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Chapter

Low-Alcohol and Nonalcoholic Wines: Production Methods, Compositional Changes, and Aroma Improvement

Teng-Zhen Ma, Faisal Eudes Sam and Bo Zhang

Abstract

Nonalcoholic wine (NW) has attracted the interest of winemakers and researchers in recent years, mainly due to the increasing market share of NW (≤ 1% alcohol by volume), the health risks associated with the consumption of wine, the global trend toward healthier lifestyles, and the uncompromising cardioprotective effects of NW. NW can be produced using several methods, particularly, dealcoholization of wines, which is mainly achieved by physical dealcoholization methods. However, the dealcoholization of wine has two major drawbacks. The first drawback is legal since the laws vary according to each country. The second disadvantage is technical since it is difficult to dealcoholize a wine while maintaining its original organoleptic characteristics. Both the aromatic qualities (volatile composition) and taste (sensory characteristics) of the dealcoholized wine (DW) tend to worsen the greater the decrease in its alcoholic strength. This makes the resulting wine have a different flavor and aroma. Improvement of the aroma of DW after dealcoholization could help wine producers limit undesirable effects and increase consumer acceptance. This chapter is focused on the popular techniques used in wine dealcoholization, their impact on the phenolic composition, volatile composition, sensory characteristics, and the state-of-the-art methods of improving the aroma profile of DW.

Keywords: wine, nonalcoholic wine, dealcoholization, volatile compounds, phenolic compounds, sensory quality, aroma profile

1. Introduction

Wine is an alcoholic beverage commonly produced from fermented grape juice. It can be categorized as dry wine, semidry wine, semisweet wine, sweet wine, still wine, and sparkling wine based on its sugar or carbon dioxide content. Depending on the production methods or materials used, it can also be classified as a special wine (including liqueur wine, carbonated wine, icewine, noble rot wine, floral wine, flavored wine, low alcohol wine, nonalcohol wine, and V.amurensis wine) [1].
In addition to the categorization of wine regarding its alcohol content, one with an alcohol content above 10.5% v/v, from 5.5 to 10.5% v/v, from 1.2 to 5.5%, from 0.5 to 1.2% v/v, or below 0.5% v/v may be classified as an alcoholic wine, lower-alcohol wine, low-alcohol wine, or nonalcoholic wine (NW) [2, 3]. However, these classifications differ from one winemaking region or country to another [4]. Over the years, with health risk awareness and social demands related to road safety, consumer preferences are now shifting toward new product offerings and alternatives, with an increasing percentage of the adult population seeking lower alcohol wines more frequently. This has boosted the production and sales of nonalcoholic wines with the global nonalcoholic wine market worth over $10 billion and is still estimated to increase at a significant CAGR above 7% between 2019 and 2027, attaining a profit share of over $30 billion [5].

Lower, reduced, low, and NW wines can be produced at the various stages of wine production (pre-fermentation, fermentation, and post-fermentation stages) using several methods such as reduction of the juice fermentable sugars before fermentation, the reduction of alcohol production during fermentation, and the separation by membranes and thermal treatment after complete fermentation of the wine [6–9]. The latter methods, also known as physical dealcoholization (ethanol removal) methods are usually used after complete fermentation of the wine (i.e., at wine post-fermentation stage) and can achieve good results when used on a finished wine. Studies have reported the ability of some physical dealcoholization methods in preserving the phenolic compounds [10], volatile compounds [11], and sensory quality [12, 13] of the final wine product at certain levels of ethanol removal with a taste almost similar to the original wines (in the case of partially dealcoholized wines), contrarily to the former methods (commonly used before and during fermentation), which produces unbalanced wine products (high acidity, unfermented juice, and low fermentative aroma compounds) with legality issues in the case of the juice fermentable sugars dilution with water [14].

Wine produced by physical dealcoholization methods (i.e., alcohol removal from finished wines) is termed dealcoholized wine (DW). The dealcoholization of wine can be complete or partial. A completely DW is a beverage obtained exclusively from wine by dealcoholization with a final alcohol content below 0.5% v/v (resolution OIV-ECO 432-2012), while a partially DW is a beverage obtained exclusively from wine by dealcoholization with a final alcohol content ≥0.5% v/v (resolution OIV-ECO 433-2012). NW (< 0.5% v/v ethanol) produced from a finished wine by dealcoholization may be termed DW, whereas low, reduced, and lower alcohol wines (0.5–10.5% v/v ethanol) may be termed partially dealcoholized wines. In this chapter, we focus on the methods used for producing of NW from high-strength alcoholic wines after complete fermentation (wine post-fermentation stage), specifically, their impact on the aroma profile and sensory characteristics of NW. In addition, the state-of-the-art methods of improving the aroma profile of DW/NW are discussed.

2. Methods of lower, reduced, low, and NW wines production

The production of NW can be achieved by several methods as shown in Figure 1. These methods can be broadly classified into three groups based on the principle or mechanism of ethanol reduction and removal at the various stages of wine production, including reduction of fermentable sugars (pre-fermentation stage), reduction or limitation of ethanol production (fermentation stage), and ethanol removal by membrane separation or thermal treatment (post-fermentation stage) [6–9].
2.1 Decrease of ethanol production through reduction of fermentable sugar content

The reduction of fermentable sugars in the pre-fermentation stage of wine is one of the common methods for the production of wines with lower or reduced alcohol content. It includes techniques such as juice dilution [15, 16], juice filtration with membranes [17, 18], the use of enzymes (e.g., glucose oxidase) [19, 20], early harvest and blending with mature harvest [21], viticultural practices (e.g., use of growth regulators, photosynthetic activity reduction, reduction of leaf area, pre-harvest irrigation) [22, 23].

2.1.1 Reduction of fermentable sugars by juice dilution

Juice dilution involves adding water to grape juice or mixing the juice with green harvest to reduce the concentration of fermentable sugars. In countries such as South Africa, New Zealand, Australia, and the United States of America (excluding California where it is only permitted for preventing stuck fermentations), water is only allowed as a processing aid. The substitution of grape juice with water or the direct addition of water to reduce the concentration of fermentable sugars has been effective in reducing the ethanol content of the final wine product by 4-6% v/v [15, 16].

