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The Impact of Climate Change on Grape Crops Development in Western Ukraine

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ABSTRACT

Climate change is becoming more noticeable and affects agriculture, particularly grape growing, which determines the relevance of research. The aim is to analyse the impact of climate change on the development of grape crops, yield, and quality. To this end, the study was conducted in the temperate climate zone from 2010-2022 by phenological observations and chemical and organoleptic methods. The results indicate a delay in the phenological stages of grapes, particularly budding and earlier flowering, which can affect yield. Changes in the composition of berries have also been identified, including a decrease in vitamin C and anthocyanins and an increase in sugar content due to the increased temperature. Recommendations include the selection of climate-resistant varieties, the use of irrigation systems and moderate watering. The novelty of the research lies in understanding the impact of climate change on grapes in a particular region. It is of strategic importance for the adaptation of agriculture to new conditions. Further research could focus on using cooling and biological products to ensure optimal growing conditions for grapes and increase resilience to climate change.

KEYWORDS: Crops, vitamin C, malic acid, temperature, precipitation.

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El impacto del cambio climático en el desarrollo de los cultivos de uva en el Oeste de Ucrania

RESUMEN

El cambio climático es cada vez más notorio y afecta a la agricultura, en particular al cultivo de la vid, lo que determina la relevancia de la investigación. El objetivo es analizar el impacto del cambio climático en el desarrollo, rendimiento y calidad de los cultivos de uva. Para ello, el estudio se realizó en la zona de clima templado durante el período 2010-2022 mediante observaciones fenológicas y métodos químicos y organolépticos. Los resultados indican un retraso en las etapas fenológicas de la uva, particularmente en la brotación y floración más temprana, lo que puede afectar el rendimiento. También se han identificado cambios en la composición de las bayas, incluida una disminución de la vitamina C y de antocianinas y un aumento del contenido de azúcar debido al aumento de temperatura. Las recomendaciones incluyen la selección de variedades resistentes al clima, el uso de sistemas de riego y riego moderado. La novedad de la investigación radica en comprender el impacto del cambio climático en la uva en una región particular. Es de importancia estratégica para la adaptación de la agricultura a las nuevas condiciones. Otras investigaciones podrían centrarse en el uso de productos biológicos y de refrigeración para garantizar condiciones óptimas de crecimiento de las uvas y aumentar la resiliencia al cambio climático.

PALABRAS CLAVE: Cultivos, vitamina C, ácido málico, temperatura, precipitación.

Introduction

Climate change has become one of the most urgent problems in the modern world and significantly impacts many aspects of life, including agriculture and grape growing. Grapes are an essential crop for winemaking, and their growth and development are closely linked to climatic conditions and weather. In addition, developing grape crops determines the quality and quantity of wine produced in different regions (Alikadic et al., 2019).

The impact of climate change on the development of grape crops is the subject of serious scientific research, as climate change is associated with an increase in average annual temperatures. These changes in precipitation distribution and other weather anomalies can affect grape-growing processes and wine quality. In this context, it is essential to investigate what adaptation strategies winemakers can use to preserve grape crops and ensure sustainable wine production (Mansour et al., 2022).

The impact of climate change on grape crops is essential from an economic and environmental perspective. An average annual temperature increase can have positive and

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negative effects on vineyards. At first glance, higher temperatures can help improve grape ripening, which can impact wine quality. However, too much heat can lead to overdrying of the soil and stress for the plants (Arrizabalaga-Arriazu et al., 2020).

Climate change may lead to uneven distribution of precipitation. Some regions may become drier, affecting water availability for vineyard irrigation. The risks of droughts and dry summers may also increase. Unusual weather conditions, such as heavy rains or spring frosts, can negatively affect the flowering and fruiting of grapes, leading to yield losses (Cola et al., 2020; Theron and Hunted, 2022).

In addition, it is essential to consider that climate change can affect the spread of diseases and pests that can damage vineyards. Increased humidity and heat can contribute to the development of fungal diseases such as mildew and botrytis (Kelly et al., 2022).

At the same time, different grape varieties may show additional resilience to climate change. Some varieties may be more adaptable to new climatic conditions and continue to grow, while others may be negatively affected and reduce their yield or quality (Liles and Verdon-Kidd, 2020).

It is worth noting that climate change can also affect the sugar content of grapes, an essential indicator for producing wine and other grape products. Rising temperatures can contribute to an increase in the sugar content of grapes since higher temperatures foster active photosynthesis and the accumulation of sugars in the fruit. However, too high temperatures can also lead to a loss of acidity, which can affect the quality of the wine. Uneven precipitation can affect the distribution of moisture in the soil and, consequently, the sugar content of the grapes. Excessive humidity can cause grape bunching and dilution of sugars, while moisture deficits can reduce yields and degrade fruit quality (Leolini et al., 2020).

