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# The effects of climate change on wine composition and winemaking processes

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**REVIEW ARTICLE**

## Abstract

Climate change strongly affects the wine industry, with impacts on grapevine vegetative behavior, grape primary and secondary metabolites and wine composition. The increase of ethanol is one direct consequence, creating the necessity of new oenological strategies. Nowadays, a challenging objective is the production of wines with reduced or removed alcohol content. Different strategies are developing, divided in pre-fermentative, fermentative and post fermentative. Those are also technologies able to reduce or remove alcohol content through physical methods. This review examines the effects of climate change on wine composition and winemaking processes, considering new technologies used to produce removed or low-alcohol-content wines.

*Keywords*: Alcohol, Climate change, Grape composition, pH, Volatile organic compounds, Wine composition

## Introduction

Climate change (CC) has become one of the most important topics being debated in recent years. It is well known that CC impacts political decisions, government policies, and human activities, including the agricultural sector. Agriculture is a nature-based and climate-dependent sector; hence, it is strongly influenced by CC. The viticulture and wine industry are affected by this situation, with technological and economic consequences (Costa *et al.*, 2023). It is easy to understand that climatic variations impact grapevine vegetative behavior and therefore on grape musts and composition of wines.

Wine is a complex beverage and its composition and final quality depends on various factors. Quality is the result of a balance between wine and its characteristics, and this balance defines the typicity (Drappier *et al.*, 2017). The typicity reflects the terroir, defined as the result of an interaction between climate, soil, and topography, creating together a unique environment that characterize each vineyard's area (Rogiers *et al.*, 2022). Moreover, agronomical and technological choices, such as vineyard management, varieties, clones, and winemaking techniques, influence quality of the final product and its value on the market (van Leeuwen *et al.*, 2019).

The wine composition is the result of numerous molecular compounds present at the time of harvest. The main objective of a winemaker is to modulate these compounds through the choice of optimal grape maturity (van Leeuwen *et al.*, 2022). In the past, maturity was referred only to technological parameters, that is, sugar accumulation and ratio of acids; nowadays the concept of maturity has evolved and other types of maturity parameters have been defined, such as physiological, technological, phenolic, and aromatic. These depend on climatic conditions, particularly temperature, water, and sun exposure. So, in the context of CC, finding the perfect grape maturity, and able to obtain balanced wines, is a new challenge for winegrowers and winemakers (Allamy *et al.*, 2023). The aim of this review was to analyze the effects of CC on grape composition, and their consequences on winemaking and the final quality of wine.

## Impact of Climate Change on Grape Composition

### Temperature

Grape maturation, and consequently the produced wines, is governed by climatic factors. Among these, temperature is one of the most important factors influencing the physiology of grapevine. In fact, during the growing season, temperature is a key factor for vegetative cycle. Several viticultural climatic indices, based on temperature recorded in the vineyard and developed with the aim to relate the needs of cultivar to climatic conditions, are widely used to assess the effects of CC (Piña-Rey *et al*., 2020). For example, the Winkler Index (WI), calculated as the sum of daily mean temperatures above 10°C from 1st April to 31st October, provides information on heat accumulation during the growing season. It is well known that temperature above 10°C drives budburst (Amerine and Winkler, 1944), defining commonly a new vegetative cycle. The value of WI is related to the rate of vine growth, influencing the final wine quality. Other bioclimatic indices, such as the Huglin Index (HI), calculated as daily average between mean and maximum temperatures above 10°C from 1st April to 30th September, are connected with the rate of vine-growing. Indeed, a climate with HI above 3000 on a day is considered as 'very warm' and can create stress in the physiology of vine. In fact, extreme temperature of above 35°C induces leaf or bunch damages and reduces photosynthesis and anthocyanin concentration, with repercussion on berry composition and wine quality (De Rességuier *et al*., 2020; Rogiers *et al*., 2022). On the contrary, HI below 1200 on a day is considered 'too cold' for vine growth (Massano *et al*., 2023). In addition, during the growing season, temperature is a key factor. Mean temperature during vegetation period (TmVeg), which is the daily mean temperature between 1st April and 31st October, determines the timing of phenological phases. For example, higher TmVeg leads to an anticipation of phenological cycle and TmVeg above 24°C and below 13°C is classified as unfavorable for grapevine cultivation (Massano *et al*., 2023).

In the context of global warming, increase in temperatures observed in the last decade is expected to continue. Different studies undertaken globally have underlined the impact of temperature and change in climate on quality of wine. Figure 1 shows differences in global temperature from 1976 to 2023, compared to the 1901–2000 average. This increasing trend has influenced both phenology and metabolism of grapevine, inducing an earlier response from plants, with an acceleration of their phenological phases and maturation (Drappier *et al*., 2017; Petrie and Sandras, 2008). Some studies have observed that more days with temperature >30°C during flowering and veraison can lead to an early harvest by up to 17 days (Jones *et al*., 2005a, 2005b). Furthermore, a heat stress can reduce phenological intervals and length of the growing season (Jones *et al*., 2000).

Temperature has a huge influence on grape ripening and berry composition. Heat stresses are able to impact the concentration of primary metabolites, namely, sugars, acids, and their ratios, as well as secondary compounds, such as amino acids, flavonoids, and aroma compounds, with an effect on the produced wines (Rogiers *et al*., 2022).