Regarding the use of green harvest in juice dilution, this range of ethanol reduction is determined by the harvest date. The pre-fermentative substitution of a matured Shiraz juice (obtained from Shiraz grapes harvested at 25.5° Brix) with water or direct water addition at rates of 10.2, 34.0, and 47.2% v/v resulted in lower alcohol wines with 14.5%/14.4%, 12.0%/11.7%, and 10.6%/9.6% ABV, respectively, after fermentation to dryness (<1 g/L of total sugar). The lower alcohol wines (10.6%/9.6% ABV) produced by substituting or diluting the juice with 47.2% v/v water decreased the total...
phenolics, anthocyanin concentration, tannin concentration, color density, and SO₂-resistant pigments compared with the control (15.5% ABV) [16]. Furthermore, sensory attributes such as “body,” “astringency,” “flavor intensity,” and “alcohol” flavor were lower in wines with 9.6% ABV compared with the control, which was attributed to the alcohol concentration difference of 1% ABV between the lower alcohol wines produced by substitution (10.6%) and those produced by direct water addition (9.6% ABV) [16]. However, in some European winemaking countries such as France, Spain, Italy, and Germany, this practice is illegal because it can significantly affect most physicochemical parameters, phenolic and volatile components, and the sensory quality of the resulting wine [15, 16, 21].

2.1.2 Reduction of fermentable sugars by filtration of juice

Filtration of the juice with membranes is another method of producing lower or reduced alcohol wines, based on the principle of sugar reduction of the juice before fermentation. In this method, a portion of the sugar-rich juice is filtered with nanofiltration, ultrafiltration, or reverse osmosis membranes, which have a very small pore size and can retain the sugar. The filtered juice is then mixed with the other portion of the sugar-rich juice and fermented to obtain lower or reduced alcohol content wine [17, 18]. To produce a lower or reduced alcohol content wine (≤ 10.5% v/v ethanol) by this method, optimal operating conditions and a suitable membrane configuration with a good molecular weight cutoff (MWCO) should be considered to increase the retention of volatile compounds and maintain good taste in the wine. On the contrary, this could lead to a lower content of polyphenols, anthocyanins, and color intensity and consequently affect the sensory properties of the nonalcoholic wine [17, 24].

2.1.3 Reduction of fermentable sugars using glucose oxidase

The use of glucose oxidase is another way to produce lower or reduced alcohol wines. This enzyme is found in the fungus Aspergillus niger and can be extracted to reduce glucose in grape juice before fermentation [19]. In this method, glucose oxidase converts β-D-glucose to D-glucono-lactone in a first reaction step reaction, releasing hydrogen peroxide, and catalyzes the conversion of D-glucono-lactone to gluconic acid in a second reaction step to produce gluconic acid. These reactions cause the oxidation of the fermentable sugars in the juice (especially glucose), which prevents the formation of ethanol from the fermentation of the sugar [25]. Treatment of a Riesling grape juice with 2 g/L glucose oxidase prior to fermentation resulted in a reduction of ethanol in the resulting wine (reduced alcohol wine) by about 4.3% v/v after 6 hours of fermentation [25]. In addition, Röcker et al. [19] achieved an ethanol reduction of 2% v/v by treating a white grape juice with glucose oxidase. This method can produce higher amounts of gluconic acid, causing the wine to become acidic and have a weak fruity odor [19, 25]. In contrast, Pickering [26] reported that the use of glucose oxidase had no significant effect on the color, aroma, flavor, and acidity of the resulting wine.

2.1.4 Reduction of fermentable sugars through early harvesting and blends

Early harvesting of fruit and blending with ripe grapes is another strategy that can be used to reduce the ethanol concentration in wine. In one study, using this strategy
resulted in a 3.2% v/v reduction in ethanol content of red wines with ideal aroma profiles [27]. Similarly, a 3% v/v reduction in ethanol concentration was observed when an acidic and low alcohol blend of early harvested white and red grapes was added to a ripened grape ferment [28]. According to Piccardo et al. [29], this strategy can lower not only ethanol content but also pH and total acidity without significantly affecting other wine components. Contrary to other studies, acidity and “raw” aromas can be perceived in the resulting wine [28].

2.1.5 Reduction of fermentable sugars through viticultural practices

About half of the total fermentable sugar in grape juice is glucose [30], which is the main substrate converted to alcohol by yeasts during fermentation. Viticultural practices such as reducing photosynthetic activity, using growth regulators, reducing leaf area, and preharvest irrigation have been used to regulate grape fermentable sugars so that low-alcohol or nonalcoholic wines can be produced from grape juice [22, 23]. As indicated by some studies, the degree of sugar accumulation in berries can be influenced by reducing the leaf area [31–33], resulting in a reduction of ethanol content in the resulting wine [23, 34, 35]. For example, a lower alcohol content in the finished wine was observed after leaf area reduction of Shiraz vines [22]. A similar observation was made after post-veraison leaf removal in a Sangiovese vine, with no negative effects on phenolic compounds [36].

2.2 Reduction or limitation of alcohol production during alcoholic fermentation

Reducing or limiting alcohol production is another principle used in producing nonalcoholic or low-alcohol wines during fermentation. This principle basically includes three techniques such as interrupted fermentation [2], reduction of yeast biomass [37], use of modified yeast strains with low alcohol production ability [38, 39], and use of non-\textit{Saccharomyces} yeasts with low alcohol production during fermentation [40, 41].

2.2.1 Reduction of alcohol production by interrupted or limited fermentation

Interrupted or limited fermentation is the intentional termination of alcoholic fermentation before it is complete by controlling the fermentation time and temperature during fermentation [2]. Generally, during fermentation, the ethanol concentration is monitored until the desired concentration is reached. Then, fermentation is stopped either by lowering the fermentation temperature or by adding sulfur dioxide. When producing nonalcoholic or low alcohol wines using this method, the fermentation time is usually short in order to achieve a very low ethanol content. However, this usually results in sweet nonalcoholic or low alcohol wines with high residual sugar content that require further post-fermentation treatments, such as heat treatment or addition of sulfur dioxide to combat microbial instability and difficult storage [42].