In addition, changes in the length of the growing season caused by climatic factors can affect the development of grape crops. A longer growing season may allow grapes to accumulate more sugars. However, modern agricultural technologies, such as irrigation, weather protection and hybrid grape varieties, can help maintain fruit sugar content even in the face of climate change (Ramos and de Toda, 2020).

Therefore, to preserve grape crops and wine production in the face of climate change, it is essential to develop adaptation strategies, such as selecting more resilient grape varieties, introducing irrigation systems, protecting against diseases and pests, and developing

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agricultural practices that promote soil and water conservation. These measures can help preserve vineyards and ensure sustainable wine production in a changing climate.

Thus, the relevance of the study of the impact of climate change on the development of grape crops is that this research considers the urgent challenges and problems posed by climate change for viticulture and the wine industry, the need to adapt and develop agriculture and the wine industry, provides practical information for farmers, winemakers, and policymakers to make decisions and develop strategies to increase the resilience and productivity of viticulture in a changing climate.

The study aims to investigate the impact of climate change on the development of grape crops and determine their effect on the quality and quantity of grape products to develop effective strategies for adaptation and increase the resilience of this agricultural sector to climate change.

Research objectives:

1. To analyse the impact of changes in climatic parameters (temperature and precipitation) on the development of phenological stages of grapes, such as budding, flowering, bunching, and ripening, as well as on the chemical composition of grape berries.

2. To identify which grape varieties are more resistant to climate change and have the best yields and product quality.

3. To find out what possible adaptation strategies winegrowers can use to optimise grape growing in the face of climate change.

These objectives will help to understand the importance of researching the impact of climate change on viticulture and wine production and to identify ways to improve the sustainability and productivity of this industry in the face of growing climate challenges.

1. Literature Review

Venios et al. (2020) and Yan et al. (2020) claim that with increasing temperatures, different phenological stages of grapes (e.g. flowering and ripening) can shift in time. This can lead to a shorter growing season, which affects crop yields and wine quality. Reduced precipitation or changes in rainfall patterns can lead to droughts and affect plant moisture availability, leading to grape stress, stunting and reduced vine yields.

Kolstad and Moore (2020) also found that early flowering and ripening can change the chemical composition of grapes. In contrast, a shorter ripening period can lead to increased

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sugar content and decreased acidity in berries, which can affect the taste and quality of wine. In addition, faster flowering can increase the risk of late spring frost, damaging shoots and flowers. This can threaten the crop and require the application of protection methods.

Climate change can lead to changes in solar insolation levels in different regions, which impacts the climatic conditions for viticulture. Studies have shown a significant impact of solar insolation on grape growing and wine production. It has been found that solar insolation determines the phenology of grape growth, affects photosynthesis, the accumulation of sugars in berries and the formation of chemical compounds such as polyphenols and aromatic substances that affect the taste and aroma characteristics of wine (Rienth et al., 2020).

High temperatures can lead to problems during fermentation and vinification of grapes, significantly impacting wine quality and making it challenging to control wine production processes such as fermentation and storage temperatures. This can lead to the loss of aromatic compounds, oxidation and other harmful effects on wine's taste and aroma characteristics. Winemakers must make additional efforts to ensure the correct temperature conditions and control production processes to ensure high-quality wine even at high temperatures (Wohlfahrt et al., 2021; Drappier et al., 2020).

Arias et al. (2022) also notes that extreme climatic conditions, such as heat, drought, and intense sun exposure, significantly impact the quality and chemical composition of grape berries. For example, high temperatures can decrease phenolic compounds, particularly anthocyanins, in some grape varieties, while intense solar radiation can increase flavonoid levels. However, it is essential to note that access to water is also a critical factor for optimal vine growth and productivity. Even a tiny water deficit, particularly during the ripening period, can affect the activity of essential enzymes in the phenylpropanoid and flavonoid pathways, which can affect the composition of phenolic compounds and the quality of grapes and wine.

Cabré and Nuñez (2020) think that a lack of moisture due to changes in precipitation can lead to a reduction in grape yields. Plants need water for average growth, flowering and fruit ripening. A lack of moisture can limit fruit development and reduce fruit quantity and quality. In addition, a lack of water creates stress for plants, reducing photosynthesis and organic matter production.

Blancquaert et al. (2019) considers that a critical aspect of improving the resilience of

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grapevines is developing the plant root system. A deep, dense, buffered root system can provide plants access to moisture and nutrients and protect them from damaging environmental influences.

Thus, the expected increase in climate change requires additional efforts to improve the resilience of vines to new environmental conditions. In other words, winegrowers and winemakers should prepare for climate change and take measures to protect their vineyards.

Teslić et al. (2019) emphasises the importance of developing adaptation and mitigation strategies at the regional level. Climate and soil conditions can vary significantly from region to region, so strategy must be tailored to the specific conditions of each area. Small-scale data on terroir (local conditions) play an essential role in decision-making on grape cultivation.

