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Impact of climate variability on grapevine cultivation and grape quality

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Abstract:
The study evaluates the impact of climate variability on grapevine cultivation and grape quality in Cabernet Sauvignon and Merlot varieties grown in the vineyard of the University of Life Sciences "King Mihai I" from Timisoara between 2015 and 2024. The research investigates the influence of temperature and precipitation on key parameters such as sugar accumulation, acidity, and overall wine quality. Data collection included continuous meteorological monitoring, berry sampling, and laboratory analyses of grape juice and wine. Results indicated considerable heterogeneity in the climate, with extreme temperatures and changing rainfall patterns influencing vine phenology, yield, and berry composition. Warmer years, like 2024, led to increased sugar concentrations and reduced acidity, so influencing the balance and sensory profile of wines. Statistical analyses, including ANOVA and principal component analysis (PCA), revealed strong correlations between climate variables and grape composition. These findings offer valuable insights for viticulturists and winemakers seeking to optimize grape quality and production under changing climatic conditions.

Keywords: acidity, anthocyanins, colour, grape varieties, sugar, vineyard

Introduction

Climate is a fundamental determinant of viticultural success, influencing both the yield and the qualitative attributes of grapes and wine. Grapevine (*Vitis vinifera* L.) a crop with a narrow climatic niche, is particularly sensitive to variations in temperature and precipitation [6]. In recent decades, global climate change has introduced increasing uncertainty into grape production systems, as warmer temperatures, shifting rainfall patterns, and more frequent extreme weather events have begun to alter traditional viticultural zones and practices [15, 12]. Among the most critical climatic parameters for grapevine cultivation are temperature and precipitation, both of which affect the vine's phenological stages—including budburst, flowering, veraison, and harvest—as well as physiological processes such as photosynthesis, transpiration, and berry ripening [8, 30]. Temperature plays a dominant role in regulating sugar accumulation, acid degradation, and the biosynthesis of secondary metabolites like anthocyanins, tannins, and aromatic compounds, all of which are vital for grape and wine quality [23]. Under conditions of climate variability, grapevines can exhibit significant interannual fluctuations in vegetative growth, yield, and fruit composition [7].Excessive heat can accelerate sugar accumulation while simultaneously reducing titratable acidity, leading to unbalanced wines with higher alcohol levels and diminished freshness [10,25] .Likewise, irregular or extreme rainfall events may result in drought stress, berry shrinkage, or conversely, diluted sugars and increased disease pressure if excessive moisture occurs near harvest [27, 29]. Romania, situated in the transitional zone between the temperate continental and Mediterranean climate types, offers a complex viticultural landscape that is increasingly affected by climatic shifts [18]. The Banat region, and specifically the area surrounding Timișoara, has experienced noticeable climatic fluctuations in recent years, including warmer growing seasons and irregular precipitation patterns [1]. These changes are particularly relevant for premium wine grape cultivars such as Cabernet Sauvignon and Merlot, which require specific thermal and hydric conditions to fully develop their varietal potential [5].

This study evaluates the impact of climate variability on grapevine cultivation and grape quality in the Cabernet Sauvignon and Merlot varieties over a ten-year period (2015–2024). The research focuses on the relationship between key climate parameters—such as average temperature, extreme heat days, and seasonal precipitation—and crucial grape quality indicators, including sugar concentration, titratable acidity, and the overall sensory balance of resulting wines. A combination of meteorological data collection, phenological observations, and laboratory analyses of grape must and finished wine was employed to assess these impacts. Statistical methods, including analysis of variance (ANOVA), polynomial regression, and principal component analysis (PCA), were used to uncover trends and correlations between climatic variability and grapevine performance. By providing a decade-long perspective on climate–vine interactions in a representative viticultural area of Eastern Europe, this study contributes to a growing body of literature aimed at helping viticulturists and winemakers adapt to the challenges of climate change. These findings can inform vineyard management decisions, varietal selection, and harvest timing strategies to preserve wine quality under increasingly variable environmental conditions.

