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Review

Viticultural Manipulation and New Technologies to Address Environmental Challenges Caused by Climate Change

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Abstract: Climate change is a critical challenge for the global grape and wine industry, as it can disrupt grapevine growth, production, and wine quality. Climate change could influence the cost-effectiveness and growth of the wine industry in different wine regions since grapevine development is deeply dependent on weather (short-term) and climate (long-term) conditions. Innovation and new technologies are needed to meet the challenge. This review article addresses the impact of climate change on grapevines, such as vine phenology, pest and disease pressure, crop load, and grape and wine composition. It also reviews recent advances in the areas of viticultural manipulation and relevant technologies to potentially reduce the impact of climate change and help growers improve grape quality. Remote sensing is used for vineyard microclimate monitoring; thermal sensors combined with UAVs, aircraft, or satellites are used for water management; soil electrical conductivity sensors have been developed for soil mapping. Viticultural manipulations, such as regulated deficit irrigation for water use efficiency and berry-ripening delay for growing quality fruit, are also discussed. The review assesses future directions for further technological development, such as soil and vine water monitoring devises, precision viticulture, and artificial intelligence in vineyards.

Keywords: climate change; viticultural manipulation; grapevines; wines; new technology; adaption

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1. Introduction

"Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer" [1]. The global average temperature change started in 1880 [2]. According to the latest U.S. Climate Normals 2021 [3], the average temperature in 1981–2010 for the contiguous USA was 52.8 °F, and in 1991–2020, it was 53.3 °F. Carbon dioxide (CO_2) emissions from human activities are the main drive toward global climate change [4]. As the CO_2 concentration is predicted to continue rising, Earth surface temperature will keep increasing [5].

Changing climate can lead to agricultural change. Severe warming due to climate change has led to increased drought in agricultural production areas and, thus, negatively affects plant water availability and crop production and quality. For example, based on a new released U.S. Drought Monitor, some areas of Kansas and Texas reached exceptional drought levels, which reduced surface water, dried out soils and vegetation, and altered the timing of water availability [6]. The grape and wine industry are no exception to the climate change impacts. For instance, grape growing relies heavily on the length of the growing season, and environmental temperatures and changes in the climate affect these factors [7]. Global warming is expected to change the temperature range in most viticultural areas and will directly influence wine quality. Thus, there is a need to investigate the multiple ways climate change has modified the grape and wine industry.

This review article focuses on the impact of climate change on grapevines, such as phenology, pest and disease pressure, yield, and grape and wine composition. The recent advances in the areas of viticultural manipulation and relevant technologies are also reviewed. This review article contributes to the literature on supporting grape growers and winemakers to better understand the challenges presented by climate change issues. It will also provide them with adaptation options to face the challenges and improve grape and wine quality.

2. Overview of Climate Change Models for Wine-Producing Regions

Climate change constitutes a double-edged sword for wine regions. The warming temperature in cool climate areas improves grape and wine quality. For example, with temperature increases of 2.3–5.3 °C in the northern European regions [8], the extended frost-free growing seasons will make it possible to grow warmer-climate varieties and improve current fruit production and quality [8,9]. An empirical study in Moldova also found that both land size and labor have positive significant influences on the productivity of wineries. This finding could be an inspiration for other countries that have similar potential in rural areas to increase wine production [10]. In addition, cool climate regions in North America, such as Oregon and Washington State (USA) and British Columbia (Canada), would also be able to grow new varieties [11]. Grape production in Michigan in the USA has increased due to its shift in climate; the warmer temperatures have been canceling out early season frost. Michigan's future climate is more likely to be suitable to growing all varieties of grapes, including grape varieties that are climatically sensitive to cold temperatures [12,13]. Climate change will also cause grape-growing regions to be more suitable for growing at higher elevations [7].

However, other warm-climate wine regions will be negatively affected by high temperatures and water stress due to the reduction in the amount of water available or irregular precipitation. It is predicted that temperatures will increase by 0.42 °C per decade, which will make it challenging for some wine regions to produce high quality grapes and wines [14]. Regions with Mediterranean climatic conditions are the largest wine regions in the world owing it to long growing seasons with dry/hot summers and mild/wet winters [15]. The regions are located on the western sides of continents between 30° and 40° latitude and will likely face the most severe impacts from climate change [16]. Other wine regions, such as southern Europe, are becoming too hot to produce premium wine since they have already reached, or even exceeded, the optimum range of growing conditions for the currently cultivated grape varieties. Australian wine regions have reported early ripening of Chardonnay, Shiraz, and Cabernet Sauvignon due to increased temperatures [17]. California's climate is one of the most challenged in North America. During the last decade, California has faced several of the most extreme climate and environmental conditions, such as severe drought and wildfires [18].

In our study, ten wine regions were selected as representative of the main producing regions and of the diversity of climatic conditions encountered in wine production. The average annual temperature was used for the climatic conditions and climate change conditions. The data analysis consisted of calculating the mean temperatures for each region under a baseline condition and two climate change periods (mid-century = 2040–2060 and end-century = 2080–2100). The difference between the temperatures in relation to the baseline was calculated to identify the direction of change in temperature. A positive sign indicated a warming condition, while a negative sign indicated a cooling condition. Given the global scope of our analysis, the use of average annual temperature was justified, as these data are commonly used to characterize producing regions, even though average annual temperature can mask extreme weather events that would be prejudicial to grapes or to the quality of the wine [19].

The data for the geographic areas were based on the maps produced by vineyards.com and manually digitized by the authors. The data for the baseline were average annual temperature data for 1970–2000 and were obtained from the WorldClim 2.0 dataset at a spatial resolution of 30 s [20]. The data for average annual temperature under the climate change condition were from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) climate model [21]. We used the downscaled version of GISS data under shared socioeconomic pathway (SSP) 585 at 30 s spatial resolution for 2040–2060 and 2080–2100 from the WorldClim 2.0 database [14]. The GISS data under SSP 585 represent a climate model calibrated under representative concentration pathway 8.5 and shared socioeconomic pathway 5, which represent intensive use of fossil fuels and energy and economic development. From now on, we will refer to the downscaled version as GISS.

For the baseline conditions (Figure 1), annual average temperatures in the ten regions varied from 9.11 °C for the Mosel Valley region, Germany, to 16.54 °C for the Stellenbosch region, South Africa (Figure 1). It is interesting to note the difference between Mendoza, Argentina, and Maipo Valley, Chile, as Mendoza recorded 10 °C and Maipo Valley was 4 °C warmer at 14.38 °C. In the baseline, five regions were in the two lower temperature ranges.

