Chapter

Alcohol Reduction by Physical Methods

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Abstract

Alcohol reduction of wine has gained significance worldwide. There are several technologies available to reduce the alcohol content in a targeted way. This chapter explains the principles of alcohol reduction by physical methods. Different membrane processes such as osmotic distillation and the two-step dealcoholization process of reverse osmosis combined with osmotic distillation are compared with distillation processes such as vacuum rectification and spinning cone column. An alternative approach the membrane coupling of ultra- and nanofiltration is described as well. All those technologies appear more or less suitable to reduce the alcohol content in a targeted way. Nevertheless improper handling can cause severe quality losses for the wine. Therefore, enologists should have a thorough understanding of the technologies to avoid negative impact on wine quality through the treatment.

Keywords: alcohol reduction, dealcoholized wine, low- and reduced-alcohol wine, vacuum rectification, osmotic distillation, spinning cone column

1. Introduction

Studies from several countries show rising alcohol contents for wine over the last decades. There are many factors contributing to that phenomenon. Better viticultural practices and improved plant material lead to elevated sugar levels in grapes. In higher alcohol yields of selected yeast strains, modern vinification techniques furthermore lead to an increase in alcohol. The other driving factor for that development is the climate change which cannot be turned back that easily as the other factors. With rising alcohol contents, some wines appear outbalanced and alcoholic which can lead to the consumers' rejection. Additionally, enologists run into fermentation problem caused by elevated sugar contents of grape must and excessive alcohol contents at the end of fermentation. Especially the production of sparkling wine requires moderate alcohol contents to avoid problems with second fermentation.

As a result alcohol management has taken a new direction, from mainly maximizing alcohol contents to minimizing alcohol levels, as well. There are several physical methods available for reducing the alcohol content to a targeted level. They are either based on membrane processes such as osmotic distillation and reverse osmosis coupled with another treatment or on distillation under vacuum. The physical methods for alcohol reduction allow a targeted optimization of the alcohol content according to marked demand or to adapt to taxation and import tariffs based on actual alcohol content of the wine.

2. Comparison of different methods for alcohol reduction

There are several strategies available to produce wine with less alcohol. The most interventions take place before the wine status either in the vineyard, prior, or during fermentation (**Table 1**).

The strategies based on grapevine breeding and selection of clones as well as all strategies in viticulture are preventative and require a certain plan in advance. If, contrary to the assumption, the weather conditions for grape ripeness are very unfavorable, the desired maturity delay or reduced sugar storage in the berry is counterproductive.

In the field of microbiology, two different approaches are possible to produce less alcohol from the initial sugar present.

One possible way is to reduce the sugar content before fermentation by using the enzyme glucose oxidase. The glucose present in the must is converted to gluconic acid in the presence of molecular oxygen by the enzyme glucose oxidase (GOX). The challenge with this process is to reduce the oxidation of other constituents of the must and to reduce excessive acidity in wine [50, 53].

Another microbiological strategy is the use of special yeasts with lower alcohol yield. These yeasts usually show a higher content of fermentation by-products. Due to these other metabolites, the quality as well as the typicality of the wines produced may suffer. The use of genetically modified yeasts is probably seen as very critical by most consumers [60].

Also the metabolism of yeast can be rearranged by taking advantage of the so-called Pasteur effect. For this purpose, a yeast culture is kept in a solution with always less than 5 g/l of sugar. However, the control and addition of must has to be very precise in this process. Automatic measurement and control technology should help to facilitate this process for the user.

2.1 Sugar reduction through membrane coupling

Sugar reduction through membrane coupling can be seen as a unique technological approach for reducing elevated alcohol levels. Before problems arise due to excessive sugar levels in must, fermentation problems are prevented by a selective intervention. The sugar reduction of must is performed in two steps. Subsequent

Grapevine breeding	Viticulture	Microbiology	Enology
New varieties with reduced sugar content	Early harvest at lower sugar levels	Yeasts with reduced alcohol yield	Membrane processes before fermentationSugar reduction by membrane coupling
Clones with reduced sugar accumulation	Adaptation by different training systems	Alternative metabolization of sugar (e.g., enzymatically by glucose oxidase)	Distillation treatments(a) Vacuum distillation(b) Vacuum rectification(c) Spinning cone column
	Canopy management like defoliation or shading		Membrane processes after fermentation(a) Osmotic distillation(b) Nanofiltration or reverse osmosis coupled with second treatment

Table 1.
Overview of strategies to achieve wines with lower alcohol content [57].

treatment with ultrafiltration and nanofiltration removes sugar from the must. Consequently, the fermentation produces a wine with lower alcohol. This technology may help to prevent stuck and sluggish fermentations due to high sugar contents and consequently elevated alcohol levels. These high alcohol levels also have a negative influence on malolactic fermentations [5, 49].