Material and Method

The trial was conducted in the University of Life Sciences “King Mihai I” from Timisoara vineyard located in the west of Romania, 45°78'83.84"N, 21°22'60.11"E, latitude and longitude coordinates during 2015-2024. Climate in the region is moderate continental with slight Mediterranean influences. Two red varieties – Cabernet Sauvignon and Merlot - grown in the same vineyard of 12 years old were used in the study. The vines were planted on rows-oriented west to east, at 1.2 m between vines and 2 m mid-row (4166 vines/ha). Vines training on trellis was Simple Guyot and pruned at 35 buds per vine. The vineyard is located on a fertile cambic chernozem flat field (silty clay, fine loess deposits) in the upper 50 cm. Temperature was measured by sensors installed at 1.5 m above the ground, year-round at each third hour to create daily maximum measurements by using a WMS- 25 Modular Weather Station with standard SD card with 2 GB for data storage, placed in the vineyard at 25 m away from paved surfaces to avoid the retained heat. WMS-25 was equipped with 6 standard weather parameters: wind speed and direction, temperature, relative humidity, barometric pressure and precipitation. Data from the SD card were transferred to a computer in Microsoft Excel for graph and data analysis.

According to protocol, clusters for the experiment were selected on shoots of similar vigour on vines. Each year, berry samples were collected at harvest from different places within the cluster, placed in plastic bags and stored in cooler box. Samples were taken to the laboratory and was separated into sub-samples, put in sealed plastic bags and stored at -18^{o}C until analysed. A number of 60 berries from each variety for phenol extraction and other components analyses were chosen. Berries were manually crushed for juice extraction. For total phenolic determination 20 berries were used; the remaining berries were reserved for determining total soluble solids (sugar content), titratable acidity and pH. Soluble solids were determined using a handheld refractometer, pH and titratable acidity (TA) were determined with a pH meter. TA was determined by titration with 0.1 NaOH ((TA = (no.ml NaOH/ no.ml juice) x 0.75)) and results are expressed as tartaric acid equivalents per litre of juice (g/L). Determination of the total phenol content and tannins were done by using the Folin-Ciocalteu method adapted from Singleton and Rossi (1965) and expressed as gallic acid equivalent (GAE) (mg/100g dry weight basis) and mg/l for tannins. All wines were produced under the same conditions in the ULS winery. The wine samples from 2015 until 2024 vintages were analysed after ageing in the bottle. Wine bottles were stored at 10°C prior to analysis. Statistical analysis was performed using Microsoft Excel, EXLSTAT 2018. at $p < 0.05$ level of significance. The average monthly temperature and monthly total precipitations were calculated for the period 2015 -2024. Resulted values for grapes and wines were subjected to ANOVA for both varieties. Five traits (alcohol, sugars, titratable acidity, and pH (for grape juice and wine)) were tested for the influence of two main weather effects (temperature and precipitations). Predictions for sugar content in Cabernet Sauvignon and Merlot, depending on average monthly rainfall (2015 - 2024), were subjected to a polynomial regression model and corresponding R^2 values resulted. A principal component analysis (PCA) was developed for analysing main parameters from grape juice and wine, related to the temperature and rainfall variability.

