Review Article

Arif Atak*

Climate change and adaptive strategies on viticulture (*Vitis* spp.)

https://doi.org/10.1515/opag-2022-0258
received October 23, 2023; accepted January 12, 2024

Abstract: Climate change has many negative effects on the viticulture sector, as it does in all sectors. In recent years, global climate change has also shown its effect in the form of sudden climatic events. There is an urgent need to develop preventive/protective activities for all plant species in order to prevent the increasing world population from being negatively affected by many negative consequences of climate change such as increasing temperatures, drought, floods, and sudden climatic events. Grape industry is among the sectors that feel the negative effects of climate change the most, and this effect is increasing every year. Along with global warming, there are also important problems in accessing water. Particularly, there is a need to develop cultivars that are more resistant to drought stress and to make applications that will protect grapevine plants from drought stress. One of the most important issues to be overcome is to develop new cultivars that can withstand different stress conditions and to use them more in production. In addition, environmental and human health awareness is increasing day by day. Adaptation strategies to be taken against the negative effects of climate change and the studies to be carried out, as well as the use of new environmentally friendly varieties (requiring less input costs) to be developed in accordance with the sustainable agriculture model, will make significant contributions to protecting both the environment and human health.

Keywords: adaptation strategies, stress factors, grape, extreme climate events, sustainable viticulture

*** Corresponding author: Arif Atak**, Department of Horticulture, Agriculture Faculty, Bursa Uludağ University, 16059, Bursa, Turkey, e-mail: arifatak@uludag.edu.tr, tel: +90 505 4804130
ORCID: Arif Atak 0000-0001-7251-2417

1 Introduction

The total vineyard area in the world is about 6.7 million hectares, and the production from this area is around 73.5 million tons. The countries with the highest vineyard area in the world are Spain (13%), China (12%), France (11%), Italy (9%), and Turkey (6%) (Figure 1). These five countries represent about half of the global vineyard area [1].

Despite the fact that grapes are produced quite a lot in terms of area and quantity, they have been rapidly affected by the changing climatic conditions in recent years and some negative results of this effect have begun to be seen in the vineyard areas. The effects of climate change have become a global threat that has increased in recent years and caused very important problems, and it has many negative effects on the viticulture sector as in all sectors. When the data of last years are compared, significant decreases are observed in terms of both area and amount. It is reported that this situation is significantly related to the increasing negative effects of climate change [2].

Among the most important effects of climate change, increasing air temperatures and their significant abiotic stress on plants, resulting in negative effects on plant growth and fruit quality, can be shown. Especially, the table grape sector is one of the sectors that feel the negative effects of climate change the most, and this effect is increasing every year [3,4]. With global warming, water resources are limited and there are significant problems in accessing water. As a solution, there is a need to develop varieties that are more resistant to drought stress and to make applications that will protect grapevine plants from heat [5].

In recent years, global climate change has also shown its effect in the form of sudden climatic events (excessive precipitation, heavy wind, hail, etc.) [6].

Especially in many countries where grapes (mainly table grapes) are grown, different covering systems have started to be used in more areas to protect the grapevine plants against increasing extreme weather and climatic events/disasters [7].

In addition, today's developing technology can help us fight against the negative effects of climate change. With

Open Access. © 2024 the author(s), published by De Gruyter. This work is licensed under the Creative Commons Attribution 4.0 International License.

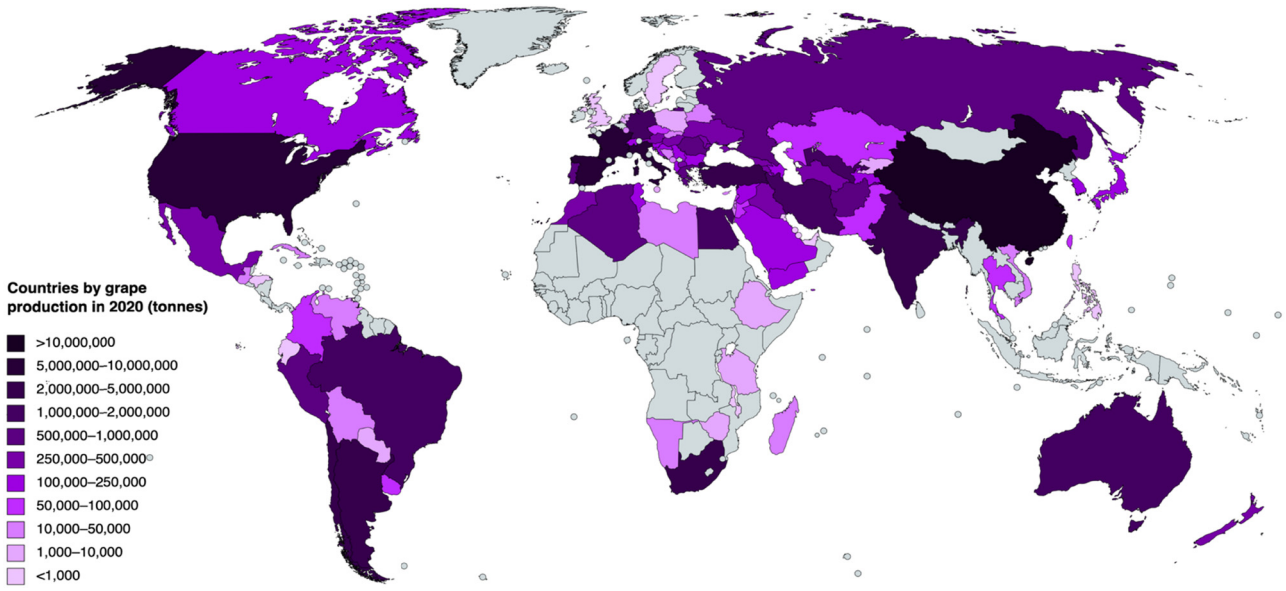


Figure 1: Grape production amounts of countries on the world map [1].

the integration of smart agriculture and artificial intelligence applications into vineyard areas, preventive measures can be taken with preliminary information against many extreme weather events, the frequency of which has increased as a result of the negative effects of climate change [8].

In recent years, with the negative effects of climate change, diseases seen in grapevine plants and different *Vitis* species have diversified and their scope has expanded. In addition, pathogens have become more immune to many drugs used to protect grapevines against disease-causing agents. Against this situation, unfortunately, many growers use more chemicals in order to maintain efficiency and quality. Sometimes excessive application of chemicals used against fungal diseases poses a significant threat to human and environmental health. Some strict laws are needed to prevent the overuse of these fungicides and to prevent them from causing toxic effects. The increasing disease pressure, especially with climate change, increases the need for these regulations [9–11].

Scientists report that different biotic and abiotic stress conditions are among the negative effects of climate change on viticulture. In this case, new varieties that are more resistant to these stress conditions should be developed and used more in production. It is predicted that these new varieties, developed especially by taking advantages of biotechnology, will constitute a large part of the production in the near future [12,13]. With the increasing world population, more and healthier food is needed [14]. However, in order to meet the negative effects of climate change in viticulture, there is a need to focus on breeding studies and to revise the methods and techniques used in viticulture in a way that will reduce the negative effects of climate change.

In this study, a detailed information is given about climate change, whose negative effects have increasingly increased in recent years, in areas where different *Vitis* species are grown, especially table grapes, and what needs to be done by scientists and grape growers against these negative effects.

2 Effects of climate change on viticulture

Climate change has many negative effects on viticulture. Farmers who produce for us have to cope with many negative effects of climate change, such as increasing temperatures, drought, water stress, diseases, and extreme weather conditions. Among those experiencing this problem are table and wine grape growers [8,15–17]. The most important negative effects of climate change are given in the following sections:

2.1 High temperature

Although many people think that human-induced climate change will occur in the very distant future, this is not actually the case. Unfortunately, climate change is still

actively ongoing and has been occurring for over a century. It is reported that global temperatures have increased by more than 1°C. In fact, it is understood that climate change is not only limited to the increase in temperature but also causes many adverse conditions [18].

Rising temperatures caused by global warming have become a major threat in many areas of agricultural production, as increased temperatures may inhibit both development and plant growth and cause their complete death in extreme conditions [19,20]. As a result of extensive research conducted in recent years, it has been explained that chloroplasts are highly sensitive to heat stress, which affects various photosynthetic processes such as chlorophyll biosynthesis, CO_2 assimilation, photochemical reactions, and electron transport. In order to protect these photosynthetic organelles, heat stress response mechanisms have been defined by plant cells (Figure 2). In addition, in recent years, it has been reported that chloroplasts have important roles in inducing the expression of some nuclear heat response genes during the response to heat stress [21].

In some studies conducted in recent years, it has been reported that many growth and development stages in the grapevine begin at an earlier period, considering that it is highly related to temperature increases. As a result of increasing global temperatures, the duration of many phenological stages has been shortened, and the composition and quality of grapes and their products have been negatively affected. As a result of all these changes, in order to keep the quality of the final product at the desired level, vineyard areas are transferred to more northern regions or high-altitude regions where the average temperature is slightly lower [22,23].

High temperatures can cause serious irreversible damage to grapevine plants in the period close to harvest. Against this situation, studies conducted in recent years on the identification of key genes in the molecular regulatory network of grapevines against heat stress and subsequent breeding of new high temperature-resistant varieties containing these genes attract attention [24].

Changes in air temperature, and especially increases, affect vine phenology, fruit metabolism, and composition very significantly. Global warming poses a serious threat to both grape and wine production in many viticulture regions around the world [25,26]. Above the optimum condition [20], heat stress disrupts cellular homeostasis, leading to a significant retardation in growth and development and sometimes even death. While increasing temperatures in the vine encourage vegetative growth, it disrupts the carbon balance of the plant and negatively affects flower formation and young fruit development [27].