Regarding primary metabolism, it is directly related to photosynthesis. Because of increasing temperatures, many studies underline higher sugar accumulation, with a decrease of organic acids and an increase in pH. Temperature above 30°C generates stress in the plant, leading to reduced berry weight and size, and ceasing of sugar accumulation, but high levels of sugar are not due to photosynthesis but to the concentration by evaporative loss (Mira de Orduña, 2010). Indeed, one of the impacts of high temperature is an important phenomenon, called 'berry shriveling'. It occurs through berry water loss because of an alteration in grape water budget when transpiration and potential water backflow exceeds phloem unloading. Different types of berry shriveling are reported in literature, such as sun burn, resulting

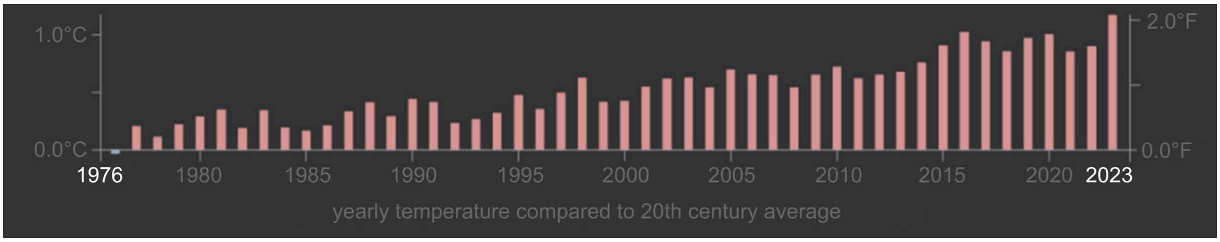

**Figure 1. Differences in global temperatures from 1976 to 2023, compared to the 1901–2000 average (adapted from NOAA National Centers for Environmental Information, 2024).**

in development of poor color in red varieties and raisin formation in severe occasions; late season fruit dehydration, with an increase of total soluble solid concentration; and sugar accumulation disorder, resulting in soft and irregular-shaped berries with low fresh weight, reduced sugar accumulation, and low amount of anthocyanins (Šuklje *et al*., 2016).

Concerning the titratable acidity, there are different behaviors regarding the two main acids in grapes. Tartaric acid is not affected by temperature and its quantity remains relatively stable after veraison until berry maturation. However, its concentration decreases by dilution with increase in berry volume. Reduced content of tartaric acid also occur under particular condition as well as late harvest or grape berry drying (Plantevin *et al*., 2024). Meanwhile, accumulation and permanence of malic acid is related to maturity and decreases with high temperature because it is easily respired by the berries, making malic acid more unstable (Ganichot, 2002; Neethling *et al*., 2012). However, heat stress during grape ripening increases phloem transport, resulting in higher accumulation of $K^+$. The overaccumulation of $K^+$ ions leads to an excessive neutralization of organic acids and an increase of pH. The pH increases with increase in the level of ion exchange. Acid degradation reduces titratable acidity and raises the level of exchange. If the tartaric-to-malic acid ratio increases due to malic acid respiration, the pH may stay stable or may rise if there is concurrent mineral uptake. This loss of acidity strongly affects the final wine quality (Boulton 1980; Mira de Orduña, 2010; Monder *et al*., 2021).

Considering the effect of temperature on secondary metabolites, the flavonoid composition is affected, including tannins, anthocyanins (on red varieties), and flavonols. These components are fundamental to achieve phenolic maturity and to produce quality red wines, influencing color and gustative perception, especially bitterness and astringency (Adams, 2006). Rise in temperatures implies increased sun exposure and consequentially more ultraviolet-A (UV-A) and UV-B radiations, with a subsequent decrease in flavonoid content of grape berries because of a combination of degradation and synthesis inhibition (Martínez-Lüscher *et al*., 2014).

Regarding flavonols, high temperature could generate a decrease in their metabolism, depending on heat intensity, duration, and phenological stage (Gouot *et al*., 2019; Rogiers *et al*., 2022). However, some studies showed that UV-B radiation has particularly strong effect on the synthesis of flavonols. The total flavonol concentration in berry skins can increase in grapes exposed to UV-B, while individual flavonol concentration is affected by different ways. With an increase of UV-B, the proportions of mono- and disubstituted flavonols increase, while that of trisubstituted flavonols decrease (Martínez-Lüscher *et al*., 2014; Matus, 2016). Quercetin is a flavonol that shows the strongest response to UV-B radiation. Some studies proposed that some monovarietal wines could develop a quercetin precipitation during wine aging because of the hydrolysis of aglycon. This excess was attributed to a strong copigmentation effect of flavonols, particularly quercetin having with anthocyanins; this helps to maintain quercetin in solution form even at high concentrations, creating a significant commercial problem for global wine market (Gambuti *et al*., 2020; Waterhouse *et al*., 2016).

The responses of phenolic compound to UV are different. Flavonols are the most UV-responsive compounds whereas anthocyanins are hardly affected by them. Different responses of the two groups of compounds are due to different regulation systems that control biosynthesis (Del-Castillo-Alonso *et al*., 2016). Nevertheless, the heat stress generated by high temperatures impacts the biosynthesis of anthocyanin. Anthocyanins have their optimum synthesis at around 30°C, although berry skins under these conditions show a poor coloration. This is due to a combination of factors, such as changes in gene expressions, enzyme activity, and degradations undergone by anthocyanins to protect berries from extreme heat by acting as antioxidants and reducing color in grapes (Gouot *et al*., 2019). For tannins, the effects are not clear; however, some studies underlined the effects of vintage on their accumulation, observing that high temperatures lead to an increase in the concentration of tannins (Chira *et al*., 2011; Gouot *et al*., 2019; Lorrain *et al*., 2011).

Rise in temperature has a direct effect on grape varietal aroma compounds. Some primary aroma compounds, belonging to the class of isoprenoids, such as monoterpenes, terpenes, and C-13 norisoprenoids, responsible of relevant fruity, floral, and spicy flavors of wines, are affected in different ways by temperature (Ruiz *et al*., 2019).

Terpenes are present in all grape varieties; they contribute to the aroma with a usual floral, fruity, and muscatel scent. These are present in the exocarp of grapes and occur in many forms, such as free, volatile, or bound glycosidically; however, they have lower concentration in non-Muscat grape varieties (Mele *et al*., 2021). Monoterpenes are important for aroma and flavor of grapes, as they impart floral and citrus notes to wines (Ebeler, 2001). Terpenes and monoterpenes need sun exposure for their accumulation, but an excessive increase in temperature causes a decrease of their content, limiting the aromatic potential of produced wines (Belancic *et al*., 1997). Moreover, high temperatures have different effects on some terpene compounds, for example, linalool is affected and its content is reduced, meanwhile the concentration of geraniol does not change in the berries (Duchêne *et al.*, 2016). On the contrary, C-13 norisoprenoids, which are derived from the degradation of carotenoids, increase with exposure to the sun. They are usually found as glucosides and represent a group of flavors. Typical norisoprenoid aromatic compounds include β-damascenone (megastigma-3,5,8-trien-7-one), vitispirane (6,9-epoxy-3,5(13)-megastigmadiene), and 1,1,6-trimethyl-1,2-dihydronaphthalene (TDN). Their characteristic aroma varies from leafy, minty, and fruity to various floral hints. Syrah's typical varietal aroma of violet is due to these specific compounds. Exposure of grape bunches to sunlight is a key factor that significantly affect the concentration of norisoprenoids in grapes. Indeed, enhanced light and temperature conditions can break down carotenoid pigments, thereby increasing C-13 norisoprenoids (Asproudi *et al.*, 2016; Li *et al.*, 2024; Reynolds and Balint, 2014).

