

Review Article

Effects of Production Methods on Flavour Characteristics of Nonalcoholic Wine

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The growing awareness on the negative effects of alcohol on health and other factors like religious beliefs, responsible driving, and strict alcohol regulatory laws have contributed to the overwhelming demand for nonalcoholic wines. Numerous methods are available for producing nonalcoholic wines which encompass both restrictive ethanol production processes (interrupted fermentation, cold fermentation, juice/wine blends, use of unripe fruit, enzyme, and special and immobilized yeasts) and alcohol removal methods (heat, membrane, and extraction techniques). Studies have shown that these methods significantly affect the flavour characteristics of the wine, which is a key quality parameter in wine purchasing and consumption. It is in view of this that this work seeks to review current articles on the effects of production methods on the flavour characteristics of nonalcoholic wine. This review will provide insight on nonalcoholic wine production methods, their merits and demerits, and contributions to flavour characteristics. It will also unfold research opportunities in the field of nonalcoholic wine production for continual improvement and development of the wine industry.

1. Introduction

Wines are alcoholic beverages produced from the fermentation of fruit juices of grape, berry, apples, and other pome fruits [1–3]. They exist in the forms of red, white, sparkling, dessert or sweet and rose, or fortified wines depending on the composition of the fruit juice and the fermentation conditions. Wines are noted and consumed for the phenolic compounds they offer, which are very good for scavenging free radicals, enhancing fat oxidation, reducing stress, inflammation, DNA damage, aging, and cancer, and improving immune system and cardiac functioning [4]. Wine production involves the conversion (fermentation) of carbohydrates, sugars, and other food components into alcohol and flavour compounds. Due to this, most wines have high alcohol content which limits its consumption by majority of

people and patronage or marketability due to alcohol regulatory laws [5, 6].

The nonalcoholic wines, also referred to as alcohol-free or dealcoholized wines, are beverages that have less than 0.5% alcoholic content by volume [7]. However, there are some other wines with reduced alcohol (1.2–6.5% v/v) and low alcohol content (0.5–1.2% v/v) [8, 9]. This classification system is indicated on wine bottles as labeling and legislative requirements and differs from one country to another [10]. Nonalcoholic and reduced alcohol wines are becoming popular and attaining remarkable acceptance as a result of issues concerning good health, religion, and moral backgrounds. A research by Wittwer et al. [11] discovered that low alcohol wine consumption is on the increase constituting about 40% of total wine consumption in the USA. A similar study also revealed that 16% of the study population

preferred low alcohol wine because of the adverse effect alcohol has on health and responsible driving [5, 9]. Another study investigating the importance of choice cues on UK wine consumers' wine purchasing decisions disclosed that about 43% of wine consumers place premium on alcohol content of wine [12]. Wittwer et al. [11] identified great market opportunity for low alcohol wine in Australia and UK.

There are diverse methods of nonalcoholic wine production which are usually based on limiting alcohol production in the course of the fermentation process or removing or distilling alcohol after the fermentation. Methods for limiting alcohol production include restrictive fermentation, use of special yeast, reduction of fermentable sugar concentration, and cold fermentation [13, 14], whereas removal of alcohol from the wine following completion of fermentation can be achieved either through the application of thermal distillation processes, with or without vacuum, or the transport of ethanol across a semipermeable barrier or membrane [7, 15]. Studies have shown that these methods significantly affect the flavour characteristics of the wine, which is a key quality parameter in the wineries [14, 16]. Wine flavour comprises taste, aroma, and visual attributes, with aroma (smell) being the major contributor to the overall flavour perception. The chemical composition of wine is the foundation of the sensory response and is usually affected by the variety, microbial ecology, and geographical and viticultural conditions of the grape, as well as fermentation processes and winemaking practices [17]. This work therefore seeks to review the effects of the various production methods on the flavour characteristics of nonalcoholic wine. The review will provide insight on nonalcoholic wine production methods, their merits and demerits, and contributions to flavour characteristics. It will again reveal new research prospects in the field of nonalcoholic wine and its related activities, thus promoting the sector.

1.1. Production Methods of Nonalcoholic Wine. Numerous methods are available for the production of nonalcoholic wines as summarized in Table 1. These methods are broadly categorized into two types, namely, restrictive ethanol production and alcohol removal methods [13, 14]. Restrictive ethanol production methods are based on the principle of reducing or limiting alcohol production before or during fermentation through a number of approaches, whereas alcohol removal methods aim at reducing the alcohol content of the wine after fermentation (post-fermentation) through alcohol distillation processes [7, 18, 19].