Increasing temperatures also affect the primary and secondary metabolism of fruit, disrupt the harmony of sugar and organic acid metabolism, and delay the accumulation of sugar and polyphenols during ripening. As a result, it can significantly affect the organoleptic properties of wine and cause deterioration in its quality [25,28]. High temperatures greatly disrupt carbohydrate and energy metabolism, and it has been reported that these effects depend on the stage of development and duration of treatment. Also, transcript amounts were weakly correlated with protein expression levels in fruits of high temperature, highlighting the value of proteomic studies in the context of heat stress (Figure 3). It has been reported that high temperatures alter essential proteins that enable fruit development and ripening. Potential markers and proteins for the development or selection of grape varieties that can adapt to warmer climates have been found by researchers [29,30].

2.2 Drought

Drought has become an increasing problem and has increased its impact in many countries. Higher temperatures can cause plants to lose or transcribe more water, which means that farmers have to give them more water. Growers and vineyard owners began to use more water, especially for agriculture. This situation, which emerged in places where resources were limited, caused growers to seek different solutions [31].

Climate changes, which cause increased water use by plants, increase the frequency and magnitude of water stress in plants along with the decrease in available water resources. In terms of viticulture, this situation requires the development of new grape varieties that are more drought-resistant or increasing the dependence on irrigation to maintain productivity. Strategies to relieve plant water stress present significant challenges. The most important strategy is that the grapevine plant is a perennial plant. Since the grapevine plant will remain in its area for many years, the negative effects of climate change in the coming years should be taken into account when choosing the variety, rootstock, and vineyard area [32].

Accessing water is one of the important problems after the climate change for the table grapes. Due to increased water competition with other related sectors of the economy and climate change, water used for agriculture will become more scarce in the future, leading to more frequent droughts [33]. Drought stress is a major problem for *Vitis* species, and in recent years, researchers have begun to use

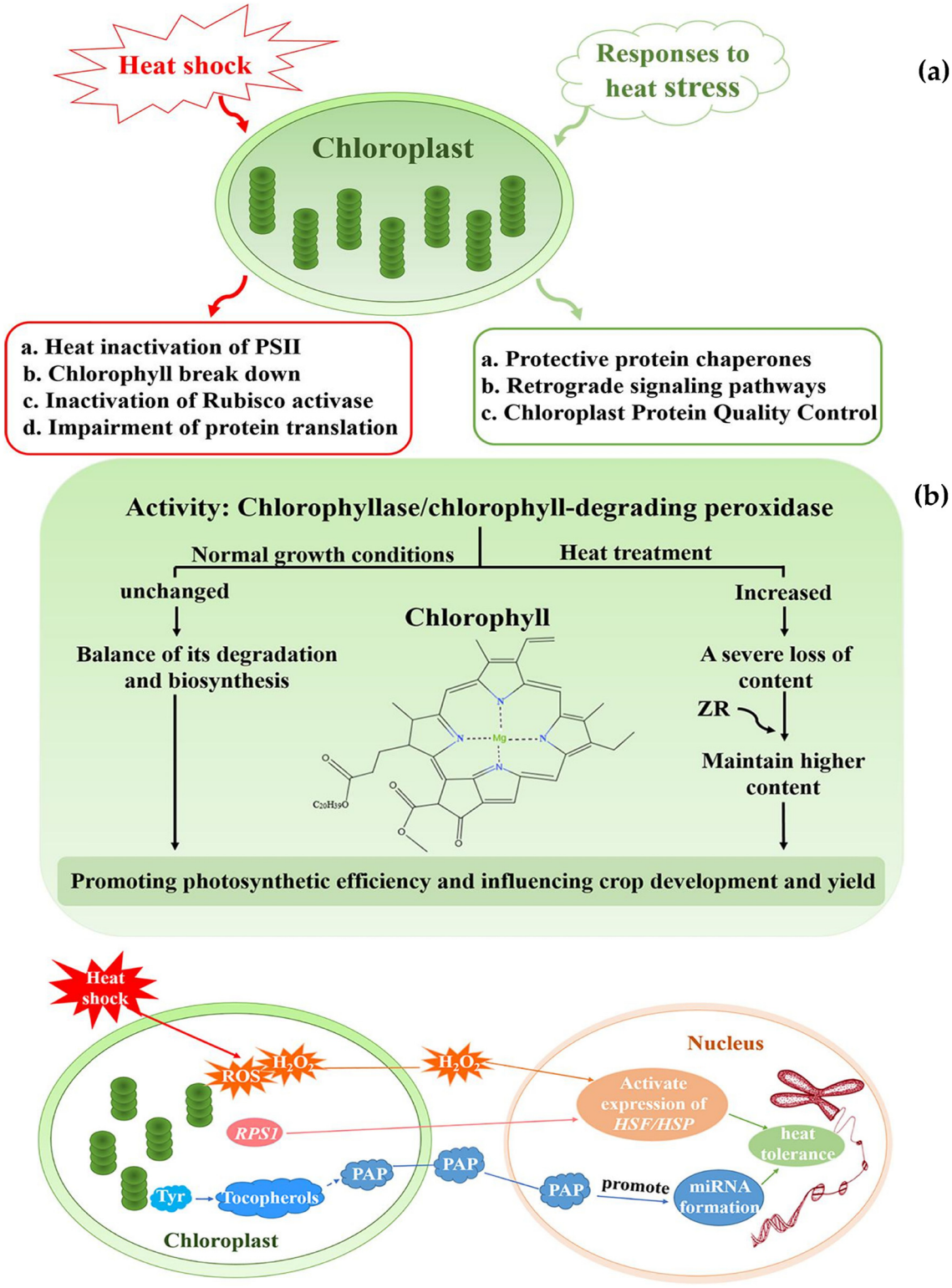


Figure 2: Sensitivities and responses of chloroplasts under high temperature stress: (a) main effects of heat stress on chloroplasts include heat inactivation of photosystem II, degradation of chlorophyll (Chl), inactivation of Rubisco, and disruption of protein translation; (b) chlorophyllase and Chl-degrading peroxidase activity are seen in heat stress condition. Under normal conditions, the biosynthesis and degradation of Chl are at constant rates, while under heat stress, the activity of chlorophyllase and chlorophyll-degrading peroxidase increases, resulting in a severe decrease in Chl content. In the case of exogenous application of zeatin riboside, a higher Chl content is observed (b); and (c) illustration of retrograde signaling pathways in chloroplasts under heat stress [21].

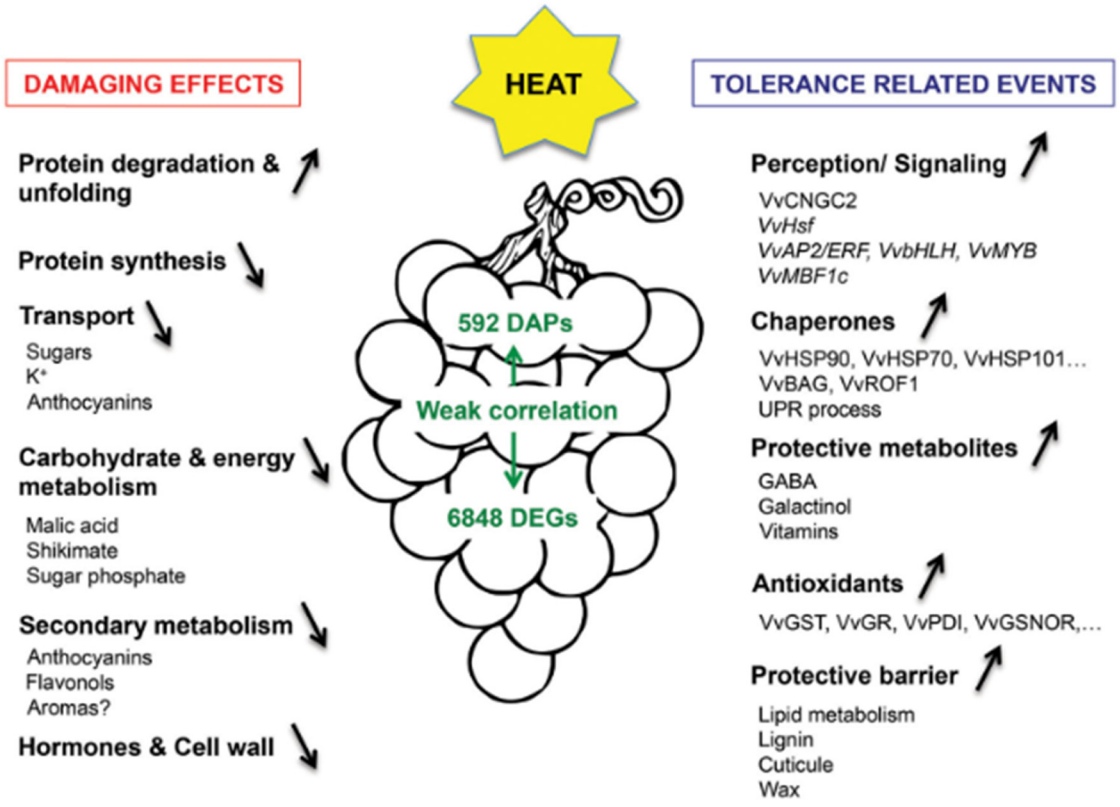


Figure 3: Diagram showing the effects of heat stress on fruits of Cabernet Sauvignon (the up and down arrows reflect the accumulation levels of the corresponding transcripts, proteins, or metabolites in the heated fruit) [29].

different techniques such as rootstock breeding, subsurface irrigation, and integration of agrivoltaic (AV) systems into vineyards, to recover drought problem.

2.3 Flooding

Snow is one of the most important fresh water resources and also plays a very important role in preserving the existence of many underground and surface water resources. However, due to global warming, snowfall is decreasing and ultimately causes a serious threat to the amount and continuity of freshwater resources [34]. In this case, unfortunately, many resources used to irrigate the vineyards dry out and the effects of drought increase.

Changes in water resources have great effects on our world and plants. As our climate changes, extreme climatic events such as floods have become an increasing problem. Since the beginning of the 20th century, many countries experience stronger and more frequent extreme and heavy rainfalls. Especially with the emergence of increasing climate changes in many countries, the issue of predicting flood events attracts considerable attention [35].