Methoxypyrazines are a class of chemical compounds responsible for bell pepper, tomato leaf, and vegetal aromas in wines of certain varieties, such as ‘Cabernet Franc’, ‘Cabernet Sauvignon’, and ‘Merlot’. Methoxypyrazines action depends on climatic conditions and decrease with high temperatures (Falcão *et al.*, 2007; Ruiz *et al.*, 2019). The concentration of varietal thiols in wines is related to the concentration of their precursors in grapes and depends on different factors, such as water deficit and grape variety. However, their concentration is not affected by changes in temperature (Roland *et al.*, 2011).

## Water availability

In last few years, winegrowers and winemakers are facing unexpected changes in terms of water availability. Figure 2 shows the mean annual precipitation over the decade of 2011–2020, expressed as a percentage of the mean of the 1951–2000 reference period. It displays that northern part of Europe and Asia experienced significant above-average rainfall from 2011 to 2020, with precipitation levels of 10–20% higher than the 1951–2000 average precipitation. In addition, an increase in the frequency of extreme meteorological and hydrological factors, such as heavy rainfall and flooding, alternated with long periods of drought, impacted the final wine quality (Piña-Rey *et al.*, 2020). In January 2023 itself, 14 different significant climatic anomalies and events were recorded in globally (Figure 3).

As observed for temperature, availability of water also impacted grape composition, influencing the accumulation of both primary and secondary metabolites. Water availability, depending on phenological state, can affect vegetative growth of the plant, on the development, and berry set and its maturation. Flooding, because of extreme and violent rainfall, could generate hypoxia

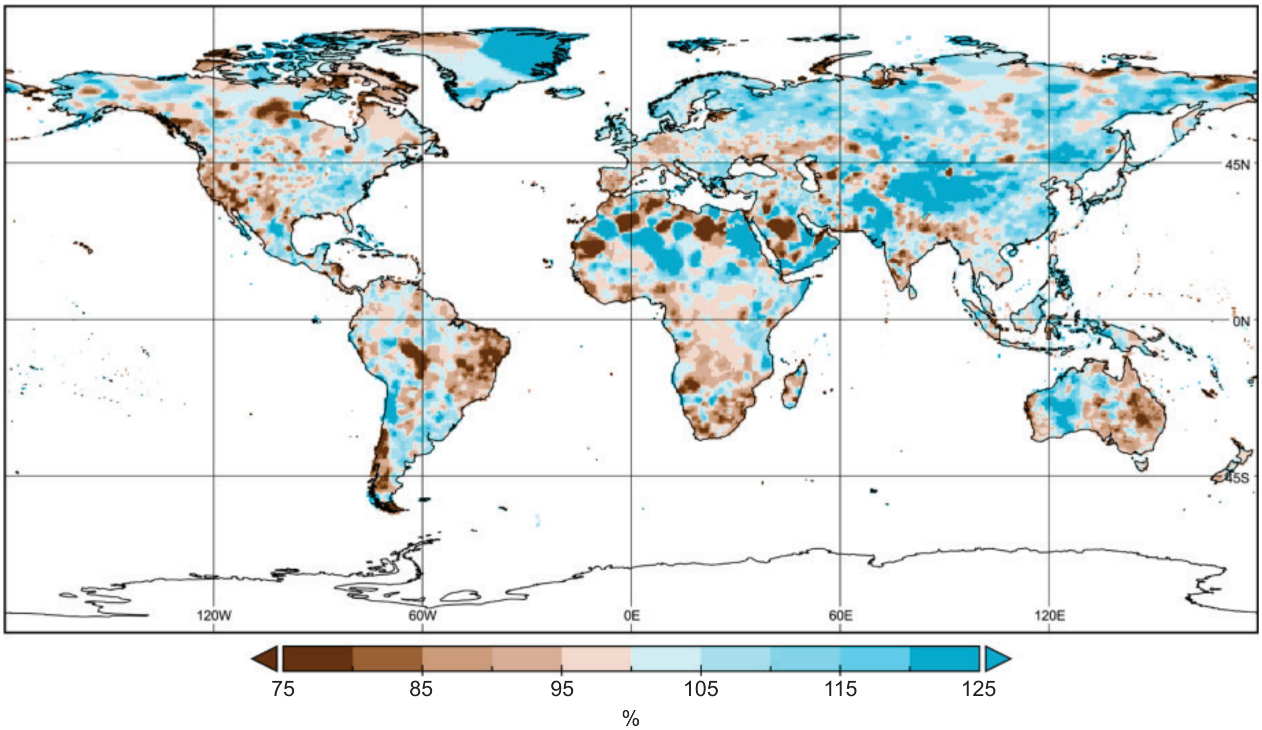

**Figure 2. Report of mean precipitation in the decade of 2011–2020, compared to the 1951–2000 reference period (adapted from World Meteorological Organization [WMO], 2023).**