Climate change may encourage growers to choose other varieties better adapted to new conditions. This may lead to a change in the varietal composition of wine-growing regions. Therefore, some studies demonstrate that winegrowers are already actively preparing for climate change by adopting new cultivation methods and selecting resilient grape varieties (Urvieta et al., 2011; Gaiotti et al., 2018).

According to Plank et al. (2019), winemakers use various adaptation strategies, including changes in grape processing methods, new technologies, and climate change insights to plan production.

These results indicate the complex interaction between climate change and viticulture and highlight the importance of research in developing industry adaptation strategies and sustainability. Therefore, further research will allow for more accurate and practical approaches to adapt winegrowers and winemakers to changing climate conditions and ensure the sustainability and quality of grape production.

2. Materials and Methods

2.1. Research Area

The research was conducted at sites in western Ukraine's temperate climate zone. The long-term average temperature and precipitation are shown in Figures 1 and 2.

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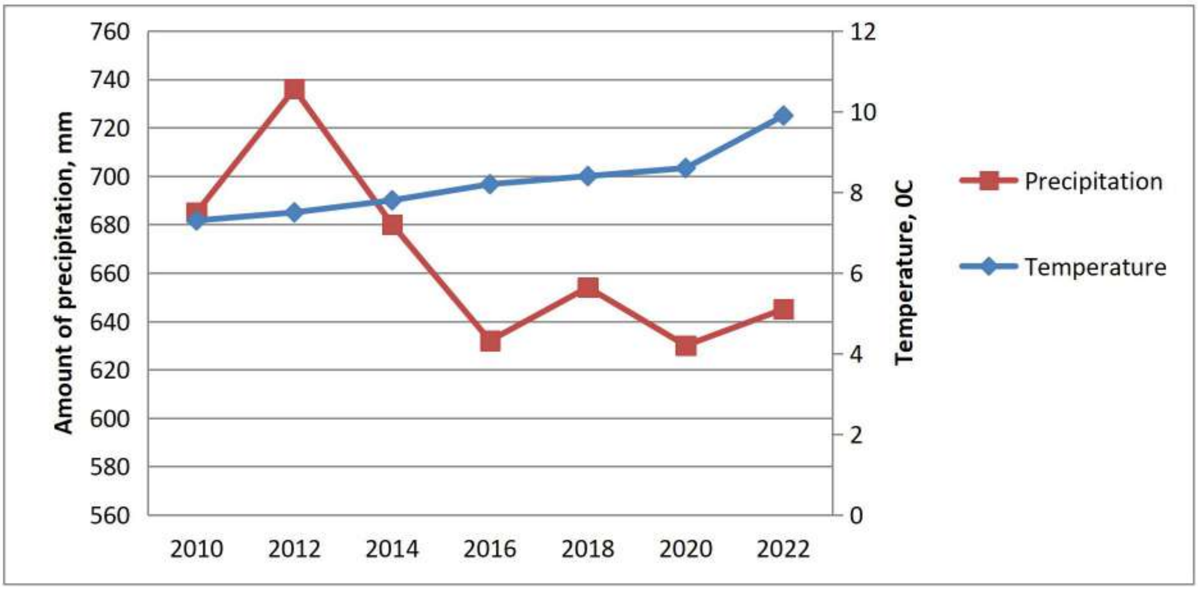
Figure 1. Long-term average temperatures, 0^{C} and precipitation, mm



The soils in the area are dark grey podzolised medium loamy soils, characterised by a deep humus horizon (50-60 cm), relatively low humus content (2-3%), high base saturation and low acidity. The soil has N content (according to Kornfield) of 102 mg per 1 kg of soil, P_2O_5 (according to Chirikov) of 103 mg per 1 kg of soil and K_2O (according to Maslova) of 177 mg per 1 kg of soil. The soil has an excellent water-air regime created by a good soil structure and the absence of a compacted illuvial horizon. The soil is water-resistant and does not float much. The relief of the territory is flat, with no forest vegetation.

2.2. The Phenology of Grapes

Grape plants were grown with a planting pattern of 3 m between rows and 1.5 m between plants. The vineyards were grown under irrigation. Phenological observations were used to analyse the impact of local climate change on grape phenology. The phenology of three varieties was analysed for 2010-2022: Cabernet Sauvignon, Aligote, and Chardonnay. The sampling included different grape varieties to study their adaptability and characteristics under other conditions.

The date of budding, flowering, bunch formation, and berry ripening for each variety was determined based on the moment when 50% of the vine sample reached the corresponding phenological stage. Each research phase included the analysis of four vines of the variety, conducted according to the same criteria during the analysed period. A sample of four vines was chosen to ensure the results were representative and to reduce the

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influence of random factors on the study. This number of vines allowed us to obtain reliable data and consider the possible variability of grapes. Maturity was determined based on the soluble solids content of the grape juice (measured in degrees Brix) and ranged from 22.0 to 24.5 degrees Brix.