Figure 1. Average annual temperature for selected wine-producing regions for baseline period (1970–2000) in Celsius. Source: Average annual temperature [20], wine-producing regions manually created by the authors, World Imagery by Esri and Earthstar Geographics.

Under the future climate conditions estimated by the GISS, there will be remarkable warming in all regions. Figures 2 and 3 show an increase in temperature, which prompted us to add new temperature ranges to our scale to accommodate it. For the mid-century period, the temperature range was from 11.33 °C to 18.22 °C. There was no region under 10 °C. We identified the highest increase in temperature (2.5 °C) as occurring in Piedmont, Italy, and the lowest increase in temperature (1.6 °C) in Central Coast California, United States. For the end-century period, the temperature range was from 12.72 °C to 20.09 °C. The lowest temperature class for this period corresponded to a mid-to-high temperature in the baseline climatic condition. We identified the highest increase in temperature (4.4 °C) as occurring in Piedmont, Italy, and the lowest increase in temperature (3.3 °C) in Bordeaux, France. Furthermore, three regions (Maipo Valley, South Australia, Stellenbosch) had temperatures in the range from 18.2 °C to 20.1 °C.

Figure 2. Average annual temperature for selected wine-producing regions for middle of century period (2041–2060) in Celsius. Source: GISS—average annual temperature for 2041–2060 [20], wine-producing regions manually created by the authors, World Imagery by Esri and Earthstar Geographics.

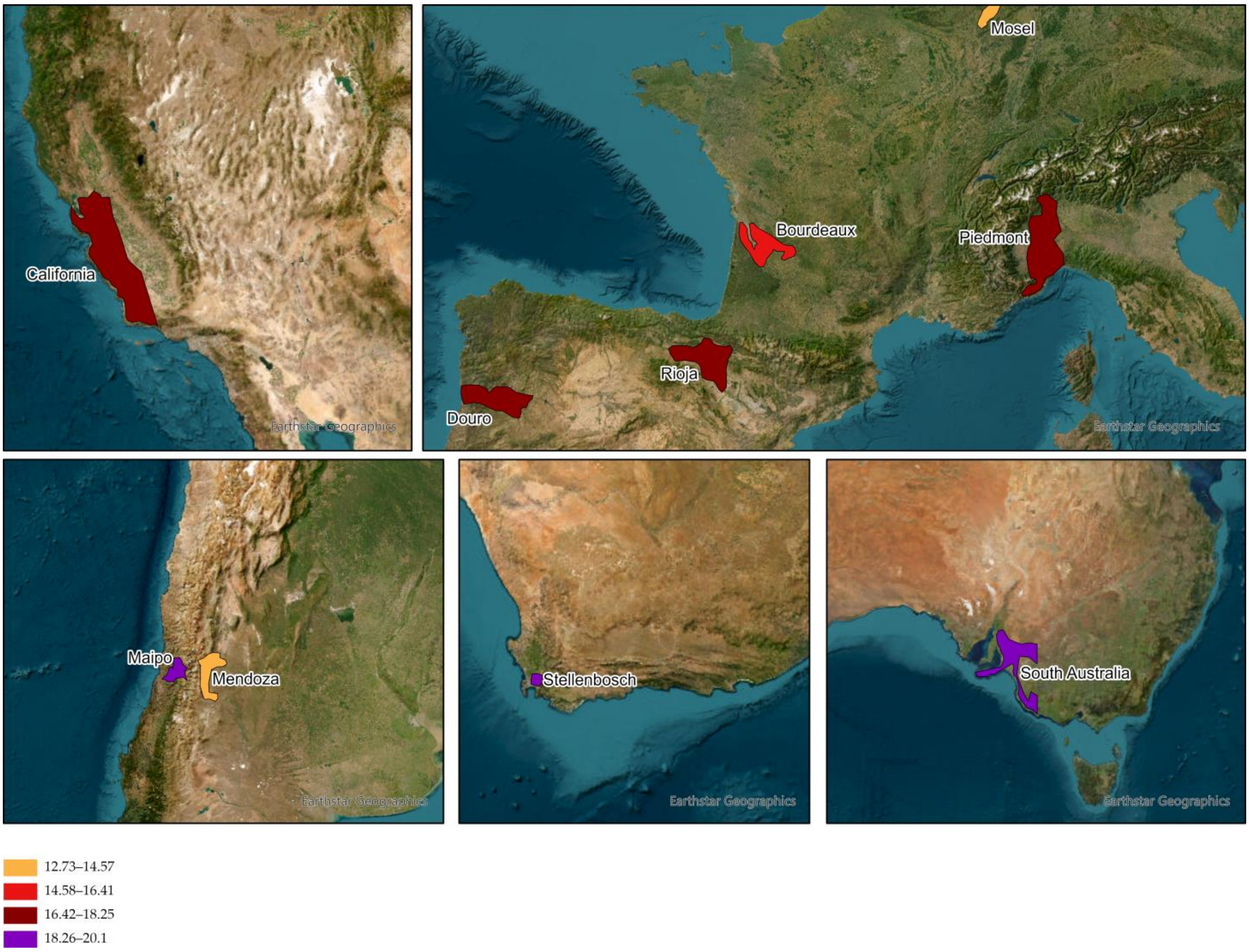

Figure 3. Average annual temperature for selected wine-producing regions for end of century period (2081–2100) in Celsius. Source: GISS—average annual temperature for 2081–2100 [20], wine-producing regions manually created by the authors, World Imagery by Esri and Earthstar Geographics.

3. Impact of Climate Change on Grapevines, Berries, and Wine

Grapevine and wine production is vulnerable to the effect of climate change. Heat and water stress related to climate change can affect vine phenology, pest and disease pressure, crop yield, and berry and wine composition.

3.1. Grapevine Phenology

Grapevine phenology has two developmental cycles known as the vegetative and reproductive cycles. These cycles are complex and include vine and fruit growth for the current season as well as the next. These cycles are responsible for berry formation and growth of the vine. There is a strong correlation between grapevine phenology and environmental factors, such as daylight length, heat, water, soil, and light. Climate change factors, such as elevated CO_2, elevated temperatures, and water stress, have played an important role in grapevine growth patterns [22].

