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Geography

Impact of climate change on grape composition: a review

Impacto das mudanças climáticas na composição da uva: uma revisão

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ABSTRACT

The objective of this study was to prepare a literature review on the main implications of climate change for the composition of grapes and wine. A literature review was carried out with articles, books, and other scientific materials available in internet databases for indexing terms. A systematic literature review was adopted to prepare this review. Initially, the question for the development of the research was formulated. Soon after the search strategy was defined, the search for manuscripts related to the subject in the databases began. The manuscripts were selected for their relevance and relationship with the key subject of this review. Results inferred that the problems caused by the greenhouse effect, not only globally but also at regional and local levels, are worrying for the agricultural sector. In Brazil, projections for the end of the century indicate an increase of approximately 2°C in temperature, and the vine is a crop highly influenced by the climate, considered a factor of utmost importance for its development, productivity, and quality in the vineyard. Studies have shown that climate change causes changes in temperature, solar radiation, water, and CO_2, consequently compromising the composition of sugars, organic acids, phenolic compounds and aromatic compounds, in grapes and wine. It is concluded that the problems caused by climate change in both the composition of grapes and wine are worrying, as they can cause great losses for producers and vineyards. However, more studies and research are needed to propose strategies that can minimize the effects of climate implications.

Keywords: Vineyard; Phenolic compounds; Physical-chemical composition; Global warming; Viticulture

RESUMO

Objetivou-se com o presente estudo, elaborar uma revisão de literatura com as principais implicações das mudanças climáticas na composição da uva e do vinho. Foi realizada uma revisão de literatura com artigos, livros e outros materiais científicos disponíveis em bases de dados da internet termos de indexação. Uma revisão sistemática da literatura foi adotada para preparar esta revisão. Inicialmente foi formulada a questão para o desenvolvimento da pesquisa. Logo após e definida a estratégia de busca, iniciou-se a busca de manuscritos relacionados ao assunto nas bases de dados. Os manuscritos foram

selecionados por sua relevância e relação com o assunto chave desta revisão. Resultados inferiram que, os problemas ocasionados pelo efeito estufa não só em âmbito global, mas também em níveis regional e local são preocupantes para o setor agrícola. No Brasil, as projeções para o final do século indicam aumento de aproximadamente 2°C na temperatura, e a videira é uma cultura altamente influenciada pelo clima, considerado fator de suma importância para o seu desenvolvimento, produtividade e qualidade do vinhedo. Estudos apontaram que, as mudanças climáticas provocam alterações na temperatura, radiação solar, água, CO_2, comprometendo consequentemente a composição de açúcares, ácidos orgânicos, compostos fenólicos e compostos aromáticos da uva e do vinho. Conclui-se que, os agravos ocasionados pelas mudanças climáticas tanto na composição da uva quanto do vinho são preocupantes, pois podem gerar grandes prejuízos para os produtores e vinhedos. No entanto, são necessários mais estudos e pesquisas propondo estratégias que possam minimizar os efeitos das implicações climáticas.

Palavras-chave: Vinhedo; Compostos fenólicos; Composição físico-química; Aquecimento global; Vitivinicultura

1 INTRODUCTION

The role of climate change is considerable across all agricultural crops. Climate change has become frequent in recent decades, due to changes in atmospheric concentrations of greenhouse gases and the alteration of the Earth's surface through deforestation, desertification and urbanization (Jones et al., 2022).

Viticulture is one of the most economically important agricultural sectors in the world (Costa et al., 2016). Although both variables depend on the genetics of each variety, the vine's response to climatic conditions and their effects on the biosynthesis, translocation, degradation and accumulation of substances in the grape can determine the physical and chemical parameters of the fruits (Zocche et al., 2017; Stein et al., 2018).

For Ramos et al. (2020), among all the factors that influence vine cultivation, climate plays an extremely important role. Early phenological periods and shortening of the grapevine growing season have been reported by several authors due to the current moment of global warming (Sadras, Moran, 2012; Fraga et al., 2016; Fraga, Santos, 2018; Gutiérrez-Gamboa, Zheng, De Toda, 2021). The trends observed in the last decade of changes that occur (both in temperatures and precipitation) during the vegetative-productive cycle of the vine have direct impacts on the beginning and

duration of the phenological phases, which can become detrimental to the quality of the grape and the wine (Ramos, Yuste, 2023).

Many of the current traditional wine regions have been or will be affected by climate change (Gutiérrez-Gamboa, Zheng, De Toda, 2021). Several scientific manuscripts have reported the impacts of climate change on the global viticulture sector (Fraga et al., 2020; Jones et al., 2022; Sgroi, Sciancalepore, 2022; Straffelini et al., 2023). Climatic effects such as variations in temperature with more frequent heat waves, drastic increases in rainfall volumes and excessive solar radiation are among the factors most discussed in scientific reports.