2.2.2 Reduction of alcohol production through yeast biomass reduction

The reduction of yeast biomass during fermentation can also be used to produce nonalcoholic or low-alcohol wines. In this method, the yeast population is reduced from time to time during fermentation to keep the fermentation rate of fermentable sugars as low as possible. This prevents the production of high amounts of ethanol.
during fermentation. Through centrifugation, Fan et al. [37] reduced the biomass of dry yeast \(10^6\) CFU/ml during the fermentation process of an apple cider, resulting in a cider with low alcohol content and fruity aroma. Similar to limited fermentation, the final product of this technique is sweet with a high residual sugar content and requires attention for its microbial stability and storage [42]. Nevertheless, this method is useful for producing a sweeter and more pleasant nonalcoholic or low-alcohol beverage [43].

2.2.3 Reduction of alcohol production using modified yeast

The literature also reports the use of modified yeast in the production of low-alcohol and nonalcoholic wine [38, 39]. Through gene modification or adaptive evolution and selection, modified yeast strains with low ethanol production ability are developed and can be used to reduce the alcohol content in wine during fermentation [44]. A *Saccharomyces cerevisiae* strain V5 was genetically modified with an \(H_2O-NADH\) oxidase extracted from a Champagne wine yeast and used in the fermentation of a synthetic must [38]. The results showed that the modified *Saccharomyces cerevisiae* stain drastically decreased the intracellular NADH concentration and significantly altered the distribution of metabolic fluxes in the cell, resulting in the production of a lower ethanol concentration [38]. Also, genetic modification of commercial yeast strains using low-strength promoters active at different stages of fermentation regulated the expression of the *TPS1* gene, resulting in a decrease in ethanol production [39]. The problem with this technique is the release of undesirable secondary metabolites such as acetaldehyde, acetoin, and acetate [39, 45], which can negatively affect the sensory properties of the wine. In addition, the use of this technique in the production of nonalcoholic or low alcohol wines is hindered by the strong advocacy of non-GMO organisms and foods by some consumers.

2.2.4 Reduction of alcohol production using non-Saccharomyces (NS) yeasts

Non-*Saccharomyces* (NS) yeasts capable of diverting carbon or sugar metabolism to other pathways, thus preventing high ethanol production during fermentation, can be used to reduce the ethanol content of wine during fermentation [46]. Previous studies have reported the ability of NS yeast to reduce ethanol concentration within the range of 0.1–2% v/v [41, 47, 48]. For example, the sequential fermentation of *M. pulcherrima* with *S. cerevisiae* after 72 hours resulted in wines with a significant reduction in ethanol content (1.5% v/v) [49]. In addition to reducing ethanol, NS yeasts can also improve the sensory profile of wines [50–52] and control wine spoilage yeast such as *Zygosaccharomyces* species during fermentation [53].

2.3 Physical methods for removal of alcohol from wine

The complete fermentation of grape juice with high amounts of sugars produces wines. Wines are generally characterized by bitterness, hotness, good viscosity, and intense aroma and flavor. Wines can be further processed into low or nonalcoholic wines based on the final alcohol content. There are basically three methods of alcohol removal including extraction processes, membrane processes, and heat treatment [8, 9, 54].
2.3.1 Removal of alcohol by extraction processes

Extraction processes use extraction media such as gases (carbon dioxide), solvents (liquid carbon dioxide, pentane, hexane), and absorbents (zeolites) to remove ethanol from wine to produce alcohol-free or low-alcohol wine [30, 54–56]. Carbon dioxide in the form of gas or liquid can be used to extract of ethanol from wine. Carbon dioxide has a critical pressure (73 atm) and temperature (31 °C) [57], above which it behaves as a supercritical fluid (i.e., both liquid and gas) that can be used to extract organic compounds such as ethanol from wine due to its affinity for the carbon chain (as a liquid) [55] and then immediately evaporates (as a gas), leaving the extracted compound (ethanol) with a high concentration of aroma compounds [54] and no residue [7]. This method offers several advantages because carbon dioxide is inexpensive, easy to handle, does not require hazardous substances, and has a low supercritical temperature [30]. In addition, extraction solvents such as pentane and hexane are also used to remove ethanol from wines, where the ethanol dissolves in the solvent and is subsequently removed from the wine [55]. However, these extraction solvents can also remove other soluble aroma compounds along with the ethanol, which can negatively affect the aroma profile of the final product [56]. Hydrophobic adsorbents such as zeolites can also extract ethanol from wine by absorbing and filtering the ethanol from the wine. This method can be used to produce nonalcoholic wines with an ethanol content of 0.5% v/v [58]. Nevertheless, extraction methods for alcohol reduction are expensive and are rarely used in the production of low-alcohol and nonalcoholic wines.

2.3.2 Removal of alcohol by membrane processes

Membrane processes are physical separation processes that can reduce or remove ethanol from wine using a semipermeable membrane. In this method, natural osmotic pressure is created by the pressure exerted on two solutions of unequal solution concentration flowing tangentially, parallel, or circularly through a semipermeable membrane. To restore the equilibrium of natural osmotic pressure, the alcohol and water in the wine pass through the semipermeable membrane from the high-concentration solution to the low-concentration solution [30, 59]. This phenomenon reduces or removes the ethanol from the wine, resulting in a low- or non-alcoholic wine, depending on the remaining ethanol content. The most commonly used membrane separation processes at the commercial level include reverse osmosis (RO), osmotic distillation (OD), and pervaporation (PV) (Figure 2) [6, 8, 9, 30].