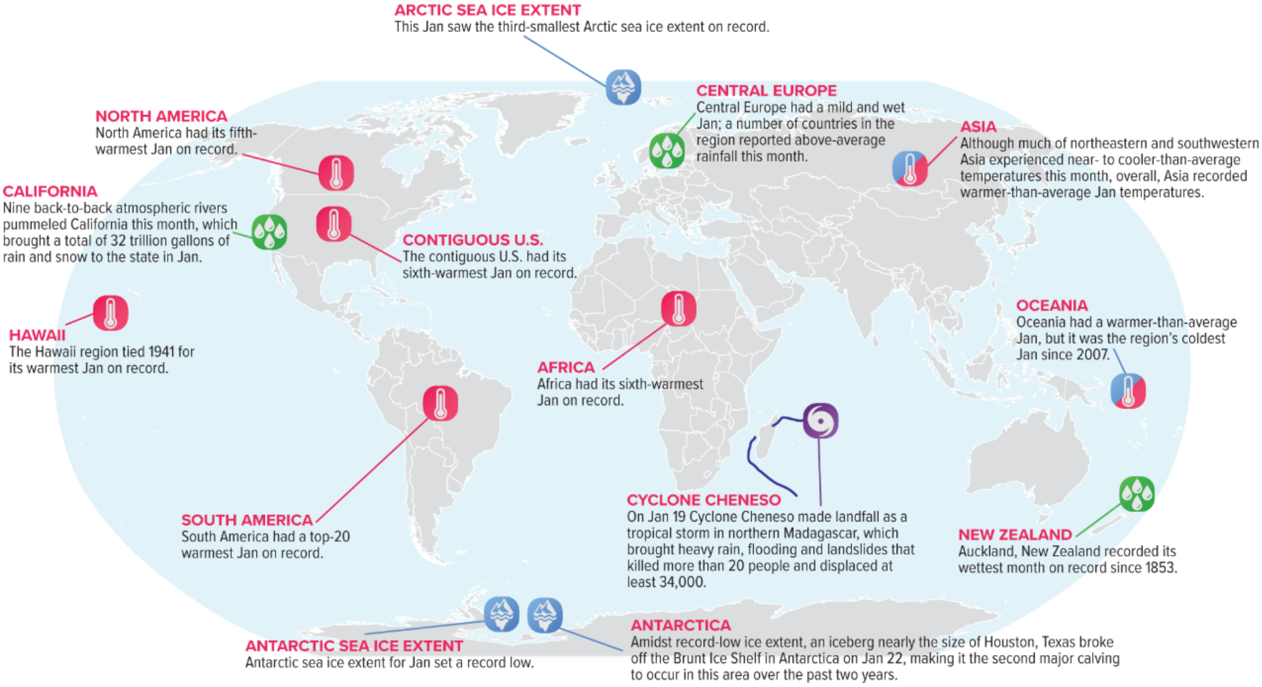

**Figure 3. Report of significant global climatic anomalies and events in January 2023 (adapted from NOAA's State of the Climate Reports, 2024).**

and/or anoxia, leading to plant oxidative stress that may eventually result in the death of the vine (Rogiers *et al.*, 2022). At the same time, water deficit can impact vine-growing and consequently composition of berries. Different studies have demonstrated that a controlled water deficit helps to improve bunch microclimate, benefitting production of quality wines, although in the prospective of CC, with a drier future, these management techniques need to be revised (Bonada *et al.*, 2015).

Indeed, a controlled water deficit leads to a reduction in berry size, a higher skin-to-pulp ratio, and affects concentration of grape compounds. Moreover, a moderate water deficit during veraison leads to a greater accumulation of sugar, flavanols, flavonoids, and anthocyanidins (Cáceres-Mella *et al.*, 2017; Intrigliolo *et al.*, 2012). The intensity of water stress and the affected vegetative period could have different effects. During pre-veraison stages, it induces metabolic changes in berries and can be maintained up to the harvest. Meanwhile, in post-veraison, the modifications are more variable, with both positive and negative influences. Generally, grapevine response to drought reduces berry weight because of a dehydration effect, and concentrating of sugar and anthocyanin content. At the same time, water stress influences some secondary metabolic pathways, affecting flavor and characteristics of final products (Bonada *et al.*, 2015; Mirás-Avalos *et al.*, 2017). In fact, water availability influences varietal aroma concentration and their precursors. In the case of norisoprenoids, water stress shows an increasing trend (Koundouras *et al.*, 2006). On the other hand, changes in terpenoids, such as in 'Chardonnay', seem to be a part of metabolic response, particularly the accumulation of monoterpernes, that is, linalool, nerol, and α-terpineol (Savoi *et al.*, 2016). Concentration of methoxypyrazines is more affected by temperature and exposure to the sun than water availability; however, their accumulation is higher in highly irrigated vines (Belancic and Agosin, 2007). Concerning thiols, even a light water stress leads to an increase in content, but long periods of drought tend to decrease their concentration (Peyrot des Gachons *et al.*, 2005).

## Winemaking Consequences

### Harvest time

For wine producers, CC has created new challenges because of the modified grape chemical characters. This new scenario has led to the necessity of oenological strategies to obtain quality wines. The first problem that winemakers deal with is the time of harvest. As already described, the main effects of CC on grape composition from the technological point of view are increase in sugar content, decrease of titratable acidity, and consequently a higher pH. Moreover, higher temperature and water stress are able to affect the size of berries, concentrating not only sugar content but also flavonoids.

In addition, CC influences the aromatic composition of grapes; therefore, harvesting of grapes at correct time, with an adequate maturity is the key to produce quality wines (van Leeuwen *et al*., 2022). For these reasons and according to oenological aim, nowadays the harvest date is anticipated. Particularly in hot vintages, for white wines, it is preferred to choose an early harvest to maintain a lower sugar content and higher acid concentration. In the production of red wine, a good phenolic maturity is preferred. In fact, managing grapes with low amount of anthocyanins or immature tannins is challenging. Often, phenolic and technological maturities do not happen at the same time, so to achieve good phenolic maturity one must tolerate an excessive accumulation of sugars and a drastic drop in acidity. However, high temperatures affect phenolic maturity, thus reducing accumulation of anthocyanins (Drappier *et al*., 2017). Hence, winemakers prefer red wines and an earlier harvest date.