In Brazil, climate change projections for the end of the century indicate an increase of approximately 2˚C in temperature throughout the national territory (Stocker et al., 2013). Projections of change in precipitation infer heterogeneous trends, with an increase in precipitation in some areas and a reduction in others (Woldemeskel et al., 2016). These predictions indicate that a large part of Brazil will be affected by climate change (Torres, et al., 2012), especially in regions where the economy is linked to agribusiness (Cera, Ferraz, 2015), reaching areas suitable for cultivation of certain cultures (Assad et al., 2013).

In this sense, several meteorological events can intervene with regard to the physiology of the vine and viticultural activity, such as temperature, precipitation, vapor pressure deficit, potential evapotranspiration, hours of sunlight and wind. Thus, these factors are related to other edaphic particularities, such as soil type, relief, altitude, latitude, as well as the production system used and chosen cultivars, which can trigger problems in the production and quality of the grape, and consequently reflect on the wine properties (Stocker et al., 2013; Santos, Martins, Torres, 2017).

Therefore, the wine sector around the world is being challenged by ongoing climate change, requiring adaptation at different levels. Climate change will inflict progressively dry or rainy, excessively hot or cold conditions, with changes in the frequency and intensity of climate extremes (Fonseca, Fraga, Santos, 2023).

Therefore, understanding related to the damage caused by climate change is essential, so that both researchers and producers have strategies in management practices, aiming to minimize the negative aspects caused by the greenhouse effect. It is essential to gain in-depth insight into the impacts of global warming on grape yield and quality. Therefore, the objective of this study was to prepare a literature review with the main implications of climate change on the composition of grapes and wine.

2 MATERIAL AND METHODS

The present study is a literature review based on the issue of climate change that has been occurring over the years on the planet, and the influence of these changes on the agricultural culture of grapes, on the quality and composition of grapes and wine.

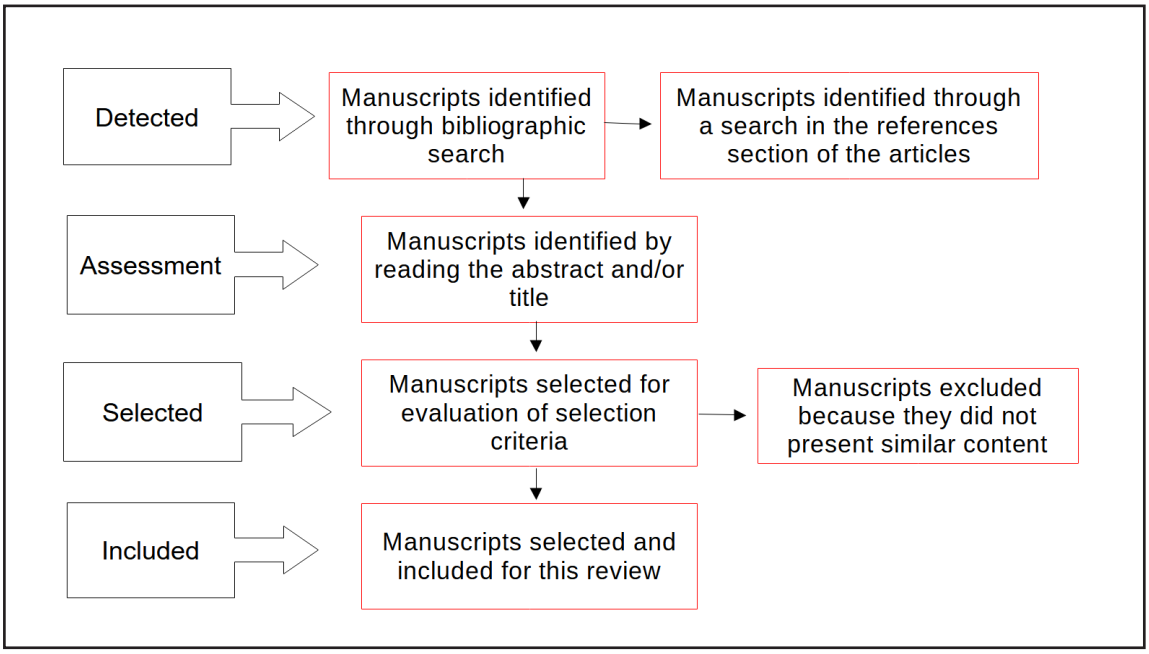
To this end, a literature review was carried out with articles, books and other scientific materials available in internet databases, such as Google Scholar, Scielo, Science Direct and Frontier, using the indexing terms: “climate change” or “alterations climate change” and “impacts of climate change on vine cultivation” or “climate change and effects on viticulture”.

A systematic literature review was adopted to prepare this review (Galvão, Pereira, 2014). Initially, the question was formulated for the development of the research. Soon after and after defining the search strategy, the search for manuscripts related to the subject in the databases began. The articles were identified through titles and/or abstracts and selected according to the inclusion and exclusion criteria adopted in this methodology.

The inclusion criteria for the article searches were the similarity and relevance of the subject and writing, in relation to the preparation of this review, in addition to the potential contribution of each manuscript. The exclusion criteria adopted in the searches were articles repeated in the databases and articles that did not return the subject of the search. All materials used are in English and/or Portuguese.