In PV, the transfer of compounds (by adsorption, diffusion, and desorption) occurs through a close-packed polymer membrane based on the partial evaporation of liquid mixtures with similar boiling points confined in an azeotropic mixture, with the liquid phase changing to the vapor phase [59, 60]. PV has been used to remove ethanol and recover aromatics from wines [61, 62]. It is highly selective, consumes little energy, operates at lower temperatures, causes less loss of aromatics, and is a clean method (i.e., it produces water and ethanol as by-products that can be recycled or reused). Nevertheless, the high cost of the PV machine and membranes, the low diffusion rate at low temperatures, and the limited market for PV membranes are some disadvantages of using PV to produce low-alcohol and nonalcoholic wines.

RO also works on the principle of membrane separation, in which a concentration gradient between two solutions through a hydrophilic, semipermeable hollow fiber membrane causes the solvent to flow from the high-concentration solution through
the membrane to the low-concentration solution, retaining salts, peptides, and proteins [30]. The use of RO in the production of wines and beverages with or without alcohol content has been reported [8, 9, 63, 64]. In a diafiltration configuration, an industrial-scale plant of RO was used to produce nonalcoholic red, white, and rosé wines with a final alcohol concentration of 0.7% v/v, but most of the basic oenological parameters, volatile composition, and sensory quality of the wines were affected [65]. In contrast, some studies reported that low-alcohol or nonalcoholic wines produced with RO had no negative effects on the main aroma compounds and had similar taste and aromas to normal wines [66, 67]. RO can be operated at low temperatures and meets the requirements for a clean technology, as it can recover and reuse ethanol from the dealcoholization byproduct (water and ethanol solution). However, adding water during diafiltration to achieve effective alcohol removal is a drawback of this method, as the addition of water to wine is prohibited in some wine-producing countries or regions.

Another modern membrane separation process that has found application in the production of low-alcohol and nonalcoholic wine is osmotic distillation (OD), also known as evaporative pertraction (EP). In this membrane-based technology, two liquid phases, wine and a stripping liquid (usually water), circulate in countercurrent on opposite sides of a hydrophobic hollow fiber membrane, as shown in Figure 2. In this process, the vapor pressure of the volatile solutes in the wine and the stripping liquid is the driving force [68]. The mechanism for ethanol removal in the OD process is as follows: evaporation of ethanol from the wine on one side of the membrane, followed by diffusion of ethanol vapor through the membrane pores, then finally exit of ethanol vapor from the opposite side of the membrane and condensation in the stripping water solution [68]. Minimal loss of aroma compounds was observed after alcohol reduction up to 5% v/v in Garnacha, Xarelo, and Tempranillo wines by OD [69].
Similarly, alcohol reduction up to 6% v/v in fermented beverages with OD at 10 °C–20 °C did not result in significant losses of aroma compounds [70]. Moreover, OD was used to reduce the alcohol content (~10.5% v/v) of Montepulciano d’Abruzzo red wine (13.23% v/v) and produce a low-alcohol wine with good aroma profile and unchanged wine color [12]. Contrarily to other studies [11, 71], adverse effects on volatiles were reported after alcohol reduction by OD.

2.3.3 Thermal (heat) processes for removing alcohol from wine

Thermal processes such as spinning cone column (SCC) and distillation under vacuum/vacuum distillation (VD) are two very common methods for reducing alcohol in wine and other alcoholic beverages based on the principle of heating and evaporation [8, 9, 30]. The SCC is a falling film separator consisting of a rotating vertical shaft and vertically stacked cones that rotate alternately and are fixed in place (Figure 3a). The SCC process is considered very cost-effective and efficient for retaining aroma compounds from wine, beverages, and other liquid foods [30]. In particular, it has reportedly been used to recover concentrates from grape juice, lower the ethanol content in wines, remove sulfur dioxide from grape juice, and recover aroma compounds from wines and beer [2, 9, 30, 72]. To reduce the alcohol content of the finished wine, the SCC technique uses a two-stage process. In the first stage, the wine is passed through the SCC at a reduced vacuum pressure (0.04 atm) and temperature (about 28 °C) to extract the wine aroma compounds in about 1% of the total wine volume. Subsequently, the ethanol content of the wine is reduced to produce a low-alcohol or nonalcoholic wine (depending on the final alcohol content) in the second stage at a slightly higher vacuum pressure and temperature (about 38 °C) to remove the alcohol. The aroma of the low-alcohol or alcohol-free wine is then improved by adding the recovered wine aromas (i.e., the aroma compounds extracted in the first stage) [30]. In a previous study, SCC was successfully used to recover about 97–100% of aroma compounds from white, rosé, and red wines by regulating the extraction percentage and flow rate of the base wines [72]. Moreover, 94% of ethanol was recovered from a water-ethanol mixture (14.8% v/v ethanol) using SCC at medium-high stripping rates (0.1–0.6), high feed and medium temperatures (40–50°C). However, when the alcohol content of a Chardonnay grape juice (2% v/v) was reduced halfway through fermentation with SCC, a reduction in volatile compounds

![Figure 3. Production of nonalcoholic wine using (a) spinning cone column; and (b) vacuum distillation.](image-url)
of about 25% was observed. The significant change in the concentration of volatile aroma compounds after alcohol reduction could be due to the remaining ethanol content [65], the chemical-physical properties of the aroma compounds [73], and the composition of the nonvolatile matrix of the wine [74]. The high cost of SCC technology and the costs associated with its operation are two of its main drawbacks [75].

VD is another interesting technique used to reduce the alcohol content of wines and alcoholic beverages (Figure 3b). In this technique, the feed (usually wine) from the feed tank or flask is heated to a temperature (15–20°C) [74] suitable for the evaporation or vaporization of the ethanol of the wine from the wine medium under vacuum [72], which then condenses as a distillate in a still flask, leaving a low-alcohol or alcohol-free wine, depending on the remaining ethanol content. In some cases, some important volatile aroma compounds removed along with the ethanol could be recovered from the first distillate and added back to the nonalcoholic wine. At the same time, the ethanol could also be recovered and used for ethanol correction of wines. Previous studies have reported the use of VD to reduce the alcohol content (at 0.7–5% v/v) of wines [65, 74]. For example, the alcohol content of rosé and red wines was reduced to 5% v/v, producing reduced-alcohol wines without significantly affecting polyphenols, anthocyanins, cations, and organic acids. However, significant losses in volatile aroma compounds were observed [74]. Also, VD was used to produce nonalcoholic wines (0.7% v/v ethanol) from white, rosé, and red wines, but also significantly affected most chemical parameters and volatile composition. In particular, pH, free sulfur dioxide, total sulfur dioxide, and volatile acidity decreased significantly, while reducing sugar, color intensity, and total acidity increased significantly [65]. In addition, 92–99% of esters and terpene compounds were lost [65]. VD can significantly improve the nonvolatile components in wine compared with membrane separation methods [74]. Nevertheless, VD can significantly reduce almost all volatiles in wine, especially ethyl esters, alcohols, and terpenes [65].