2.3. Chemical Analysis

The acidity and malic acid content were determined using the titrimetric method. The content of anthocyanins was determined by spectrophotometry, recalculating into the main component of the anthocyanin complex, cyanidin-3-rutinoside. For this purpose, a filtrate was extracted with a 1% hydrochloric acid solution. The content of vitamin C and flavonoids was determined by liquid chromatography using an LC-2030 chromatograph (Shimadzu, Japan). The sugar content was determined by an ATAGO refractometer (Japan).

The grape yield is defined as the weight of the harvested crop per hectare of vines. To determine the average berry weight, a representative sample of berries from one vine was collected from different parts of the vine to exclude the random influence of one individual bush on the study results. After that, the weight of all these berries was determined and divided by their number in the sample.

2.4. Organoleptic Evaluation

A seven-member testing panel conducted the organoleptic evaluation on a five-point scale, and considered the leading indicators: appearance, colour, taste, and aroma.

2.5. Statistical Analysis

All the data obtained were statistically analysed. The mean value and standard error were obtained for each parameter. The research results were processed for reliability by multivariate analysis of variance (MANOVA) using Microsoft Excel software and Statistica 10 software package. Differences in the results obtained are possible at a level of $P \leq 0.05$ according to the Student's criterion.

The study also used an integrated environmental adaptability assessment method, which thoroughly evaluated how well the grape crop was adapted to local ecological conditions, including climatic and soil characteristics. This method was based on systematic observations and analysis, which allowed us to determine which grape varieties could cope with the environment and were most efficient in cultivation and yield.

3. Results

The development and growth stages of grape plants, the transition from one stage of vegetation to another, are mainly controlled by the thermal conditions of the environment and the accumulation of active heat. One of the most important indicators is the sum of operational temperatures, which is considered at temperatures above +10 °C. During 2016-2022, the accumulation of these temperatures was quite intense, which can lead to a shift in the dates of phenological phases, such as the beginning of flowering and bunch formation.

Comparing the phenological observations, we can see a certain irregularity; in particular, the date of budding in grapes is 2-4 days later, and the flowering is 5-7 days earlier. The period from budding to flowering was reduced by 4-6 days. Also, the period from flowering to ripening was decreased by 3-4 days (Table 1).

Table 1. Phenological growth of grape varieties

Variety	Year	Budding	Flowering	Formation of bunches	Berry ripening	Vegetation period from budding to
Cabernet Sauvignon	2010	18 April	7 June	18 July	6 August	110 days
	2012	18 April	8 June	16 July	5 August	110 days
	2014	19 April	7 June	17 July	4 August	110 days
	2016	20 April	6 June	17 July	5 August	109 days
	2018	20 April	5 June	17 July	4 August	110 days
	2020	20 April	5 June	16 July	3 August	108 days
	2022	21 April	3 June	16 July	3 August	107 days
Aligote	2010	14 April	8 June	17 July	7 August	115 days
	2012	15 April	8 June	17 July	7 August	115 days
	2014	15 April	8 June	17 July	7 August	114 days
	2016	16 April	7 June	18 July	6 August	114 days
	2018	16 April	7 June	16 July	5 August	113 days
	2020	17 April	5 June	16 July	4 August	113 days
	2022	18 April	5 June	15 July	4 August	112 days
Chardonnay	2010	16 April	10 June	19 July	6 August	114 days
	2012	16 April	9 June	18 July	6 August	114 days
	2014	17 April	9 June	18 July	5 August	113 days
	2016	17 April	8 June	17 July	4 August	113 days
	2018	18 April	6 June	17 July	3 August	112 days
	2020	18 April	6 June	16 July	3 August	112 days
	2022	19 April	5 June	16 July	2 August	111 days

Source: developed by the author.

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Thus, the analysis of the phenological development of three grape varieties (Cabernet Sauvignon, Aligote and Chardonnay) revealed certain variations in the dates of phenological events for each variety and year. The years 2016-2022 were marked by a later start of phenological phases compared to previous years, which may be due to changes in climatic conditions, particularly lack of moisture. These variations may generally result from the influence of climate, varietal characteristics and cultivation methods.

The acidity of grapes can vary depending on the grape variety, degree of ripeness and growing conditions. Malic acid is the leading organic acid commonly found in grapes. Typically, the malic acid content in grapes ranges from 0.2% to 0.7%. However, these values can vary between grape varieties and depend on the growing conditions.

The acidity of grapes is vital in determining their flavour. Sweet grape varieties may have lower acidity, while sour grape varieties have more pronounced acidity. The acid content can also affect the preservation of grapes and wine, as acid helps prevent microbial growth and oxidation.

The study found no particular differences in acidity and malic acid content over the years in grape varieties. Still, there were slight fluctuations in the direction of a decrease in these indicators (Table 2). The reduction of malic acid content and acidity can be explained by the fact that grape berries begin to produce more sugar at higher temperatures.