2. Restrictive Ethanol Production Methods

There are basically seven (7) techniques employed in reducing the alcohol content of a wine just before or in the course of the fermentation process, which include interrupted fermentation, yeast cold contact fermentation, juice/wine blend, and use of unripe fruit, special, or immobilized yeasts [13, 18, 20, 21].

2.1. Interrupted Fermentation. It is also called partial fermentation and involves the process of arresting or halting the fermentation process when desired amount of alcohol has been produced in the fermenting must. The fermentation is performed at a temperature lower (4–15 °C) than a regular fermentation (17–30 °C), until reaching an ethanol content below 0.5%, and halted through the addition of sulphur dioxide, centrifugation, or pasteurization to stabilize the wine, i.e., to prevent further fermentation [10, 22]. The halting processes either inhibit the growth of the yeast (sulphur dioxide) or cause destruction, fragmentation, and breakage of yeast cells (centrifugation and pasteurization). This implies that the fermentation process is brought to end upon reaching a certain alcohol content whether or not there is the presence of fermentable sugars. The process is usually practiced in UK to attain an alcohol content of 5.5% in order to attract lower tax [10].

Interrupted fermentation produces wine with low alcohol content and good fruity colour and taste due to the high unfermentable sugars. However, there is restriction on the development of aroma and flavour compounds resulting from the incomplete fermentation. This gives the wine a fruity aroma/flavour instead of actual wine flavour that develops through complete fermentation [23–25]. There is limited literature on the effect of interrupted fermentation on the flavour characteristics of nonalcoholic wine, in terms of volatile or aroma compounds determination and sensory evaluation. Further research is required to explore the possible ways of improving the aroma or flavour of these wines in order to meet consumer expectations.

2.2. Yeast Cold Contact Fermentation. Yeast cold contact fermentation, simply referred to as cold fermentation, is a type of fermentation process which is usually done at low temperatures (0–4°C). Studies have shown that, at such reduced temperatures, oxygen solubility and diffusivity in the must are high which favour aerobic fermentation that results in low alcohol production [26, 27]. In such a situation oxygen serves as an electron acceptor (energy) for the yeast, other than sugars, thereby limiting sugars utilization. This results in the wine having none or low alcohol content with the retention of flavour or aroma compounds [28]. High temperature (25–30°C) fermentation has been identified to favour alcoholic fermentation which normally produce high alcohol wines [27]. At low temperature, yeast is able to break down carbonyl compounds (aldehydes) from the must to produce wine aroma compounds [24, 29]. On the other hand, yeast also metabolizes aldehydes from amino acids in the must, producing undesirable or off-flavours during cold fermentation [25, 30].

A study by Mortazavian et al. [13] involving the use of *S. cerevisiae*, *S. ludwigii*, and *S. rouxii* at different fermentation temperatures of 4, 12, and 24°C revealed that fermentation at 4°C recorded the lowest alcohol content in all the yeasts used, but fermentation at 24°C had the highest flavour attributes and consumer acceptability. This observation is supported by the fact that cold fermentation does not bring out those flavour compounds that are extracted at

TABLE 1: Summary of non-, low, or reduced alcohol wines production methods.

Principle	Methods
Restrictive ethanol production or reduction of fermentable sugar concentration in grape or juice	(i) Use of unripe fruit (ii) Juice blends or wine dilution (iii) Use of enzymes (e.g., glucose oxidase) (iv) Arresting fermentation early (v) use of special and immobilized yeasts
Removal of alcohol from wine	(i) Thermal: distillation under vacuum or atmospheric pressure; spinning cone column (ii) Evaporation: pervaporation (iii) Freeze concentration (iv) Membrane: dialysis; reverse osmosis (v) Adsorption: resins; silica gel (vi) Extraction: organic solvents; supercritical carbon dioxide

Source: Pickering [10], Mortazavian et al. [13], Kontoudakis et al. [20], Goh et al. [7].

high temperatures, for complete body and structure of the wine. There is the need, therefore, for studies that focus on optimizing temperature, time, and yeasts combinations for the production of nonalcoholic and low or reduced alcohol wines using cold fermentation.