Carbon dioxide is a major concern with climate change as the atmospheric CO_2 concentration is expected to reach 600 ppm. High CO_2 levels may promote physiological changes in vines. Increasing CO_2 levels will limit the production of plant hormones, such as ethylene and jasmonic acid, which are both significant in the plants' defense response [23].

Temperatures can affect grape quality by leading to an earlier onset of the growing season, creating premature véraison from early heat, which can affect enzyme activation or cause poor ripening. This would cause the growing season to be shortened and accelerate berry ripening [24]. When the sugar accumulation starts earlier and progresses more rapidly in the warmer periods of the growing season, the phenolic composition and berry anthocyanin concentration can be negatively affected, causing less than desirable harvest levels. For example, during flowering and the berry growth period, heat extremes can cause berry softening and changes in berry color. It has been shown that the accumulation of anthocyanins, which are responsible for berry coloration, is lower when maturation occurs at higher temperatures [25]. Premature véraison might lead to less aroma and flavor compound accumulation, which can affect berry flavor development [26]. Similar observations have been made in different wine regions [27–30]. In summary, increasingly high temperatures would lead to negative outcomes for grape and wine quality.

A major factor affecting the growth and productivity of the vine is water availability. Climate change is associated with unpredictable precipitation patterns and more severe drought conditions that can be expected to impact yield and the overall growth of vines. When water shortages occur early in the season, they can reduce yield by affecting bud fertility, as the reproductive structures inside the dormant buds are sensitive during this time [31]. Once the grapevine gets past budbreak, the reproductive growth is relatively unaffected. Another effect of climate change is the combination of higher temperatures and unpredictable precipitation, leading to water deficits. High rates of evapotranspiration and increased plant water requirements are caused by higher temperatures [32]. When water deficits are up to 50% of the evapotranspiration threshold, there is almost no effect on yield; however, when the threshold is surpassed, the yield decreases. This phenomenon is more prominent during the budbreak to bloom phenological phase [33,34].

3.2. Pest and Disease Pressure

Studies have found that climate change is inducing greater pest and disease pressure in vineyards. A healthy vine can create resistance or fight off potential attacks due to the plant's defense system. Pests or pathogens usually affect the vine during specific exposed periods of the vine's lifecycle. However, climate change can modify the period a plant will be exposed to a pathogen. For instance, high temperatures would promote pathogen development and increase survival rates, which can change the susceptibility of a host (plant) to pests and diseases [35].

Plant diseases can be used as an indicator of climate change. This can be complicated with all the biological interactions that result in disease [35]. Disease will occur more often when the vines are stressed in warmer climates. There is a concern regarding diseases that increased CO_2 levels will decrease plants' ability to decompose, so leaves or plant material on the ground can cause fungal spore development if not managed properly [36,37]. This, along with extremely hot temperatures that can cause berry sunburn and damage the berry skin, could increase the Botrytis cinerea infection rate in grapes [38]. When the phenology of the plant and the pathogen align, more plant diseases can occur.

Depending on the magnitude of global warming, it may influence the phenology of insects by impacting the timing of their emergence and feeding patterns. Since there may be a change in the timing of grapevine phenology—for example, budbreak or foliar growth—this could lead to a change in insect survival, since insects' timing is determined by the plant. If they are not emerging at the stages of growth needed for survival, it could cause the population to undergo food starvation or be unable to meet survival needs [39]. Elevated CO_2 concentrations can lead to the accumulation of non-structural carbohydrates in plant, which results in lower tissue nitrogen concentrations. This can lead to the need for insects to consume more foliage to meet their nitrogen needs [40–42]. Thus, the effects of climate change on insects are complex and involve several unknown factors, such as the introduction of new pests, competition among pests, and the presence of beneficial insects.

However, many of the highly mobile enemy insects can track climate change conditions, while this could take a while for less mobile species [39]. Vine mealybugs, for example, are less likely to leave their hideouts under the bark and on the roots to migrate towards leaves and fruit during hot conditions. However, if the daily temperatures are to increase by 2 °C or 4 °C, most regions would expect to see an increase in overall mealybug density. In California, the mealybug densities are predicted to be higher in the cooler vineyards, such as Napa and Sonoma, while being lower in warmer areas, such as the Coachella Valley [43]. The extremely hot summer temperatures in the Coachella Valley can cause mealybug mortality. In comparison, the summer temperatures in the San Joaquin Valley are not hot enough to cause high mortality rates; thus, the mealybug populations can increase significantly during the growing season. In cooler areas, such as the coastal regions, mealybug abundance follows a similar pattern to the San Joaquin Valley but with fewer summer generation cycles [44]. As many of the distributions of the pest and pathogens will be changed, interactions between them and the plants will need to be monitored. Additionally, researchers have found that pest and weed management are the main hotspots for greenhouse gas emissions in the lifecycle of grape production [45,46].

3.3. Grapevine Yield

Grapevine yield depends on soil fertility and climatic conditions. High yields can be achieved with moderately high temperatures, sufficient light conditions, and enough nitrogen and water. Increased temperatures are beneficial for crop yield in some cool climate regions. Nemani et al. (2001) [29] found that yields and berry quality were improved in Napa and Sonoma Valleys due to lower occurrence of frost and a longer growing season. However, grapevines grown under excessive heat stress suffer photosynthesis limitation, thus contributing to significant yield reductions. Heat waves may result in a yield decrease of up to 35% in some viticultural regions [47]. Drought conditions impair grape yield, and the decrease can be variety-dependent [48]. During drought conditions, stomatal closure and the impairment of the photosynthetic machinery limit photosynthesis [48]. Increased water deficit due to reductions in precipitation in conjunction with increases in evapotranspiration influences yield. Studies have found that water deficit negatively affects yield [49,50]. Berry weight is one of the yield components most affected by water availability and is used for calculating the yield of a vineyard. A study showed that Shiraz vines with water deficit after flowering demonstrated significant reductions in berry weight compared to sufficiently watered vines, particularly during high-temperature seasons [51]. Another source of yield variability is temperature. A study on Sangiovese and Cabernet Sauvignon in Italy in relation to climate change reported that warmer weather resulted in higher yield variability [52].

3.4. Berry and Wine Composition

Grape berries are composed of several hundreds of chemical compounds, including water, fermentable sugars, organic acids, nitrogen compounds, minerals, pectins, phenolic compounds, and aromatic compounds [53]. Environmental conditions, such as soil, topography, and climate, influence yields, grape composition and sensory attributes, and the quality of the wines. Higher temperatures can accelerate grape metabolism, leading to changes in the biosynthesis of basic components [54]. A report found that metabolic pathways in grapes changed once the ambient temperature was 30 °C [25]. Many studies provide evidence of grape and wine composition changes, including dramatic changes in pH, total acidity, and alcohol [5,14,55].