The most important problem seen in plants during flood is O_2 deficiency. Severe reduction in O_2 availability due to waterlogging affects plant metabolism and hence crop growth and productivity. Information regarding the responses of grapevine (*Vitis* spp.) to waterlogging is not very clear, and basic information regarding the molecular and metabolic responses of grapevine roots to hypoxia has not yet been adequately elucidated. Due to the fact that cultivated grapevines are hybrid plants resulting from different rootstockxscion combinations and therefore the complex interactions between different genotypes and the environment, the mechanism related to flooding cannot be fully explained [36].

Comprehensive metabolic and transcriptomic studies should be carried out to explain how *Vitis* species used as broodstock, such as *V. riparia*, *V. rupestris*, and *V. berlandieri*, are affected by waterlogging in the short and long term. It is also reported that the hormonal regulation occurring in the roots of different *Vitis* species and genotypes may differ significantly [37].

2.4 Extreme weather events

With climate change, extremes began to be seen in many climatic events. The incidence of many undesirable climate events such as floods, drought, uncontrollable fires, strong winds, hail, extreme heat, extreme cold, and heavy snow has increased. With the changing climate, extreme weather events, which are under threat today and occur more and more frequently, bring many problems for traditional viticulture [38–40]. It has become very important to follow all climate events regularly and to be informed about possible anomalies in advance. It can be very useful for strategic climate communication to predict the current consequences of climate change and to create longer-term climate strategies in the future [41].

Among the sudden climatic events seen in viticulture, especially hailstorms cause serious damage. There is a significant increase in hail events all over the world. Depending on the phenological stage of the vine, hail can damage shoots, leaves, and fruits and sometimes even cover systems [42].

In addition, strong winds and typhoons are a significant threat to both vineyards and trellis systems. In recent years, there has been a significant increase in the number of these sudden climate events and they cause serious damage [43,44].

2.5 Other effects

Climate change actually means much more than it seems. Many things that we depend on and value – such as water, energy, transportation, wildlife, agriculture, ecosystems, and human health – are experiencing the effects of a changing climate [45]. Our food supply is highly dependent on climate and weather conditions. While farmers and scientists can adapt some farming techniques and technologies or develop new ones, managing some changes really is not as easy as it seems [46]. With the changing climate, serious problems have begun to occur in the field of viticulture all over the world. Table grapes, wine grapes, and dried grapes are all significantly affected by these changing climate and climatic events. Unfortunately, this situation has a largely negative effect and causes undesirable situations in both the yield and quality of the grapes. For wine grapes, this situation generally occurs when increasing temperatures change the chemical content of the berries [29]. For table grapes, these negative effects are increased water need, increased disease pressure, and increases in production costs [47]. Although the problems in dried grapes are largely similar to those in table grapes, sudden climatic events, especially during the drying of grapes, also pose an additional problem [48].

With climate change in the coming years, grape growers will face rising temperatures and changing precipitation patterns. Especially, the vine phenology and the water availability in the soil will be among those most affected. Unsuitable conditions in summer, especially (hotter summers), affect both the chemical composition and flavor of the grapes. Higher evapotranspiration rates will be seen due to rising temperatures and vines will grow in more water stress conditions as a result of changing precipitation ratio. It is strongly expected that these changing conditions will have significant effects on grape yield as well as quality. In light of these expectations, species and cultivars that can more easily adapt to forcings in grapevine phenology and limited water availability in the soil will come to the fore [49,50].

When the transcriptomic and metabolic reactions of fruits as a result of heat and drought stress in wine grapes were examined, it was reported that heat stress not only alone but also in conjunction with water stress had significant effects on important quality parameters such as organic acid content, pH, and titratable acidity of the fruit. It is also reported that environmental stresses show a distinct organ-specific response, in contrast to previous research for grape leaves and fruits that respond more strongly to water stress. Heat stress has been reported to have a much more significant effect on gene expression in grape fruits than water stress [51].

Researchers have reported that fruits of different species (especially *V. labrusca*) with a more biochemically rich content under arid conditions can be an excellent genetic resource [52].

Global warming increases sugar and decreases anthocyanins and acidity in grapes. Climate adaptation strategies are essential to face global warming in viticulture. Certain viticultural techniques may delay grapevine ripening close to 15 days. Forcing bud regrowth delays ripening 2 months, which is essential in very warm areas [22].

3 Adaptation strategies in response to climate change

The viticulture sector is going through an important process for adaptation to climate change [53]. In viticulture, climate change not only has effects on the yield and quality of grapes, but is also important because of some difficulties

brought by the social demand for environmentally friendly farming techniques [54,55]. Viticulture must adapt to these changing conditions in order to guarantee its sustainability. Climate change will create major problems for all sectors of viticulture in the coming years.

In recent years, in most viticulture regions, both fruit and wine quality have improved, while yields have decreased due to rising temperatures and lack of water. This situation may negatively affect the quality in the near future. Growers need new and sustainable strategies for quality production at economically acceptable yields in a warmer, drier climate. Especially for this purpose, varieties developed from different breeding programs seem to be one of the best solution proposals due to their environmentally friendly and more cost-effective production advantages [55,56].

3.1 Cultivar/variety and rootstock breeding programs

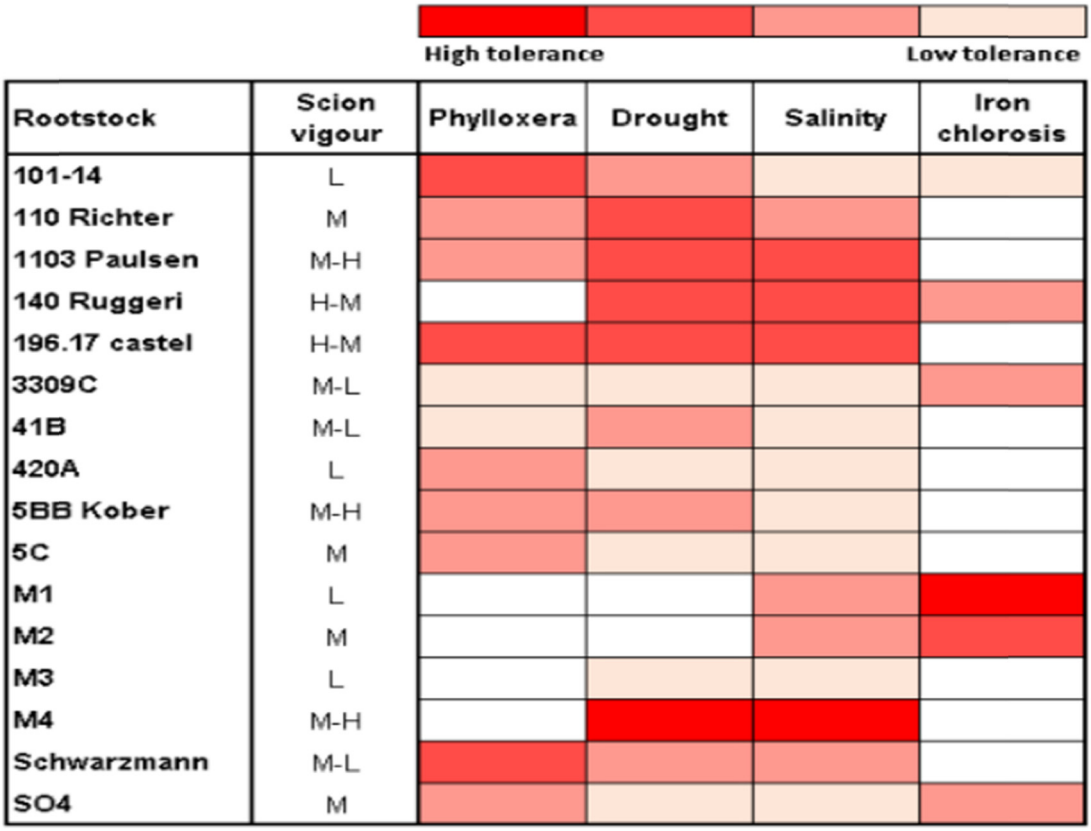
Rootstock selection is important for adaptation to climate change in viticulture. Rootstocks commonly used in viticulture were obtained from crosses of some American species. Rootstocks obtained from different *Vitis* species and hybrids, especially *V. berlandieri, V. riparia, and V. rupestris* species, are widely used. These American grapevine rootstocks are resistant to phylloxera and have also been reported in many studies to provide resistance or tolerance to various pathogens and biotic/abiotic stress conditions [57,58]. In addition, grape rootstocks can affect the grape berry quality and make the varieties grafted on them more resistant to different abiotic stress conditions [59,60]. Rootstocks can provide resistance or tolerance to a wide variety of abiotic stresses, in addition to their ability to help the scion cope with different biotic stresses. It is known that rootstocks have significant effects on the grapevine's tolerance to abiotic stress factors (especially high salinity, drought, and iron deficiency). These stress factors are among the very important factors that limit the productivity of the grapevine plant and cause serious yield loss [61]. The breeding of new grape varieties and rootstocks that use water more efficiently is a very important strategy against global climate change. According to global climate models, which predict that drought will increase in the future, there will be significant reductions in water resources and this will be among the main limiting factors of vineyard areas. Therefore, rootstocks are expected to play an important role in limiting crop loss by improving water use, plant survival potential, growth capacity, and adaptation of items to different stress conditions.

One of the priorities of today's viticulture research is to develop new rootstocks that are more drought resistant. The biggest advantage of adapting the cultivars to increasing drought stress is that these rootstocks are drought resistant, and their biggest advantages are that they make a significant contribution to reducing production costs [62].

Rootstocks and varieties grafted on them differ in their resistance to drought. For example, rootstocks such as 101-14 and Schwarzmann are less drought tolerant, while rootstocks such as Kober 5 BB, 1103P, Richter 110, and 140R are more resistant and can provide higher drought tolerance to grafted scions [5,63]. The ability of rootstocks to tolerate water stress is related to some structural characteristics. Stomata, which have particularly important roles in regulating water loss, are organs that need to be taken into consideration in managing water stress. Closure of stomata is one of the earliest responses in grapevines during a lack of water. Stomatal closure is guided by many factors, such as phytohormone accumulation. Abscisic acid (ABA) is one of the most studied hormones in grapevine plants, as in many plant species, and is very sensitive to water stress. Therefore, ABA synthesis is among the fastest plant responses under abiotic stress conditions [64,65].