2.3. Use of Special Yeasts. *Saccharomyces cerevisiae* is the major yeast for wine fermentation due to its capability of converting sugars to alcohol and preeminent tolerance to the tense conditions encountered during alcoholic fermentation. Although numerous *S. cerevisiae* wine strains are available commercially for wine production, they all show a similar high ethanol yield [18]. Production of nonalcoholic and low or reduced alcohol wines can be accomplished through the use of special yeast strains such as *Saccharomyces ludwigii*, *Saccharomyces uvarum*, *Saccharomyces* or *Zygosaccharomyces rouxii*, *Hanseniaspora uvarum*, *Lachancea thermotolerans*, *Metschnikowia pulcherrima*, *Pichia kluyveri*, *Schizosaccharomyces malidevorans*, *Starmerella bacillaris*, *Torulaspora delbrueckii*, or *Zygosaccharomyces bailii* other than the traditional wine yeast (*S. cerevisiae*) during fermentation [14, 31]. Some of these yeasts such as *S. rouxii* have the potential of fermenting glucose and fructose but not maltose into alcohol, and others are capable of preventing the alcohol formation stage or utilizing the alcohol being produced in the course of the fermentation, resulting in a nonalcoholic or low/reduced alcohol wines [27, 32]. In addition, some yeast strains like *S. ludwigii* also lack the alcohol dehydrogenase that is responsible for converting acetaldehyde (intermediate product from sugars for alcohol synthesis) to alcohol [33]. The higher concentration of unfermented sugars renders some of these wines sweet with fruity flavours compared to traditional alcoholic wines [23, 24].

Bely et al. [14] recorded 0.34% and 10% v/v ethanol content for *S. uvarum* and *S. cerevisiae*, respectively, with the wine from the *S. uvarum* having undesirable flavour profiles and complexity. Sequential fermentation trials employing *Lachancea thermotolerans* (formerly *Kluyveromyces thermotolerans*) carried out under industrial conditions using a high inoculation level (10^7 cell/ml) with a delay of the second inoculum (*S. cerevisiae* strain) for 2 days resulted in an

ethanol reduction of 0.7% v/v with improved sensorial properties and distinctive flavour [34]. A study undertaken by Contreras et al. [35] using *Metschnikowia pulcherrima* also had a lower alcohol content (0.9–1.6% v/v), with higher concentrations of esters and higher alcohols responsible for its good flavour and organoleptic or sensory properties comparable to those of *S. cerevisiae*. Mortazavian et al. [13] researched on the use of *S. cerevisiae*, *S. ludwigii*, and *S. rouxii* for nonalcoholic wine production and discovered that *S. ludwigii* and *S. rouxii* are capable of producing wine with alcohol content less than 0.5% v/v although *S. cerevisiae* had good flavour profiles. A current study involving the use of *Saccharomyces ludwigii* and *S. cerevisiae* recorded ethanol content of 5.8%–9.7% and 10%, respectively, and similar trend for other non-*Saccharomyces* yeasts like *Wickerhamomyces anomalus*, *Starmerella bacillaris* (*Candida zemplinina*), *Metschnikowia pulcherrima*, *Cyberlindnera saturnus*, *Wickerhamomyces subpelliculosus*, and *Cyberlindnera jadinii* [36]. The wines prepared from the non-*Saccharomyces* yeast strains had spicy, acidic, and solvent aroma notes compared to the *Saccharomyces* strains, which had ripe fruit and floral aroma. Research into the numerous non-*Saccharomyces* yeast strains will help to discover other yeast strains that may give lower alcohol yield with enhanced flavour characteristics.

2.4. Use of Glucose Oxidase (GOX). The enzyme glucose oxidase (GOX) obtained from the fungus *Aspergillus Niger* converts glucose into gluconic acid and hydrogen peroxide, thereby reducing the amount of sugars available for alcohol production. The enzyme has no significant effect on the aroma, flavour, acidity, and colour of the grape and hence the resultant wine [8, 37]. On the contrary, other studies have reported on an increase in total acidity and a slight decrease in pH due to GOX activity, which can affect the sensory properties (taste and flavour) of the wine [38, 39]. The addition of GOX also increases the number of carbonyl compounds that can bind sulphur dioxide (SO₂), resulting in higher SO₂ concentration in wine and its allergic effects on consumers [38, 40]. As GOX works more efficiently when oxygen is supplied, this outcome could potentially be improved upon by must aeration. The effect of hydrogen

peroxide on wine colour or phenolic substances has not been extensively investigated, but higher values for browning of wines treated with GOX were reported [37]. Increased oxidation of phenolic substances is a likely explanation for these observations. Commercial preparations of the enzyme added to grape juice were found to reduce ethanol concentration in the resulting wine by 0.68% v/v compared with that of untreated wines [8]. Sensory analysis showed that wines produced from GOX treated must had a lower intensity of fruit aromas, reduced length of flavour, and higher acidity than those of untreated wines [39]. A similar study by Biyela et al. [21] resulted in a reduced alcohol wine of 6.4% v/v alcohol content. However, the sensory analysis revealed that the GOX treatment process modified the taste and colour while flavour remained the same. Additional research work is needed to understand the factors that can help improve the flavour of nonalcoholic and low or reduced alcohol wines produced from the use of GOX.