Generally, CC affects aroma and their precursor levels, impacting the harvest date. In white wine production, maintenance of higher levels of floral nuances in grapes because of some terpenes, such as linalool, is preferred to harvest when technological maturity is reached, which occurs early if temperature is high. In fact, the concentration of these compounds is moderate prior to verasion, increases during ripening, but decreases with overripening (Costantini *et al*., 2017). Other classes of aroma compounds, such as methoxypyrazines, are strictly related to grapes maturity and harvest. Allamy *et al*. (2023) showed that in the case of cv Cabernet Sauvignon wines, delayed harvest date increased cooked fruit notes and induced a decrease of fresh vegetable indications. Moreover, other studies underlined that early harvesting of '*Cabernet Sauvignon*' was marked by fresh fruit and green aromas, while late harvesting resulted in wines with black fruit notes and cooked fruit sensations (van Leeuwen *et al*., 2022), thus confirming that the aromatic maturity is strictly related to harvest time.

## Effect of high sugar concentration and higher pH

In wine industry, one of the direct consequences of CC is the increased alcohol content of wines. It is estimated that in the past decade, 50% increase in alcohol levels in globally produced wines is related to CC (Jones, 2007); this factor represents a problem not only for technical aspects but also for market trends. Indeed, if a moderate consumption of wine can have beneficial effects on health, higher levels of alcohol consumption can cause various diseases and injuries; hence, consumers must reduce alcohol beverages (Bucher *et al*., 2018). From an oenological point of view, ethanol interacts with different wine compounds, thus modifying sensory profile, reducing fruity notes, and amplifying unpleasant notes such as bitterness and astringency (Goldner *et al*., 2009). During wine production, increased concentration of ethanol may slow down or stop alcoholic fermentation because of its toxic effect on yeasts, and could be a limiting factor for malolactic fermentation (Drappier *et al*., 2017). Moreover, high sugar accumulation in grape musts leads to yeast cells exposed to high osmotic stress, potentially causing a stuck fermentation (Ishmayana *et al*., 2011), and thus leading to the production of increased amounts of fermentation secondary products, such as glycerol and acetic acid (Mira de Orduña, 2010).

Climate change during grape ripening has a direct effect on the wine's acidity and thus on the quality of the final product. Increase in pH and the lower content of titratable acidity induces lower biological stability to wine, resulting in more susceptibility to alterations. Particularly during the first stage of alcoholic fermentation, when the amount of ethanol is low, there is a risk of uncontrolled growth of spoilage yeast, such as *Brettanomyces bruxellensis*, which is responsible for off-flavors belonging to the category of volatile phenols (Mira de Orduña, 2010). In addition, increase in pH affects the chemical behavior of different metabolites, including anthocyanins, which are essential for the stability and aging of red wines. At $pH < 3$, the predominant anthocyanin form in solution is flavylium cation, which exhibits red color. However, if $pH \geq 3.7$, the more prevalent form becomes colorless carbinol pseudo bases, reducing the contribution of anthocyanin to red wine color (Brouillard and Dubois, 1977). Moreover, when in their flavylium form, anthocyanins can either associate with each other or interact with other organic compounds, primarily flavonoids and phenolic acids, to form co-pigments. These copigments typically contribute to blue-purple tones in red wines. Consequently, at higher pH levels, there is a lower concentration of anthocyanins in their flavylium cation form available for copigmentation (Forino *et al*., 2020).

Furthermore, increase in pH impacts the activity of sulfur dioxide ($SO_2$). It is well known that $SO_2$ is a strong antioxidant and important antimicrobial agent used as a preservative in wines. A large proportion of $SO_2$ is bound to carbonyl compounds. The so-called free $SO_2$ in wine is predominantly in the form of bisulphite ions ($HSO_3^-$) and only a small proportion is present as a molecular $SO_2$. Therefore, the chemical equilibrium of the two species depends on the wine pH, and with increasing pH, the molecular $SO_2$ fraction decreases, thus reducing the antiseptic activity (Divol *et al*., 2012; Giacosa *et al*., 2019). $SO_2$ also acts as an antioxidant by reacting with hydrogen peroxide, derived by oxidation of polyphenols in wine and by reducing the quinones back to their phenol form. Moreover, $SO_2$ in sulfurous acid form combines with acetaldehyde to form aldehyde sulfurous acid, competing with hydrogen peroxide to prevent the formation of aldehyde (Boulton *et al.*, 1996; Yildirim and Darici, 2020).

Finally, the pH is able to influence the hydrolysis rate of acetate esters and the equilibrium kinetics of ethyl esters of fatty acids. Indeed, these compounds influence the fruity character of young wines. However, during storage, the esters tend to hydrolyze, causing a reduction in some fresh aroma of wine. This behavior is accelerated by low pH and higher temperature. Accordingly, rise in pH due to the effects of CC leads to a greater ester stability and preservation of fruity aroma in wines; nevertheless, this effect must be assessed in the context of overall balance of wines, also considering the risks associated with microbiological and oxidative stability at higher pH levels (Makhotkina and Kilmartin, 2012; Pérez-Coello *et al.*, 2003; Ramey and Ough, 1980).

## Techniques to reduce or remove alcohol content in wine

Nowadays, to confront the main effects of CC in winemaking, one of the most challenging objectives is the production of wine with reduced or removed alcohol content. Precisely, different strategies have developed that are categorized depending on the vinification time of application. These strategies are divided as pre-fermentative, fermentative, and post-fermentative techniques.

### *Pre-fermentative techniques*

The reasons that have led to an increase in the concentration of sugars in musts are to be discovered for improving vineyard management practices, as for many years it has been attempted to increase the concentration of grapes in primary and secondary metabolites (Smart *et al.*, 1990); however, CC has contributed to exacerbating the effects. The first fundamental choice that an oenologist faces is related to harvest time. In the case of grapes for producing white wines, opting for an early harvest can lead to satisfactory results; however, it is necessary to implement early ripening controls and adopt adequate organizational strategies (Varela *et al.*, 2015).

The advancing of harvest in the case of red grapes for the production of red wines is not always practicable because the content of polyphenols and aromas may not have reached the maximum potential. In particular, in grapes characterized by high levels of tannins contained in the skins or seeds, the advancing of harvest appears to be impractical because of sensory imbalances that could be generated in wines (van Leeuwen *et al.*, 2022).