Salt stress is another important abiotic stress factor and negatively affects both the growth and yield of grapevines. High salt levels cause problems in the uptake of micronutrients as well as water uptake of the soil, and as a result, the toxic ion concentration increases and some deteriorations in the soil structure may occur. Salt stress can affect plants in different ways. First of all, this negative effect is seen as affecting photosynthesis in the leaves. Tolerant varieties defend against this negative effect with their own mechanisms, and sometimes they can eliminate this effect. It has also been reported that different grape species, varieties, and genotypes have significant differences in the main signaling pathways and gene expressions that cause salt stress [66]. In recent years, it has been reported that engineered nanoparticles give positive results in combating abiotic stress factors such as salinity in different species, including vine plant [67].

Iron (Fe) chlorosis is among the most important abiotic stressors affecting grapevines grown in calcareous soil. Iron chlorosis caused by iron deficiency is among the main nutritional disorders seen in susceptible grape varieties or genotypes due to high bicarbonate levels in the soil. Fe deficiency causes a decrease in the productivity of the grapevine plant, reducing both its growth and yield [68]. Moreover, as a result of some wrong practices over many years, the negative effects of climate change are becoming more evident in grapevine plants. For example, many acidic fertilizers used excessively can sometimes cause



Rootstock	Scion vigour	Phylloxera	Drought	Salinity	Iron chlorosis
101-14	L				
110 Richter	M				
1103 Paulsen	M-H				
140 Ruggeri	H-M				
196.17 castel	H-M				
3309C	M-L				
41B	M-L				
420A	L				
5BB Kober	M-H				
5C	M				
M1	L				
M2	M				
M3	L				
M4	M-H				
Schwarzmann	M-L				
SO4	M				

Figure 4: Commonly used vine rootstocks and abiotic stress responses: low (L), medium (M) and high (H) (Scion vigor) and different degrees of tolerance to abiotic stress (phylloxera, salinity, drought, and iron chlorosis) [75].

some negative effects on vine leaves and therefore on crop yield. Particularly, in high pH and calcareous soils, it is necessary to prevent chlorosis by creating very careful plant fertilization programs for the uptake of microelements and iron [69].

Non-vinifera rootstocks have higher tolerance or resistance to both phylloxera and nematode damage than *V. vinifera*, provide better resistance to grafted varieties against these pests. In Figure 4, the characteristics of some commonly used rootstocks and their abiotic stress resistance status are reported. Also, a diagram of commonly used rootstocks and their parents is given in Figure 5. The breeding of new rootstocks that can provide tolerance or resistance to biotic/abiotic stresses and improve positively to grape ripening and also quality is a very important stage for the next-generation viticulture. In this regard, breeding studies are still continuing in different institutions and countries [63].

3.2 Site and cultivar/variety selection

Choosing the right place in viticulture is a very important issue, and climate change has increased the importance of this issue even more. Establishing a connection to a wrong place at the beginning of such an investment will both affect the efficiency and quality and increase the production costs significantly. For a sustainable viticulture, it is necessary to examine the place where the vineyard will be established for both wine and table grape cultivation in terms of many characteristics, including mainly climate and soil data [70]. With climate change, it is expected that there will be changes in the determination of suitable areas for viticulture.

While determining new vineyard areas, bioclimatic indexes are used and these indexes provide important information for suitable areas. It is predicted that new areas suitable for viticulture will emerge with the increasing temperatures, especially in the north of Europe [71–74].

New areas will be selected for viticulture; they will be areas with higher altitudes, higher annual precipitation, and less impact on vines from higher temperatures. However, as different plant species are already grown in these new areas, the grapevine may have to compete with them [75].

In order to be protected from the negative effects of climate change in viticulture, particular attention should be paid to the selection of location, direction, and variety.

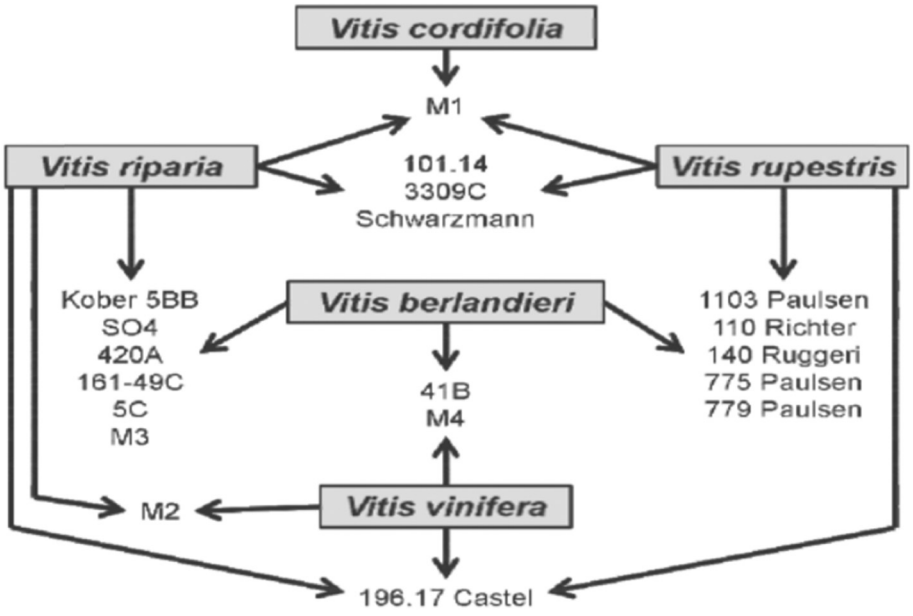


Figure 5: Main rootstocks and their parents [75].

Local differences are very important to reduce the negative effects of climate change on viticulture [76].

It is possible for grape growers to benefit from local conditions such as topography, slope, and direction to adapt to climate change. Temperatures in the higher elevations differ from those in the lower elevations by several degrees. Grape growers can adapt their vineyard areas to changing temperatures by taking advantage of these local differences. With climate change, the risk of sudden frost events in many vineyard regions has started to increase in recent years [77].

Although the most effective method for active protection from frost events is the operation of suspended sprinkler systems during frost events, wind machines and different heating applications are also widely preferred [78]. The most effective passive methods against late spring frosts include choosing a suitable location and choosing the appropriate grapevine cultivars. Grape growers may be advised not to plant vineyards in regions where frost events occur frequently or to plant cultivars that bud burst late [79]. In order to be protected from the negative effects of climate change in viticulture, it will be necessary to pay more attention to the selection of varieties. In studies carried out for this purpose, local varieties that may be less affected by high temperature conditions are determined, and new hybrid varieties are developed with breeding programs [80–83].

3.3 Covered systems

In many countries where table grapes are grown, different covering systems to protect the grapevine plants and fruits on them against the increasing extreme weather and climate events/disasters have started to be used in more areas [84]. In addition, with the integration of smart agriculture and artificial intelligence applications into these systems, it has become possible to have prior knowledge and preventive action against many extreme weather events [85,86]. There is a significant correlation between fungal diseases and climate change. Because increasing temperatures may create more favorable conditions for these diseases [87].

Producing more sustainable production and using decreasing water resources effectively in arid and semi-arid regions where table grapes are produced is a very challenging issue. Water use is significantly affected by some climatic conditions (such as excessive solar radiation, high air temperature, strong wind, high humidity). In recent years, table grapes have been covered with different plastic materials in different countries of the world in order to reduce the negative effects of climate-related increasing temperatures, strong winds, hail damage, frost damage and excessive rainfall. This situation has a direct relationship with the negative effects of climate change [88,89]. These covers are used protection for hail, high temperature, wind, and botrytis disease. In the coming years, it is inevitable that they will be used more widely against the increasing negative effects of the climate [90]. Sometimes bunches are partially or completely covered for different purposes. While almost all of the table grape vineyards are covered, especially in countries such as Korea and Japan, the number of covered table vineyards is also quite high in Italy and Spain. It is estimated that the

use of these systems will increase in the case of an increase in grape prices in countries such as Chile, South Africa, Turkey, Egypt, and Iran, where table grape production is high [91].

Agronomic and physiological measurements were compared in the studies carried out by covered cultivation with different plastic films. Plastic covers are very effective in providing specific leaf area with adequate shoot growth rate. When grapevines without plastic cover are compared with those with which plastic cover is applied, great differences are observed in terms of values such as leaf area, leaf chlorophyll content, and pruning weight. Additionally, plastic cover for grape vines causes low photosynthesis, transpiration, and stomatal conductance. It has been reported that plastic covers do not change the amounts of important components such as starch, glucose, and fructose in the leaves, but only transparent plastic covers can reduce the amount of sucrose in grape leaves. In addition, plastic cover increased the water potential of leaves and stems, reduced rotting, and increased bunch weight, resulting in higher yields. Also, berries under common plastic showed the highest concentration of anthocyanins. These results show that greenhouse cultivation gives very advantageous results, especially under increasing temperatures and limited irrigation opportunities [92,93].

Along with climate change, excessive precipitation that can sometimes be seen in summer causes significant quality loss in table and wine grapes harvested in this season. Moisture-related rain increases the incidence of vine botrytis as well as other fungal diseases. Additionally, increased soil moisture due to increased rainfall destabilizes plant growth and increases pH and acid content in grape berries. In addition, excessive shoot growth shades the berries and negatively affects the anthocyanin content and therefore color formation [94,95].