2.5. Use of Immobilized Yeasts. Yeast immobilization refers to the physical detention of intact cells while maintaining biological activity on a carrier or support material. The use of this process for nonalcoholic wine production confers a lot of advantages such as high cell densities, product yield improvement, lowered risk of microbial contamination, better control and reproducibility of the processes, and reuse of the immobilization system for batch and continuous fermentation technologies over the conventional free yeast cell methods [41, 42]. The carrier material usually used in yeast immobilization processes involves using natural supports (e.g., fruit pieces or agricultural byproducts), organic supports (e.g., alginate), inorganic supports (e.g., porous ceramics), membrane systems, and multifunctional agents [43].

Immobilized yeasts help in producing nonalcohol wine by preventing the formation of ethanol in the fermentation process. The carrier support used in the immobilization process serves as point of attachment for the yeasts to form colonies, implying that the yeast growth is not dependent on the sugar in the must. In the process, the must flows continuously through the packed bed of the colonized carrier. The regulation of temperature and must flow rate (residence time) influences the extent of fermentation and, consequently, the alcohol content of the wine exiting at the bioreactor outlet. Production of alcohol is restricted, yet the yeasts convert must aldehydes into homologue alcohols (flavour compounds) [24, 25, 41, 42]. Notwithstanding the development of wine flavour compounds, the process is difficult to control because of the high cost of the carriers and high risk of contamination beyond the need of a continuous bioreactor [41].

2.6. The Use of Unripe Fruits. Alcohol level of wine is mainly determined by the sugar content of the grapes or fruit to be used in the wine production. The sugar content of fruits increases during ripening and continues to rise in the course of dehydration. The higher the sugar concentration, the higher the alcoholic fermentation, thus increasing

alcohol content of the wine [44]. Therefore, it is important to consider the viticultural practices to control final alcohol concentration of wines which principally involve harvesting the fruit at the primary stage of development. The use of unripe fruit results in production of nonalcoholic and low or reduced alcohol wines; however, 'unripe' aromas and unacceptably high acid levels in the finished wine lead to a product of inferior quality [45]. Kontoudakis et al. [20] reported that reduced alcohol wines from first harvest fruits had 0.9%, 1.7%, and 3.0% less alcohol content than their corresponding control wines of second harvest, but a decrease in flavour and texture (mouthfeel) of wines from the first harvest compared to the second harvest during sensory evaluation. An earlier study by Stillman [44] also recorded a similar trend where the alcohol content of the unripe fruits was low but had a decrease in flavours compared to fully ripe fruits. These discrepancies were attributed to reduced development of flavour precursors of the fruits prior to harvest, high acidity levels, and yeast-contributed flavour compounds. Not so much research has been done in this area, and therefore a lot more studies may be required to truly understand the mechanism and other contributing factors since it is one of the cheap and surest ways of producing nonalcoholic and low or reduced alcohol wines.

2.7. Blends and Dilution of Juice or Wine. With respect to blends and dilution, dilution with water is the easiest method of reducing alcohol concentration. Alcohol dilution also can be achieved by unification or amalgamation of full-strength, reduced alcohol, or partially fermented wine with fruit juice(s), as in the commercial production of wine coolers (alcoholic beverage prepared from combination of wine and fruit juices). Some works in this area included the development of a reduced alcohol wine product by blending grape must with kiwifruit juice (*Actinidia chinensis Planch*) and low alcohol wine coolers from blends of red table wine and blood orange juice [46]. In Australia, water added as part of wine additions, such as fining agents, is limited to 7% v/v which potentially lowers alcohol concentration by almost 1% v/v. Factors other than sugar, like titratable acidity, colour, tannins, and wine flavour, are also affected by water addition. Harbertson et al. [47] added water to merlot must to produce a wine with 2% v/v less ethanol concentration with an increased fresh fruity flavour compared with that of the untreated or unblended wine.