Another evolving technique used in the production of low and nonalcoholic wines and beverages is an integrated membrane/distillation system known as a multistage...
membrane/distillation system. This technique involves the combination of two or more alcohol removal methods to remove ethanol from wines and beers while minimizing the loss of important volatile aroma compounds associated with individual membrane and thermal separation processes such as RO, PV, OD, and VD [8, 9, 12, 65, 73, 74]. Commonly used multistage membrane/distillation systems include integrated PV and distillation units [76], reverse osmosis-evaporative pertraction (RO-EP) [77], and nanofiltration-pervaporation system (NF-PV) [78], of which RO-EP is the most commonly used (Figure 4). These integrated systems have proven successful in producing reduced-flavor, low-alcohol, or alcohol-free wines and beers with similar or improved aroma and flavor compared with the original wine or beer product [76, 78, 79]. However, significant losses of alcohols (up to 27%), acids (up to 24%), esters (up to 22%), phenols (up to 18%), and lactones (up to 14%) have been reported at ethanol reduction up to 5.5% v/v in the case of RO-EP used for alcohol reduction of a Montepulciano d’Abruzzo red wine with an alcohol content of 13.2% [80].

3. Impact of production methods on the quality of low- and nonalcoholic wines

As mentioned earlier, this chapter is focused on low and nonalcoholic wines production methods used after complete fermentation (post-fermentation stage) of wine since these methods are mostly preferred to those used at pre-fermentation and concurrent fermentation stages of wine due to their ability to achieve best results, thus, produce low and nonalcoholic wines with high concentration of fermentative aroma compounds resulting from fully fermented juice. Therefore, in this section we discuss the effect of these methods on the quality of low and nonalcoholic wines, in particular, their effect on the phenolic composition, volatile compounds, and sensory characteristics.

3.1 Effect on phenolic compounds

The phenolic composition of wine (both alcoholic and non-alcoholic) is one of the key factors influencing its quality, especially red wine, which mainly includes flavonoids (anthocyanins, flavanols, flavones, flavonols, and proanthocyanidins) and non-flavonoids (hydroxybenzoic acids, hydroxycinnamic acids, and resveratrol) [81–83]. Table 1 summarizes some reported effects of production methods on the phenolic composition of lower, reduced, low, and nonalcoholic wines. The production of nonalcoholic wines at the post-fermentation stage of winemaking using physical methods is mainly applicable to finished wines based on the principle of ethanol reduction. During the reduction of alcohol from wine, water is also removed together with the ethanol, which can have either a positive or negative effect on the phenolic composition of the final product. Wine ethanol reduction has been reported to impact wine phenolic compounds [79, 87]. The removal of ethanol from 2011 vintage Barbera red wine (14.6% v/v), Verduno Pelaverga red wine (15.2% v/v), and Langhe Rosè (13.2% v/v) by VD and membrane contactor method to a final ethanol content of 5% v/v resulted in the loss of anthocyanins and polyphenols [74]. In contrast, reduction of the alcohol level in a white wine from 12.5% v/v to 0.3% by OD had no significant effect on the total phenols and flavonoids of nonalcoholic wine compared with the base wine [11]. Similarly, flavonoids, total anthocyanins, and total phenols were not affected after the removal of ethanol (−10.5% v/v) from a red wine (13.2% v/v) [12].
whereas a reduction of up to 5% v/v ethanol in a red wine by RO-EP caused an increase in the color intensity and phenolic compounds concentration [88]. Furthermore, SCC was reported to modify the phenolic composition of red wines reduced to less than 0.3 % v/v such that the concentrations of phenolic compounds including total phenols, anthocyanins, stilbenes, flavonols, flavan-3-ols, and non-flavonoids increased significantly [87].

3.2 Effect on volatile components

The aroma and flavor of wines are mainly associated with volatile aroma compounds belonging to different chemical groups such as esters, organic acids, alcohols, terpenes, monoterpenes, C-13 norisoprenoids, aldehydes, ketones, lactones, and sulfur compounds [89]. These compounds are either of varietal (imparted from the grape skins), fermentative (produced during wine fermentation) or post-fermentative

<table>
<thead>
<tr>
<th>Method used</th>
<th>Type of wine</th>
<th>Final alcohol content (% v/v)</th>
<th>Phenolic composition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>Montepulciano d’Abruzzo red wine</td>
<td>5.4</td>
<td>Insignificant decrease in the concentrations of total anthocyanins and total phenols</td>
<td>[84]</td>
</tr>
<tr>
<td></td>
<td>Barbera red wine, Langhe Rosé wine, and Verduno Pelaverga red wine</td>
<td>5.0</td>
<td>Increased the concentrations of total flavonoids and total anthocyanins</td>
<td>[83]</td>
</tr>
<tr>
<td></td>
<td>Aglianico red wine</td>
<td>0.4–4.9</td>
<td>Increased the content of total phenols</td>
<td>[80]</td>
</tr>
<tr>
<td></td>
<td>Montepulciano d’Abruzzo red wine</td>
<td>2.7</td>
<td>Flavonoids and phenolic compounds remained unaffected</td>
<td>[21]</td>
</tr>
<tr>
<td></td>
<td>Falanghina white wine</td>
<td>0.3</td>
<td>No significant effect on the contents of total flavonoids and total phenols</td>
<td>[20]</td>
</tr>
<tr>
<td>RO</td>
<td>Montepulciano d’Abruzzo red wine</td>
<td>9.0</td>
<td>Total anthocyanins decreased Total phenols increased</td>
<td>[84]</td>
</tr>
<tr>
<td></td>
<td>Merlot, Cabernet Sauvignon, and Tempranillo red wines</td>
<td>2.0–4.0</td>
<td>No significant effect on the concentrations of total anthocyanins and phenolic compounds Increased color intensity by 20% due to high concentration of anthocyanins</td>
<td>[85]</td>
</tr>
<tr>
<td>SCC</td>
<td>White, rose, and red wines</td>
<td>&lt; 0.3</td>
<td>Increased the contents of flavonols, anthocyanins, total phenols, and phenolic compounds contents by 24%</td>
<td>[86]</td>
</tr>
<tr>
<td>VD</td>
<td>Langhe Rosé wine, Verduno Pelaverga red wine, and Barbera red wine</td>
<td>5.0</td>
<td>Increased the contents of total anthocyanins and total flavonoids</td>
<td>[83]</td>
</tr>
<tr>
<td>RO–EP</td>
<td>Montepulciano d’Abruzzo red wine (cv.)</td>
<td>5.5</td>
<td>Increased the content of total phenols Decreased the content of total anthocyanins</td>
<td>[84]</td>
</tr>
</tbody>
</table>