AV is a new concept that can protect plants from the harmful effects of climate for quality production, while providing the energy needed in agricultural production by placing photovoltaic panels a few meters above the soil surface and vegetation. In the current situation of energy demand from renewable sources, AV systems with grape plants under photovoltaic panels tend to become increasingly common. It has been determined that photovoltaic panels affect the microclimate of the vineyard. While vine productivity parameters (especially yield, number of clusters, and weight) affect it to a limited extent, it has been reported that anthocyanins, total soluble solids, and polyphenols are reduced in grape must. These findings have been reported in studies that affect the vine microclimate and physiology of the panels and that yield decreases may occur under photovoltaic panels, but the results should be evaluated together for both energy and fruit production in hot and dry weather conditions [96].

3.4 Soil management practices

As a result of the effects of climate change on grapevine plants, especially the issue of soil management has gained importance in this process. When we look at the studies carried out to protect from the negative effects of the climate in the vineyards produced for different purposes, we see that the issues of soil cultivation, weed control, and optimum utilization of the decreasing water resources come to the fore [3,8]. It has been reported that the yield in the grapevines with irrigation and tillage is generally increased by almost two times compared to the tillage system without irrigation. The lack of tillage can reduce the negative impact of the no-irrigation system on yield. Decreases in leaf stomatal conductivity were observed in vines that were not irrigated during the veraison period, regardless of whether or not tillage was done. In addition, at veraison, tillage in non-irrigated vines can significantly increase the phenolic substance ratio compared to the no-tillage system. The grapevines can accumulate more N, P, and K and less Mg during the flowering stage compared to the veraison. During the veraison period, reductions in K content in vines with irrigation and tillage and in Mg content in vines without tillage were noted. The total amount of soluble dry matter and anthocyanins of the berries increased in irrigation and no-tillage systems. It was observed that there was an increase in total phenolics with tillage in plants grown both irrigated and non-irrigated [97]. Soil management practices in grapevine plants are used to better manage water resources and also to prevent soil erosion. In Europe, demands for environmental precautions are increasing after increasing environmental awareness, and in recent years, alternative suggestions against the use of herbicides and new soil cultivation tools have started to be used more frequently. It is possible to reduce summer drought problems with less evaporation as a result of more superficial cultivation of the soil. The use of grass cover increases the soil's bearing capacity of the soil, especially during rainy periods, and can further limit the vigor of the grapevine [98].

The adaptation of the roots, which is the hidden and often overlooked part of the grapevine in the soil, to different soil types has a significant effect on the adaptation of grapevine plants to climate change. Due to the complexity of soil–root interactions, it is necessary to determine strategies to improve the adaptation of viticulture to the existing and possible threats to be encountered in the future, with a comprehensive approach that will combine different disciplines such as physiology, genetics, and pathology. Rootstocks have played an important role in viticulture since the introduction of phylloxera into

Europe at the end of the 19th century. In order to adapt to climate change, new rootstocks with different soil types and resistant to stress conditions need to be developed for both wine and table grapes. To cope with the effects of climate change and emerging soil-borne pests and pathogens, rootstocks need to be addressed with soil management [99,100].

3.5 Irrigation

One of the most important effects of climate change in viticulture and especially in table grape cultivation is related to irrigation water. Increasing temperatures not only cause more water consumption in plants, but also decrease irrigation water resources. It is reported that irrigation management in table grapes has become more important with climate change [101].

It is reported that water availability for table grapes will decrease further as a result of increased water demands and competition forecasts, which may affect high sensitivity and uncertainty for both production and human consumption. Conventional surface-applied irrigation methods can include easier installation and maintenance, along with lower infrastructure costs. However, these irrigation methods promote water loss through evaporation and seepage of soil water, which reduces water-use efficiency, which is a critical problem in semi-arid and arid regions [102,103]. Different microirrigation methods, a low-pressure, low-flow irrigation technique, with a relatively higher initial cost, have the capacity to reduce the use of water resources and increase the yield and economic return of vine crops. Although drip irrigation has become the most common microirrigation method used in vineyards, it is insufficient to use water more efficiently with increasing temperatures [104].

Direct root zone irrigation is a novel subsurface drip irrigation strategy for water conservation. When surface drip irrigation and direct root zone irrigation are compared, it can improve grape yield by 9–12% and crop water-use efficiency by 9–11% in different climatic conditions. It has been reported that direct root zone irrigation can potentially promote deep rooting in vines under drought stress to alleviate water stress and can be used as a successful tool to increase yield and quality [105].

Irrigation of vines is an important part of vineyard management, and it is especially important for table grapes. In addition, increasing temperatures and decreasing water resources due to climate change have increased this importance even more. With more precise and efficient programming of water resources, water needs can be met more efficiently. Typically, irrigation plans are created using mathematical models. While irrigation systems can be created with the help of technology in many developed countries, such models often have significant problems in implementation in most developing countries, often due to incomplete data [106,107].

3.6 Smart (precision) viticulture

Climate change is becoming an increasingly big problem for the grape industry on a global scale, affecting all aspects of the different development stages of the vine and also deteriorating the quality of the fruits. Because grapevine development is highly dependent on the weather and some climatic conditions, climate change can affect production costs and growth in different regions. Innovative technologies are needed against these problems. One of the most significant and recent conceptual developments in viticulture is precision viticulture (PV). With PV, it can be applied effectively especially in the following topics: weather monitoring, pest management, water management, harvest management, soil management, canopy management, and weed management. Recently, different remote sensing systems have begun to be used to monitor the microclimate of vineyard areas and vine plants. Different sensors integrated with drones, mini planes, or satellites began to be used for irrigation programs. Also, soil electrical conductivity sensors for soil mapping have also been developed in recent years. Soil and vine water-monitoring devices will be used more in vineyard areas in order to protect from the negative effects of climate change due to more technological developments such as sensitive viticulture and artificial intelligence in vineyards [108,109]. It is based on combining technical advances in global positioning system (GPS), onsite or aerial measurements of local microclimatic conditions, details of vineyard water and nutrient status, with measurements of several vine physiological parameters. These data can be correlated with the level of individual vines and their topographic details. It can help to make protective applications in the vineyard in advance, especially against sudden climatic events and the negative effects of climate change [110–112].

It is reported that by combining sensor monitoring and precision farming techniques, it can provide yield and quality improvements in grape production in plants under plastic cover systems [113].

4 Medium–long-term adaptive strategies

In order to ensure sustainability in the production of *Vitis* species, measures must be taken to adapt to climate change. Adaptation strategies should be evaluated meticulously, and the results must be analyzed well. After all factors are evaluated for the region together with these results, effective applications may be taken together with all decision-makers for a sustainable viticulture model. This situation should be taken into account sufficiently when determining the real effects of climate change and adaptation mechanisms. It would be beneficial to urgently develop medium–long-term adaptation strategies against the negative effects of climate change on viticulture. Many studies have been conducted on the adaptation mechanisms of climate change in viticulture. Looking at the contents of these studies, it has been reported that adaptation studies are carried out in three different ways (experimental, modeling, and expert judgment) on irrigation, plant material, vineyard design, canopy management, management of soil, site/location selection, farm strategy, and harvest management (Figure 6) [114]. In these studies, particular emphasis has been placed on experimental studies, and it is expected that these studies will soon include more application-oriented solutions that will be recommended to growers.

There is a need to develop biotechnology for varieties, clones, and rootstocks that are more resistant to abiotic stress such as water scarcity, thermal, and radiation excess. By examining the genetic mechanisms of local varieties in terms of adaptation to changing radiation, temperature, lack of vapor pressure, and water availability more effectively, suitable varieties can be determined and used in breeding studies.

Some cultural practices can be partially combated against climate change factors that significantly affect the quality of wine grapes. First of all, different applications can be selected by re-evaluating the criteria for the selection of growing systems and vine spacing. However, while doing this, too many changes should not be made in traditional methods that may adversely affect the quality. For example, a later maturation can be achieved with a simple application such as postponing the winter pruning. In addition, grain sugar accumulation and fruit alcohol content can be limited by using methods such as natural antitranspirant and new canopy management techniques [115,116].

5 Conclusions

Climate change is causing increasing damage to table, wine, and raisin grapes around the world. Climate change brings with it many negativities for vineyard areas, but it is important to prevent loss of income for growers by developing adaptive strategies to this situation in the short, medium, and long term. Nowadays, scientists first try to understand the negativities in the grapevine plant with

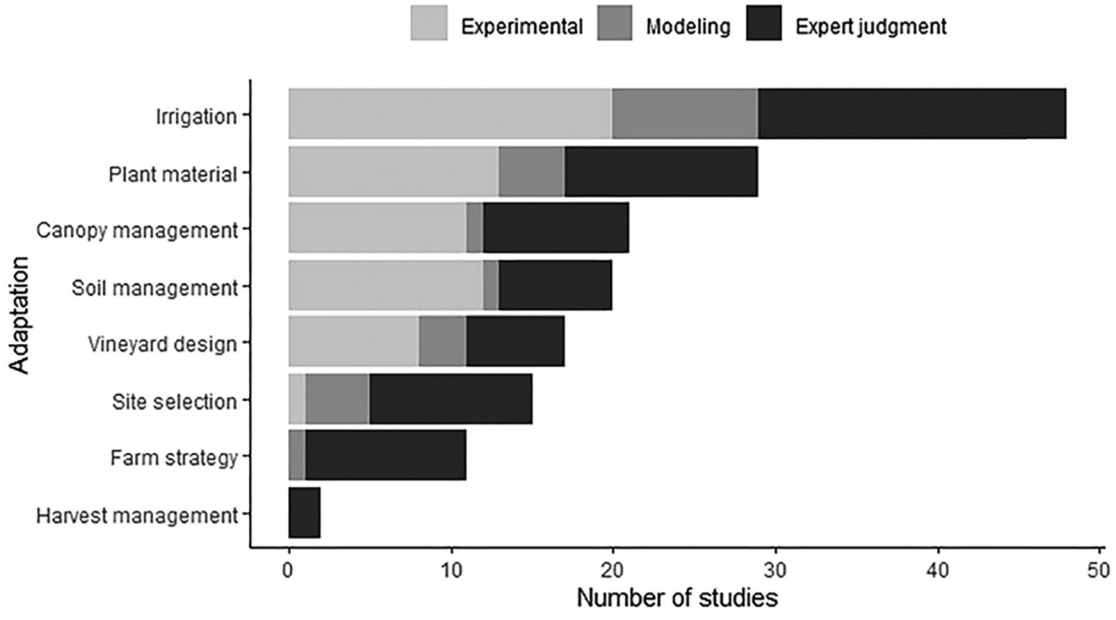


Figure 6: Type, number, and content of publications on the adaptation mechanisms of climate change in viticulture [114].

their studies, and on the other hand, they try to produce solutions that can be developed against this situation. Using the opportunities provided by technology, very promising results have begun to be achieved in recent years.