The study also noted an accumulation of sugar content over time. In general, it can be said that the sugar content of all three grape varieties (Cabernet Sauvignon, Aligote, Chardonnay) increased over the years. Chardonnay had the highest sugar content, with a sugar content of 22.4% in 2022. At the same time, Aligote has a lower sugar content than other varieties and has remained almost at the same level over the years. Cabernet Sauvignon shows a consistent increase in sugar content from 2010 to 2022. Changes in sugar content may reflect the influence of weather conditions and agronomic practices in grape growing (Figure 2).

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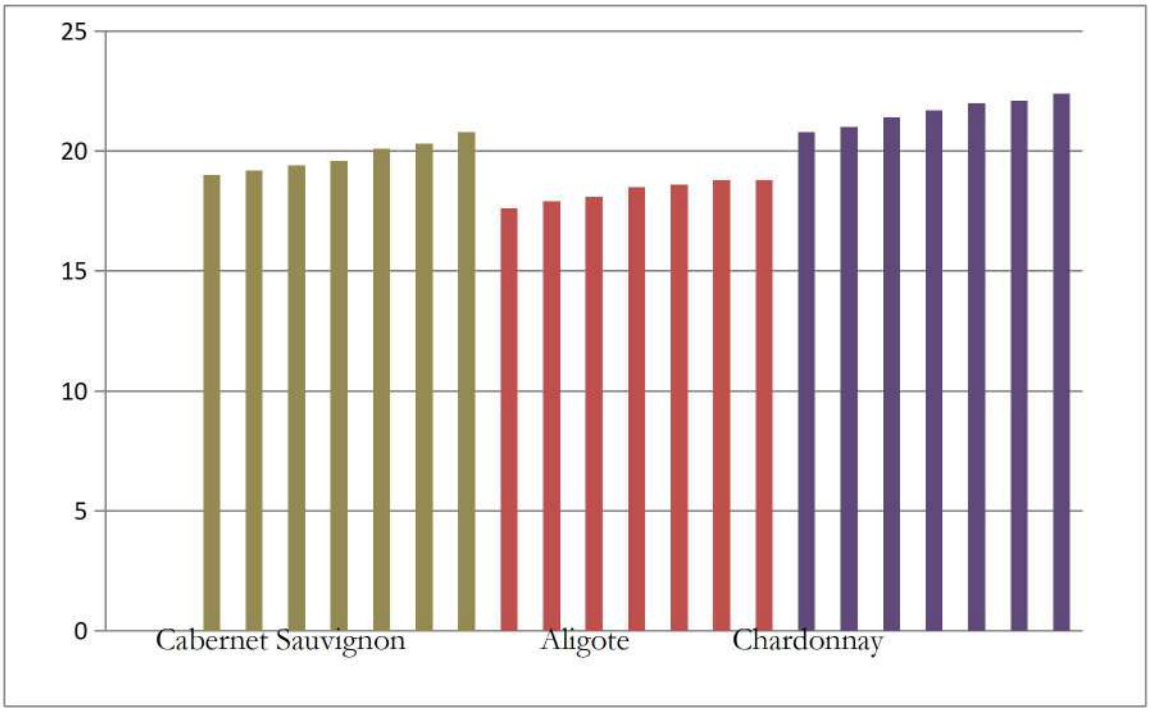
Table 2. Acidity and malic acid content in the studied grape varieties

Variety	Year	Acidity, g/dm^3	Malic acid content, mg/l
Cabernet Sauvignon	2010	8,7	720
	2012	8,3	725
	2014	8,8	730
	2016	8,6	690
	2018	8,8	700
	2020	8,9	680
	2022	8,0	680
Aligote	2010	7,5	700
	2012	7,5	720
	2014	7,6	700
	2016	7,4	690
	2018	7,6	700
	2020	7,7	690
	2022	7,7	690
Chardonnay	2010	7,6	710
	2012	7,7	720
	2014	7,7	710
	2016	7,7	690
	2018	7,8	690
	2020	7,8	680
	2022	7,8	680

Source: developed by the author.

Figure 2. Sugar content in grape varieties (2010-2022)



Source: developed by the author.

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Grapes contain various nutrients essential for the human body. For example, flavonoids are antioxidants that help fight stress from free radicals in the body cells, which can support heart health, boost the immune system and prevent inflammation. Grapes contain vitamins, including vitamin C, which supports the immune system, and B vitamins, essential for the nervous system and metabolic health. Anthocyanins are naturally occurring compounds that impart colour to many fruits, berries and flowers. They are also potent antioxidants and may help reduce the risk of cardiovascular disease and inflammation. It's worth noting that white grape varieties have a significantly lower anthocyanin content than red and darker grape varieties.

It was found that an increase in temperature during grape cultivation caused a decrease in the synthesis of vitamin C and anthocyanins in berries. Still, the content of flavonoids did not change significantly (Table 3).