The selected manuscripts were then evaluated and synthesized for the inclusion of pertinent data, and inserted into the present review.

Figure 1 – Exemplification of the methodology adopted with the systematic review of manuscripts to prepare this review work



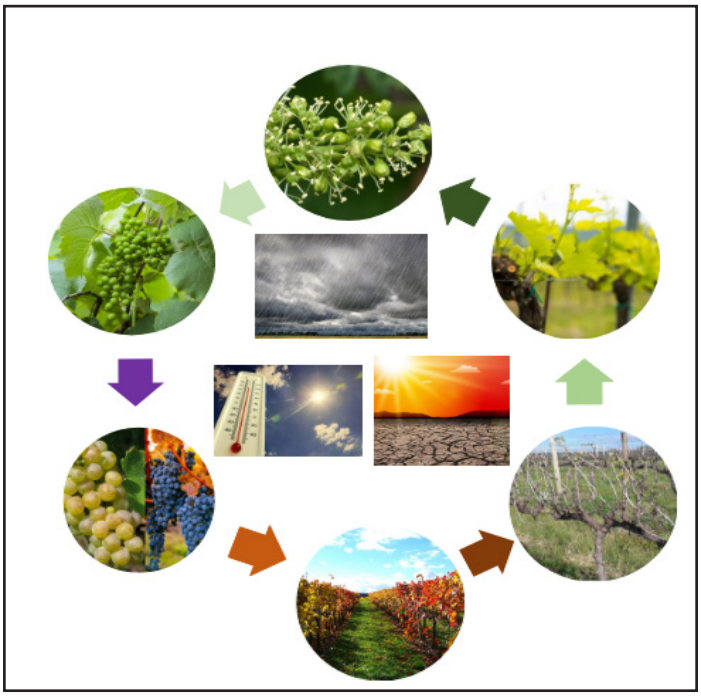
Source: The authors (2024)

3 IDEAL CLIMATE CONDITIONS FOR VINE

For the vine, time and climate are the most critical aspects for its good development and for obtaining the desired quality attributes, maximizing the winemaking potential of each cultivar in a given location (Fonseca; Fraga; Santos, 2023). Climatic aspects influence the physical-chemical aspects of grapes, interfere with productivity, grape quality, phenological stages and fruit maturation (Pessenti et al., 2021).

The most common climate information needed to assist in agricultural planning is related to the most important variables, such as rainfall, air temperature and incident solar radiation (Rufato et al., 2021). These variables have a strong influence on the growth and development of the vine culture (Mihailescu, Soares, 2020).

Figure 2 – Influence of climatic factors on the different development cycles of vine cultivation



Source: The authors (2024)

3.1 Temperature

Climatic conditions, especially air temperature, are one of the most important drivers of vine growth and productivity (Fonseca, Fraga, Santos, 2023).

The vine provides good adaptability to a wide range of temperatures, however, extreme conditions can cause negative impacts on the crop. Furthermore, increased temperatures can produce greater water stress, damaging phenology and, consequently, grape productivity and quality (Ramos, 2017).

The global increase accelerates the vine's vegetative and reproductive cycle. As a result, there is a change in the development stages of grape berries in the warmer months (Gambetta et al., 2021).

The phenological precocity established due to increased temperature causes changes in secondary metabolites, such as phenolic and aromatic compounds, especially anthocyanins, which are very sensitive to high temperatures (Gambetta et

al., 2021). In this sense, it is highlighted that phenolic compounds are of paramount importance, as they contribute to the organoleptic properties of wine, that is, flavor, color and aroma, and in addition, they provide benefits to human health due to their antioxidant capacity (Torres et al., 2012; Cera, Ferraz, 2015).

However, when phenolic compounds are exposed to recurrent high temperatures, they tend to reduce the quality characteristics of grapes and wine, as they accelerate the accumulation of sugars in the berries, increasing their alcohol content, reducing acidity due to the rapid depletion of organic acids (Gashu et al., 2020).

Elevated temperatures associated with climate change decouple the phenolic composition of berries and sugar metabolism, leading to low-color, highly alcoholic wines (Arrizabalaga-Arriazu et al., 2020).

However, very high temperatures, combined with intense solar radiation, can also cause damage to the pedicel and rachis, consequently causing the wilting of entire sections of the bunch (Kizildeniz et al., 2015; Gambetta et al., 2021).

This is potentially due to the limitation of water import for the berries, with the vapor pressure deficit being extremely high, which may partially contribute to the evaporation of water from the berries, affecting yield and quality (Gouot et al., 2019).

3.2 Carbon dioxide (CO_2)

Human intervention in the ecosystem, since the Industrial Revolution, has caused several changes in the microclimate and environment, promoting a significant increase in the volume of CO_2 in the atmosphere, resulting from the burning of fossil fuels and forest burning (Vieira, Garcia, Bruch, 2015).

Thus, from the exchange of matter and energy, environments are affected by the concentration of CO_2 and other greenhouse gases in the atmosphere, such as methane gas (CH_4) and nitric acid (HN_3), impacting the temperature of the planet (Vieira, Garcia, Bruch, 2015).