Similarly, using early harvested low sugar grapes to dilute final ethanol concentration in wines made from more mature grapes will also upset final wine composition and sensory attributes. The high acidity, immature phenolic substances, and unripe flavours of the early harvested grapes can produce unbalanced musts and consequently wines with less desirable flavour profiles [38, 46]. Taking into account the potential impact of flavour profile on wine demand and purchasing and alcohol regulatory requirements, dilution, and blending strategies might be useful strategies to reduce alcohol content in wine while maintaining a cohesive organoleptic appeal. A study to determine the appropriate fruit

blends and the proportions or standardized dilution factor for wine to water will be an insightful and a useful advancement in the wine industry.

3. Alcohol Removal Methods

It is expected for any normal or uncontrolled fermentation process to end up with alcohol production, since fermentation in its actual sense is the conversion of carbohydrates or sugars to alcohol by yeast. Alcohol removal methods are basically founded on the principle of removing or distilling alcohol from the wine after fermentation. It is termed in other contexts as postfermentation processes. These methods for alcohol removal are grouped into three (3) and comprise heat treatment, extraction processes, and membrane processes based on the principle or medium of alcohol removal [7, 19].

3.1. Heat Treatment Processes for Wine Alcohol Removal.

The removal of alcohol from wine following the completion of fermentation can be achieved through the application of thermal distillation processes, with or without vacuum. This process involves the removal of ethanol by the application of heat. Ethanol and water have boiling points of 78 and 100°C, respectively, and therefore heating wine slightly above 78 °C causes alcohol to vaporize preferentially, leaving water and other components with reduced alcohol content behind. Heat treatment for alcohol removal includes vacuum evaporation (wine is heated with steam in plate evaporators under vacuum) [48], vacuum distillation (employs distillation columns operating under vacuum) [49], and centrifugal distillation (uses column with especial design called spinning cone column, which consists of a gas-liquid countercurrent column, where the stripping medium extracts the ethanol from the wine or beverage as shown in Figure 1) [15, 19, 50, 51]. On the contrary, elevated temperatures used in the dealcoholization process have been found to destroy heat labile molecules and other volatile compounds that contribute to the overall flavour, body, and structure of the wine [52]. Studies have revealed the application of low pressure or vacuum with reduced temperature as a way to reduce the deleterious effect of heat treatment on the volatile compounds in nonalcoholic wines [48, 49].

Garcia et al. [54] dealcoholized wine using centrifugal distillation or spinning cone column to alcohol content of about 0.5% v/v but reported low sensory scores for taste, aroma, flavour, and overall acceptability compared to its corresponding alcoholic counterpart containing 6% v/v alcohol content produced by reverse osmosis. A study involving the use of vacuum distillation also had a reduced alcohol content but a drastic loss of volatile compounds, resulting in nonalcoholic wine with poor flavour profile [55]. The low residence time and temperature of operation of spinning cone column or centrifugal distillation helps to reduce the impact of heat on the wine aroma compounds [19, 50], though certain volatile compounds are removed by stripping medium along with ethanol [56]. Studies by Kujawski [48] and Montgomery [52] established that heat

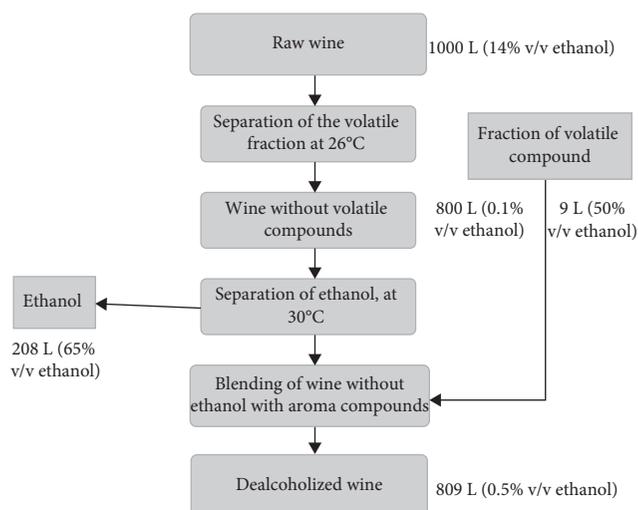


FIGURE 1: Production of nonalcoholic wine using spinning cone column [53].

treatment processes significantly affect the aroma, flavour, and taste of the nonalcoholic wines, even those that operate at moderate temperatures or use strip streams.