Table 3. Content of vitamin C, flavonoids and anthocyanins in the studied grape varieties

Variety	Year	Vitamin C, g/100 g	Flavonoids, mg/100 g	Anthocyanins, mg/100 g
Cabernet Sauvignon	2010	11.1±0.21	15.0±0.04	50.12±0.09
	2012	11.1±0.26	14.9±0.23	49.85±0.12
	2014	10.9±0.14	14.9±0.26	49.79±0.26
	2016	10.7±0.16	15.1±0.17	49.20±0.24
	2018	10.8±0.32	15.0±0.16	49.38±0.48
	2020	10.8±0.27	14.9±0.22	48.82±0.27
	2022	10.8±0.19	15.0±0.31	49.45±0.14
Aligote	2010	10.3±0.36	14.2±0.21	6.34±0.05
	2012	10.1±0.27	14.4±0.19	6.31±0.15
	2014	10.1±0.16	14.3±0.32	6.28±0.12
	2016	10.2±0.32	14.2±0.47	6.31±0.21
	2018	9.8±0.31	14.5±0.28	6.28±0.19
	2020	9.8±0.17	14.4±0.19	6.16±0.24
	2022	9.9±0.26	14.3±0.23	6.14±0.26
Chardonnay	2010	10.8±0.16	13.1±0.18	5.38±0.41
	2012	10.6±0.18	13.6±0.26	5.24±0.26
	2014	10.6±0.24	13.4±0.21	5.23±0.31
	2016	10.7±0.17	13.6±0.17	5.16±0.26
	2018	10.5±0.28	13.3±0.32	5.12±0.17
	2020	10.5±0.34	13.1±0.33	5.01±0.16
	2022	10.6±0.31	13.2±0.24	5.12±0.24

Source: developed by the author.

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It is worth noting that the average weight of berries and grape yields differs for each variety and year. The Cabernet Sauvignon variety has increased average berry weight over time, from 1.20 g in 2010 to 1.33 g in 2022. Yields also increased from 7.8 tonnes per hectare in 2010 to 8.6 tonnes per hectare in 2022. Aligote showed a stable average berry weight over the years, ranging from 1.70 g to 1.82 g. Yields also increased from 8.6 t/ha to 9.3 t/ha over this period. Chardonnay showed a slight increase in average berry weight and yield over the years. The average weight of berries varied from 1.30 g to 1.41 g, and the yield from 7.5 t/ha to 8.3 t/ha (Table 4).

Table 4. Average berry weight and grape yield

Variety	Year	The average weight of berries, g	Yield, t/ha
Cabernet Sauvignon	2010	1.20	7.8
	2012	1.23	8.1
	2014	1.25	8.4
	2016	1.28	8.2
	2018	1.30	8.4
	2020	1.32	8.6
	2022	1.33	8.6
Aligote	2010	1.70	8.6
	2012	1.75	8.7
	2014	1.77	9.0
	2016	1.80	9.1
	2018	1.81	9.2
	2020	1.82	9.3
	2022	1.82	9.3
Chardonnay	2010	1.30	7.5
	2012	1.30	7.5
	2014	1.32	7.6
	2016	1.33	7.8
	2018	1.38	8.0
	2020	1.40	8.2
	2022	1.41	8.3

Source: developed by the author.

Colour, taste and aroma are the critical characteristics of grapes that determine the quality and flavour of grape berries and, consequently, the wine made from them. No significant differences or inconsistencies with quality norms and standards were found during the organoleptic evaluation of the grapes. Still, the Chardonnay and Cabernet Sauvignon varieties were sweeter than the Aligote variety. In terms of colour, the varieties were consistent with their varietal characteristics (Figure 3).

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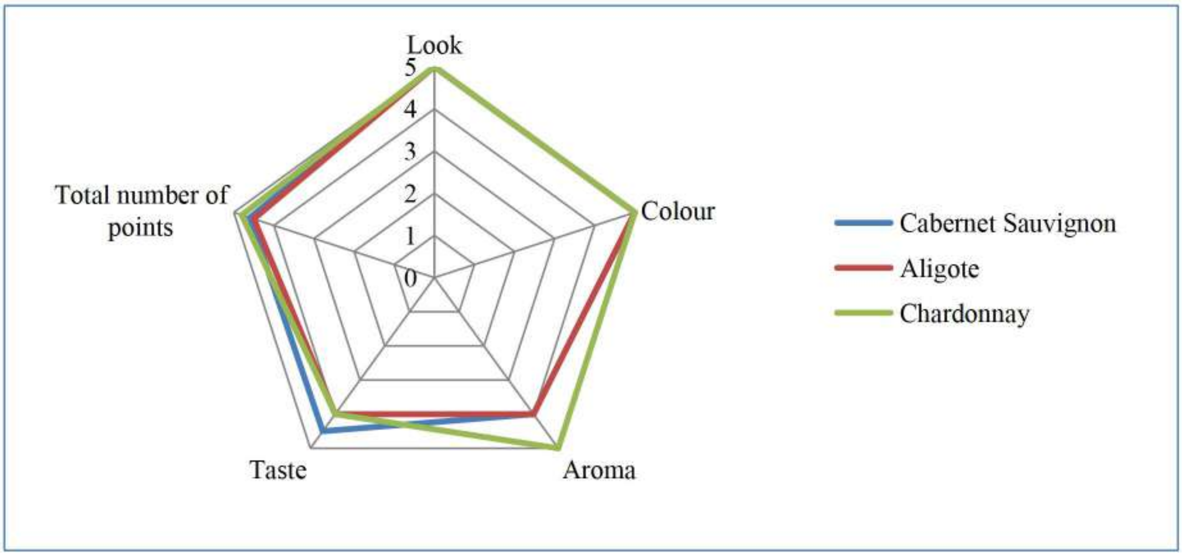
Figure 3. Organoleptic analysis of grape varieties