By capturing CO_2 through photosynthesis and transforming it into biomass, plants

play an important role in mitigating the impacts caused by increasing concentrations of CO_2 in the atmosphere. However, plants capture CO_2 up to a certain limit, and when CO_2 in the atmosphere increases, they tend to capture more and grow more (Nobre et al., 2012).

The increase in the concentration of this gas causes the temperature of the atmosphere to increase. As it increases, the photosynthetic assimilation point of 43°C can be exceeded, in response to the high temperature, and from then on, photosynthesis begins to decrease or paralyze (Nobre et al., 2012).

In plants, carbon fixation is directly related to environmental factors. In the grapevine, plant production is limited by high levels of carbon, and in the long term, biochemical and molecular changes occur, decreasing the photosynthetic capacity and the regulation of the opening and closing of stomata (Martínez-Lüscher et al., 2015).

The influence of climate change is a harmful factor for plants, and according to projections for the middle of this century, if the temperature continues to rise and affects photosynthetic efficiency, plants may reduce CO_2 absorption, in addition to oxidizing organic matter soil, resulting in even higher CO_2 emissions (Nobre et al., 2012).

3.3 Water

Vine is one of the perennial crops that can be most affected by climate change, even though it is tolerant to periods of drought, excessive water deficits combined with high temperatures can generate water stress to the plant, mainly by increasing evapotranspiration and causing problems in phenology, productivity and grape quality (Assad et al., 2013.).

Plants confer several adaptive responses in order to minimize the effects of water stress, one of which is related to the closure of their stomata, with the intention of keeping the water potential low, and consequently, avoiding dehydration (Skirycz, Inzé, 2010).

However, in addition to the water deficit being a harmful factor for the vine, excessive rainfall can also cause problems in it, for example, one can infer the unevenness of rainfall in some regions during the vegetative cycle, which have

consequences for maturation. of the grapes and the quality of the wine (Ramos, 2017). In this way, in some areas, precipitation tends to increase, while in other areas the tendency is to decrease or not change. Thus, in a scenario of climate change, vineyards can be greatly affected, due to greater evaporative demands and less water stored in the soil (Ramos, 2017).

The vine regulates the flow of water to the leaf and from the leaf to the atmosphere, through aquaporins, vessel anatomy and stomatal conductance (Griesser et al., 2015; Lovisolo et al., 2010; Vandeleur et al., 2009). However, when performing this process, plants rapidly reduce their growth, decreasing the size of leaves and shoots, measurable by the inhibition of internode length, leaf expansion, tendril elongation and decrease in the average diameter of xylem vessel diameters (Griesser et al., 2015).

Therefore, the impact of water deficit on grapevine development will depend on the intensity and duration of this stress, as well as the stage of development in which it will occur (Rienth et al., 2021).

3.4 Solar radiation

One of the climatic factors that is related to grape quality and its physicochemical characteristics is solar radiation (Torres et al., 2020). The vine is a resilient perennial crop, however, as with countless other fruit trees, the grape is sensitive to exposure to solar radiation, which can cause fruit damage or even fruit abortion (Tinyane, Soundy, Sivakumar, 2018; Torres et al., 2020).

The combination of visible and UV radiation has the ability to positively regulate some genes, such as structural and also regulators responsible for the synthesis of anthocyanins and flavonols (Martínez-Lüscher et al., 2020).

Light acts both as a source of heat and as a conductor of photochemical and oxidative reactions in the berry. An excessive amount of light promotes the production of triplet chlorophyll and reactive oxygen species (ROS), superoxide anion, hydrogen

peroxide and hydroxyl radical (HO), all promoters of oxidative stress in the photosystems of plants and fruits (Gambetta et al., 2021).

Plants have multiple photoreceptors that are responsible for activating signal transduction, which regulates light-dependent responses and related gene expression (Gambetta et al., 2021). These include the phytochrome superfamily, which consists of photoreceptors absorbing red/far red light, cryptochromes (blue, green, and UVA), phototropins (UVA/blue light) and UVB photoreceptors (Gambetta et al., 2021). Upon exposure to PAR or UV, these receptors upregulate the expression of genes encoding photoprotective molecules such as carotenoids and flavonoids to protect the berry's DNA and photosynthetic apparatus from further damage (Gambetta et al., 2021).

Sunburn of berries results from a combination of high light intensity, high temperature and UV radiation (Rustioni et al., 2014). The incidence and severity of damage depend on the biochemical, physiological and morphological conditions of the berry, all depending on the phenological stage, cultivar and adaptation to meteorological conditions (Gambetta et al., 2021). The symptoms are linked to the appearance of brown/necrotic spots on the epidermis of the grapes and the complete desiccation of the berries, causing significant losses in the quality and yield of the grapes (Gambetta et al., 2021).

With regard to photosynthesis, UVB is considered a growth modulator, capable of activating metabolic switches between primary and secondary metabolism. In fact, in the current situation, UVB radiation levels can constitute a strong limitation for biomass production (Martínez-Lüscher et al., 2015).