Moreover, another thermal method, although infrequently used, is freeze concentration. In this method, water in wine is reduced by freezing and the alcohol in the residual liquid is removed by vacuum distillation. Also, the wine can be cooled until crystals are formed, which are separated and later thawed. The resultant wine can be adjusted to any alcohol content with the separated alcohol fraction. The process is relatively delicate and expensive [57, 58].

3.2. Extraction Processes for Wine Alcohol Removal.

Extraction processes are techniques that use extraction medium to eliminate ethanol from wine rendering it non-alcoholic, and such extraction medium may include solvents, gases, and adsorbents [50, 59]. Extraction media such as pentane or hexane as applied in solvent extraction process have the potential to cause ethanol to dissolve in it, thereby being removed from the wine [50]. The solvent extraction process has the effect of leaving traces of solvents in the wine and causing the removal of aroma compounds that are soluble in the solvent with ethanol, which subsequently affect the overall flavour and quality of the nonalcoholic wine [60].

Carbon dioxide extraction is also another extraction or alcohol removal process that makes use of supercritical or liquid carbon dioxide as extraction medium. Above certain specific critical temperature and pressure, carbon dioxide behaves as an organic solvent that has the potential to extract alcohol from wine thereby making it nonalcoholic with good sensorial attributes and flavour profile [50, 52, 61]. Reports indicate that the process also strips aroma compounds from the wine. Therefore, the best way to implement it is to have a two-phase extraction stage, the first stage extracts aroma compounds and incorporates them back after the alcohol extraction [62, 63]. Ruiz-Rodríguez et al. [64] conducted dealcoholization experiments on different wines (white and

red wines) employing supercritical CO₂ as extraction medium and discovered that there were a lot of aroma compounds in both alcoholic and the emerged low alcohol wine, though sensory analysis was not done. The operation cost of this process is usually high [50, 52].

Adsorption is a solvent extraction method for removing alcohol from wine, with resultant alcohol content of less than 0.5% v/v (nonalcoholic wine). In this process, the wine is made to pass through a column stacked with hydrophobic adsorbents like zeolites, which adsorb and sieve ethanol from the wine. The aroma compounds extracted along with ethanol are reverted by having a similar two-stage process that extract the aroma compounds and reintroduce them into the dealcoholized wine [59, 60, 65]. In general, alcohol removal extraction processes are extremely expensive, and their application in the food industry for nonalcoholic wine production is becoming rare [59, 65, 66].

3.3. Membrane Processes for Wine Alcohol Removal.

Membrane processes (MP) are types of separation methods which can be used to reduce alcohol content of wine. MP involves two solutions with unequal solute concentration separated by a semipermeable membrane which establishes a concentration or pressure gradient known as osmotic pressure [67, 68]. The created concentration or osmotic gradient causes the alcohol and water in the wine to permeate to a region of lower alcohol concentration, hence decreasing the alcohol content of the wine. Reverse osmosis (RO) and dialysis are two of such processes that make use of membranes and both are used commercially [69, 70]. RO system operation involves pressure filtration of the wine through a fine porous membrane as shown in Figure 2. Dialysis is based on the use of membrane contactors (like hollow-fibres) where wine flows countercurrently to the dialysate (e.g., water) made for concentrating compounds with molecular weights between 250 and 2000 Da and removing monovalent salts, methanol, and/or ethanol from aqueous solutions of these compounds [48, 49, 69]. They have the advantage of working at low temperatures of approximately 5–10°C, where there is minimal negative influence on taste [57]. These membranes provide permeability for alcohol and water, but not for most of the dissolved extracts, hence, the preservation of some aroma compounds (e.g., esters and aldehydes), organic acids, and potassium [57]. In addition to being expensive, dialysis also loses a great deal of wine aroma compounds to the dialysate as reported in the works of Pilipovik and Riverol [66], Kujawski [48], and Mulder [49]. Nanofiltration works on the same principle as reverse osmosis and dialysis [69]; however the later requires higher pressure than the former, which could be detrimental to aroma compounds as disclosed by Mulder [49] and Baudot et al. [71].

The application of reverse osmosis and diafiltration by Lopez et al. [72] in producing a low alcohol cider resulted in a cider with a reduced alcohol content and desirable aroma compounds. Contrary to this finding, two dealcoholized wines produced through reverse osmosis by Meillon et al. [73] were revealed to have contained unpleasant aroma

compounds which resulted in some odour sensations during sensory evaluation. A research by Labanda et al. [74] looking at the removal of ethanol from a model white wine by means of reverse osmosis and nanofiltration discovered a high retention of aroma compounds in the nonalcoholic wine. Extensive research is required to determine the sensory characteristics of wines produced by the alcohol or ethanol removal methods.