It was found that all the grape varieties under study proved to be hardy and provided stable yields at small temperature increases.

However, climate change may include more extreme temperatures. Uneven precipitation and other factors may affect grape growing. Therefore, it is advisable to apply possible strategies of adaptation to external factors in the cultivation of grape crops:

1. *Selection of grape varieties.* Winegrowers can choose grape varieties that are more adapted to the specific climatic conditions of their region. Some varieties may be less sensitive to high temperatures or dry climates.

2. *Irrigation* can be helpful in regions with insufficient rainfall, as it helps to provide grapes with moisture during hot and dry periods.

3. *Microclimate.* Winegrowers can use techniques to create favourable microclimatic conditions in the vineyards, including awnings, greenhouses or micro-seedbeds.

4. *Processing and soil preparation.* Keeping the soil in good condition and using organic methods can help to protect plants from stress and increase the soil's water-holding capacity.

5. *Selection of optimal places for the cultivation.* Winegrowers can choose vineyard locations where climatic conditions may be less vulnerable to climate change, for example, elevations or locations with more sunlight.

6. *Irrigation systems.* Smart irrigation systems that can adapt to plant needs and climatic conditions can be beneficial in conserving moisture and reducing heat stress.

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7. *Monitoring and technology.* Using technology to monitor plant growth and conditions can help winegrowers respond quickly to changes in climate and grape production.

8. *Breeding and genetic development.* Researchers and winegrowers can work to develop new grape varieties that are more adapted to climate change.

Climate change is a challenge for winegrowers, and effective adaptation strategies may depend on the specific conditions in each region. Careful observation and research are essential to develop optimal approaches to growing grapes in the face of climate change.

4. Discussion

The challenges posed by climate change to grape crops include threats to vineyards, the quality and quantity of wine production, and the global wine market and consumers. Adaptation to new climate conditions is critical to ensure sustainable wine production and the preservation of this vital industry.

In general, climate change is a significant factor for grape cultivation. Producers and researchers should constantly monitor and adapt to ensure sustainable wine production and preserve vineyards in a changing climate (Venios et al., 2020; Yan et al., 2020).

Early flowering and rapid ripening of grapes can affect the chemical composition of berries, which in turn affects the quality of wine. Reducing the duration of the ripening period can increase sugar content and decrease acidity in berries, which is also reflected in the study (Kolstad and Moore, 2020; Zamorano et al., 2021).

High temperatures, drought, and intense solar radiation significantly impact the quality and chemical composition of grape berries. In particular, increased temperature can lead to a decrease in the amount of anthocyanins. However, the flavonoid content in grapes is stable, which may result from a combination of genetic and agricultural factors (Arias et al., 2022; Martínez-Gil et al., 2018).

Another confirmation of the study can be found in the works of scientists who have found that with increasing temperature, there is a risk of a 0.5% to 1% decrease in malic acid in grape berries. This effect may be due to changes in physiological processes in grape plants at high temperatures. Increased temperatures can promote faster growth and development of berries, as well as increased photosynthesis and accumulation of sugars. This can affect the balance between sugars and acids, reducing malic acid content. Such changes can be necessary for the quality and flavour characteristics of grapes and their

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products, such as wine (Cardell et al., 2019; Plank et al., 2019).

Uneven precipitation and extreme weather events can lead to significant fluctuations in the yield of grape vines, which may result in insufficient grapes for wine production, affecting the supply of wine and its prices on the market. This volatility can create difficulties for wine producers and consumers (Cabré and Nuñez, 2020; Muñoz et al., 2021).

Research shows that a lack of moisture caused by changes in precipitation can lead to a reduction in grape yields. A lack of water can limit grape development and affect grape quantity and quality. In addition, a lack of moisture creates stress for plants, which can reduce the production of organic compounds (Drappier et al., 2020). Thus, water scarcity is a critical factor that affects grape production and yield, which is also reflected in the study.