Acclimatization to UVB radiation includes the biosynthesis of phenolic compounds that protect plant tissues from the harmful effects of UVB. UVB radiation triggers antioxidant enzymes, and even photosynthetic activity can be transiently reduced during the UVB acclimatization process (Martínez-Lüscher et al., 2015).

4 GRAPE COMPOSITIONS

4.1 Sugars

Sugars are the main structural components of plants, responsible for providing energy for plant growth and reproduction (Romero et al., 2021), and sucrose is the main transported constituent of the photosynthetic process to tissues in formation (Durand et al., 2018).

Once in the fruit, sucrose can be hydrolyzed into hexose (fructose and glucose) or it can serve as a building block for carbohydrate polymer synthesis, such as starch or cellulose.

Sucrose, fructose and glucose are the most abundant sugars present in fruits, and these are directly related to their flavor (Romero et al., 2021). The sugar concentration is also related to the synthesis of metabolites, as it promotes the accumulation of anthocyanins and carotenoids, which are linked to the appearance of the fruits (Giampieri et al., 2015; Pott, Osorio, Vallarino, 2019).

Sugars, in addition to playing important roles in the development and quality of grapes, as a primary metabolite and source of energy, modulate several vital processes, such as the accumulation of anthocyanins and aromatic compounds (Xu et al., 2015). The sugar content in the berries is one of the main contributing factors to the quality of the wine grape (Ren et al., 2020; Alem et al., 2021).

4.2 Organic acids

The organic acids present in grapes are called tartaric and malic acids, and also citric acid, present in smaller concentrations (Sirén, Sirén, Sirén, 2015). Therefore, the organic acid profile can be an indicator of the grape growing processes, as well as the winemaking process (Lima et al., 2022).

These make up the acidity and contribute to the sensory perception of the wine, such as flavor, aroma and color. In addition, these compounds influence the pH, microbiological, physical and chemical stability (Ivanova-Petropulos, Petruševa, Mitrev, 2020).

Tartaric acid, which is present in higher concentrations in both grapes and wines, plays a significant role in maintaining the chemical stability of wines, including color and flavor (Ivanova-Petropulos, Petruševa, Mitrev, 2020). Tartaric acid is formed during the initial cell division of the berry, and remains until the berries are ripe.

Normally, the tartaric acid concentration is stable per berry during subsequent ripening. During winemaking processes, microorganisms do not metabolize tartaric acid, but its concentration can be reduced through physicochemical mechanisms, such as the precipitation of potassium bitartrate (Lima et al., 2022).

Malic acid is also formed early in the growing season, however different its fate during grape maturation and winemaking than tartaric acid. This is found in high concentrations before ripening, but is metabolized during berry ripening (Lima et al., 2022). Depending on the conditions of the microenvironment, the concentration of malic acid is generally lower in warmer regions than in colder regions (Robles et al., 2019; Waterhouse, Sacks, Jeffery, 2016).

4.3 Phenolic compounds

Among the components of wines, polyphenols stand out for playing a key role in quality, especially in red wines, due to their contribution to their sensory properties, such as color, taste, flavor, astringency and bitterness (Garrido, Borges, 2013). Furthermore, polyphenols are the main phytochemicals associated with the beneficial properties of red wine on human health (Nemzer et al., 2021).

Flavonoids are the most important group of compounds in red wine (Nemzer et al., 2021). This family comprises anthocyanidins, flavanols, flavanones, flavones, chalcones and tannins (condensed tannins and hydrolysable tannins) (Gutiérrez-Escobar, Aliaño-González, Cantos-Villar, 2021). Flavanols, also known as flavan-3-ols, contribute to the color and sensory characteristics, such as the astringency and bitterness of wines (Martínez-Lüscher et al., 2015; Durand et al., 2018).

Anthocyanidins are natural water-soluble pigments responsible for the red color

of grapes and red wines. Anthocyanin pigments are composed mainly of aglycones and bound sugar (Gutiérrez-Escobar, Aliaño-González, Cantos-Villar, 2021), and the levels of this constituent in wines are variable, due to the stability of these anthocyanidins, which depend on pH, storage temperature and raw materials used during processing (Nemzer et al., 2021). In vines of the Vitis vinifera species, anthocyanins accumulate in the leaves during senescence, responsible for the coloration of the grape skins in the red and pink cultivars, and in some cases, these pigments are also predominant in the grape pulp (Garrido, Borges, 2013).

Flavonols are yellow pigments found in the skin of grapes, they are usually present in glycosidic forms, linked to a sugar (glucose or rhamnose), but others such as galactose, arabinose, xylose or glucuronic acid may also be present (Garrido, Borges, 2013; Gutiérrez-Escobar, Aliaño-González, Cantos-Villar, 2021). The main flavonols present in grapes and wines are: myricetin, quercetin, laricitrin, kaempferol, isorhamnetin and syringeatin (Gutiérrez-Escobar, Aliaño-González, Cantos-Villar, 2021), and these are present in both white and red wines, playing an important role in the astringency and bitterness of wines (Gutiérrez-Escobar, Aliaño-González, Cantos-Villar, 2021, Nemzer et al., 2021).