Osmotic distillation (OD) also known as evaporative pertraction is another membrane process with proven potential of removing ethanol from beverages or wine. It removes alcohol from wine through the use of hydrophobic porous membrane that ensures ethanol transfer from the alcoholic wine to the strip solution (water) that countercurrently flows downstream of the module. The separation is caused by the difference in the vapour pressure of ethanol between the wine and the strip solution [71, 75, 76]. Significant amount of wine flavour compounds is lost in the course of the process as revealed by studies of Dobrak et al. [75] and Baudot et al. [71]. The evaluation of mass transfer of ethanol and aroma compounds during wine dealcoholization by Diban et al. [69] using osmotic distillation revealed significant losses of aroma compounds in the process; yet, sensory panelist could not detect any difference between the alcoholic wine and nonalcoholic or reduced alcohol wine during sensory testing. A similar study involving the use of osmotic distillation by Varavuth et al. [77] also noticed loss of important aroma compounds like ethyl acetate and isoamyl alcohol which contribute significantly to flavour characteristics of wine, though sensory analysis was not carried out.

Another modern membrane process that has found application in the production of nonalcoholic wine is the pervaporation. During pervaporation, the wine is forced through a dense polymeric membrane kept under high vacuum, which causes alcohol and volatile compounds to permeate and vaporize at the downstream of the membrane. The driving force of the separation is based on the chemical potential gradient through the membrane thickness which is a function of the partial pressures and the corresponding activity coefficient of the operating system [68, 78]. Economic analysis studies by Karlsson et al. [68] identified pervaporation as one of the best methods for producing high quality nonalcoholic wines, but very expensive due to low fluxes of pervaporation membranes, high cost of dealcoholizing vacuum and condensing system, and therefore the process not being economically feasible for commercial production.

3.4. Flavour Compounds Profile of Nonalcoholic versus Alcoholic Wines.

The flavour profile of alcoholic wines has been found to contain higher alcohols and secondary metabolites like terpenes, monoterpenes, C-3 norisoprenoids, C-6 alcohols, among many others [79, 80]. Studies have shown that these compounds are produced during the complete fermentation process and undergo biochemical interactions to produce a more pleasant flavour [38, 46]. These higher alcohols and secondary metabolites are

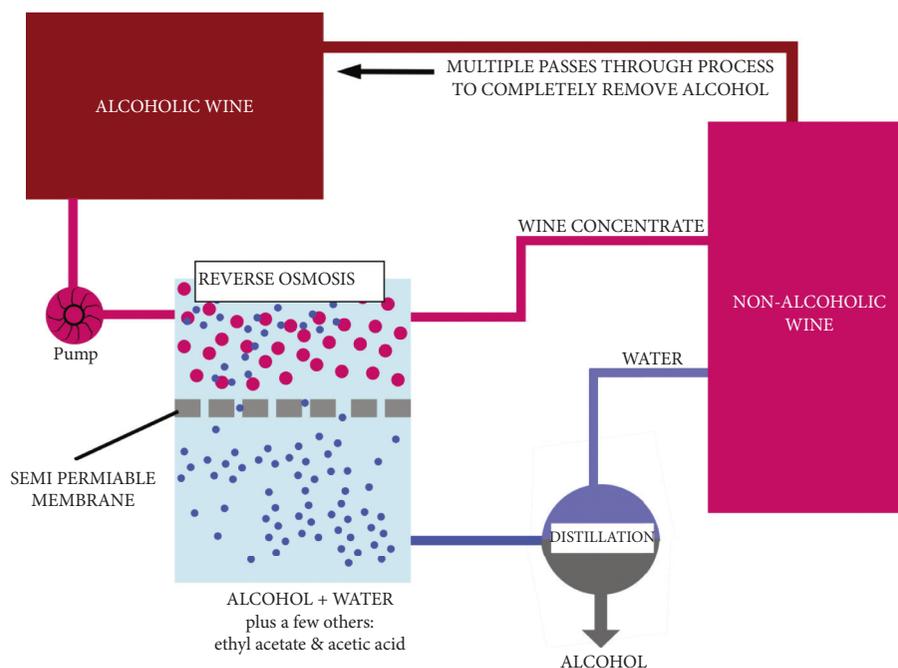


FIGURE 2: Production of nonalcoholic wine using reverse osmosis.