First membranes for ultrafiltration were commercialized in 1926 by membrane filter GmbH [1]. The surface of the membranes is porous, and the pore sizes in ultrafiltration are 10–1000 Å. The retained particles are usually 0.1–10 μm and larger. Common applications of ultrafiltration in food production are dairy processing in milk processing plants and clear filtration in fruit juice production. The use of ultrafiltration for protein removal is conceivable in winemaking [22, 23, 29, 62].

Nanofiltration was developed in the late 1980s. It has been described as a technique between ultrafiltration and reverse osmosis. Nanofiltration usually retains molecules such as sugars and organic acids. The pore size of the membranes is 1–10 nm, and the molecular weight cutoff (MWCO) is at 100–500 Da. The usual working pressure is up to 40 bar. Nanofiltration has many possible applications in winemaking. It is used to remove volatile acidity or to reduce the amount of malic acid. Nanofiltration is also used to concentrate must and wine. If nanofiltration is coupled with another process, the alcohol content of wine as well as the sugar content in the must can be reduced [11, 16, 17, 19, 26, 40, 44, 57].

In this case the permeate of an ultrafiltration is separated in the first step. This fraction contains besides water, acid, and sugar only a few anthocyanins and tannins. During the second step, this fraction is concentrated by nanofiltration. The permeate of the nanofiltration contains then mainly water, some acids, and barely sugar. This aqueous solution is finally blended back to the retentate of the ultrafiltration. The sugar content of the must is thereby reduced after the treatment. The byproduct of that process is the retentate of nanofiltration. This fraction is viscous and high in sugars. The ratio of fructose and glucose is maintained because nanofiltration withholds equal amounts of fructose and glucose. Tartaric acid and potassium are retained only to a small extent, whereby the acidity and pH value are not or hardly changed. Anthocyanins and polyphenols are concentrated in the retentate of nanofiltration due to their molecular size. Consequently, they would be missing in the treated must. Therefore, it is important for red wine to perform the procedure before maceration. A "saignée" has to be done before fermentation. This fraction has to be clarified and treated by the two-step process to avoid color and tannin losses. This pre-clarified fraction is then reduced in sugar content and finally added to the original red wine mash [25, 26, 57].

2.2 Osmotic distillation

The English-language literature contains various synonyms for osmotic distillation, such as membrane distillation, transmembrane distillation, capillary distillation, or pervaporation. Other sources also speak of isothermal membrane distillation [28, 36].

In the process of osmotic distillation, two liquids are separated by a microporous, non-wettable membrane. Both fluids are directed along this membrane, with none of the fluids permeating the membrane pores. Only the volatile components present in the respective liquids can pass the membrane by evaporating and permeating through the pores of the membrane. This gas phases then go into solution of the other side of the membrane. Due to the hydrophobic nature of the membrane, water cannot penetrate the pores of the membrane. Thus, ions, colloids, and macromolecules that do not evaporate and diffuse through the membrane are completely retained.

Osmotic distillation is an isothermal membrane process at atmospheric pressure. The driving force for the molecule passage is the vapor pressure difference of a substance between the two sides of the membrane. The volatile components permeate from the membrane side with higher vapor pressure to the side with lower vapor pressure until equilibrium sets [12, 13].

In osmotic distillation for the partial reduction of alcohol in wine, water is used as strip medium. Apart from possible losses of volatile aroma components, the ethanol flux is of considerable interest. The flux is the amount of permeate that pass through the membrane per unit time. In osmotic distillation, it can be described as follows:

$$Je = Kov\ \Delta Pb \tag{1}$$

In this equation, Je (kg/m^2 h) is the ethanol flux, ΔPb is the vapor pressure difference in terms of ethanol (mmHg) on both sides of the membrane, and Kov is the mass transfer coefficient (m/s). The ethanol flux is influenced by a number of factors. Higher feed and strip media speeds will increase the alcohol transfer through the membrane. Furthermore, the temperature has an influence. As temperatures rise, the flux of volatile components increases. For the efficiency of osmotic distillation, it is important that both sides of the membrane are sufficiently hydrophobic. The pores should not get wet, and no water should penetrate the membrane by capillary action [36, 64].