3.4.1. Sugar, Acid, and Alcohol

Elevated temperatures have been associated with sugar accumulation and organic degradation, resulting in an unbalanced sugar–acid ratio [56]. Wine made from these kinds of berries contains higher alcohol content and falls short in freshness and aromatic complexity. Warmer conditions in Slovenia led to a large reduction in total acidity in early-ripening wine varieties [57,58]. Grape malic acid levels are typically low in warm climate regions, since it tends to degrade at high temperatures. Lecourieux et al. found that imposing heat treatment (+8 °C, 14 days) on grape clusters at véraison and during berry ripening significantly decreased the berry concentration of malic acid, while it increased some amino acids, such as phenylalanine, γ-aminobutyric acid, proline, and leucine. The alterations in acid concentrations could have been due to the deep remodeling of transcriptomes in heated berries [59].

3.4.2. Anthocyanins

Anthocyanins in berries are phenolic compounds that are responsible for berry coloration. Temperature has been found to be a critical factor affecting anthocyanin synthesis due to enzymes in the metabolic pathway being temperature-sensitive [60,61]. If sugar accumulation starts earlier and proceeds more rapidly in the growing season under high temperatures, the berry anthocyanin concentration cannot reach the desirable levels at the harvest. This is especially true in warm-climate wine regions. Ripened berries typically have an unbalanced composition, with higher total soluble solids, low acidity, and fewer anthocyanins. Moreover, anthocyanins are highly unstable and susceptible to thermal degradation. Research has indicated that anthocyanins tend to accumulate better at 20 °C than 30 °C [62]. The anthocyanin accumulation decreases once the temperature rises above 30 °C [63,64]. Véraison, heat treatment, and ripening heat treatment (+8 °C, 14 days) decreased the concentrations of anthocyanins at harvest, such as delphinidin-3-O-glucoside, cyanidin-3-O-glucoside, petunidin-3-O-glucoside, peonidin-3-O-glucoside, delphinidin-3-O-(6′-acetyl) glucoside, cyanidin-3-O-(6′-acetyl) glucoside petunidin-3-O-(6′-acetyl) glucoside, and peonidin-3-O-(6′-acetyl) glucoside [59].

3.4.3. Aroma

Increased temperatures and solar radiation will alter the secondary metabolites in berries, thus impacting flavor development [5]. The temperature range of 20–22 °C appears to be optimal for aroma formation during the grape maturation stage for most varieties [65]. Increased volatilization of aroma compounds at high temperatures has been observed. Belancic et al. reported that the terpenol content of Moscatel de Alejandria (Muscat of Alexandria) and Moscatel Rosada (Muscat Rose) was lower as a result of the vines' overexposure to sunlight and higher berry temperature [66]. The concentrations of some aroma compounds may increase due to high temperatures, but this imparts negative effects on the wine since it breaks the balance of the aroma profile. For example, Marais et al. found that the concentrations of 1,1,6-trimethyl-1,2-dihydronaphthalene (TDN) varied with climatic regions. Warm temperatures increased the formation of TDN, which might have had a negative effect on Riesling wine, with overpowering petrol notes [67]. In a study by Lecourieux et al. (2017) [59], Cabernet Sauvignon berries exposed to high temperature showed decreased aromatic potential due to deregulation of numerous aroma and aroma precursor-related genes. The results suggested that heat treatment contributed to the decrease in volatile terpenoids caused by the repression of many key enzymes in the biosynthetic pathway. Carotenoid biosynthesis also decreased with heat treatment. High-temperature exposure also led to a drastic reduction in 2-methoxy-3-isobutylpyrazine (IBMP) content in ripe berries due to the repression of the key gene VviOMT3. VviOMT3 was reported to be responsible for the synthesis of the IBMP [68].

The impact of climate change on grapevines, berries, and wine are summarized and presented in Table 1.

Table 1. Summary of impact of climate change on grapevines, berries, and wine.

Category	Effects of Climate Change	References
Grapevine phenology	Shortens the growing period and fastens berry ripening Causes high rates of evapotranspiration and increases vine water requirements	[31,33,34]

Table 1. *Cont.*

Category	Effects of Climate Change	References
Pest and disease pressure	Promotes pathogen development and pest increased survival rate Changes the susceptibility of vines Reduces beneficial insects	[35–37,40]
Grapevine yield	Improves yields in cool wine regions due to less frost occurring and longer growing season Limits vine photosynthesis and decreases significant yields due to excessive heat stress Causes higher yield variability	[29,47,48,52]
Berry and wine composition	Accelerates grape metabolism Increases sugar accumulation and reduces organic acid, resulting in an unbalanced sugar–acid ratio Increases alcohol content Decreases anthocyanin accumulation Has an impact on flavor development	[57–59,66,67]

4. Strategies for Climate Change Adaptation

"Climate change adaptation is the process of adjusting to current or expected climate change and its effects" [1], and it is the key to the future of agriculture, which depends heavily on weather and climatic conditions. To continuously achieve high quality grapes and wine, different viticultural manipulations and technological solutions are being developed to mitigate the negative effects of climate change.

4.1. Vineyard Location and Vine Row Orientation

The radiation intercepted by the grapevine canopy is dependent on several factors, such as topography, slope direction, steepness, and vineyard altitude. Vineyard location selection could be a cost-effective way to allow the winegrower to adapt locally to climate change. For example, cultivating wine grapes at a higher altitude is a useful strategy since vineyard altitudes play a significant role in combatting the impact of climate change [7]. High-altitude viticulture exposes the vine to more ultraviolet light but allows a low temperature to be maintained, which favors higher quality grapes and premium wine. One study conducted in Southern Brazil found that fully mature Cabernet Sauvignon berries could be produced in a high-altitude vineyard with high total soluble solids and phenolics contents [69].

Row orientation may also be a useful tool as a viticulture practice to adapt to climate change. There is a climate and temperature difference between the Northern and Southern Hemispheres. Due to sun exposure, north-facing slopes are typically cooler than south-facing slopes in the Northern Hemisphere. The Southern Hemisphere has the opposite situation. Studies have demonstrated that row orientation could influence vine physiology, the grapevine growth cycle, crop load [70–72], and berry and wine quality [73]. Research conducted in a Shiraz vineyard in Robertson, South Africa, found that (1) the highest skin anthocyanin and phenolic contents were present in grapes grown with a northwest–southeast (NW-SE) row orientation and (2) grapes from the NW-SE and NE-SW rows carried the most favorable sensory notes [73]. Therefore, for wine regions with elevated temperatures, it would be more appropriate to select a vineyard row orientation that leads to low canopy light interception.

