sweetness, resulting in lower acceptability	[139]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
PV	Cabernet Sauvignon red wine	PDMS JS-WSM-8040 (JiuSi High-Tech, Nanjing, China)	Batch operation T = 45 VP = 0.05	12.5	0.5	High retention of fruit aroma, producing wine with better smell and taste	[192]
SCC	Chardonnay white wine	–	ns	14.9	14.6–12.9	Decrease in overall aroma intensity and hot mouthfeel sensation	[202]
RO-OD/EP	Shiraz red wine	Memstar AA MEM-074 and Liqui-Cel 2.5 × 8 Extra-flow PP hollow fiber	Qf = ns Qs = ns T = ns P = ns Time = ns	16.3	13.3–10.4	Increase in dark fruit, raisin/prune, alcohol, and astringency in all dealcoholized wines with no significant effects. Increase in black pepper note and overall aroma intensity, and decrease in herbaceous note within	[193]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
						6% v/v reduction off alcohol	
	Cabernet Sauvignon red wine A	Spiral wound 4040 and hollow fiber perstractive membrane (VA Filtration, Nuriootpa, Australia)	Qf = ns Qs = ns T = 55 P = 30 Time = 90	17.0	14.5	Increase in dark fruit aroma and decrease of green aroma, dried fruit, and chocolate flavors with no significant difference in the overall intensity. A small decrease in acidity. Small but significant decreases in sweetness and saltiness. Increase in the sensation of astringency	[165]
	Cabernet Sauvignon red wine B	Spiral wound 4040 and hollow fiber perstractive	Qf = ns Qs = ns T = 55	15.5	13.3	Decreases in hotness, bitterness, and body (attributed to	[165]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction Co (% v/v)	Alcohol Reduction Cf (% v/v)	Findings on Sensory Characteristics	Reference
		membrane (VA Filtration, Nuriootpa, Australia)	P = 30 Time = 90			lower ethanol level). Decrease in confection and ‘chocolate’ aromas. Significant decrease in the overall flavor intensity (largely due to the decreased intensity of dark fruit, sweet spice, and chocolate flavors) with no significant effect on the overall intensity	
	Cabernet Sauvignon red wine C	Spiral wound 4040 and hollow fiber perstractive membrane (VA Filtration, Nuriootpa, Australia)	Qf = ns Qs = ns T = 55 P = 30 Time = 90	14.9	13.3	Decrease in hotness (attributed to lower ethanol level). Decrease in confection, dried fruit, and chocolate aromas with	[165]

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Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
						no significant difference in the overall intensity. Decrease in the sensation of astringency	
	Cabernet Sauvignon red wine D	Spiral wound 4040 and hollow fiber perstractive membrane (VA Filtration, Nuriootpa, Australia)	Qf = ns Qs = ns T = 55 P = 30 Time = 90	14.5	13.2	Decrease in hotness (attributed to lower ethanol level). Increase in red fruit aroma with no significant difference in the overall intensity	[165]
	Cabernet Sauvignon red wine E	Spiral wound 4040 and hollow fiber perstractive membrane (VA Filtration, Nuriootpa, Australia)	Qf = ns Qs = ns T = 55 P = 30 Time = 90	16.0	14.2	Decrease in hotness (attributed to lower ethanol level). Decrease in overall flavor intensity with no significant difference in the overall	[165]

Dealcoholization Process	Wine Type	Membrane	Operating Mode/Conditions	Alcohol Reduction		Findings on Sensory Characteristics	Reference
				Co (% v/v)	Cf (% v/v)		
						intensity. Small but significant decreases in sweetness and saltiness	