The gas and vapor passage through the membrane pores takes place by diffusion. The permeation of the volatile molecules through the air space of the membrane pores can be described, depending on the pore radius, by Knudsen and Fick's diffusion. Various references suggest that simultaneous water transfer takes place between both sides of the membrane. The higher the process temperature, the higher the water transfer is. If the so-called stripping water is degassed before treatment in order to avoid an undesirable gas input into the wine, the water transfer is also increased. If the wine temperature is higher than the water temperature, the water transfer increases. In their work, Varavuth et al. [64] proved a water transfer to up to 3 l/m^2 per hour. If the membrane is damaged in its hydrophobic property by improper cleaning and storage, it can be assumed that the transfer of water increases. The water vapor permeating the membrane is relatively more composed of light oxygen atoms. The oxygen isotope ratio (O16/18) is a globally recognized indicator of water addition to wine, according to OIV Resolution OENO 353/2009 [1, 28, 36, 64].

Even if relatively small amounts of water are released into the wine, the osmotic distillation for alcohol reduction could simulate significantly higher levels of water in the wine. The technique of osmotic distillation is widely used in various industries. It can be used both for the degassing of liquids and for the alcohol reduction of beer and wine. The targeted addition of gases or degassing of wine is also summarized as gas management. In contrast to alcohol reduction, a vacuum or a gas is applied to the side opposite the wine. As a result, gas can be specifically added to or removed from the wine. Alcohol reduction of wine by osmotic distillation has been studied by a number of other authors [6, 14, 20, 27, 36–39, 42, 45–48, 51, 56–59, 64, 66].

2.3 Reverse osmosis/nanofiltration and other process

Reverse osmosis is a process for the concentration of liquids, which have a low content of solid components. The passage through the membrane takes place by diffusion through a semipermeable membrane. Consequently the passage takes place against a concentration gradient. During the treatment by reverse osmosis, pressure must be applied that exceeds the osmotic pressure of the solution to be concentrated. The separation of various substances is due to retention in terms of molecular size and by the solution-diffusion mechanism. Originally, reverse osmosis was developed for water treatment or desalination, but nowadays a number of other applications in the food and beverage industry are possible [43, 67].

Common applications of reverse osmosis in the food and beverage industry are the use in dairies or the concentration of juice. Various processes based on reverse osmosis are known in the wine industry.

For must concentration, the reverse osmosis is carried out without further process step. Other enological applications based on reverse osmosis require a second process. Depending on the purpose of the application, various other procedures are used for this subsequent step. When reverse osmosis is used to lower the alcohol content of wine, a permeate is separated in the first step. In addition to alcohol, this aqueous solution contains only a few volatile aroma components. Then, in a second step, this fraction is reduced in its alcohol content by another technology. This is done either by further membrane process, e.g., the osmotic distillation or by a common distillation at atmospheric pressure. Another approach could be replacing the permeate of the reverse osmosis by water, but that so-called diafiltration would mean the addition of water. In many countries the dilution of water is not allowed [10, 15, 18, 65].

Another approach for alcohol reduction is described by Bui et al. [7]. In experiments, they couple two reverse osmosis treatments by differentiating membrane cutoff. In the first step, a permeate with an alcohol content of about 6 vol.% separated. In a second step, this permeate is reduced by a second reverse osmosis treatment to an alcohol content of only 2 vol.%. This fraction is blended back to the initial retentate of the first treatment step to give a reduced-alcohol wine. To date, this approach has not been successful in practice, or there is no plant manufacturer pursuing this approach.

Nanofiltration is a process similar to reverse osmosis. The separation limit of the membranes is usually between 100 and 500 Da. The pore size is between 1 and 10 μm depending on the membrane, and the usual working pressure is 10–30 bar, in some applications also at 40 bar [44].

Compared to reverse osmosis, nanofiltration operates at lower pressure, producing more permeate per m^2 of membrane area. This is due to the membrane structure and the pore size of the membranes. However, other wine components permeate in a higher extent through the nanofiltration membrane. Due to that higher losses of aroma components could occur during the alcohol reduction of the permeate.