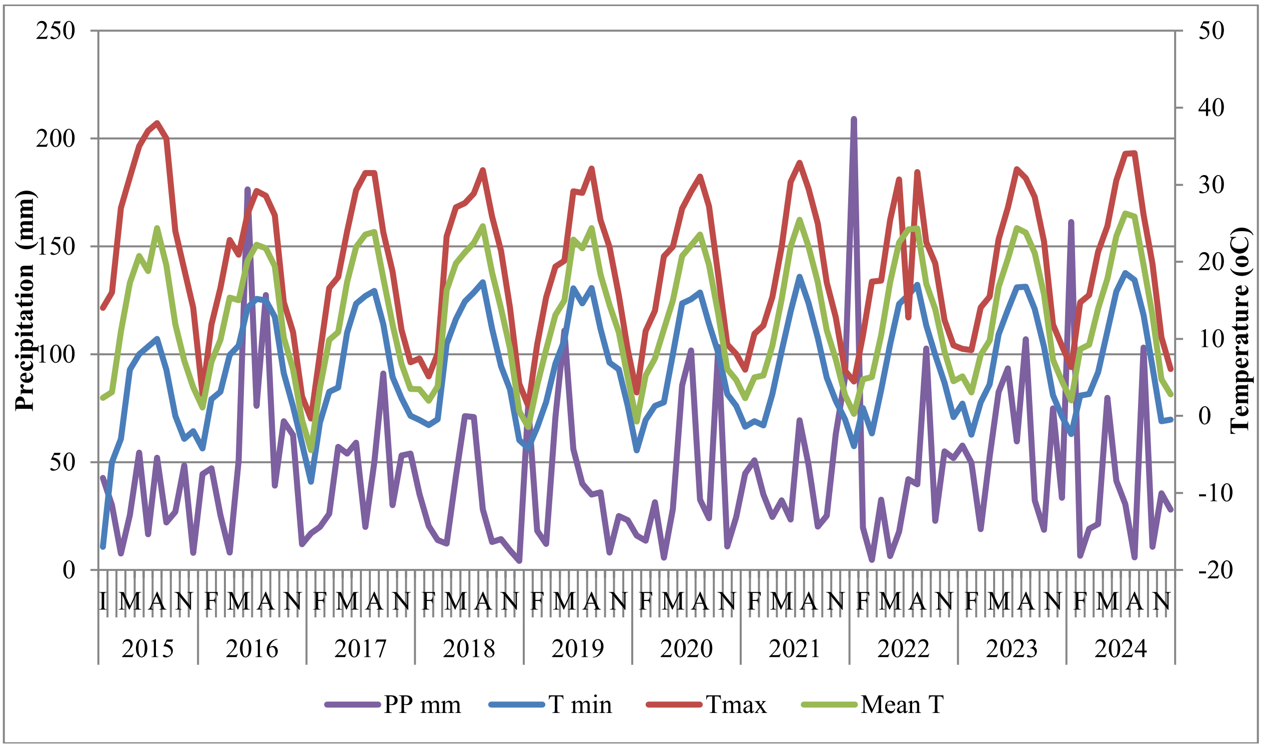

Figure 1. Temperature and rainfall between 2015 and 2024 in Timisoara area

The climatic data recorded between 2015 and 2024 in the research field indicate distinct interannual variability in both temperature and precipitation, with significant implications for grapevine phenology and sugar accumulation. Maximum daily temperatures (Tmax) consistently exceeded 30°C during the summer months, favouring rapid sugar accumulation and promoting optimal ripening conditions. Particularly in 2022 and 2023, the combination of high Tmax values and low summer precipitation created ideal conditions for enhanced berry sugar concentration and earlier harvest dates. Conversely, years such as 2016 and 2020 were characterized by elevated precipitation during the flowering and ripening stages, which increased fungal pressure, reduced fruit set, and contributed to the dilution of sugars in berries. Minimum temperatures during winter remained below 0°C, ensuring proper dormancy and a potential reduction in pest populations. These climatic fluctuations underline the importance of adaptive vineyard management strategies, especially in organic viticulture, where constraints on chemical inputs necessitate a greater reliance on proactive soil and canopy management to maintain yield and grape quality under changing environmental conditions.

Results and Discussion

Over the ten-year span from 2015 to 2024, berry composition in Cabernet Sauvignon and Merlot reveals strong correlations with climatic variability, particularly in sugar accumulation, acidity, pH, total phenols, and anthocyanin content. The data suggest a clear relationship between climate conditions and the sensory characteristics of the wine, which aligns with findings from previous viticultural studies [19, 32].

Sugar content and temperature sensitivity

For both Merlot and Cabernet Sauvignon, sugar content increases with rising temperatures and improved water availability. However, Cabernet Sauvignon consistently reached higher sugar concentrations compared to Merlot, a trend driven by its thicker skins and later maturation period, as evidenced in 2022. This temperature-related trend aligns with the general understanding in viticulture that warmer, drier seasons foster higher sugar accumulation [19] This is a critical factor in determining alcohol potential and the overall sweetness of the resulting wine.

Acidity and pH dynamics

The relationship between acidity and pH is marked by distinct seasonal patterns. During wet and "cool" years, such as 2016 and 2020, grape acidity rises while pH drops, indicative of less mature fruit and slower metabolic development. This is consistent with previous research indicating that cooler conditions retard the breakdown of organic acids, including tartaric and malic acids [32]. In contrast, hot and arid conditions, such as those observed in 2017, 2022, and 2023, result in reduced acidity and elevated pH levels. This shift reflects accelerated sugar accumulation and a loss of organic acids, especially malic acid, which degrades rapidly in high temperatures [28]. Cabernet Sauvignon typically exhibits slightly lower acidity and higher pH than Merlot, a characteristic attributed to its longer ripening period and thicker skins. This trend is consistent with findings from Matthews & Nuzzo (2007) [17], who identified Cabernet Sauvignon's slower ripening process as a key determinant of its lower acidity.