The important thing here is that we must raise awareness of all segments of society against climate change, be better prepared for different future scenarios, and accelerate research studies.

Funding information: The author states no funding involved.

Conflict of interest: The author states no conflict of interest.

Data availability statement: Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

References

[1] FAOSTAT. Available online: https://www.fao.org/faostat/en/#data/QCL(accessed on 10 April 2023).
[2] Fraga H. Viticulture and winemaking under climate change. Agronomy. 2019;9:783. doi: 10.3390/agronomy9120783.
[3] Ollat N, Cookson SJ, Destrac-Irvine A, Lauvergeat V, Ouaked-Lecourieux F, Marguerit E, et al. Grapevine adaptation to abiotic stress: an overview. Acta Hortic. 2019;1248:497–512. doi: 10.17660/ActaHortic.2019.1248.68.
[4] Grillakis MG, Doupis G, Kapetanakis E, Goumenaki E. Future shifts in the phenology of table grapes on Crete under a warming climate. Agric Meteorol. 2022;318:108915. doi: 10.1016/j.agrformet.2022.108915.
[5] Fahim S, Ghanbari A, Naji AM, Shokohian AA, Maleki Lajayer H, Gohari G, et al. Multivariate discrimination of some grapevine cultivars under drought stress in Iran. Horticulturae. 2022;8:871. doi: 10.3390/horticulturae8100871.
[6] Seneviratne SI, Zhang X, Adnan M, Badi W, Dereczynski C, DiLuca A et al. Weather and climate extreme events in a changing climate. In Climate Change 2021: The Physical Science Basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, et al. editors. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2021. p. 1513–766. doi: 10.1017/9781009157896.013.
[7] Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA. An overview of climate change impacts on European viticulture. Food Energy Secur. 2012;1:94–110. doi: 10.1002/fes3.14.
[8] Zhang P, Guo Z, Ullah S, Melagraki G, Afantitis A, Lynch I. Nanotechnology and artificial intelligence to enable sustainable and precision agriculture. Nat Plants. 2021;7:864–76. doi: 10.1038/s41477-021-00946-6.
[9] Brauer VS, Rezende CP, Pessoni AM, De Paula RG, Rangappa KS, Nayaka SC, et al. Antifungal agents in agriculture: friends and foes of public health. Biomolecules. 2019;9:521. doi: 10.3390/biom9100521.
[10] Popp J, Pető K, Nagy J. Pesticide productivity and food security. A review. Agron Sustain Dev. 2013;33:243–55. doi: 10.1007/s13593-012-0105-x.
[11] Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, et al. Food security: The challenge of feeding 9 billion people. Science. 2010;327(5967):812–8. doi: 10.1126/science.1185383.
[12] Reisch BI, Owens CL, Cousins PS. Grape. In: Badenes ML, Byrne DH, editors. Fruit Breeding. Boston, MA: Springer Science + Business Media, LLC; 2012. p. 225–62. doi: 10.1007/978-1-4419-0763-9_7.
[13] Buonassisi D, Colombo M, Migliaro D, Dolzani C, Peressotti E, Mizzottiet C, et al. Breeding for grapevine downy mildew resistance: a review of "omics" approaches. Euphytica. 2017;213:103. doi: 10.1007/s10681-017-1882-8.
[14] Sgroi F, Sciancalepore VD. Climate change and risk management policies in viticulture. J Agric Food Res. 2022;10:100363. doi: 10.1016/j.jafr.2022.100363.
[15] Gbejewoh O, Keesstra S, Blancquaert E. The 3Ps (Profit, Planet, and People) of Sustainability amidst Climate Change: A South African Grape and Wine Perspective. Sustainability. 2021;13:2910. doi: 10.3390/su13052910.
[16] Pizarro E, Galleguillos M, Barría P, Callejas R. Irrigation management or climate change? Which is more important to cope with water shortage in the production of table grape in a Mediterranean context. Agric Water Manage. 2022;263:107467. doi: 10.1016/j.agwat.2022.107467.
[17] Manolis GG, Georgios D, Kapetanakis E, Goumenaki E. Future shifts in the phenology of table grapes on Crete under a warming climate. Agric For Meteorol. 2022;318:108915. doi: 10.1016/j.agrformet.2022.108915.
[18] Meshram SG, Kahya E, Meshram C, Ghorbani MA, Ambade B, Mirabbasi R, et al. Long-term temperature trend analysis associated with agriculture crops. Theor Appl Climatol. 2020;140:1139–59. doi: 10.1007/s00704-020-03137-z.
[19] Wang Q-L, Chen J-H, He N-Y, Guo F-Q. Metabolic reprogramming in chloroplasts under heat stress in plants. Int J Mol Sci. 2018;19:849. doi: 10.3390/ijms19030849.
[20] Wahid A, Gelani S, Ashraf M, Foolad MR. Heat tolerance in plants: an overview. Environ Exp Bot. 2007;61:199–223. doi: 10.1016/j.envexpbot.2007.05.011.
[21] Hu S, Ding Y, Zhu C. Sensitivity and responses of chloroplasts to heat stress in plants. Front Plant Sci. 2020;11:375. doi: 10.3389/fpls.2020.00375.
[22] Venios X, Korkas E, Nisiotou A, Banilas G. Grapevine responses to heat stress and global warming. Plants. 2020;9:1754. doi: 10.3390/plants9121754.
[23] White MA, Diffenbaugh NS, Jones GV, Pal JS, Giorgi F. Extreme heat reduces and shifts United States premium wine production in the 21st century. Proc Natl Acad Sci U S A. 2006;103:11217–22. doi: 10.1073/pnas.0603230103.
[24] Zha Q, Xi X, He Y, Jiang A. Transcriptomic analysis of the leaves of two grapevine cultivars under high-temperature stress. Sci Hortic. 2020;265:109265. doi: 10.1016/j.scienta.2020.109265.
[25] Martínez-Lüscher J, Kizildeniz T, Vučetić V, Dai Z, Luedeling E, van Leeuwen C, et al. Sensitivity of grapevine phenology to water availability, temperature and CO2 concentration. Front Environ Sci. 2016;4:48. doi: 10.3389/fenvs.2016.00048.