Reverse osmosis can also be used in winemaking to reduce volatile acidity [63]. Here, a permeate is separated in the first process step. In addition to ethanol and water, this also contains proportionally more volatile acid. This solution is then passed through an ion exchanger in the second process step. The volatile acid content is thus reduced, and sensory errors can be remedied to a certain extent [68, 69].

Other problems in wines can also be reduced by using reverse osmosis. Fudge et al. [24] describe a method in which off-flavors caused by smoke from larger forest fires can be remedied.

This treatment requires the separation of a permeate first. Then this fraction passes in a second process step: a column with adsorber resins. This significantly reduces volatile phenols such as guaiacol and 4-methylguaiacol. A similar approach was used by Ugarte et al. [65] to remove off-flavors caused by volatile phenols formed by *Brettanomyces* yeasts. Generally speaking, reverse osmosis offers a barrier so that the desired wine constituents are not that widely lost in further treatment steps. Consequently, reverse osmosis in winemaking can be described as a universal membrane process [8].

2.4 Vacuum rectification

Distillation is a thermal separation process in which liquids are vaporized and the vapor then condensed. Generally, distillation is a process that separates substances according to their relative volatility. The relative volatility is a measure of the separability of a distillation with respect to two components to be separated. The relative volatility of two components (α) is calculated from the quotient of the K values of the respective substances [32, 34]:

$$\propto i,j = \frac{\text{K – Value Substance i}}{\text{K – Value Substance j}} \tag{2}$$

The volatility of a substance, in turn, depends on the K value. The K value of a substance describes the tendency of a substance to volatilize [32]:

$$K_i = (\text{mole fraction substance i in vapor phase}) / (\text{mole fraction substance i in liquid phase}) \tag{3}$$

The higher the *K* value, the higher the amount of the respective substance in the vapor phase. The *K* value depends on the temperature, pressure, and composition of the liquid [32].

Higher temperatures greatly increase the vapor pressure, so the K value of the substance increases as well. If the vapor pressure of the liquid mixture is equal to the ambient pressure in the distillation unit, the liquid begins to boil. The vapor pressure of the liquid mixture is composed according to Dalton's law from the vapor pressures of the individual components, also called partial pressures together. Depending on the nature of the composition of the liquid mixture, the boiling point shifts [34].

The alcohol content of the rising vapors during distillation increases when the boiling liquid contains more alcohol. In addition, the boiling point is lower with increasing alcohol content of the liquid. On the other hand, it can be seen that the gain factor decreases as the alcohol content of the solution increases. The gain factor describes the amount in which the alcohol content increases from the starting liquid until the distillate. The vacuum distillation achieves lower boiling points by applying a vacuum in the column. By lowering the pressure inside the plant, the volatility of the components is increased, and thus the boiling point of the ethanol is reduced. Consequently, the energy required to boil from the ethanol decreases. As a result, the thermal load on the ingredients of the treated liquid is minimized. Alcohol reduction of wine takes place at around 26–35°C [14].

To increase the alcohol content in the distillate, the rising vapors in the distillation column are amplified. This is done by allowing the ascending vapors to flow through the so-called caps of the column against an incoming liquid. The vapor is enriched with volatile components such as ethanol, while the incoming liquid is enriched with high-boiling components from the steam. Depending on the field of application, the columns have different numbers of amplifier caps. This countercurrent distillation or rectification mentioned method is cheaper and less expensive apparatus, as multiple repetitions of single-stage distillation [30].

In general, the alcohol content in the distillate can be up to a content of 97.2 vol.% increase. Then a so-called azeotrope occurs. With an aqueous alcohol solution of 97.2 vol.%, the boiling point at atmospheric pressure is 78.15°C and thus below the usual boiling point of ethanol. Since the rising vapors from this mixture have the same composition as the starting liquid, the gain factor is 1.0, and so no further concentration is realized [34].

In industrial vacuum rectification plants, no further reduction in temperature can be detected during evaporation when the pressure is lowered below 1 mbar. The pressure losses caused by the flow in the pipelines between distillation column and condenser are in charge of that. In order to reduce the loss of aroma during distillation, the condensate is passed to the so-called aroma leaching in countercurrent to the nonalcoholic wine following the rectification. Some of the flavors from the distillate are returned to the nonalcoholic wine [4, 33].

2.5 Spinning cone column

A special form of vacuum rectification is the spinning cone column. This unit is used in the food and beverage industry in various areas for aroma separation and aroma recovery [8].