Dilution is the easiest way to reduce alcohol content. Water addition in grapes reduces sugar content, but in general, has a negative impact on other parameters, such as reduced acidity, color, and phenolic compounds (Martínez-Moreno *et al.*, 2023). Some studies showed that decreasing the final ethanol content through water addition could increase the fruity notes of wines, producing a fresher product. However, in most wine-producing countries, the practice of grape must or wine dilution is either forbidden or strictly limited and regulated by competent authorities (Harbertson *et al.* 2009; Varela *et al.*, 2015). International Organization of Vine and Wine (OIV) admit water addition in winemaking only for aromatized wines and wine-based beverages (Resolution OIV-OENO 439-2012, 2012). The only case where water could be reintroduced is the practice of reducing sugar content in musts through membrane coupling (Resolution OIV-OENO 450B-2012, 2012). The water and organic acids filtered by nanofiltration process are reintroduced into the treated must. However, the OIV has no specific guidelines for adding water for technical purposes, such as incorporating permitted additives or processing aids; for this, every country has the responsibility to regulate legislative aspects.

Another strategy that does not foresee special equipment or additional costs is the blending of wines. For this, wines obtained from early-harvest–low-sugar grapes are blended with wines from higher-sugar grapes, obtaining a final product with reduced ethanol content. Blending wines from grapes of different maturity stages is a good method to obtain a quality product with lower alcohol content and improved color, mouthfeel, and flavor perception (Martínez-Moreno *et al.*, 2023). Moreover, this procedure that requires important volumes of low-alcohol wines reduces pH without impairing other characteristics of the final product (Kontoudakis *et al.*, 2011). Unfortunately, blending of wines is not always permitted. As in the case of dilution, this technique also depends on every state's rules and regulated by state's competent authorities.

Removal of sugar with nanofiltration is another technique to reduce ethanol content in wines. It consists of passing a fraction of grape must into a membrane under a pressure gradient to separate permeate (with a low amount of sugar) and retentate (with a higher content of sugar). At the end of filtration, the two parts are mixed in specific portions to obtain a must with desired characteristics (Varela *et al.*, 2015). Studies on the application of nanofiltration for both red and white musts showed that the final wines obtained after fermentation by a mix of original must and a portion of the must had a lower content of ethanol. However, a significant reduction of flavor and color was detected (García-Martín *et al.*, 2010).

Similar to nanofiltration, the reverse osmosis technique is applied as well to lower sugar contents before alcoholic fermentation. Reverse osmosis is a separation technique based on the application of high pressures (60–80 bar) for purification of water systems. Instead, if a pressure more than osmotic pressure is applied to the system, then water, ethanol, and other small molecules are forced through a semi-permeable membrane, leaving behind the rest of compounds and allowing isolation and removal (Afonso *et al.*, 2024; Sam *et al.*, 2021b; Török, 2023). Mira *et al.* (2017) used reverse osmosis on different varieties of grape juices to obtain permeate (with low sugars) and retentate (with high sugars), which were then mixed in different proportions to achieve the final wine with alcohol reduction of up to 5% v/v. However, these wines had a decreased color intensity, anthocyanin content, and phenols.

Finally, in a pre-fermentative stage, the enzyme glucose oxidase obtained from the fungus *Aspergillus niger* is used to reduce the content of glucose in grape juices. The enzyme first converts glucose into D-glucono-lactone, producing hydrogen peroxide, and then it catalyzes the conversion of D-glucono-lactone to gluconic acid (Sam *et al.*, 2021b; Varela *et al.*, 2015). Functioning of the enzyme leads to a lower amount of ethanol, although the production of gluconic acid decreases pH and increases total acidity. The sensory perception also is modified, with a lower intensity of fruity flavors (Röcker *et al.*, 2016).

The research community continuously develops new approaches and technologies to produce high-quality wines with a lower alcohol content. Martínez-Pérez *et al.* (2020) studied the use of high-power ultrasounds to produce quality red wines, starting from slightly less ripe grapes, hence recouping the limited extractability with an enhanced extraction technique. High-power ultrasounds typically operate at frequencies of 20–40 kHz. Acoustic cavitation phenomena are induced, forming bubbles that implode quickly. Plant or microorganism cells in the media are affected by this phenomena, as their cell walls are severely damaged leading to cell death and release of its contents in the media. In enology, this technique was applied on crushed grapes, with reduced sugar content, to facilitate the production of highly colored wines with lower amount of alcohol. The obtained wines, compared to control, had similar color characteristics, and the aroma compounds were judged positively during the sensory analysis.

### *Fermentative techniques*

The fermentation process is considered to reduce ethanol content during wine production. *Saccharomyces cerevisiae* is considered as the most efficient yeast species to convert glucose into ethanol during winemaking, also considering its alcohol and stress tolerance. In recent years, a new approach comprising research and isolation of new *S. cerevisiae* strains presenting lower ethanol yield, or mixed fermentation with non-*Saccharomyces* yeasts, is able to produce less alcohol and convert carbon metabolism to other pathways, thus developing metabolites without compromising sensory quality of wines (Rolle *et al.*, 2018; Varela *et al.*, 2015).

The developing of low-alcohol *S. cerevisiae* strains is supported by metabolic engineering. Varela *et al.* (2015) modified two strains, and were able to decrease ethanol content from 15.6% to 13.2% v/v in the first strain, and from 15.6% to 12.0% v/v in the second one. However, both strains enhanced the production of glycerol, acetaldehyde, and acetoin, affecting negatively the resulting wines. Difficulties in using genetically modified microorganisms due to consumer opposition are well known, but authors have also underlined a negative impact of modified strains on wine's flavors (Heux *et al.*, 2006; Sam *et al.*, 2021b; Tilloy *et al.*, 2015).