Scientists also point out that climate change may cause different grape varieties to exhibit other qualities and taste characteristics. Higher temperatures can lead to earlier ripening of grapes, which can affect wine production. Due to climate change, vineyards may also become more vulnerable to pests and diseases, requiring greater use of pesticides and other chemicals that affect environmental sustainability (Naulleau et al., 2021).

Given this, there is an urgent need to develop adaptation and mitigation strategies at the regional level. Understanding and considering regional differences is an essential step in maintaining the resilience and success of viticulture in the face of climate change (Teslić et al., 2019).

Climate change may also encourage winegrowers to choose other varieties better adapted to new conditions. This may lead to a reshaping of the varietal composition of wine-growing regions. Thus, some studies emphasise that winegrowers are already actively adapting to climate change by adopting new cultivation methods and selecting resilient grape varieties (Dunn et al., 2019; Gaiotti et al., 2018).

It is essential to implement innovative approaches and technologies to achieve sustainability and high yields, search for new grape varieties better adapted to climate change, and introduce them to the market. These varieties may be more resistant to high temperatures, droughts and other extreme conditions. Automated irrigation systems that allow for efficient water use and ensure uniform access to moisture for plants are also advisable (Fraga, 2020; Marfil et al., 2019).

The use of modern technologies for continuous monitoring of climatic conditions and the use of the data obtained to make decisions on grape cultivation, application of

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biological production principles that contribute to the conservation of biodiversity and resistance of vines to stressful conditions will help to prepare for climate changes. Among other possible approaches are the development of environmentally friendly methods to protect grapes from pests and diseases, optimising the use of resources, such as water, fertiliser, and energy, to ensure efficient grape growing, use of certification systems and incentives for winegrowers who implement sustainable wine growing and production practices (Leolini et al., 2020; Ramos and de Toda, 2020).

Thus, the study meets its objective, and its results emphasise the importance of observing the phenological development of grapes and their quality and yield for farmers and winemakers. Understanding the impact of various factors on plant development allows us to improve cultivation methods and adapt them to changes in climate and environment. This approach helps to increase the resilience of the viticulture industry to changing conditions and ensures a quality harvest and production of high-quality wine.

Conclusions

The study results showed that phenological stages in the growth of grapes occurred later in 2016-2022 compared to previous years, which may be due to changes in climatic conditions. Hence, analysing the phenological data, it was found that the date of budding in grapes usually occurs with a delay of 2-4 days compared to previous years, while the flowering is observed 5-7 days earlier. This is a reduction in the interval between the date of budding and flowering, which is 4-6 days. It was also found that the period from flowering to ripening is reduced by 3-4 days.

In addition, changes in the quality and content of chemical compounds in berries of different grape varieties were found. Increasing temperature affects the reduction of vitamin C and anthocyanins in berries but does not significantly affect the content of flavonoids. It was also found that acidity in grape berries and malic acid content are subject to slight fluctuations, possibly due to increased sugar accumulation at elevated temperatures. However, the overall data analysis shows that sugar content in all three grape varieties increased over the years, with Chardonnay having the highest sugar content, reaching 22.4% in 2022. Aligote, on the other hand, showed almost no change in sugar content over the years. Cabernet Sauvignon showed a consistent increase in sugar content from 2010 to 2022, and these changes may be due to the influence of weather conditions

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and agronomic practices.

Yields and average berry weight also differ in variety and year, with Cabernet Sauvignon and Aligote showing an increase in average berry weight and yield during the study period. Chardonnay showed no increase in these indicators.

To grow grapes in the face of climate change, it is recommended to implement a set of adaptation strategies: selecting grape varieties that are more resistant to the specific climatic conditions of the region, using irrigation systems to provide plants with moisture during low rainfall, using smart irrigation systems that adapt to plant needs and climatic conditions, and modern technologies for monitoring and managing vineyards.

The research findings have practical implications for the viticulture and winemaking industry, helping to select the best grape varieties, determine the best time to harvest and manage vineyards in light of climate change, and highlight the importance of research in breeding and genetic improvement aimed at creating varieties that are resistant to climate change. Further research seeks to develop effective systems for adapting grape crops to climate change, such as cooling or processing grapes and using biological products to maintain optimal plant growth and maturation conditions.

Limitations of the Study

Limited resources and lack of financial and material resources may limit the scope and scale of the research.

Duration of the study. Certain aspects of viticulture and winemaking, such as the impact of climate on grape varieties, may require long-term observation and research, which limits the speed of obtaining results.

Recommendations

Selection of varieties. It is recommended to select grape varieties resistant to climate change, particularly those that can adapt to later phenological stages of growth and reduced vitamin C and anthocyanin content in higher temperatures.

Optimal harvest time. Due to the delayed budding and earlier flowering, it is recommended that the harvest schedule be revised. Establishing the precise moment for harvesting the berries to achieve optimum wine quality is essential.

Vineyard management. Vineyards must be appropriately managed and maintained, taking into account climate change. New methods and technologies may need to be applied to ensure optimal grape growth and ripening conditions.

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