Unlike conventional columns for vacuum rectification, no static installations are used. Within the cylinder of the spinning cone, there are pairs of a fixed and a movable cone installed. The wine running down the column from the top forms a thin film due to the rotation of the cones. On the underside of the movable cones, there are fins, which swirl the rising vapors and thus allow an increased exchange between the wine and the so-called strip phase.

The special design of the spinning cone column helps to overcome the disadvantage of conventional columns for vacuum rectification. The mass transfer in the column is reduced by the application of the vacuum that instead of turbulent flow, only a laminar flow of the boiling gases prevails. This general disadvantage of distillation under vacuum is qualified by the fact that rotating inserts are mounted in the column. The liquid running down is transformed by its rotation into a thin liquid film. On average, this liquid film is less than 1 mm thick. This results in a very efficient contact between vapors and liquid, whereby the necessary residence time is reduced in the column. In addition, the construction of the spinning cone column, unlike columns for vacuum rectification, can also work with viscous or slurries with a high solid matter content [9, 35].

2.6 Further treatments

A number of further enological methods are conceivable to reduce the alcohol content of wine such as:

- Dialysis
- Pervaporation
- Adsorption of ethanol by organic resins
- Dilution

Except from dilution, all of these are of a technical nature. However, none of these methods have been really successful so far. The reasons for this can be seen either from an economic point of view or in legal aspects. The dilution with water is probably the oldest form of wine fraud and was formerly often used for volume increase. Nowadays the targeted addition of water to reduce the sugar content in must and so to reduce the alcohol content in wine is not legal in most wine-producing countries.

Nevertheless, water addition is legal under certain requirements in some countries. Article 17,010 of the California Administrative Code has the following wording: "...no water in excess of the minimum amount necessary to facilitate normal fermentation, may be used in the production or cellar treatment of any grape wine...."

This provides the enologist a simple and cost-effective way to avoid the stress of the yeast due to high sugar levels and also increase alcohol levels toward the end of fermentation. In addition, unwanted aroma components in the wine are reduced by the dilution.

Another method to achieve wines with less alcohol is the blend with low alcoholic wine. However, the wine law regulations on waste and labeling rights must be observed.

3. Critical evaluation of different technologies for alcohol reduction

The authors did several trials during the last years. The following subchapter will summarize and compare economic and user-oriented considerations [54–60].

3.1 Sugar reduction by membrane coupling

The reduction of the sugar content at must stage by membrane coupling has significant advantages in terms of later fermentation. Excessive sugar levels can be reduced directly before fermentation problems occur due to osmotic stress in the beginning of fermentation or toxic stress due to elevated alcohol at the end of fermentation. Furthermore possible stress for malolactic bacteria is reduced as well. Several trials showed that the treated lots started fermentation faster and continued the fermentation earlier and to a more complete extent.

The quicker and complete fermentation can be seen positive from an economic point of view, as the fermentation tank capacity can be used more efficiently. Moreover stuck and sluggish fermentations are clearly negative in terms of quality and economic consideration [5].

The batch treatment of ultra- and nanofiltration goes along with a certain labor need during harvest, which is in fact the most labor-intensive time during wine production. Possible automation and scale-up of such plants might help to overcome that disadvantage. This treatment could be interesting to be offered by mobile service providers. In that case no additional labor is needed, no investment is necessary, and the regular cleaning and storage of the membrane is needed.

Improper cleaning and storage over several months could cause off-flavors. Even with careful cleaning, membranes can develop an off-flavor from organic matter in the fouling layer. The application of membrane coupling appears more difficult than white wine. The ultrafiltration as the first step of the treatment requires a certain clarification level; otherwise the membranes get clogged. If red mash should be treated, a careful clarification is necessary. In that case a "saignée" is made. That subset is clarified and can be treated. During that time the remaining mash remains with a high content of solids and due to that oxidation and microbiological spoilage can cause later problems. After the membrane treatment, the liquid subset is blended back.

Compared to other treatments for alcohol reduction, the sugar reduction goes along with relatively high volume losses. The reduction of 17 g/l, which corresponds to approximately 1 vol.% less alcohol, means a volume loss of 7% from the initial volume. A further useful application of the nanofiltration retentate could be the sweetening of other wines. Even with a sugar content of 500 g/l, care must be taken to ensure sterile storage. Unlike treatments to remove alcohol, this technology is not in conflict with regulations for distillation.