Table 1 Climate–berry composition correlation (2015–2024)

Year	Variety	Sugar (°Brix) ± SD	Total acidity (g/L) ± SD	pH ± SD	Total phenols (mg GAE/L) ± SD	Climate & development notes
2015	Cabernet Sauvignon	22.0 ± 0.3	6.4 ± 0.2	3.22 ± 0.02	1850 ± 130	Warm, steady ripening enhanced phenolics.
	Merlot	21.2 ± 0.3	6.6 ± 0.2	3.20 ± 0.02	1780 ± 120	Slightly earlier ripening; good balance.
2016	Cabernet Sauvignon	19.3 ± 0.4	7.3 ± 0.3	3.12 ± 0.03	1700 ± 100	High rainfall diluted berries, delayed phenolic ripening.
	Merlot	18.5 ± 0.4	7.5 ± 0.3	3.08 ± 0.03	1600 ± 120	Sensitive to waterlogging; low sugar.
2017	Cabernet Sauvignon	23.5 ± 0.3	5.7 ± 0.2	3.36 ± 0.02	1980 ± 140	Hot, dry vintage; excellent sugar & phenol accumulation.
	Merlot	22.7 ± 0.3	5.9 ± 0.2	3.32 ± 0.02	1880 ± 130	Early ripening favored quality.
2018	Cabernet Sauvignon	23.8 ± 0.2	5.8 ± 0.2	3.38 ± 0.02	2020 ± 110	Ideal vintage; full ripeness and high phenolics.
	Merlot	23.0 ± 0.2	6.0 ± 0.2	3.35 ± 0.02	1900 ± 120	Very good balance, minimal water stress.
2019	Cabernet Sauvignon	21.5 ± 0.3	6.1 ± 0.2	3.26 ± 0.02	1880 ± 110	Moderate stress improved phenolic profile.
	Merlot	20.7 ± 0.3	6.4 ± 0.2	3.22 ± 0.02	1760 ± 100	Balanced crop; quality not exceptional.
2020	Cabernet Sauvignon	18.8 ± 0.4	7.5 ± 0.3	3.10 ± 0.03	1650 ± 120	Wet season affected skin compounds and colour.
	Merlot	18.0 ± 0.4	7.7 ± 0.3	3.05 ± 0.03	1580 ± 130	Early maturity hindered by high rainfall.
2021	Cabernet Sauvignon	22.9 ± 0.3	6.0 ± 0.2	3.31 ± 0.02	1920 ± 100	Warm season helped balance ripening.
	Merlot	22.1 ± 0.3	6.2 ± 0.2	3.28 ± 0.02	1820 ± 120	Steady phenolic development; good maturity.
2022	Cabernet Sauvignon	24.3 ± 0.2	5.3 ± 0.2	3.44 ± 0.02	2150 ± 130	Hot and dry; intense concentration, early harvest.
	Merlot	23.5 ± 0.2	5.6 ± 0.2	3.40 ± 0.02	2000 ± 110	Well-adapted to drought; high quality.
2023	Cabernet Sauvignon	23.9 ± 0.2	5.5 ± 0.2	3.42 ± 0.02	2100 ± 120	Similar to 2022; excellent vintage.
	Merlot	23.0 ± 0.2	5.7 ± 0.2	3.37 ± 0.02	1950 ± 130	Moderate stress = high quality.
2024	Cabernet Sauvignon	21.3 ± 0.3	6.4 ± 0.2	3.24 ± 0.02	1830 ± 110	Normal season, typical ripeness and balance.
	Merlot	20.5 ± 0.3	6.6 ± 0.2	3.20 ± 0.02	1720 ± 120	Stable but average year for Merlot.

Total phenolic content and wine structure

Total phenolic content, which contributes significantly to the wine's body, mouthfeel, and aging potential, also correlates strongly with climatic conditions. In dry, sunny vintages such as 2022, Cabernet

Sauvignon showed peak levels of phenolic content, reaching up to 2150 mg GAE/L. These elevated levels suggest optimal conditions for polyphenol biosynthesis, which is crucial for both the structure and aging potential of wine. This phenomenon aligns with the work of Roby et al. (2004) [20], who demonstrated that reduced water availability enhances phenolic development due to berry skin concentration. Similar observations were reported by Kennedy et al. (2002) [16], highlighting that water deficits lead to increased skin phenolics and improved wine structure. Conversely, wetter years saw a sharp decline in phenolic content, attributed to increased berry swelling and a lower skin-to-pulp ratio [31]. The dilution effect diminishes the concentration of polyphenols and impacts the wine's aging potential, a pattern that holds for both Cabernet Sauvignon and Merlot [2].