Table 1. 
Some reported effects of production methods on the phenolic composition of lower, reduced, low, and nonalcoholic wines.

whereas a reduction of up to 5% v/v ethanol in a red wine by RO-EP caused an increase in the color intensity and phenolic compounds concentration [88]. Furthermore, SCC was reported to modify the phenolic composition of red wines reduced to less than 0.3 % v/v such that the concentrations of phenolic compounds including total phenols, anthocyanins, stilbenes, flavonols, flavan-3-ols, and non-flavonoids increased significantly [87].
(produced from aging or additives after fermentation) origin. Factors such as grape variety, viticultural practices, and winemaking methods define the volatile composition of wines as well as its aroma and flavor [90]. As regards the production of lower, reduced, low, and nonalcoholic wines using post-fermentation methods such as membrane separation and heat treatment processes, the removal of alcohol can affect the volatile compounds of the final product. For example, the total removal of ethanol from a Tokaji Hárlevelű wine with an alcohol content of 13.1% v/v by PV resulted in a 70% loss of the total aroma compounds [61]. In addition, the production of a nonalcohol wine (0.5% v/v) from a Cabernet Sauvignon red wine (12.5% v/v) using PV led to losses of 99, 28, and 40% of esters, organic acids, and alcohols, respectively [62]. Furthermore, losses of about 9, 4, and 18% were observed in the total concentration of volatile compounds in white, rose, and red wines, respectively, after treated with SCC [72]. More recently, Sam et al. [65] compared RO and VD in the obtainment of nonalcoholic wines (with final ethanol content of 0.7 v/v) from white wine (13.4% v/v), rose wine (12.2% v/v), and red wine (13.9% v/v). They observed significant losses of volatile compounds in the nonalcoholic wines, in particular, VD resulted in losses of the total concentration of esters in white, rosé, and red wines by 96, 98, and 96%, respectively, whereas respective losses of 92, 81, and 87% were observed in RO-treated wines. Alcohol removal is not solely responsible for the losses of volatile aroma compounds during the production of lower, reduced, low, and nonalcoholic wines, other factors such as the type of method used, the operating conditions applied, the type of membrane used (in the case of membrane processes), the chemical-physical properties of the volatile compounds, and the nonvolatile matrix of the wine can also play a vital role [8, 9]. Some reported effects of production methods on the volatile compounds of lower, reduced, low, and nonalcoholic wines are summarized in Table 2.