[26] Fraga H, Garcia de Cortazar Atauri I, Malheiro AC, Santos JA. Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. Glob Change Biol. 2016;22:3774–88. doi: 10.1111/gcb.13382.
[27] Greer DH, Weedon MM. Modelling photosynthetic responses to temperature of grapevine (Vitis vinifera cv. Semillon) leaves on vines grown in a hot climate. Plant Cell Environ. 2012;35:1050–64.
[28] Gouot JC, Smith JP, Holzapfel BP, Walker AR, Barril C. Grape berry flavonoids: A review of their biochemical responses to high and extreme high temperatures. J Exp Bot. 2018;70:397–423.
[29] Lecourieux D, Kappel C, Claverol S, Pieri P, Feil R, Lunn JE, et al. Proteomic and metabolomic profiling underlines the stage-and time-dependent effects of high temperature on grape berry metabolism. J Integr Plant Biol. 2020;62:1132–58. doi: 10.1111/jipb.12894.
[30] Lecourieux D, Kappel C, Pieri P, Charon J, Pillet J, Hilbert G, et al. Dis-secting the biochemical and transcriptomic effectsof a locally applied heat treatment on developing cabernet sauvignon grape berries. Front Plant Sci. 2017;8:53. doi: 10.3389/fpls.2017.00053.
[31] Kogan F. Causes of climate warming. Remote sensing land surface changes. Cham: Springer; 2022. doi: 10.1007/978-3-030-96810-6_6.
[32] Gambetta GA. Water stress and grape physiology in the context of global climate change. J Wine Econ. 2016;11(1):168–80. doi: 10.1017/jwe.2015.16.
[33] Zúñiga-Espinoza C, Aspillaga C, Ferreyra R, Selles G. Response of table grape to irrigation water in the aconcagua valley, chile. Agronomy. 2015;5:405–17. doi: 10.3390/agronomy5030405.
[34] Li J, Xu X. Glacier Change and Its Response to Climate Change in Western China. Land. 2023;12:623. doi: 10.3390/land12030623.
[35] Torky M, Gad I, Darwish A, Hassanien AE. artificial intelligence for predicting floods: A climatic change phenomenon. In: Hassanien, AE, Darwish, A, editors. The power of data: driving climate change with data science and artificial intelligence innovations. Studies in big data. Vol. 118, Cham: Springer; 2023. doi: 10.1007/978-3-031-22456-0_1.
[36] Ruperti B, Botton A, Populin F, Eccher G, Brilli M, Quaggiotti S, et al. Flooding responses on grapevine: A physiological, transcriptional, and metabolic perspective. Front Plant Sci. 2019;10:339. doi: 10.3389/fpls.2019.00339.
[37] Yeung E, Van Veen, H, Vashisht, D, Sobral Paiva AL, Hummel M, Rankenberg T, et al. A stress recovery signaling network for enhanced flooding tolerance in Arabidopsis thaliana. Proc Natl Acad Sci U S A. 2018;115:E6085–94. doi: 10.1073/pnas.1803841115.
[38] Frei C, Davies HC, Gurtz J, Schär C. Climate dynamics and extreme precipitation and flood events in Central Europe. Integr Assess 200(1):281–300. doi: 10.1023/A:1018983226334.
[39] Prosdocimi M, Cerdà A, Tarolli P. Soil water erosion on Mediterranean vineyards: a review. Catena. 2016;141:1–21. doi: 10.1016/j.catena.2016.02.010.
[40] Leolini L, Fila G, Costafreda-Aumedes S, Ferrise R, Bindi M. Late spring frost impacts on future grapevine distribution in Europe. Field Crops Res. 2018;222:197–208. doi: 10.1016/j.fcr.2017.11.018.
[41] Sisco MR, Bosetti V, Weber EU. When do extreme weather events generate attention to climate change. Clim Change. 2017;143:227–41. doi: 10.1007/s10584-017-1984-2.
[42] Prabhakar M, Gopinath KA, Reddy AGK, Thirupathi M, Srinivasa RA. Mapping hailstorm damaged crop area using multispectral satellite data. Egypt J Remote Sens Space Sci. 2019;22(1):73–9. doi: 10.1016/j.ejrs.2018.09.001.
[43] LeComte D. International Weather Highlights 2013: Super Typhoon Haiyan, Super Heat in Australia and China, a Long Winter in Europe. Weatherwise. 2014;67(3):20–7. doi: 10.1080/00431672.2014.899800.
[44] Zhu J, Wu X, Sun G, Chen J. Numerical simulation of the dynamic progressive collapse of a plastic film greenhouse under typhoon. Int J Comput Appl Technol. 2016;54(1):42–50. doi: 10.1504/IJCAT.2016.077798.
[45] Lokmic-Tomkins Z, Nayna Schwerdtle P, Armstrong F. Engaging with our responsibility to protect health from climate change. J Adv Nurs. 2022;79(6):1–4. doi: 10.1111/jan.15508.
[46] Schmidhuber J, Tubiello FN. Global food security under climate change. PNAS. 2007;104(50):19703–8. doi: 10.1073/pnas.0701976104.
[47] Permanhani M, Costa JM, Conceição MAF, De Souza RT, Vasconcellos MAS, Chaves MM, et al. Deficit irrigation in table grape: eco-physiological basis and potential use to save water and improve quality. Theor Exp Plant Physiol. 2016;28:85–108. doi: 10.1007/s40626-016-0063-9.
[48] González-Curbelo MÁ, Kabak B. Occurrence of mycotoxins in dried fruits worldwide, with a focus on aflatoxins and ochratoxin A: A review. Toxins. 2023;15(9):576. doi: 10.3390/toxins15090576.
[49] Van Leeuwen C, Darriet P. The impact of climate change on viticulture and wine quality. J Wine Econ. 2016;11(1):150–67. doi: 10.1017/jwe.2015.21.
[50] Drappier J, Thibon C, Rabot A, Geny-Denis L. Relationship between wine composition and temperature: Impact on Bordeaux wine typicity in the context of global warming—Review. Crit Rev Food Sci Nutr. 2019;59(1):14–30. doi: 10.1080/10408398.2017.1355776.
[51] Hewitt S, Hernández-Montes E, Dhingra A, Keller M. Heat stress, not water stress, dominates in eliciting metabolic and transcriptomic responses of grape berries. 2023. Preprint (Version 1) available at Research Square. doi: 10.21203/rs.3.rs-2500367/v1.
[52] Güler E. Polyphenols, organic acids, and their relationships in red grapes of Vitis vinifera and Isabella (Vitis labrusca) under arid conditions. Eur Food Res Technol. 2023;249:913–21. doi: 10.1007/s00217-022-04183-9.
[53] Santos JA, Fraga H, Malheiro AC, Moutinho-Pereira J, Dinis L-T, Correia C, et al. A Review of the potential climate change impacts and adaptation options for european viticulture. Appl Sci. 2020;10:3092. doi: 10.3390/app10093092.
[54] Malik A, Mor VS, Tokas J, Punia H, Malik S, Malik K, et al. Biostimulant-treated seedlings under sustainable agriculture: S global perspective facing climate change. Agronomy. 2021;11:14. doi: 10.3390/agronomy11010014.
[55] Van Leeuwen C, Destrac-Irvine A, Dubernet M, Duchêne E, Gowdy M, Marguerit E, et al. An update on the impact of climate change in viticulture and potential adaptations. Agronomy. 2019;9:514. doi: 10.3390/agronomy9090514.
[56] Yang C, Menz C, Fraga H, Costafreda-Aumedes S, Leolini L, Ramos MC, et al. Assessing the grapevine crop water stress indicator over the flowering-veraison phase and the potential yield lose rate in important European wine regions. Agric Water Manag. 2021;261:107349. doi: 10.1016/j.agwat.2021.107349.
[57] Arrigo N, Arnold C. Naturalised Vitis rootstocks in Europe and consequences to native wild grapevine. PLoS One. 2007;2(6):e521. doi: 10.1371/journal.pone.0000521.
[58] Riaz S, Pap D, Uretsky J, Laucou V, Boursiquot JM, Kocsis L, et al. Genetic diversity and parentage analysis of grape rootstocks. Theor Appl Genet. 2019;132:1847–60. doi: 10.1007/s00122-019-03320-5.

[59] Gregory PJ, Atkinson CJ, Bengough AG, Else MA, Fernández-Fernández F, Harrison RJ, et al. Contributions of roots and rootstocks to sustainable, intensified crop production. J Exp Botany,. 2013;64:1209–22. doi: 10.1093/jxb/ers385PMid:23378378.

[60] Marguerit E, Brendel O, Lebon E, Van Leeuwen C, Ollat N. Rootstock control of scion transpiration and its acclimation to water deficit are controlled by different genes. N Phytol. 2012;194:416–29. doi: 10.1111/j.1469-8137.2012.04059.xPMid:22335501.

[61] Mariani L, Ferrante A. Agronomic management for enhancing plant tolerance to abiotic stresses—drought, salinity, hypoxia, and lodging. Horticulturae. 2017;3:52. doi: 10.3390/horticulturae3040052.

[62] Delrot S, Grimplet J, Carbonell-Bejerano P, Schwandner A, Bert P-F, Bavaresco L et al. Genetic and genomic approaches for adaptation of grapevine to climate change, in Genomic Designing of ClimateSmart Fruit Crops. In: Kole C, editor. Cham, Switzerland: Springer International Publishing; 2020. p. 157–270. doi: 10.1007/978-3-319-97946-5_7.

[63] Corso M, Bonghi C. Grapevine rootstock effects on abiotic stress tolerance. Plant Sci Today. 2014;1(3):108–13, Available from: https://horizonepublishing.com/journals/index.php/PST/article/view/64.

[64] Marusig D, Tombesi S. Abscisic acid mediates drought and salt stress responses in vitis vinifera a review. Int J Mol Sci. 2020;21:8648. doi: 10.3390/ijms21228648.

[65] Cramer GR. Abiotic stress and plant responses from the whole vine to the genes. Aust J Grape Wine Res. 2010;16:86–93. doi: 10.1111/j.1755-0238.2009.00058.x.

[66] Zhao F, Zheng T, Liu Z, Fu W, Fang J. Transcriptomic analysis elaborates the resistance mechanism of grapevine rootstocks against salt stress. Plants. 2022;11:1167. doi: 10.3390/plants11091167.

[67] Gohari G, Zareei E, Rostami H, Panahirad S, Kulak M, Farhadi H, et al. Protective effects of cerium oxide nanoparticles in grapevine (Vitis vinifera L.) cv. Flame Seedless under salt stress conditions. Ecotoxicol Environ Saf. 2021;220:112402. doi: 10.1016/j.ecoenv.2021.112402.

[68] Karimi R, Salimi F. Iron-chlorosis tolerance screening of 12 commercial grapevine (Vitis vinifera L.) cultivars based on phytochemical indices. Sci Hortic. 2021;283:110111. doi: 10.1016/j.scienta.2021.110111.

[69] Zebec V, Lisjak M, Jović J, Kujundžić T, Rastija D, Lončarić Z. Vineyard fertilization management for iron deficiency and chlorosis prevention on carbonate soil. Horticulturae. 2021;7:285. doi: 10.3390/horticulturae7090285.

[70] Nowlin JW, Bunch RL, Jones GV. Viticultural site selection: Testing the effectiveness of North Carolina's commercial vineyards. Appl Geogr. 2019;106:22–39. doi: 10.1016/j.apgeog.2019.03.003.

[71] Moriondo M, Jones GV, Bois B, Dibari C, Ferrise R, Trombi G, et al. Projected shifts of wine regions in response to climate change. Clim Change. 2013;119:825–39. doi: 10.1007/s10584-013-0739-y.

[72] Van Leeuwen C, Friant P, Chone X, Tregoat O, Koundouras S, Dubourdieu D. Influence of climate, soil, and cultivar on terroir. Am J Enol Vitic. 2004;55(3):207–17.

[73] Tóth JP, Végvári Z. Future of winegrape growing regions in Europe. Aust J Grape Wine Res. 2016;22(1):64–72. doi: 10.1111/ajgw.12168.

[74] Dunn M, Rounsevell MDA, Boberg F, Clarke E, Christensen J, Madsen MS, et al. The future potential for wine production in Scotland under high-end climate change. Reg Environ Change. 2019;19:723–32. doi: 10.1007/s10113-017-1240-3.

[75] Hannah L, Roehrdanz PR, Ikegami M, Shepard AV, Shaw MR, Tabor G, et al. Climate change, wine, and conservation. Proc Natl Acad Sci U S A. 2013;110:6907–12. doi: 10.1073/pnas.1210127110.

[76] Gladstones JS. Climate and Australian viticulture. In: Dry PR, Coombe BG, editors. Viticulture Volume 1 — resources. 2nd edn. Adelaide: Winetitles Pty Ltd; 2004. p. 90–118.

[77] Molitor D, Caffarra A, Sinigoj P, Pertot I, Hoffmann L, Junk J. Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region. Aust J Grape Wine Res. 2014;20(1):160–8. doi: 10.1111/ajgw.12059.

[78] Neethling E, Petitjean T, Quénol H, Barbeau G. Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change. Mitig Adapt Strateg Glob. 2017;22:777–803. doi: 10.1007/s11027-015-9698-0.