Regarding the use of non-*Saccharomyces* yeasts in association with *S. cerevisiae* strains, the species most studied are *Metschnikowia pulcherrima*, *Torulaspora delbrueckii*, and *Starmerella bacillaris*. *Metschnikowia pulcherrima* is an indigenous yeast with a low fermentative power, and is able to increase the release of varietal aroma compounds because of high enzymatic capacity. Moreover, under aerobic conditions, its respiratory metabolism helps to reduce ethanol content (Morata *et al.*, 2019). A study conducted by Contreras *et al.* (2014) showed the utilization of *M. pulcherrima* with *S. cerevisiae*. This combination led to a reduction of alcohol content from 0.9% to 1.6% v/v, compared to a control inoculated by *S. cerevisiae* strain only. Similar results were obtained by Varela *et al.* (2017). The use of *M. pulcherrima* with *S. cerevisiae* produced wines with a lower amount of ethanol (–1.0% v/v) and higher concentration of ethyl acetate, total esters, and total higher alcohols, affecting positively the sensory profile of wine. Regarding *Torulaspora delbrueckii,* it has a capacity to produce low content of acetic acid, release polysaccharides and mannoproteins, increase mouthfeel perception, and is able to increase the quantity of esters, thiols, and terpenes (Azzolini *et al.*, 2012; Benito, 2018), leading to positive sensory traits. Additionally, the use of *T. delbrueckii*, in combined fermentations with S. cerevisiae, showed lower accumulation of alcohol (from -0.45% to -0.52% v/v, compared to control) without compromising the sensory quality (Azzolini *et al.*, 2012; Belda *et al.*, 2017).

Finally, numerous studies were conducted on *Starmerella bacillaris*, for its fructophilic character or the ability to grow at high concentrations of sugar and low temperature, and to produce a high content of glycerol and a low amount of acetic acid and acetaldehyde. In addition, *S. bacillaris* is resistant to ethanol toxicity, surviving until the end of alcoholic fermentation (Englezos *et al.*, 2015; Rantsiou *et al.*, 2012). Mixed fermentations of *S. bacillaris* and *S. cerevisiae* influence the process, producing wines with increased volatile compounds and glycerol, as reported previously, but with a lower level of ethanol (Binati *et al.*, 2020; Englezos *et al.*, 2019). Further, some *S. bacillaris* strains increase total acidity (Englezos *et al.*, 2019), thus influencing organoleptic perceptions.

### *Post-fermentative techniques*

Alcohol content in wines can be reduced or removed at the end of alcoholic fermentation through physical methods, such as membrane processes, extraction processes, and thermal distillation.

Besides the application of pre-fermentative techniques, some membrane-based techniques, such as nanofiltration and reverse osmosis, are applied directly on wine. Several studies have underlined the effectiveness of nanofiltration and reverse osmosis for both alcohol reduction and dealcoholization (Afonso *et al.*, 2024; Sam *et al.*, 2021b) (Figure 4).

Gonçalves *et al.* (2013) showed that, similar to the application on grape juice, nanofiltration decreases polyphenols and reduces total and volatile acidity because of a higher passage of acetate ions. Reverse osmosis applied on wines reduces the content of anthocyanins, caused by membrane adsorption, and produces an alteration to wine's body and texture, particularly in red wines, because of the concentration of tannins (Török, 2023).

Osmotic distillation (or evaporative perstraction) is a separation process applies to reduce alcohol in wines. This technology is based on membranes that separate two aqueous phases: wine, containing volatile compounds, and water, used as a stripping liquid. These phases circulate in the opposite direction of a hydrophobic hollow fiber membrane module, guided by the vapor pressure of volatile solute in wine and stripping liquid. Ethanol first evaporates due to increased temperature; then, ethanol vapors diffuse through membrane pores, and finally exits from membrane pores and condenses in water media (Afonso *et al.*, 2024; Sam *et al.*, 2021a) (Figure 5).

Osmotic distillation reduces alcohol content and has a low subtractive impact on wine's final composition, preserving aroma compounds and color as well as phenolic compounds without sharp modification in the quality of wine (Corona *et al.*, 2019; Liguori *et al.*, 2012).

Another membrane separation technique used to reduce alcohol content in wine is pervaporation, also called vapor permeation. Based on the principle of partial evaporation, it separates components from liquid mixtures using dense and non-porous membranes (Afonso *et al.*, 2024). The separation relies on differences in the transport rate of individual components. Substances crossing the membrane change from liquid phase to vapor phase, desorbing from the other side pressured through vacuum stress (Sun *et al.*, 2020; Takács *et al.*, 2007). Studies on pervaporation achieved good results for producing quality wines. This process is able to separate phenolics, residual sugars, and aroma components from ethanol, obtaining alcohol-free or low-concentration wines (Afonso *et al.*, 2024; Sun *et al.*, 2020). In addition, this process has low energy consumption and operates at low temperatures, with more efficiency than other dealcoholization or traditional distillation methods (Sam *et al.*, 2021b).