### 3.3 Effect on sensory characteristics

Volatile compounds, especially terpenes and esters, contribute significantly to the aroma and flavor of wines [94, 95], and their complete loss or decrease due to the removal of ethanol from wine can significantly affect the sensory characteristics of the final wine product. Ethanol can enhance the perception of viscosity, bitterness, and hotness in wine, while masking other sensory characteristics such as astringency and acidity [85, 86, 96]. Some important findings on the effect of ethanol reduction using nonalcoholic wines production methods are presented in Table 3. Studies have shown that the production of lower, reduced, low, and nonalcoholic wines by post-fermentation techniques can significantly affect sensory attributes such as hotness, bitterness, aroma intensity, color, astringency, acidity, sweetness, wine body, red fruits, dried fruits, etc. [12, 62, 65, 71, 91, 99, 100]. A nonalcoholic white wine (0.3% v/v ethanol) produced by OD was characterized by low sweetness, aroma, viscosity, and high acidity in comparison to the original the wine with an alcohol content of 12.5%, giving it an unbalanced taste and unpleasant aftertaste [11]. Similar observations were made in nonalcohol white, rose, and red wines produced by RO and VD [65]. Moreover, the reduction of ethanol in Aglianico red wines at 5% v/v by a membrane contactor technique decreased aroma notes such as red fruits and cherry in the final reduced wine products [88]. Furthermore, when SCC was used to reduce the alcohol content of oaked Chardonnay wine, the perceptions of hotness and overall aroma intensity reduced substantially compared with the original wine [92]. It is worth mentioning that low and nonalcoholic wines (< 0.5–5.5% v/v ethanol) usually
<table>
<thead>
<tr>
<th>Method used</th>
<th>Type of wine</th>
<th>Final alcohol content (% v/v)</th>
<th>Losses of volatile compounds (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>Aglianico red wine</td>
<td>8.8</td>
<td>Ester = 60.9, Alcohols = 31.8, Acids = 17.1, Terpene compounds = 32.3</td>
<td>[91]</td>
</tr>
<tr>
<td></td>
<td>Montepulciano d’Abruzzo red wine</td>
<td>5.4</td>
<td>Ester = 19.0, Alcohols = 3.0, Acids = 25.0, lactones = 25.0, Phenols = 10.0</td>
<td>[84]</td>
</tr>
<tr>
<td></td>
<td>Langhe Rosè wine, Barbera red wine, and Verduno Pelaverga red wine</td>
<td>5.0</td>
<td>Ester = 23.8–47.8, Alcohols = 59.9–63.9, Acids = 17.4–30.9</td>
<td>[83]</td>
</tr>
<tr>
<td></td>
<td>Montepulciano d’Abruzzo red wine</td>
<td>2.7</td>
<td>Ester = 85.0, Alcohols = 84.0, Acids = 23.0, lactones = 37.0, Phenols = 37.0</td>
<td>[21]</td>
</tr>
<tr>
<td></td>
<td>Falanghina white wine</td>
<td>0.3</td>
<td>Ester = 99.0, Alcohols = 98.9, Acids = 98.7, Ketones = 99.9, Lactones = 98.2</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>Aglianico red wine</td>
<td>0.2</td>
<td>Ester = 89.9, Alcohols = 99.9, Acids = 78.9, Ketones &amp; lactones = 97.9, Aldehydes = 100, Sulfur compounds = 78.7, Phenols = 100</td>
<td>[82]</td>
</tr>
<tr>
<td>RO</td>
<td>Montepulciano d’Abruzzo red wine</td>
<td>9.0</td>
<td>Ester = 8.0, Alcohols = 30.0, Acids = 22.0, Phenols = 13.0, Lactones = 14.0</td>
<td>[84]</td>
</tr>
<tr>
<td></td>
<td>Chardonnay white wine, Pinot Noir rose wine, and Merlot red wine</td>
<td>0.7</td>
<td>Ester = 81–92, Alcohols = 58–75, Acids = 73–89, Terpenes = 48–70, Other compounds = 75–87</td>
<td>[74]</td>
</tr>
<tr>
<td>PV</td>
<td>Cabernet Sauvignon red wine</td>
<td>0.5</td>
<td>Ester = 99.9, Alcohols = 39.5, Acids = 28.2</td>
<td>[71]</td>
</tr>
<tr>
<td>SCC</td>
<td>White wine</td>
<td>0.3</td>
<td>Ester = 53.0, Aliphatic alcohols = 98.0, Aromatic alcohols = 3.0, Acids = 20.0, Ketones = 71.0</td>
<td>[92]</td>
</tr>
<tr>
<td>VD</td>
<td>Chardonnay white wine, Pinot Noir rose wine, and Merlot red wine</td>
<td>0.7</td>
<td>Ester = 96–98, Alcohols = 85–95, Acids = 85–91</td>
<td>[74]</td>
</tr>
</tbody>
</table>
have poor sensory quality and consumer preferences due to their imbalanced body and flavor, reduced hotness, and high acidity and astringency when compared with original wines [65, 91, 99] unless supplemented with additives. Meanwhile, lower and reduced wines (6.5–10.5% v/v ethanol) typically have acceptable preferences [12, 88, 93] due to less negative impact on the sensory characteristics arising from less ethanol removal and aroma compounds. For example, the reduction of alcohol in a white Chardonnay wine (14.2% v/v) by 4.5% v/v negatively affected consumer liking of the final product, while a reduction of 1.5% and 3.3% v/v had no significant effect. Also, when a red wine with alcohol content of 13.2% v/v was dealcoholized (i.e., its ethanol reduced) by 8% v/v, no substantial changes in the color intensity and overall acceptability were observed between the two wines [12]. In addition, an ethanol reduction by 3 and 5% v/v in two red wines (cv. Aglianico) with different initial alcohol contents (15.4 and 13.3% v/v) using a membrane contactor technique increased the bitterness, acidity, and astringency of the final lower alcohol wines, while a 2% v/v reduction resulted in no significant differences between the base wines and the final wine products [88]. Similarly, Meillon et al. [93] reported a decrease in consumer preference for a Syrah red wine (13.4% v/v) dealcoholized by 5.5% v/v and a nonsignificant effect on the preference at dealcoholization by 2% and 4% v/v using RO. The inability of most consumers to notice alcohol reductions ≤2% v/v may have accounted for these results [8].

4. Aroma improvement of lower, reduced, low, and nonalcoholic wines

The aroma profiles of lower, reduced, low, and non-alcoholic wines have a great impact on consumers’ acceptability and mostly depend on volatile compounds. As the removal of alcohol from finished wines usually results in substantial loss of volatile compounds leading to changes in organoleptic properties, innovative ways for correcting these adverse effects are needed. Ways of improving the aroma and