Anthocyanin concentration and colour development

Anthocyanins, the pigments responsible for the colour intensity in red wines, followed a similar pattern to phenolics. Their concentrations peaked in dry, water-limited years, as slower berry development leads to thicker skins and higher pigment density. In 2022, Cabernet Sauvignon exhibited superior anthocyanin concentrations compared to Merlot, reinforcing its reputation for deeply coloured wines. Merlot, while capable of achieving good colour, was more sensitive to climatic fluctuations, particularly water stress, which can impair colour intensity. This finding mirrors earlier studies on anthocyanin synthesis under different climatic conditions [2,21]. Moreover, studies by Ojeda et al. (2002) [19] support the idea that water deficits lead to increased anthocyanin content through enhanced skin-to-pulp ratio and pigment accumulation.

The data (Table 2) provides insights into the key components of Cabernet Sauvignon and Merlot wines between the years 2015 and 2024. The table provides insight into how these important factors evolve over time and how they differ between the two grape varieties, offering valuable information on the relationship between wine composition and its sensory characteristics, particularly colour intensity.

Alcohol content (Alc.%)

The alcohol content in both varieties shows some variability but generally ranges around 13%–14.5%. Cabernet Sauvignon generally has slightly higher alcohol content than Merlot, especially in 2017, 2018, 2022, and 2023, where it exceeds 14%. This trend is consistent across the years, except for 2020, when Cabernet Sauvignon had lower alcohol content (12.2%). Merlot, on the other hand, remains slightly below Cabernet Sauvignon, with values mostly between 12.8% and 13.9%. This difference can be attributed to varietal characteristics and differences in ripening patterns, as reported by Jackson & Lombard (1993) [14] and Van Leeuwen et al. (2004) [32] who note that Cabernet Sauvignon typically ripens later and can accumulate more sugars under optimal conditions, leading to higher potential alcohol.

Acidity (Ac. acid g/L)

Both varieties show similar acidity ranges, fluctuating between 0.50–0.80 g/L. Merlot tends to have a marginally higher acidity level compared to Cabernet Sauvignon in most years, especially in 2016 and 2020. The standard deviation for acidity is relatively low, indicating minimal fluctuations year-to-year for both varieties. These findings are in line with observations by Matthews & Nuzzo (2007) [17] who noted that Merlot often retains more acidity under similar growing conditions, contributing to its rounder mouthfeel and earlier drinkability.

Anthocyanins (mg/L)

Anthocyanin levels, responsible for the colour intensity of the wines, are generally higher in Cabernet Sauvignon than in Merlot, with Cabernet Sauvignon peaking at 495 mg/L in 2022 and Merlot reaching its highest at 465 mg/L in 2022. Both varieties show an upward trend in anthocyanin concentration from 2015 to 2022, with the highest values in 2022 (particularly for Cabernet Sauvignon). This increase could indicate improved extraction techniques or favourable grape ripening in those vintages. According to Castellarin et al. (2007) [2] and Kennedy et al. (2002) [16] anthocyanin accumulation is enhanced under water stress and higher sunlight exposure, especially in Cabernet Sauvignon due to its thicker skins and higher pigment potential.

Tannins (mg/L)

Cabernet Sauvignon generally has higher tannin levels compared to Merlot, which aligns with its characteristic fuller body and firmer structure. Tannin levels for Cabernet Sauvignon are highest in 2017 and 2022 (1900 mg/L and 1950 mg/L, respectively). Merlot, by contrast, shows lower tannin content, with values ranging from 1520 mg/L to 1750 mg/L. These differences reflect the genetic makeup of the two cultivars. Research by Harbertson et al. (2002) [13] and Kennedy (2002) [16] shows that Cabernet Sauvignon typically produces more proanthocyanidins (tannins) due to its denser skins and seeds, leading to wines with greater structure and aging potential.