[79] Mosedale JR, Abernethy KE, Smart RE, Wilson RJ, Maclean IMD. Climate change impacts and adaptive strategies: lessons from the grapevine. Glob Change Biol. 2016;22:3814–28. doi: 10.1111/gcb.13406.

[80] Parker AK, De Cortázar-Atauri IG, Chuine I, Barbeau G, Bois B, Boursiquot JM, et al. Classification of varieties for their timing of flowering and veraison using a modelling approach: a case study for the grapevine species Vitis vinifera L. Agric For Meteorol. 2013;180:249–64. doi: 10.1016/j.agrformet.2013.06.005.

[81] Reis S, Fraga H, Carlos C, Silvestre J, Eiras-Dias J, Rodrigues P, et al. Grapevine phenology in four portuguese wine regions: modeling and predictions. Appl Sci. 2020;10(11):3708. doi: 10.3390/app10113708.

[82] Rodrigues P, Pedroso V, Reis S, Yang C, Santos JA. Climate change impacts on phenology and ripening of cv. Touriga Nacional in the Dão wine region, Portugal. Int J Climatol. 2022;42(14):7117–32. doi: 10.1002/joc.7633.

[83] Pertot I, Caffi T, Rossi V, Mugnai L, Hoffmann C, Grando MS, et al. A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. Crop Prot. 2017;97:70–84. doi: 10.1016/j.cropro.2016.11.025.

[84] Gianfranco R, Katerji N, Introna M, Hammami A. Microclimate and plant water relationship of the "overhead" table grape vineyard managed with three different covering techniques. Sci Hortic. 2004;102(1):105–20. doi: 10.1016/j.scienta.2003.12.008.

[85] Fuentes S, Tongson EJ. Editorial: Special Issue "Implementation of Sensors and Artificial Intelligence for Environmental Hazards Assessment in Urban, Agriculture and Forestry Systems". Sensors. 2021;21:6383. doi: 10.3390/s21196383.

[86] Tardaguila J, Stoll M, Gutiérrez S, Proffitt T, Diago MP. Smart applications and digital technologies in viticulture: A review. Smart Agric Technol. 2021;1:100005. doi: 10.1016/j.atech.2021.100005.

[87] Bois B, Zito S, Calonnec A. Climate vs grapevine pests and diseases worldwide: the first results of a global survey. OENO One. 2017;51(2):133–9. doi: 10.20870/oeno-one.2017.51.2.1780.

[88] De Palma L, Vox G, Schettini E, Novello V. Reduction of evapotranspiration in microenvironment conditions of table grape vineyards protected by different types of plastic covers. Agronomy. 2022;12:600. doi: 10.3390/agronomy12030600.

[89] Silva JR, Rodrigues WP, Ferreira LS, Bernado WD, Paixão JS, Pattersonet AE, et al. Deficit irrigation and transparent plastic covers can save water and improve grapevine cultivation in the tropics. Agric Water Manag. 2018;202:66–80. doi: 10.1016/j.agwat.2018.02.013.

[90] Tarricone L, Debiase G, Masi G, Gentilesco G, Montemurro F. Cover crops affect performance of organic scarlotta seedless table grapes under plastic film covering in southern italy. Agronomy. 2020;10:550. doi: 10.3390/agronomy10040550.

[91] Pisciotta A, Barone E, Di Lorenzo R. Table-grape cultivation in soilless systems: A review. Horticulturae. 2022;8:553. doi: 10.3390/horticulturae8060553.

[92] Souza CR, Mota RN, Dias NFA, Melo ET, Pimentel RMA, Souza LR, et al. Physiological and agronomical responses of Syrah grapevine under protected cultivation. Bragantia. 2015;74(3):270–8. doi: 10.1590/1678-4499.0047.

[93] Holcman E, Sentelhas PC, Conceição MAF, Couto HTZ. Vineyard microclimate and yield under different plastic covers. Int J Biometeorol. 2018;62:925–37. doi: 10.1007/s00484-017-1494-y.

[94] Jackson DI, Lombard PB. Environmental and management practices affecting grape composition and wine quality: a review. Am J Enol Viticul. 1993;44:409–30.

[95] Dry PR, Loveys BR. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Austr J Grape Wine Res. 1998;4:140–8. doi: 10.1111/j.1755-0238.1998.tb00143.x.

[96] Ferrara G, Boselli M, Palasciano M, Mazzeo A. Effect of shading determined by photovoltaic panels installed above the vines on the performance of cv. Corvina (*Vitis vinifera L.*). Sci Hortic. 2023;308:111595. doi: 10.1016/j.scienta.2022.111595.

[97] Chrysargyris A, Xylia P, Litskas V, Mandoulaki A, Antoniou D, Boyias T, et al. Drought stress and soil management practices in grapevines in cyprus under the threat of climate change. J Water Clim Change. 2018;9:703–14. doi: 10.2166/wcc.2018.135.

[98] Vanden Heuvel J, Centinari M. Under-vine vegetation mitigates the impacts of excessive precipitation in vineyards. Front Plant Sci. 2021;12:713135. doi: 10.3389/fpls.2021.713135.

[99] Marín D, Armengol J, Carbonell-Bejerano P, Escalona JM, Gramaje D, Hernández-Montes E, et al. Challenges of viticulture adaptation to global change: Tackling the issue from the roots. Austr J Grape Wine Res. 2021;27(1):8–25. doi: 10.1111/ajgw.12463.

[100] Aguirre-Liguori JA, Morales-Cruz A, Gaut BS. Evaluating the persistence and utility of five wild Vitis species in the context of climate change. Mol Ecol. 2022;31:6457–72. doi: 10.1111/mec.16715.

[101] Sharma J. Upadhyay AK, Adsule PG, Sawant SN, Sharma AK, Satisha J, et al. Effect of Climate Change on Grape and Its Value-Added Products. In: Singh H, Rao N, Shivashankar K, editors. Climate-resilient horticulture: adaptation and mitigation strategies. India: Springer; 2013. doi: 10.1007/978-81-322-0974-4_7.

[102] Li T, Zhang J. Effect of pit irrigation on soil water content, vigor, and water use efficiency within vineyards in extremely arid regions. Sci Hortic. 2017;218:30–7. doi: 10.1016/j.scienta.2017.01.050.

[103] Marino G, Di Martino S, Amico Roxas A, Caruso T, Ferguson L, Barone E, et al. Sustainability of pistachio production (Pistacia vera L.) under supplemental irrigation in a Mediterranean climate. Sci Hortic. 2018;241(7):260–6. doi: 10.1016/j.scienta.2018.06.032.

[104] Jensen CR, Ørum JE, Pedersen SM, Andersen MN, Plauborg F, Liu F, et al. A short overview of measures for securing water resources 606 for irrigated crop production. J Agron Crop Sci. 2014;200(5):333–43. doi: 10.1111/jac.12067.

[105] Xiaochi M, Karen A, Sanguinet P, Jacoby W. Direct root-zone irrigation outperforms surface drip irrigation for grape yield and crop water use efficiency while restricting root growth,. Agric Water Manage. 2020;231:105993. doi: 10.1016/j.agwat.2019.105993.

[106] Zhai Z, Martínez JF, Martínez NL, Díaz VH. Applying case-based reasoning and a learning-based adaptation strategy to irrigation scheduling in grape farming. Comput Electron Agric. 2020;178:105741. doi: 10.1016/j.compag.2020.105741.

[107] Tsirogiannis IL, Malamos N, Baltzoi P. Application of a generic participatory decision support system for irrigation management for the case of a wine grapevine at epirus, northwest greece. Horticulturae. 2023;9:267. doi: 10.3390/horticulturae9020267.

[108] Sun L, Gao F, Anderson MC, Kustas WP, Alsina MM, Sanchez L, et al. Daily mapping of 30 m LAI and NDVI for grape yield prediction in California vineyards. Remote Sens. 2017;9:317. doi: 10.3390/rs9040317.

[109] Sun Q, Granco G, Groves L, Voong J, Van Zyl S. Viticultural manipulation and new technologies to address environmental challenges caused by climate change. Climate. 2023;11:83. doi: 10.3390/cli11040083.

[110] Baluja J, Diago MP, Balda P, Zorer R, Meggio F, Morales F, et al. Assessment of vineyard water status variability by thermal and multispectral imagery using an unmanned aerial vehicle (UAV. Irrig Sci. 2012;30:511–22. doi: 10.1007/s00271-012-0382-9.

[111] Bellvert J, Marsal J, Girona J. Seasonal evolution of crop water stress index in grapevine varieties determined with high-resolution remote sensing thermal imagery. Irrig Sci. 2015;33:81–93. doi: 10.1007/s00271-014-0456-y.

[112] Bellvert J, Mata M, Vallverdú XC, Paris C, Marsal J. Optimizing precision irrigation of a vineyard to improve water use efficiency and profitability by using a decision-oriented vine water consumption model. Precis Agric. 2021;22:319–41. doi: 10.1007/s11119-020-09718-2.

[113] Li Z, Huang H, Duan Z, Zhang W. Control temperature of greenhouse for higher yield and higher quality grapes production by combining STB in situ service with on time sensor monitoring. Hellyon. 2023;9:e13521. doi: 10.1016/j.heliyon.2023.e13521.

[114] Naulleau A, Gary C, Prévot L, Hossard L. Evaluating strategies for adaptation to climate change in grapevine production–Ap systematic review. Front Plant Sci. 2021;11:6078592021. doi: 10.3389/fpls.2020.607859.

[115] Palliotti A, Tombesi S, Silvestroni O, Lanari V, Gatti M, Poni S. Changes in vineyard establishment and canopy management urged by earlier climate-related grape ripening: A review. Sci Hortic. 2014;178:43–54. doi: 10.1016/j.scienta.2014.07.039.

[116] Li W, Liu M, Chen K, Zhang J, Xue T, Cheng Z, et al. The roles of different photoselective nets in the targeted regulation of metabolite accumulation, wine aroma and sensory profiles in warm viticulture regions. Food Chem. 2022;396:133629. doi: 10.1016/j.foodchem.2022.133629.