Therefore, different factors alter the phenolic composition of grapes and wines, depending on the cultivar and environmental factors, such as climatic conditions and seasonal climate variation.

5 INFLUENCE OF EXTREME WEATHER EVENTS ON GRAPES

As we saw in the previous section, climatic events can directly influence the production of wine grapes, especially in terms of fruit quality. Adapting to climate change is a major challenge facing the viticulture sector, considering that climate change has already caused several problems in global production.

Among these, it is possible to mention the advancement of harvest dates, the increase in diseases in wetter regions, water stress, wines deficient in freshness and

aromatic composition, excessive increase in alcohol content, loss of production due to more frequent extreme events and increased concern about damage caused by spring frosts in some wine-growing regions (Leolini et al., 2018; Santos et al., 2020; Santos, Figueiredo, 2023).

Meteorological variations change the yield and ideal environmental conditions for grape maturation and, therefore, the typicality of the wine for a given 'terroir' or wine region (Blanco-Ward et al., 2019). This is known as the "vintage effect," with climate having a greater impact on productivity and quality relative to other factors such as soil type or cultivar (Blanco-Ward et al., 2019).

The vine's vegetative-productive cycle is modulated by several factors, two of the most important of which are temperature and water availability (Santos, Figueiredo, 2023; Bonada et al., 2020). Temperature severely influences the main physiological processes, development, quality and productivity of the vine (Santos, Figueiredo, 2023).

Although a base temperature of 10 °C is necessary for the beginning of the vine's vegetative cycle, it is also known that if the high temperature threshold reaches its peak at critical points of development, negative impacts occur on photosynthesis, berry size, sugar accumulation and ripening (Carreiras et al., 2023). Furthermore, increasing temperatures lead to increased thermal stress and, consequently, water stress (Jones et al., 2022).

Considering the climatic parameters, it is inferred that the high temperatures after the summer modify the primary and secondary metabolism of the vines, resulting in changes in the maturation process and imbalance in the composition of the berries (Modesti et al., 2021).

The drastic increase in temperature has an impact on viticulture and, as a consequence, the desiccation of plants and fruits occurs, significantly altering their composition (Gutiérrez-Escobar, Aliaño-González, Cantos-Vilar, 2021). Events of high maximum temperatures can evolve into heat waves, damaging flowers during spring flowering, resulting in reduced fruit production and increased temperature and fruit wilting (Straffelini et al., 2023).

The best conditions for wine production are generally achieved at the time when the grapes reach full ripeness, when temperatures are still high (25–30 °C) enough to obtain optimal ripeness (Gutiérrez-Gamboa, Zheng, De Toda, 2021).

As an example, Fraga et al. (2020), through a modeling exercise, found that heatwave events of up to 9 days can decrease yields by 35%. In studies carried out with the Tempranillo cultivar, the authors found that water deficit combined with high temperatures were the main factors that reduced the vine's performance (Kizildeniz et al., 2015).

In vineyards cultivated close to southern areas and at low latitudes, the increase in temperature promotes changes in the phenology, development and biochemical composition of the berries, in addition to a greater incidence of pests and diseases (Mihailescu, Soares, 2020).

Temperature changes will also affect the duration of the crop's vegetative cycle, a critical aspect due to its impact on grape ripening and fruit quality and, consequently, on the cultivar's adaptation to certain regions (Meggio, 2022). Furthermore, extreme heat events (temperatures above ~35 °C) can significantly affect vine yield by restricting photosynthesis mainly due to the closure of stomata (Fraga et al., 2020), hindering aroma, fruit development and color, the production of anthocyanins and changes in the flavor of the wine (Droulia, Charalampopoulos, 2022).

While high temperatures can be beneficial to fruit ripening potential, excessive heat stress can lead to a variety of effects, particularly depending on the developmental stage of the vine (Fonseca, Fraga, Santos, 2023). Maturity arrests are frequent at very high air temperatures, particularly when water availability in the soil is already at very low levels (Fonseca, Fraga, Santos, 2023).

During the summer, 35 °C is a critical temperature threshold for vine physiology and fruit ripening, resulting in a decrease in titratable acidity, anthocyanin content and aromatic compounds (Teker, 2023). As long as the temperature is above the threshold degree, sunburn problems can increase and negatively affect grape quality (Gambetta et al., 2021).

Sunburn is a physiological disorder that affects the visual and organoleptic properties of grapes. The appearance of brown and necrotic spots seriously affects the commercial value of the fruit and, in extreme cases, significantly reduces yield (Gambetta et al., 2021). Sunburn results from a combination of excessive photosynthetically active radiation, UV radiation and temperature which can be exacerbated by other stress factors, such as water deficit (Gambetta et al., 2021).

Phenolic compounds are also influenced by high temperatures, and when stress is moderate these compounds increase, but under severe and prolonged stress their content is reduced (Ayenew et al., 2015). As an example, tannins and anthocyanins can be cited (Gouot et al., 2019).