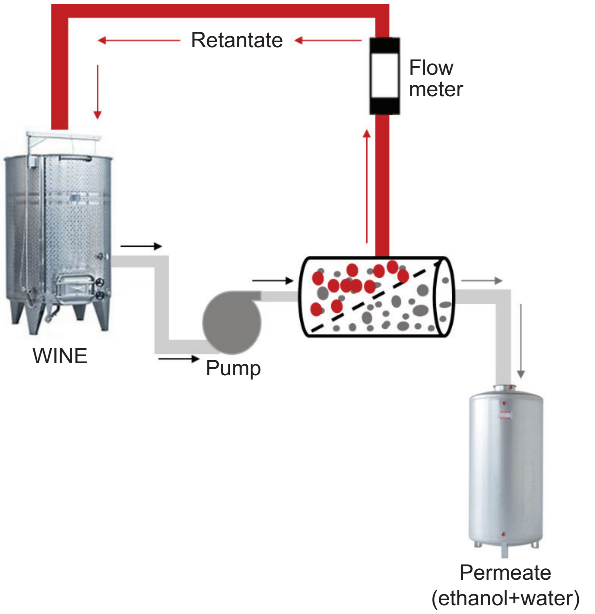

**Figure 4. Reverse osmosis process to remove alcohol from wine.**

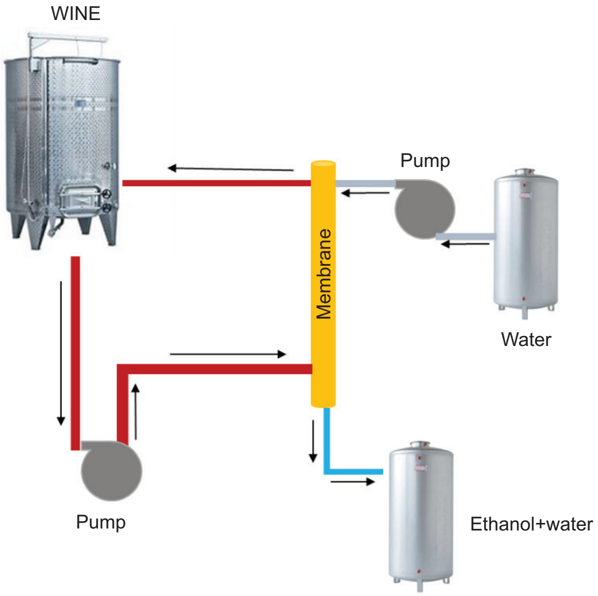

**Figure 5. Process of osmotic distillation.**

Decrease in the ethanol concentration of wine is also accomplished by extraction methods by using gasses. Compression of a gas under specific conditions and above its critical point transforms it in a supercritical fluid, which is able to extract organic compounds, such as ethanol. In the winemaking industry, $CO_2$ is used due to its characteristics, such as no toxicity and low critical temperature (31°C). In its liquid state $CO_2$ in wine has an affinity with ethanol's carbon chain that facilitates its dissolution, however if $CO_2$ has a transition back into a gaseous state it carries dissolved ethanol, reducing the wine alcohol content (Afonso *et al.*, 2024; Schmidtke *et al.*, 2021). This technique has the disadvantage of decimating aroma together with ethanol. However, studies conducted by Ruiz-Rodríguez *et al.* (2010, 2012) demonstrated that the application of supercritical $CO_2$ extraction is an attractive process because it does not remove or denature water, salts, proteins, and carbohydrates. Furthermore, this process does not modify the antioxidant power and aromatic profile of wines with reduced alcohol content. Some trials showed that supercritical $CO_2$ extraction is employed to recover aroma compounds, and ethanol from raffinate is separated in a subsequent distillation column. Finally, alcohol-free wine is produced by mixing extracted aroma compounds into the product of distillation. Differently, ethanol and aroma can be removed in the first step of distillation, and sequentially aroma compounds are extracted from distillate by supercritical $CO_2$ and recycled to the bottom through distillation to have a no-alcohol product (Ruiz-Rodriguez *et al.*, 2012).

Vacuum distillation and spinning cone column are two thermal distillation methods applied in the wine industry to partially or completely remove alcohol from wines. Vacuum distillation separates ethanol from wine through evaporation. The process is performed at low temperatures, generally between 15°C and 20°C, under vacuum conditions. The operating conditions allow separating alcohol as vapors and then to condense it into a liquid form, producing a distillate with extracted ethanol (Gómez-Plaza *et al.*, 1999; Motta *et al.*, 2017). Vacuum distillation can maintain high concentration of flavonoids, organic acid, and anthocyanins, and can increase total acidity. On the contrary, this technology affects the sensory profile of wines, particularly floral and fruity sensations. The final product results in the depletion of volatile compounds (Gómez-Plaza *et al.*, 1999; Sam *et al.*, 2021a).

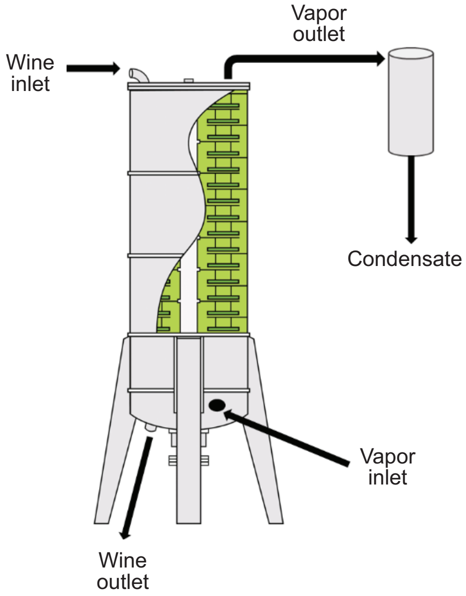

**Figure 6. Scheme of a spinning cone column process.**

Spinning cone column is one of the most common methods to remove alcohol, and is mainly used in the beverage and winemaking industry. It is based on a vertical rotative column, formed by stacked cones, which operate under vacuum and at low temperature to change volatile compounds into gaseous phase. The extraction takes place in two steps: in the first step, conducted at 26–28°C under reduced pressure (about 0.04 bar), aromatic compounds are extracted. In the second step, ethanol is extracted at high pressure and temperature (38°C). At the end of the process, a recovering system is used for the volatile compounds removed in the first step to reconstitute the final aroma of wine (Belisario-Sánchez *et al.*, 2009; Zamora, 2016) (Figure 6).

Studies conducted on the use of spinning cone column underlined its low aggressivity to remove or reduce alcohol content in wines. In fact, phenolic compounds, anthocyanins, and flavonols have a low increasing trend due to concentration. In addition, beneficial compounds, such as resveratrol, with antioxidant activity increased after the application of this technique (Belisario-Sánchez *et al.*, 2009). Nevertheless, an important usage of this technique is that it can be paired with adsorbent materials for removing ash and smoke taint from wines produced from grapes exposed to bushfire smoke; increasing occurrence of wildfires represent another effect of CC. In some regions, the phenomena of wildfires has become more relevant in the last few years, an issue reflected in wine production (Mirabelli-Montan *et al.*, 2021; Puglisi *et al.*, 2022).

## Conclusions

The current situation that the wine community confronts due to CC has forced producers to implement strategies to reduce alcohol content in wines. Choice of the approach to achieve results is made primarily considering the aims, effectiveness, and sustainability of the process. Therefore, it is essential to adopt innovative and environment-friendly techniques, such as low-alcohol yeasts, optimized management of grape ripening, and usage of more efficient winemaking methods. In addition, the research and development of grape varieties more resistant to high temperatures and drought is crucial. Collaboration between wine producers and wine researchers is essential to find and develop effective and sustainable solutions. This is the only way to guarantee the quality of wine without compromising the ecosystem and well-being of future generations while ensuring that winemaking traditions can adapt and thrive in a changing environmental context.

## Author Contributions

Both authors contributed equally to this paper.

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## Conflicts of Interest

The authors declared no conflict of interest.

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