4.2. Plant Material

The selection of plant material is an affordable and useful solution for adapting to climate change. Drought-resistant varieties, rootstocks, and clones are expected to decrease the vulnerability of vineyards to water deficits and help avoid reductions in quality caused by elevated temperatures during berry ripening.

4.2.1. Rootstocks

Drought-tolerant rootstocks can support scions' growth and increase grape production when water supply is limited. Grapevine rootstocks with different degrees of drought resistance are summarized in Table 2. Among these rootstocks, 110 Richter, 140 Ruggeri, 196.17 Castel, and 44–53 M show a high degree of drought tolerance, while O39-16, 420A, 1616C, Riparia Gloire, and 5C have low resistance. Other known rootstocks have low, low to moderate, and moderate to high drought tolerance [74]. Newer rootstocks, such as Matador, have not been evaluated for drought tolerance [75], and no information is available for RS-3, RS-9, Minotaur, or Kingfisher.

With the changes in climate conditions causing higher drought incidence, water and soil salinity is becoming an increasingly serious problem for grapevines. Certain rootstocks can protect scion varieties from accumulating significant amounts of saline ions. These mechanisms are not fully understood and research is underway. Existing rootstocks have been tested to determine their salt tolerance levels. Rootstocks such as Ramsey, Dogridge, 140 Ruggeri, and 1103 Paulsen have shown high tolerance to salt in the field [76].

Table 2. Grapevine rootstocks: degrees of drought tolerance.

		Grapevine Rootstock Drought Tolerance		
High	**Moderate to High**	**Medium**	**Low to Moderate**	**Low**
110 Richter	99 Richter	5BB	101–14 Mgt	O39-16
140 Ruggeri	1103 Paulsen	Schwarzmann	Harmony	420A
44–53 M	Ramsey	Dogridge	SO4	5C
196.17 Castel		Freedom	St. George	1616C
			3309C	Riparia Gloire

Source: Adapted from [74,77].

4.2.2. Varieties

Switching to drought-resistant and heat-tolerant grape varieties could also help winemakers adapt to climate change [78]. Based on historical cultivation, grape growers have selected several varieties for drought tolerance, such as Grenache, Carignan, Cinsault, and most Mediterranean varieties. Several studies have been conducted to explore drought-resistant varieties [79,80]. In a study conducted in the Denominación de Origen Calificada Rioja in Spain, the red varieties Garnacha Roya, Alicante Bouschet, Trepat, Morate, and Agawan and the white varieties Maturana Blanca and Garnacha Blanca were the promising varieties for addressing global warming. These varieties have been shown to produce berries with lower sugar levels and higher acidity content during harvest in comparison to other traditional grapevine varieties [81]. Since berry maturity and ripening times vary significantly between the different varieties, grape growers can also select later-ripening varieties, such as Cabernet Sauvignon, Grenache, Sangiovese, Barbera, Nebbiolo, Mourvedre, Aglianico, Marsanne, Cortese, etc., to extend the harvest date and to ensure that the desired grape quality parameters are met.

4.2.3. Clones

A certain level of genetic variability exists within a given grape variety. Clones have been historically selected for traits such as high productivity, disease resistance, cold hardiness, etc. In the context of a changing climate, new clones can be selected for drought resistance and improved water use efficiency. It would also be a useful strategy to change the grape growing cycle to delay maturity and reduce sugar accumulation at an early stage. Van Leeuwen conducted a study on different Cabernet Franc clone characteristics and found a difference in berry sugar accumulation between clones, providing valuable guidance for growers in choosing appropriate clones in warm climate regions [82].

4.3. Training Systems and Canopy Management

Training system selection can be used to reduce high temperatures in the fruit zone of grapevines. The goblet system is an ancient untrellised vine-training method developed by wine growers in the Mediterranean region. This system made it possible to grow grapes in semi-dry and dry areas for a long time period because it was cost-effective and drought-resistant [83]. However, goblet-trained vines tend to produce a low crop load and cannot easily be adapted to mechanical cultural practices, such as mechanized shoot thinning, berry/cluster thinning, pruning, and harvesting. Hence, it is not practical for wine regions that focus on high-yield grape production. The San Joaquin Valley in California is a major wine production area characterized by a hot climate. Many of the wine grapes planted in this area adopted the California sprawl training system or the simple curtain system. Grapes are grown on two wires (a fruiting/cordon wire and a foliage wire), resulting in sprawling vines without rigorous shoot positioning [84]. Sprawl systems can provide the canopy shading required to prevent sunburn on the grapes, and they are also cheap to construct and suitable for grape varieties with moderate to high vigor.

Canopy management is increasingly recognized as an important tool for improving vineyard water management since it can affect the vine leaf area index and the transpiration rate. Various canopy management practices can be adopted throughout the year that enable the grower to mitigate the negative effects of climate change. Shoot trimming or topping is one useful canopy management strategy to delay berry ripening and slow down sugar accumulation that has been reported in several studies [85–87]. Leaf removal after véraison has been reported as an efficacious technique to adapt to climate change because it delays sugar accumulation and postpones the harvest date. A two-year study on mechanical post-véraison leaf removal from Sangiovese in a commercial vineyard in central Italy showed a significant reduction in total soluble solids (from 23.9°B to 22.7°B) and similar concentrations of other chemical components [88]. This study demonstrated that the timing and intervention intensity of canopy management are critical.

4.4. Water Management

Grapevines are more drought-tolerant compared to other fruit crops, but a certain amount of water is needed to support vine growth and berry development. The water demand for a grapevine is dependent on the region, variety, rootstock, training system, planting density, and yield. A study found that grapevines needed annual rainfall of between 34 and 503 mm from April to October in a cool climate region of California (Carneros district of Napa Valley) [89], while in the other five warm climate regions in California (Madera, Livermore, Kearney, Paso Robles, and Temecula), grapevines needed between 450 and 800 mm of water from April to September [90]. Irrigation management is one of the strategies adopted in wine regions across the world to address climate change.