Anthocyanins at high temperatures tend to accumulate more in berries (Afifi, Obenland, El-Kereamy, 2021), as these phenolic compounds are the most modulated under these conditions. However, at temperatures elevated to very high levels, anthocyanins are considerably reduced (Ivanova-Petropulos, Petruševa, Mitrev, 2020). In addition to genotype and developmental stage, stress severity can modulate anthocyanin content (Romero et al., 2021). Anthocyanins are responsible for color (Savoi et al., 2017), bitterness, and mouthfeel properties (Ferrero-del-Teso et al., 2020).

The physiological effect of high temperature stress also involves the induction of reactive oxygen species, which act as a stress factor by inhibiting the biosynthesis of anthocyanins and promoting their degradation through the activation of enzymes such as peroxidases (Afifi, Obenland, El- Kereamy, 2021). Reactive oxygen species are normally found in cells that are not under stress, but when they experience these conditions, they lead to an exacerbated increase in highly reactive molecules and a reduction in photosynthetic CO_2 fixation (Gambetta et al., 2021).

A significant physiological outcome of climate change is also the decoupling between grape ripening based on soluble solids and ripening based on secondary metabolites such as anthocyanins, phenols and aromatic constituents (Jones et al., 2022).

In recent decades, the sugar content of grapes has increased in several regions, while the content of organic acids and anthocyanins has decreased, leading to an unfavorable balance (Van Leeuwen, Darriet, 2016). It is inferred that the occurrence of this imbalance occurs due to the kinetic disorganization of the accumulation of anthocyanins and sugars in the fruit due to high temperatures, thus modifying the quality of wines, especially red wines (Sadras, Moran, 2012).

Malic and tartaric acids are the main acids found in grapes (Kizildeniz et al., 2015). However, during the respiration process, both are lost and, consequently, there is a reduction in their quantity in the fruits. Thus, with the presence of high temperatures caused by climate change, acidity tends to decrease, due to greater degradation of acids at higher temperatures in vineyards (Sweetman et al., 2014). This is a worrying fact, as acidity is of paramount importance when it comes to wine quality, playing a role in freshness, in addition to acting as a buffer to preserve the wine for longer (Modesti et al., 2021).

However, climate change can create an imbalance in wine, mainly due to the low level of malic acid and the high concentration of sugars in its composition. Thus, the need for complementary additions of acids is inferred, aiming to reestablish adequate pH and TA levels so that the quality of the wine is maintained (Van Leeuwen, Darriet, 2016).

Finally, high temperatures during the ripening process, combined with excessive radiation, cause harmful effects to the berries, altering the acidity and flavonoid content, causing an imbalance in the aromatic profile, with modifications in the biosynthetic genes related to aroma precursors (Lecourieux et al., 2017).

Therefore, the change of different abiotic factors will continue to impact viticulture globally (Rienth et al., 2021). Some authors predict that, in a more promising scenario, there will be a 2°C increase in temperature and in the most pessimistic scenario an increase of 4°C is expected. However, 56 to 85% of current wine-growing regions will become climatically unsuitable for viticulture by the end of the 21st century (Morales-Castilla et al., 2020).

6 FUTURE PROJECTIONS

Observed and projected climate trends already present a warmer climate and an increase in precipitation in wine-growing regions for the near future (Templ et al., 2021). Higher temperatures during the ripening of grape berries are already being observed, resulting in lower acidity levels and higher sugar contents, with implications, ultimately, on the quality and style of the wine (Gashu et al., 2020). Therefore, ongoing warming trends will alter these already established varietal niches, where each cultivar is better suited to the current local climate.

Direct impacts correspond to changes in abiotic factors, in this case, the effects of increased atmospheric CO_2 concentration and temperature, and changes in precipitation regimes, as well as the impact of extreme weather events, such as hail, heat waves and floods in crop yield (Santos, Figueiredo, 2023).