3.2 Osmotic distillation

Osmotic distillation is a technically simple approach to partial alcohol reduction. Membrane contactors are used in the wine industry in numerous processes such as aeration and degassing of wine. These membranes are more and more widely used by many manufacturers for the preparation of wine and semi-sparkling wine. Such systems are usually based on a membrane contactor with a membrane area of 20 m^2. Depending on the equipment and the degree of automation, the costs for such systems are quite low. Simple systems with manual control valves start from approximately 7000 €. The durability of the membranes highly depends on the care of the membranes and is thus an important factor determining the economic efficiency of the plants. With proper cleaning and storage, the membrane contactors, which are the main cost of the equipment, can be used up to for 5 years before being exchanged by a new membrane. So the method of partial alcohol reduction can be used inexpensively in many businesses. The treatment by the osmotic distillation for alcohol reduction is relatively easy to perform if significant parameters are considered. The amount of previously degassed strip water must be limited to avoid harming the wine quality too much during the treatment. It is advisable to circulate the strip water in a closed and inert system. In many trials it could be shown that an alcohol reduction by 8 g/l should go a long with 14% of the wine volume as strip water. This proved to be the ideal compromise between a quick and aroma-saving treatment.

In order to prevent membrane fouling, the wine to be treated should first be subjected to a wine filtration of min. Separation limit of 5 μm.

The work required to clean and preserve the membranes can be compared to that of conventional cross-flow filtration. Nevertheless the hydrophobic property of the membranes does not allow backflush or use of cleaning enhancers and surfactants.

The alcohol reduction by osmotic distillation is continuous and needs little or no supervision during treatment. If the alcohol reduction is to be carried out close to the maximum permissible limit, it is advisable to reduce a portion of the alcohol content strongly and then adjust the alcohol content precisely by blending with the initial wine.

The performance of the alcohol reduction is not constant as the driving force; the vapor pressure difference between both sides of the membrane gets lower during the treatment. So the alcohol permeation rate decreases during the treatment. The strip water accumulates in the alcohol content. In the experiments, it had alcohol contents between 4 and 7 vol.% [27].

Due to alcohol reduction, the density of the treated wine increases. During the treatment of larger containers, the change in density can cause certain layer formation in the tank. Before assessing the final degree of alcohol reduction, the tank has to be homogenized carefully. Without this mixing, it can lead to errors in the measurement of the alcohol content, and thus a wine may be treated in too high extent. Since the systems for osmotic distillation are relatively small and mobile, it is conceivable to perform such a treatment with a mobile plant. For this purpose, the wine does not need to be brought to a plant as is the case for common systems based on distillation-based processes. The treatment can be carried out within the winery.

If alcohol is separated from the wine, a number of custom regulations might be affected even if the separated alcohol fraction is not very high in alcohol (4–7 vol.%), and so it is not economically interesting to separate the ethanol further in another distillation process. The recycling of the strip water as brandy is neither economically interesting nor from quality aspects to be recommended.

3.3 Reverse osmosis/nanofiltration and other process

Reverse osmosis or nanofiltration alone does not lower the alcohol content of wine. The permeate from that treatment has to be reduced in alcohol content by another step. This alcohol reduced fraction is finally blended with the concentrate from the first step.

The plant from the company Oenodia (Pertuis, France) is a mobile system that combines reverse osmosis, respectively, nanofiltration with osmotic distillation and is used as mobile service in wineries.

In the first step, permeate is reduced in alcohol by osmotic distillation.

The strip water for the osmotic distillation is not pumped in a closed circuit; there is a continuous flow of heated water through the membrane contactor. These process parameters are chosen so that as much alcohol as possible can be separated with this system per time. The alcohol transfer through the membrane is increased by elevated temperatures, and the vapor pressure difference of the respective substances is significantly higher with continuous supply of new strip water than with a closed strip water cycle and limited water amounts [14, 27].

The first step of treatment by reverse osmosis or nanofiltration reduces fouling at the membrane contactor for osmotic distillation as the permeate is free of solids and low in colloid content. In comparison to the expensive and complex membrane contactors, the membranes for the first step can be cleaned more easily. In addition, their prices are much lower.

The oxygen uptake was measured during several treatments and was between 0.6 and 0.8 mg/l on average for the two-stage process. In comparison to that, the single-step osmotic distillation for alcohol reduction showed on average an oxygen uptake of 1.4 mg/l. So the alcohol reduction by membrane systems can be compared with a common gentle wine filtration. In both cases the strip water was degassed. Without degassing the oxygen uptake could have been 4 mg/l and more [61].