Irrigation systems can be selected to maximize water use efficiency, such as subsurface irrigation, drip irrigation, and high-pressure irrigation systems. "Subsurface irrigation system is below the ground surface so that water is supplied directly to the root zone of the plant" [91]. This system has benefits such as reducing evaporation losses and providing less hindrance to surface cultivation works. "Drip irrigation is a process of slow application of water on, above or beneath the soil by the surface, sub-surface, bubbler, and spray or pulse system" [91]. This is an efficient water application method since the applied rate is almost equal to the use rate of the crop. "Sprinkler irrigation is an advanced method of irrigation in which water is sprayed to air and allowed to fall on the ground similar to rainfall" [92]. In this method, the water is distributed through a nozzle connected to a network of pipes while under pressure. The main advantages of sprinkler irrigation are the savings in water/labor, and it is suitable for all soils with infiltration rates lower than 4 cm/h. Drip irrigation systems combined with regulated deficit irrigation (RDI) at an early or late stage provide the most control over water use. In other words, the grape grower can apply the precise amount of water that each grapevine needs. Precision scheduling and timing of the irrigation water supply are needed, and this can be accomplished with vine water status monitoring through stem water potential measurements. The RDI technique can be applied for different vines and berry growing stages to accomplish different objectives. McCarthy et al. (1997) reported that application of RDI after flowering successfully reduced the berry weight of Shiraz vines [51]. Dry et al. (2001) reported that RDI induced an accumulation of anthocyanins in red wine grape varieties in Australian vineyards [93]. In Australia, RDI is current a vineyard management tool that is widely used to improve grape and wine quality. RDI is also a valuable management strategy to enhance vineyard profitability. Bellvert et al. (2020) used cost–benefit analysis to calculate the total savings in a 247-acre vineyard with the precision irrigation strategy for Tempranillo, Cabernet Sauvignon, and Syrah varieties. They reported a net benefit of USD 9.6 per acre in 2016 and USD 19.7 per acre in 2017 [94].

Remote sensing is a new technology used in vineyards to optimize precision irrigation and improve water use efficiency. Manned aircraft and satellites are currently the two main platforms for collecting data remotely. However, these systems are not widely used in vineyards due to several limitations, such as low spatial resolution, the high initial investment cost, and susceptibility to climatic conditions [95]. Bellvert (2014) successfully used airborne imaging from unmanned aerial vehicles (UAVs) to map the spatial variability in water requirements across a 27-acre block of Pinot Noir vineyards located in Lleida in Spain [96]. UAVs interlinked with wireless sensor networks (WSNs) represent a promising monitoring approach in vineyards. Using a multi-sensor approach (high-resolution UAV remote sensing and WSN proximal sensing), Di Gennaro et al. (2017) obtained a combined dataset that could be used to predict individual vine stress levels and berry quality [97]. Sun et al. (2017) used Landsat satellite imagery to predict grape yields and the effects of drought on the yield for Pinot Noir vineyards in California [98].

4.5. Soil Management

Soil management is an important tool to prevent water loss in vineyards. Soil affects available water capacity, water infiltration, and evapotranspiration. Agronomic practices and soil amendments can be used to improve the soil surface state and soil structure in terms of porosity, stoniness, and deepness. With increasing drought conditions in semi-dry and dry areas, drought-tolerant soils could be reserved for vines sensitive to water stress. Chrysargyris et al. (2018) found that combining no-irrigation and no-tillage practices was a useful vineyard strategy for Maratheftiko, a heat-resistant variety native to Cyprus [79]. Pinamonti (1998) reported that the use of compost mulched soils in a Merlot vineyard improved soil structure, water-holding capacity, and the nutrient profile [99]. Soil water evaporation and temperature variations were also reduced [99]. Monteiro and Lopes (2007) conducted a 3-year study on the effects of permanent resident vegetation and permanent sown cover crops on a 15-year-old Cabernet Sauvignon vineyard located in the Estremadura region of Portugal [100]. Cover crop treatments showed significantly low daily water use during berry ripening due to low soil evaporation. Vineyard cover crop usage also reduced vine vegetative growth and increased total phenols and anthocyanins in grape berries. Cover cropping is a useful vineyard floor management tool as it can also help maintain living microorganisms in the soil. Clover and native grass planted in soils had greater microbial biomass than tilled soil in a Merlot vineyard located in Sacramento, California [101].

It is important to manage cover crops within a reasonable time frame. Water competition between vines and cover crops needs to be avoided; otherwise, it can lead to severe water stress in vines and have negative effects on vine growth, yield, and berry quality. The accurate selection of species and varieties is also critical. A study in an organic Manto Negro vineyard located in central Majorca, Spain, reported that self-seeding or perennial species, such as *Trifolium* sp., *Medicago* sp., *Brachycalycinum* sp., and *Dactylis* sp., improved soil properties. Vine vigor and yield were reduced due to water resource competition between cover crops and vines [102].

Soil amendments are traditionally used to improve soil structure. Biochar application is the most studied amendment strategy. Biochar is a co-product of the thermochemical conversion of biomass, and it has a microscopically porous structure that makes it possible to hold water. The effects of biochar depend on its physical and structural characteristics, the application rate, and the soil properties. Baronti et al. reported that biochar application in a central Italian vineyard increased soil water content and improved photosynthetic activity but had no effect on soil hydrophobicity [103]. A study carried out in a non-irrigated vineyard in Tuscany, Italy, investigated the effects of biochar applications on crop load and berry quality. The results demonstrated that biochar improved soil properties and increased soil water content. The crop load increased from 16% to 66% during the four years of research conducted without an effect on berry quality [104]. All these findings support the feasibility of a biochar-based strategy for vineyards in drought area adaptations to climate change and water shortages. For California growers, the Sonoma Biochar Initiative implemented by the Sonoma Ecology Center (SEC) provides farm manager training and education on how to produce and use biochar (https://sonomabiocharinitiative.org/, (accessed on 10 July 2022)).