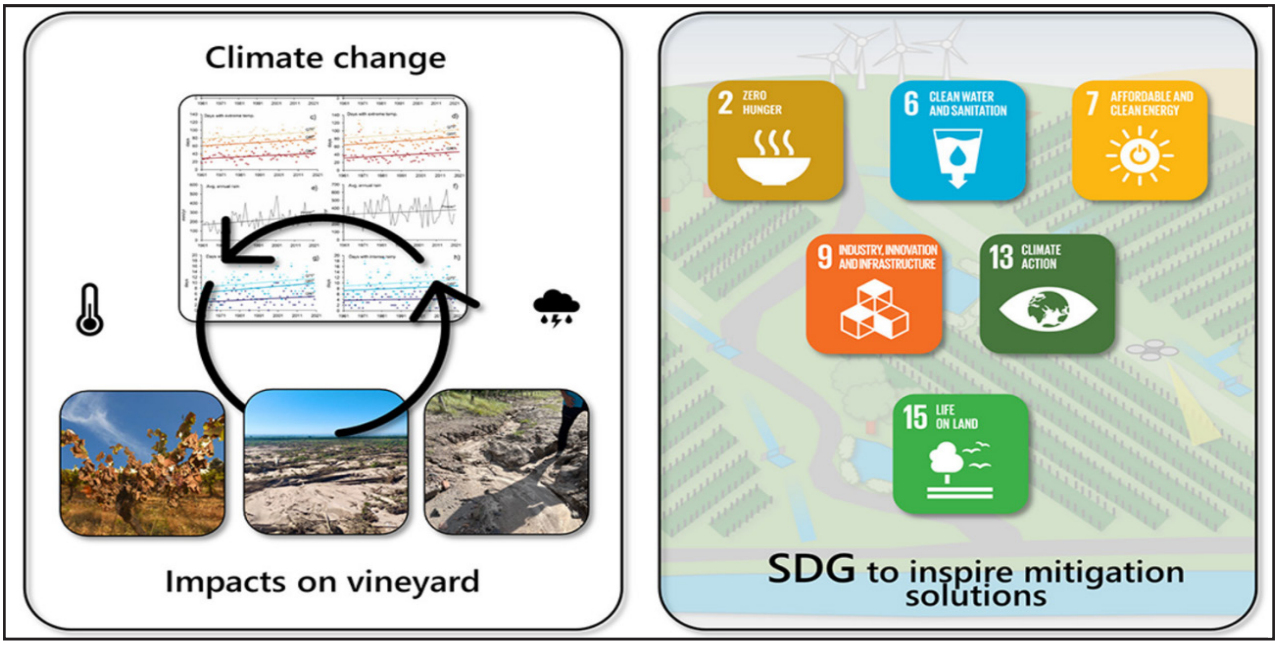
According to Santos et al. (2020), temperature and precipitation play an important role in global viticulture. In the particular case of precipitation, it is expected to decrease in the subtropical zone (Dai, Zhao, Chen, 2018). Nevertheless, the continued intensification of global warming is expected to intensify extreme precipitation events, due to the increase in the concentration of water vapor in the atmosphere (Ingram, 2016), thus affecting water balance and water availability.

These impacts lead to a drier surface, less evaporation and lower relative humidity, aggravating drought conditions and causing water stress in crops, causing harmful impacts on leaf growth, weight, quality and fruit yield (Fonseca, Fraga, Santos, 2023). Sustainable management of water resources, including the use of new technologies for combined high-resolution monitoring can help address the challenge of adapting to climate change in these important wine-growing areas, both under conditions of heavy rainfall and water shortages (Straffelini et al., 2023) (Figure 3).

Numerous vineyards share similar threats around the world, but especially those located in the hottest and driest regions. Thus, the strong relationship between

composition and production, wine quality, geographic origins and climatic conditions make the current trajectory of climate change a challenging issue for this agribusiness sector (Fonseca, Fraga, Santos, 2023.). At the scale of the wine region, there is an urgent need for planning and implementing appropriate, sustainable and cost-effective adaptation strategies (Ollat et al., 2017).

Figure 3 – Climate change and consequences for viticulture, given the need to adopt adaptation strategies combined with sustainability



(Straffelini et al., 2023)

In this sense, the authors Mihalescu and Soares (2020) suggest some strategies to minimize the impacts caused by climate change, highlighting canopy management, phytosanitary treatments, especially in areas of low latitudes, use of clones with late maturation and climate tolerance warm temperatures, in addition to the planting site.

Santos et al. (2020), highlights the importance of adopting timely, economical and appropriate adaptation strategies, which could significantly contribute to reducing risks, thus reducing the sector's susceptibility and increasing its resilience

in the face of a changing climate. It is worth understanding the new challenges to enable optimal adaptation to new conditions and ensure the resilience of local viticulture (Straffelini et al., 2023).

Although the potential of different adaptation options to reduce harmful impacts still involves many uncertainties and requires further research, implementing a combination of effective measures in the vineyard, in tune with terroirs and local climate change projections, could contribute to the socioeconomic future of existing wine regions (Santos et al., 2020).

7 FINAL CONSIDERATIONS

This review set out to clarify that the damage caused by climate change to the quality and composition of wine grapes is worrying, at the current time and will be in the future, in almost all wine growing regions in the world. This is because the damage caused by exacerbated climate changes is causing economic losses to producers in numerous regions.

It is worth mentioning that research on the effects of climate change on the photosynthetic apparatus considering the composition of fruits is far from complete. Furthermore, these plant responses vary with the stage of fruit development, the degree of stress tolerance and the interaction with other environmental and biological factors.

As temperature, drought and other stress conditions increase with climate change, the frequency of damage caused by these factors is expected to increase, be it sunburn, disproportionate fruit composition, poor quality and productivity.

It is necessary to consider that climate changes have been occurring for a few decades to the present day, and could continue to occur over the next few years, if the environmental crisis and polluting effects continue worldwide.

However, studies and research are needed to propose strategies that can mitigate the effects of climate change, and above all, minimize losses in production

and fruit quality, avoiding greater damage to the grape and wine production chain. This problem is not restricted to a specific region, however it is a worldwide phenomenon that leads to non-negligible economic losses and as such, requires attention and study of prevention and correction measures.

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