The resulting strip water from the second step had similar alcohol content as in the direct osmotic distillation of wine. The alcohol content was in a range of 5–7 vol.%. Compared to treatments based on distillation, the membrane treatments are compact build and mobile. They just require electricity and water of certain softness. Furthermore small lots can be treated, allowing pretrials to assess the final sensory character of the wine.

3.4 Vacuum rectification

Vacuum rectification is a continuous process, and the systems which are used in the beverage industry have a capacity of 300 l/h upward.

Corresponding plants already exist in Germany for more than 100 years.

The number of companies offering dealcoholization based on vacuum rectification has grown significantly during the last years. Common systems are designed for flow rates of 1000–5000 l/h of wine. The respective rectification columns are on site, and the legal settlement terms in distillation are in charge of the service-offering company.

The usual minimum quantity to be treated is 1000 l. At the end of the treatment, the alcohol content of the wine is below 0.5 vol.%.

For example, if 1000 l wine with 14 vol.% are treated, 135 l of pure ethanol are separated. According to the operation of the column, the spirit fraction has an alcohol content up to 80 vol.% Values above that are not to be recommended as the hazard of explosion increases by such high ethanol contents. Assuming an alcohol content of 80 vol.%, 168 l of spirit are separated. Approximately 830 l of alcohol-free wine are remaining that can be used for diluting the alcohol content of the initial wine to any value desired. The alcohol-free wine fraction is very susceptible to microbiological spoilage as the content of free SO2 is reduced by 75% of the initial content and the microbiological effect of ethanol is missing as well. Within hours alcohol-free wine can develop a flor yeast layer. To avoid microbiological contamination and resulting off-flavors in wine, a blending within the next day to a common alcohol level should be done. The losses of SO2 should be replaced again as well.

3.5 Spinning cone column

The spinning cone column is generally used for the separation of volatile components from different liquid–solid mixtures.

The universal applicability of this plant explains its widespread use in various areas of the flavor, food, and beverage industries. In the wine industry, it is used for desulfurization, dealcoholization, and partial alcohol reduction.

Similar to vacuum rectification systems, the spinning cone column is due to its size and infrastructure requirements not suitable for mobile use. Already the pilot plant for trials has a height of 4 m and a weight of 5 t. The need for steam is approximately 85 kg/h with required working pressures of 6–8 bar for a problem-free operation. These parameters are very difficult to realize with common steam generators and pipes applied in the beverage industry. For optimal operation a cooling system of 60 kW is recommended. Systems of that size are to be found just in bigger wineries or cooperatives. Corresponding aggregates for cooling and steam can be rented as mobile systems, but this will generate further costs.

The treatment takes place in two passages at different process temperatures. The performance of the SCC is therefore significantly reduced compared to a conventional rectification column. The spirit fraction resulting from the spinning cone column treatment has just an alcohol content of about 50 vol.% For the commercialization in bulk, a further distillation step, to increase the alcohol content, is recommended. This would be easy to realize with another distillation stage directly at the plant. This could also reduce the loss of volume by returning the nonvolatile residue to the wine. The two passages through the spinning cone column allow a recovery of a very volatile fraction that is separated and blended back to the alcohol fraction after the second passage. Due to that practice, the most volatile components are recovered and are not lost in the ethanol fraction. The declaration of that pre-run as aroma is irritating and led to many misinterpretations of the process. The pre-run of the process is not selectively positive. It is coined by descriptors such as pungend, sulfur coined, and solvent.

From a business perspective, the use of the spinning cone column in the wine industry is conceivable above all as a contracted service. Permanently installed it is used for dealcoholization, partial alcohol reduction, and desulfurization.

3.6 Water addition

The dilution of must with water is the simplest and cheapest solution to reduce the sugar content and thus the subsequent alcohol content. The addition of water dilutes all wine components. This concerns the positive and negative sensory aspects. The water used is not really a cost factor. On the other hand, the volume increase by adding water can have a significant impact in terms of sales. In order to avoid possible negative influences on the subsequent wine quality, the amount of water should be minimized and neutral in terms of taste, free of microorganisms and microbiologically active substances.