New technologies are playing an important role in soil management aimed at adaptation to climate change. The use of geographic information systems (GISs) and remote sensing can improve the management of vineyards by providing information at the field level more quickly than manual data collection [105,106]. Soil moisture sensors have emerged as a promising approach in vineyards, and they can support growers in making correct and timely decisions regarding irrigation, prevent vines from suffering drought stress, and save considerable water. Soil moisture content can be determined using gravimetric methods, nuclear gauges, or other methods based on electromagnetic, tensiometric, hygrometric, or remote sensing processes. The most common sensors are based on electromagnetic technology. Dilrukshi et al. (2019) evaluated the accuracy and repeatability of a commercial soil moisture sensor (SKU: SEN0193) [107]. They also integrated the sensor with a data acquisition system and developed a cost-effective automated soil moisture monitoring system to reduce soil moisture stress and avoid excessive water application. Stevanato et al. (2019) assessed the capabilities of a novel cosmic-ray neutron sensor (CRNS) in two different fields located in Potsdam in Germany and Lagosanto in Italy [108]. The study demonstrated that the CRNS could be a powerful tool for soil moisture measurements in large agricultural areas. Soil electrical conductivity sensors have been developed for soil mapping purposes. Rodriguez-Perez et al. (2021) evaluated the feasibility of using apparent electrical conductivity (eCa) in a Napa Valley vineyard in California [109]. The investigation indicated that eCa could be used to predict soil physical and chemical properties. The study clarified the feasibility of using soil electrical conductivity sensors to estimate soil properties to save time and cost.

4.6. Other Adaptation Strategies

Further promising strategies to adapt to climate change include the use of shade nets; antitranspirants, such as kaolin particle film and chitosan; and late pruning. These strategies could be used to mitigate the impact of high temperature and have been examined for some cultivars and climatic conditions.

Sabir et al. (2020) investigated the effects of different colored shade nets on the berry skin color and functional properties of "Alphonse Lavallée" table grapes under controlled glasshouse conditions [110]. The results demonstrated that application of yellow netting led to the highest anthocyanin content (15.1 mg/100 mL juice), followed by green (14.2 mg/100 mL juice) and black (13.2 mg/100 mL juice) nets. Caravia et al. (2016) found that overhead shade treatment imposed on Shiraz vines from véraison to harvest gave the most consistent effect in mitigating heat stress [111]. The treatment also delayed berry mass loss and decreased wine alcohol content.

Antitranspirants are used in vineyards to counteract climate change since they can reduce excessive water loss and improve berry water moisture. Two types of plant antitranspirants are currently available with different functions: film polymers (e.g., kaolin, Vapor Gard, etc.) and stomatal closing compounds, such as chitosan. Kaolin ($Al_2Si_2O_5(OH)_4$) is a white, chemically inert, and non-toxic clay material. It can reflect photosynthetically active radiation (PAR), ultraviolet (UV), and infrared radiation (IR) and can be used to mitigate the effects of excessive heat and radiation [112]. It is a promising and cost-effective mineral for the improvement of grape composition and wine quality in hot-climate regions with severe drought conditions. Garrido et al. (2019) found that kaolin film applied to leaves increased the photosynthetic activity of both exocarps and seed integuments of "Alvarinho" berries growing under low-light canopy conditions in the Demarcated Region of Vinho Verde, Braga, Portugal [113]. Dinis et al. (2016) showed that foliar kaolin application was beneficial to Touriga Nacional grapevines in the Douro Region of northern Portugal, which has a Mediterranean climate with a warm temperate and dry summer [114]. Palliotti et al. (2013) investigated the post-véraison application of the film-forming antitranspirant Vapor Gard (VG; a.i. di-1-p-menthene) on Sangiovese grapes in central Italy [73]. Their research showed that antitranspirant application delayed grape ripening and reduced berry sugar accumulation. The effectiveness of the Vapor Gard antitranspirant spray was also confirmed in [115]. The authors applied antitranspirant sprays to Barbera vines pre-flowering (PF), pre-véraison (PV), and at both dates (PFPV) in 2013 and 2014 in Piacenza, Italy. They found that all antitranspirant spray treatments reduced gas exchange by up to 46%, while the PV and PFPV treatments delayed sugar accumulation in both seasons without affecting color development. Brillante et al. (2016) observed that the fruit quality and consumer preference for wines made with the traditional antitranspirant pinolen were not comparable to those for wine made with kaolin-treated berries [116]. Chitosan is a naturally occurring polysaccharide produced from seafood shells. It can be used to simulate biotic and abiotic stresses since chitosan can induce abscisic acid activity. When vines are in a stress stage, abscisic acid plays a key role in minimizing stomata opening and maintaining water. Górnik et al. (2008) studied the effect of chitosan (Biochikol 020 PC) on the response of grapevines to drought and heat stress [117]. Studies have shown that chitosan can be widely used to improve rooting and heat and drought resistance. Singh et al. (2020) found that chitosan (0.01% in 0.01% acetic acid) application also increased several monomeric anthocyanins in Tinto Cão berry skins [118]. Silva et al. (2020) undertook a comparison study of chitosan solutions and chitosan nanoparticles applied to the grape variety Sousão [119]. They found that, compared to chitosan nanoparticle treatments, chitosan solutions were more effective in increasing the total phenol, anthocyanin, and tannin contents in berries, as well as antibacterial activity.

Late spur-pruning was originally performed in cool climate regions to delay bud burst and avoid frost damage. It has emerged as a potentially viable adaptation strategy in vineyards that can alleviate the impact of global warming by delaying vine development and berry ripening. Gatti et al. (2018) applied late-pruning strategies to a cane-pruned system of Pinot Noir vines in central Italy when the distal part of the cane reached an average of three leaves [120]. Late pruning significantly delayed ripening and extended berry maturity into a cooler season over two trial seasons. It was approved as a simple technique suitable for preserving the balanced must composition required for a range of sparkling wine styles, whereas yield per vine was reduced by 35% due to lower shoot fruitfulness. Buesa et al. (2021) applied late-pruning techniques to Bobal and Tempranillo varieties in eastern Spain when budbreak initiated [121]. Late pruning delayed grape ripening in both cultivars and resulted in higher berry anthocyanins at harvest, which contributed to the wine color intensity. However, late pruning had small detrimental effects on yield, showing a 10% reduction. Moran et al. (2017) limited pruning to two to three leaves and found that it effectively spread the harvest, increased the berry anthocyanin concentration, improved the wine chemical composition, and altered sensory profiles without negative effects on the yield for Barossa Valley Shiraz [122].

In summary, there are many different practices that can be used in the vineyard to help growers combat and mitigate the effects of climate change. The opportunities and weaknesses of adaptation strategies are crucial factors for farmers to consider when planning to adopt these practices. It has been found that wineries in Sonoma Valley with more than 15 years of experience had a positive correlation with adopting sustainable practices [123]. Growers' participation in partnership arrangements also had a positive correlation with adoption of new practices [124]. Some technologies are innovative, but most are not new and have been employed for a very long time. Each adaptation practice has advantages and shortcomings. Table 3 summarizes each practice and compares the advantages and limitations of the applications. These insights into adaptations can be informative for the future development of systematic methods to optimize their effectiveness.