TABLE 2: Flavour compounds profile of wines depending on alcohol content.

Title	Method used	Alcohol content (%v/v)	Flavour compounds	Reference
Phenolic and aroma composition of white wines produced by prolonged maceration and maturation in wooden barrels	Alcoholic fermentation (<i>S. cerevisiae</i>)	13	Monoterpenes (limonene, α -terpinolene), C ₁₃ norisoprenoids, C ₆ alcohols, 4-ethylphenol, 4-vinylphenol, higher alcohols	Lukić et al. [80]
Evolution of the aroma of Treixadura wines during bottle aging	Alcoholic fermentation (<i>S. cerevisiae</i>)	10–12	Terpenes (linalool, α -terpineol), C ₆ compounds (1-hexanol), alcohols, ethyl esters, isoamyl acetate, methanol, acetone, 4-vinylphenol, volatile fatty acids	Vázquez-Pateiro et al. [79]
GC-MS analysis of reduced alcohol Muller-Thurgau wine produced using glucose oxidase-treated juice	GOX treatment	6.23	n-Butyl acetate, 2 (5H)-furanone, 4-ethylcyclohexanone, methyl 11-octadecenoate, and 10-undecenoic acid octyl esters	Pickering et al. [38]
Analysis of volatile compounds in low alcoholic wines obtained by reverse osmosis of grape must	Reverse osmosis	3.5–8.5%	Acetaldehyde, acetone, ethyl acetate, methanol, propan-1-ol, 2-methyl-propan-1-ol, isoamyl acetate, butan-1-ol, ethyl lactate	Filimon et al. [81]
Screening of new strains of <i>S. ludwigii</i> and <i>Z. rouxii</i> to produce low alcohol beer	Use of special yeast	0.51 (<i>S. ludwigii</i>) 0.93–3.32 (<i>Z. rouxii</i>)	Diacyetyl, ethyl acetate, 3-methyl-2-butanol, 3-methylpropionaldehyde, acetaldehyde, ethyl hexanoate, ethyl octanoate	Francesco, et al. [82]

responsible for the complete coherent flavour attributed to alcoholic wines. Nonalcoholic and reduced or low alcohol wines contain esters such as ethyl octanoate and hexanoate and short chain fatty acids which are responsible for their fruity flavour compared to standard or alcoholic wines as established in the study of Lukić et al. [80]. The inadequacy or absence of higher concentrations of higher alcohols, organic acids, and secondary metabolites to interact during maturation and aging towards the development of more profound aroma compounds in nonalcoholic wines may hinder the quality characteristics wine consumers may

require. The production processes of nonalcoholic wines to some extent limit the formation of these compounds during fermentation [14, 30, 47] or destroy them in the course of the alcohol removal process [49, 52, 71]. Table 2 presents information on flavour compounds of alcoholic, nonalcoholic, reduced, and low alcohol wines depending on their alcohol content. It can be realized that as the alcohol content decreases the concentration of flavour compounds (monoterpenes, C-6 alcohols, isoamyl acetate, ethyl esters, etc.) composition decreases which affects the overall flavour perception of nonalcoholic wines.

4. Conclusion

There exist a number of methods for producing nonalcoholic wines, which are classified as restrictive ethanol production processes (interrupted fermentation, use of unripe fruit, enzyme, special and immobilized yeasts, juice/wine blends, and cold fermentation) and alcohol removal methods (heat, membrane and extraction processes). However, restrictive ethanol production methods seem to conserve the biochemical composition of the wine more than the alcohol removal ones. They both have some significant effect on the flavour characteristics of nonalcoholic wines but are very pronounced in alcohol removal processes due to the usage of membranes, solvents, and heat. The effect of restrictive ethanol production methods on flavour characteristics of nonalcoholic wines is mainly ascribed to underdevelopment of flavour compounds during fermentation or fruit ripening stage whereas alcohol removal methods result in destruction or removal of flavour compounds during the alcohol removal process.

Research focus on the restrictive ethanol methods will help to produce nonalcoholic wines with reduced cost and high nutritional and organoleptic properties to meet the growing demands for nonalcoholic wines. Also, extensive research is required to determine the sensory characteristics of wines produced by the alcohol or ethanol removal methods, since most reported works focus on just determination of aroma compounds, design, and cost analysis of the ethanol removal equipment.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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