Similar to sugar reduction by membrane coupling, the key benefits to be seen are improved fermentation kinetics with less residual sugar in the end. In some wine-producing countries, this practice is legal.

4. Sensory impact of partial alcohol reduction

A detailed assessment of the processes for partial alcohol reduction of wine should include a sensory evaluation as well.

First of all it is important to understand to what degree of alcohol reduction makes the wines different from the initial wine. Furthermore the changes in terms of sensory characteristics should be pointed out. A comparative study of the different physical methods helps to assess what technology is more gentle in terms of wine quality. Several sources report that a wine with an alcohol reduction by 2 vol.% is not differed from the initial wine [2, 3, 14, 39, 41, 52, 56–58].

The extensive investigations of the authors substantiate these results. A total of 39 discriminative tests with a trained panel did not show a significant difference between untreated wines and corresponding samples with 2 vol.% less alcohol. Here the grape variety, the initial alcohol content, and wine style were irrelevant and not influencing the results. These discriminative sensory tests did not show significant differences with several white and red varieties. Even trials with sparkling wines showed that 2 vol.% alcohol difference is not perceived as a significant difference in discriminative tests [59].

The treatment goes along with several collateral damages in terms of wine quality such as excessive aroma losses, oxidation, and microbiological spoilage. So it is important to mention that the alcohol reduction has to be done carefully according to the manufacturers' recommendation.

Discriminative tests comparing the initial wine with samples that have 3 vol.% and 4 vol.% less alcohol showed clearer results. The panelists could differentiate more clearly and at a significant level the treated wines from the initial wine. Nevertheless there was no clear tendency in terms of preference. That is in line with other sources [39, 40].

Several comparative tests showed that the different methods for partial alcohol reduction, mentioned before, did not differ from each other when the same wines were reduced by 2 vol.% each. Even the samples that were diluted with water to have 2 vol.% less alcohol did not differ significantly from the physical methods. That is in line with other sources [2].

When the range of alcohol reduction was 4 vol.%, e.g., from initially 14.6 vol.% to 10.6 vol.%, there was a general tendency toward methods based on distillation under vacuum (vacuum rectification and spinning cone column). Here membrane processes could not deliver the same quality.

A severe alcohol reduction by distillation has the advantage that only a partial amount is treated severely. The membrane processes, in contrast, require a relatively long treatment by multiple passes of the total amount of wine through the plant to reduce the alcohol content to the same extent. If the membrane processes are to be used to produce products that are severely reduced in alcohol content, membrane plants should be in bigger size, and short-time heating could help to shorten the treatment, so that wine quality is potentially harmed less. With all tested physical methods, an aroma recovery out of the ethanol fraction could help to improve the final result in terms of quality.

The sensory effect of alcohol is very complex in terms of wine. The partial alcohol reduction of the wine changes several sensory attributes. Due to the lower alcohol content, the wines that have 3 vol.% less than the initial wine clearly show lowered sensations in terms of body and fullness. As this attribute is clearly desired, later enological interventions could aim to buffer that loss. Depending on wine style, sweetening and addition of CO2 or tannins could help to compensate those losses.

Bitterness and the sweetness sensation is reduced when the wines have less alcohol. The perceived acidity of the wines rises by removing alcohol. The fruitiness of the wines is reduced by the alcohol reduction contrary to the theory that wines with elevated alcohol content appear less intense in terms of fruity character. The treatment by physical methods goes along with aroma losses, and that factor is stronger than the elevated volatility of the remaining aromas due to alcohol reduction.

The theory of sweet spots in terms of alcohol has been accepted, so far, quite uncritical. With regard to wine, this term is mentioned in various publications that point out that even small differences in ranges of 0.1–0.2 vol.% can have severe influences on the taster's preference. This approach does not conform to other sources. Since an alcohol difference of less than 2 vol.% cannot be distinguished significantly, an experimental setup with alcohol steps of 0.1 or 0.2 vol.% is incomprehensible. The author's research showed that the panelist's preferences were widely spread at the respective tastings. So there was no significantly preferred spot when a set of seven samples with varying alcohol contents were tasted even though the initial and final alcohol content clearly made the wine different. It is important to note that the examiner's preferences spread evenly over the range of samples. That proves that the preferences in terms of alcohol content in wine are not uniform. Instead of small changes in terms of alcohol contents, it could be more interesting to clearly change wine style, thus creating wines that are favored by customers who prefer lighter wines [21, 31, 39, 41, 51, 57].

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