Table 3. Summary of the strategies for climate change adaptation.

Adaptation Strategies	Opportunities	Weaknesses	Application Suggestions
Vineyard location and vine row orientation	Cost-effective ways to allow the winegrower to adapt locally to climate change	Initial cost of conducting research on a new location Require collection of information of altitude, climate, soil, etc.	Workshop and field demonstrations are necessary to help growers understand research and persuade them to explore a new location
Rootstock selection	Enables growers to select for grapevines that are more resistant to drought or disease, thus making it possible to maintain or increase vine productivity Helps to overcome soil problems, such as texture, pH, and density	Selection of a rootstock can be quite complex Selection becomes even more challenging with the changing climate	Consider how closely existing rootstock choices interact with other management strategies (e.g., irrigation and cover cropping) Consider rootstock's ability to survive in specific conditions, such as with different soil, pests, and viruses
New variety selection	A natural solution to delay berry ripening	Might be difficult to perform in some wine regions with traditional appellations	Continue monitoring and evaluating the new varieties over time Workshop and field demonstrations are necessary to help growers choose the right variety for their vineyards
Clone selection	A long-term solution involving changing the berry growing cycle to delay maturity and reduce sugar accumulation	Clonal selection is time-consuming it is necessary to follow a long, rigorous procedure Requires a variety of skills and techniques and specific equipment	Continue monitoring and evaluating the new clones over time to guarantee the reliability and quality of the selections
Training systems	An efficient solution to delay berry ripening	Initial investment required to investigate a new training system	Workshop and field demonstrations are necessary to help growers choose the right training system for their vineyards
Canopy management	An efficient solution to delay berry ripening	Need to train winegrowers	Timing and intervention intensity of canopy management are critical
Water management	Optimizes water use efficiency Reduces fertilizer waste Sustainable vineyard management	Initial and maintenance costs for precision irrigation and new technology are high High labor skills are required	More seasons are needed to achieve the desirable effect
Soil management	Prevents water loss Improves soil properties, vine performance, and berry quality over the long term	A long time is required to attain healthy soil Initial costs for soil sensors and soil mapping equipment	Soil amendment should be used for several seasons to achieve the desirable effect
Colored shade nets	Protect vines from excessive solar radiation Delay berry ripening	High labor cost	Need to consider different factors, such as fabric material, density percentage, size/shape of holes, and color

Table 3. *Cont.*

Adaptation Strategies	Opportunities	Weaknesses	Application Suggestions
Kaolin	Cost-efficient Forms a physical barrier against various pests Reduces moisture to prevent diseases Acts against solar radiation to prevent berry sunburn Natural and safe agent for the winegrowers and can be used for organic vineyards	It is easily washed off by rain and kaolin spray is not suitable for overhead irrigation Requires constant application, especially for new leaves Requires strict attention to detail Missed leaves open window for pests and disease	It must be mixed thoroughly and applied via a sprayer with continuous agitation Be careful not to overspray Although it is generally regarded as safe for humans, it is still important to protect workers while spraying (long sleeves, long pants, closed-toed shoes, a mask or respirator)
Other antitranspirants	Reduce water loss through leaves by reducing transpiration Simple and viable technique to control berry sugar accumulation and obtain less alcoholic wines	Might increase fruit surface temperature and sunburn due to lack of transpiration Might decrease fruit quality and consumer preference for the wines	Application timing is critical Make sure lower leaf epidermis is fully wetted by the antitranspirant chemical Spray cautions same as for kaolin application
Late pruning	Simple and inexpensive Suitable for light-bodied wines, such as white, rosé, and sparkling	Might reduce yield for some varieties	More seasons are needed to achieve the desirable effect

Source: Author's summary of the literature cited in Section 4.

5. Conclusions and Future Work

In view of the current and continuing changes in the global climate, the grape and wine industry faces big challenges. Climate change compounds issues such as heat, drought, and water stress, which are known to affect vine phenology, pest and disease incidences, crop yield, berry quality, and wine tasting. There are potential adaptation strategies that can be used to address these issues. On the one hand, there are effective and inexpensive practices, such as kaolin application and late pruning. On the other hand, there are practices that will have a long-term effect on vineyard sustainability, such as water and soil management. Rootstock, clone, and new variety selection are time-consuming and it is necessary to follow a long, rigorous process, which also requires a variety of skills and techniques and specific equipment. New technologies, such as soil moisture sensors and soil electrical conductivity sensors, can help in monitoring the available water and soil properties. Precision viticulture can provide more control with regard to water usage and save production costs. The Natural Resources Conservation Service implemented by the USDA has developed programs to help farmers and growers with regional hub information, assessments of soil carbon, systems to help account for carbon and greenhouse gas systems, and grants. There are programs that help with incentives for growers and ranchers who will sequester carbon, reduce atmospheric greenhouse gases, and improve soil health. The present work cannot present an in-depth review of all areas being studied in terms of viticulture and winemaking. Future work can build on this review and zoom-in on specific topics or adaptations. Another limitation in the literature is the lack of an established protocol through which researchers could publish their experimental findings, which hinders direct quantitative analysis of the diverse adaptation strategies. Future researchers can expand the present review and perform a bibliometric analysis of adaptation practices and management strategies.

In order to achieve long-term benefits, modifications to plant material should be considered a priority. They offer a natural way to obtain grapes with low sugar content and high acid profiles and to maximize their quality through delayed ripening. Late-ripening varieties can be found among the traditional varieties in some wine-growing regions. These are environmentally friendly and do not increase production costs. However, this strategy is obviously difficult to perform in some wine regions with traditional appellations. For example, winegrowers can only use local varieties in European wine-growing regions. More research on the use of non-local varieties in certain regions is necessary. With more drought-resistant rootstocks and clones available, regulations for these new plant materials need to be modified. Better collaboration between the government, research institutes, industry partners, and growers will facilitate new plant material applications.

The use of new technology is a promising strategy to address global warming issues. However, some new tools are still expensive, and their uses and applications are limited for grape growers. Therefore, further development of affordable precision tools is needed. Innovation-based agriculture will need technological standardization to ensure the compatibility and safety of equipment. Meanwhile, standards should be kept updated to adapt to technological changes. Lastly, more educational workshops and technology demonstrations for growers are necessary.

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