<table>
<thead>
<tr>
<th>Method used</th>
<th>Type of wine</th>
<th>Final alcohol content (% v/v)</th>
<th>Losses of volatile compounds (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langhe Rosè wine, Barbera red wine, and Verduno Pelaverga red wine</td>
<td>5.0</td>
<td>Terpene compounds = 92–96 Other compounds = 91–99</td>
<td>[83]</td>
<td></td>
</tr>
<tr>
<td>RO-EP</td>
<td>Shiraz red wine</td>
<td>10.4</td>
<td>Esters = 49.5 Alcohols = 39.9 Terpene compounds = 35.3 Lactones = 21.4</td>
<td>[93]</td>
</tr>
<tr>
<td>Montepulciano d’Abruzzo red wine</td>
<td>5.5</td>
<td>Esters = 22.0 Alcohols = 27.0 Acids = 24.0 Phenols = 18.0 Lactones = 14.0</td>
<td>[84]</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Some reported effects of production methods on the volatile compounds of lower, reduced, low, and nonalcoholic wines.
sensory properties of lower, reduced, low, and nonalcoholic wines are rarely reported in the literature although the use of fruit-based, herb-based, and other rarely used aroma additives in enhancing the aroma profile of wines and alcoholic beverages has been reported [101]. For example, the concentration of monoterpenes and monoterpenyl glycosides significantly increased after the addition of phenolic-free glycosides, resulting in an increase in floral and fruity aroma, flavor, and aftertaste attributes, without altering the bitterness or stringency [102]. Similarly, dehydrated waste grape skins were used to improve the aroma composition of red wines [103]. Furthermore, addition of hydroalcoholic plants macerates to Vermouth and basic wines improved their sensory characteristics such as aroma, taste, and smell [104]. Moreover, when 2 g/L of Ganoderma lucidum extract was added to a Shiraz wine product, it imparted the wine with fruity and floral notes [105]. Also, the addition of oak chips to Verdejo wines imparted the wines with higher concentrations ethyl acetate, hexyl acetate,
isoamyl acetates, higher alcohols, and ethyl esters of straight-chain fatty acids [106], which are known to contribute fruity and floral aromas to the wines. Other wines aromatized with botanical extracts include Benedictine, Chartreuse, liqueurs, and bitters [97]. Possibly, the reciprocation of these studies in lower, reduced, low, and nonalcoholic wines would significantly improve their aroma profile. However, the ongoing debate at OIV whether to permit the use of flavorings or exogenous aroma additives from grapes or non-grapes origin in the aroma improvement of these categories of products is a major hindrance to the scientific exploration in this field. Nevertheless, some studies have reported on the aroma improvement of dealcoholized wines (lower, reduced, low, and nonalcoholic wines) and beers [11, 76, 107]. In an attempt to improve the aroma profile of a white wine (11.5% v/v) dealcoholized to a final ethanol content of 0.8% v/v by vacuum evaporation, glycosidic aroma precursors isolated from Muscat grapes were added to the dealcoholized wine. This increased concentrations of β-phenylethyl alcohol, linalool, and geraniol, imparting the final product with high fruity and floral odors [107]. Similarly, Liguori et al. [11] developed an alcohol-free wine beverage with improved aftertaste and flavor from an OD dealcoholized white wine (0.3% v/v ethanol) by adding grape must, sodium carbonate solution, and some floral wine flavors. Furthermore, the aroma profile of a nonalcoholic beer with alcohol content of less than 0.5% was improved by first extracting aroma compounds from non-carbonated alcoholic beer (5.67% v/v ethanol) by pervaporation. Subsequently, the alcohol was removed from the alcoholic beer by spinning cone column distillation. The dealcoholized beer was then reconstituted with about 5–10% v/v of the original beer and 0.3% v/v of the extracted aroma compounds and finally carbonated, resulting in a nonalcoholic beer with improved aroma profile similar to the original beer [76]. Recently, a study was conducted at Gansu Key Laboratory of Viticulture and Enology, College of Food Science and Engineering, Gansu Agricultural University, China to investigate the effect of rose (R. chinensis var. spontanea red) peach (Prunus persica), and lily (Lilium bulbiferum) flower extracts on the aroma profile of dealcoholized red and rose wines (0.7% v/v ethanol). The dealcoholized wines were reconstituted by the addition of the flower extracts. Sensory analysis was performed, which revealed that the aroma profile of the reconstituted

Figure 5.
Spider plot of sensory analysis (means) performed on (a) rose wine; and (b) red wine. Different letters (a–c) represent significant differences at a significant level of 0.05. OW; original merlot wine (control), DW; dealcoholized merlot wine (control), R-RDW; rose reconstituted dealcoholized wine, P-RDW; peach reconstituted dealcoholized wine, L-RDW; and lily reconstituted dealcoholized wine.
dealcoholized wines improved significantly after the addition of the extracts compared with the dealcoholized wines. In particular, the aroma attributes such as red fruits, fruity and floral, and aroma intensity increased (Figure 5), which was attributed to some aroma compounds including isoamyl acetate, ethyl hexanoate, ethyl octanoate, isoamyl octanoate, phenethyl acetate, linalool, β-damascenone, and geraniol imparted by the added flower extracts. These aroma compounds are known to contribute fruity and floral aromas to wine [98, 108–110]. In addition, the reconstituted dealcoholized wines were perceived sweeter and less acidic and astringent with improved wine body and overall acceptability among the panelists (Figure 5).

5. Perspectives

With health risks awareness, consumer preferences are shifting toward new product offerings and alternatives, with increasing percentage of the adult population seeking lower alcohol wines more frequently. This has boosted nonalcoholic wine production and sales, with many industries and researchers already abreast with different nonalcoholic wine production techniques at the various stages of winemaking. In this chapter, we focus on the methods used for the production of NW from high-strength alcoholic wines after complete fermentation (wine post-fermentation stage). Specifically, their impact on the aroma profile and sensory characteristics of NW as well as the state-of-the-art methods of improving the aroma profile of such product. Among the methods of NW production, physical dealcoholization methods are usually used as they can achieve the best results when used on a finished wine. Also, when used in the reduction of ethanol at several percent (2–4% v/v), they can preserve the phenolic compounds, volatile compounds, and sensory quality of the wine. Furthermore, the end product usually has a taste almost similar to original wine. In contrast, the other methods discussed in this chapter can produce unbalanced wines (with high acidity, unfermented juice, and low fermentative aroma compounds) with legality issues in the case of the juice fermentable sugars dilution with water. Nevertheless, some important aroma compounds can be lost using physical dealcoholization methods in the production of NW. Therefore, subsequent aroma enhancement may be needed to compensate for the loss of important volatile compounds associated with the aroma profile of the NW during dealcoholization. Currently, there are few studies that scientifically evaluate or optimize the parameters of the production process of aroma-enhanced dealcoholized wines, which could be one of the future research areas. To date, there is limited research on new types of aroma-enhanced dealcoholized wines, though there is evidence that the use of fruit-based, herb-based, and other rarely used aromatic materials in winemaking improves the aroma profiles of wines and dealcoholized wines. Moreover, the unapproved use of fruit-based, herb-based, and other aromatic materials as an oenological practice by the European Union (EU) and the International Organization of Vine and Wine (OIV) is a major setback to their use as wine additives. Nevertheless, for the category of special and aromatized wines, they could be added. The development of novel products from dealcoholized wines reconstituted with fruit-based, herb-based, or new aroma additives represents a potential new market for the wine industry. Therefore, future development of such products will benefit not only the wine industry by producing diversified and high-quality commercial NW and wine products, but also consumers by providing options for novel aroma-enhanced dealcoholized wines with unique and pleasant aroma profiles.
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Conflict of interest

The authors declare no conflict of interest.

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