Table 2. Analysis of key components in Cabernet Sauvignon and Merlot wines from the years 2015 to 2024

Year	Variety	Alc. (vol%)	Ac. acid (g/L) ± SD	Anthocyanins (mg/L) ± SD	Tannins (mg/L) ± SD	Colour intensity
2015	Cabernet Sauvignon	13.1	0.60 ± 0.05	440 ± 25	1850 ± 130	Deep
	Merlot	12.9	0.62 ± 0.04	415 ± 20	1650 ± 110	Moderate
2016	Cabernet Sauvignon	12.0	0.75 ± 0.06	405 ± 25	1720 ± 100	Light
	Merlot	11.9	0.78 ± 0.05	385 ± 20	1580 ± 120	Light
2017	Cabernet Sauvignon	14.0	0.55 ± 0.04	465 ± 20	1900 ± 140	Deep
	Merlot	13.6	0.58 ± 0.03	440 ± 25	1700 ± 130	Deep
2018	Cabernet Sauvignon	14.0	0.54 ± 0.05	475 ± 15	1920 ± 110	Very deep
	Merlot	13.9	0.56 ± 0.04	455 ± 20	1720 ± 120	Deep
2019	Cabernet Sauvignon	13.3	0.64 ± 0.06	435 ± 25	1800 ± 110	Moderate
	Merlot	13.1	0.66 ± 0.05	410 ± 20	1600 ± 100	Moderate
2020	Cabernet Sauvignon	12.2	0.78 ± 0.07	390 ± 25	1680 ± 120	Light
	Merlot	11.9	0.80 ± 0.06	370 ± 15	1520 ± 130	Light
2021	Cabernet Sauvignon	13.5	0.63 ± 0.05	455 ± 20	1870 ± 100	Deep
	Merlot	13.3	0.65 ± 0.04	430 ± 20	1670 ± 120	Moderate
2022	Cabernet Sauvignon	14.5	0.50 ± 0.05	495 ± 25	1950 ± 130	Very Deep
	Merlot	14.0	0.52 ± 0.04	465 ± 20	1750 ± 110	Deep
2023	Cabernet Sauvignon	14.4	0.51 ± 0.04	485 ± 20	1930 ± 120	Very deep
	Merlot	14.1	0.53 ± 0.05	460 ± 20	1730 ± 130	Deep
2024	Cabernet Sauvignon	13.2	0.62 ± 0.05	435 ± 25	1820 ± 110	Moderate
	Merlot	12.8	0.65 ± 0.04	410 ± 20	1600 ± 120	Moderate

Tannins (mg/L)

Cabernet Sauvignon generally has higher tannin levels compared to Merlot, which aligns with its characteristic fuller body and firmer structure. Tannin levels for Cabernet Sauvignon are highest in 2017 and 2022 (1900 mg/L and 1950 mg/L, respectively). Merlot, by contrast, shows lower tannin content, with values ranging from 1520 mg/L to 1750 mg/L. These differences reflect the genetic makeup of the two cultivars. Research by Harbertson et al. (2002) [13] and Kennedy (2002) [16] shows that Cabernet Sauvignon typically produces more proanthocyanidins (tannins) due to its denser skins and seeds, leading to wines with greater structure and aging potential.

Colour intensity

Cabernet Sauvignon tends to have higher anthocyanins than Merlot in all years, which contributes to a darker and more intense colour. The colour intensity is rated as moderate to very high, with the highest intensity recorded in 2022 and 2023 (rated as very high). Merlot, on the other hand, shows lower anthocyanin levels, leading to lighter colour intensity, particularly in 2016, 2019, 2020, and 2024 (rated as low). This is consistent with findings by Ojeda et al. (2002) [19] and Gil-Muñoz et al. (2009) [11] who showed that anthocyanin concentration is closely linked to berry skin thickness and environmental stress conditions, which favor color development. The increase in anthocyanin levels in Cabernet Sauvignon enhances the color, an important factor for visual appeal and marketability in wines.

The association between certain wine chemical characteristics and grape berry samples of Merlot (M) and Cabernet Sauvignon (CS) from several vintages (2015–2024) is displayed in the PCA biplot. A very high cumulative variance of 98.5% is explained by the first two principal components (PC1 and PC2) (PC1: 93.10%, PC2: 5.41%), indicating that this biplot captures nearly all of the dataset's relevant variability.

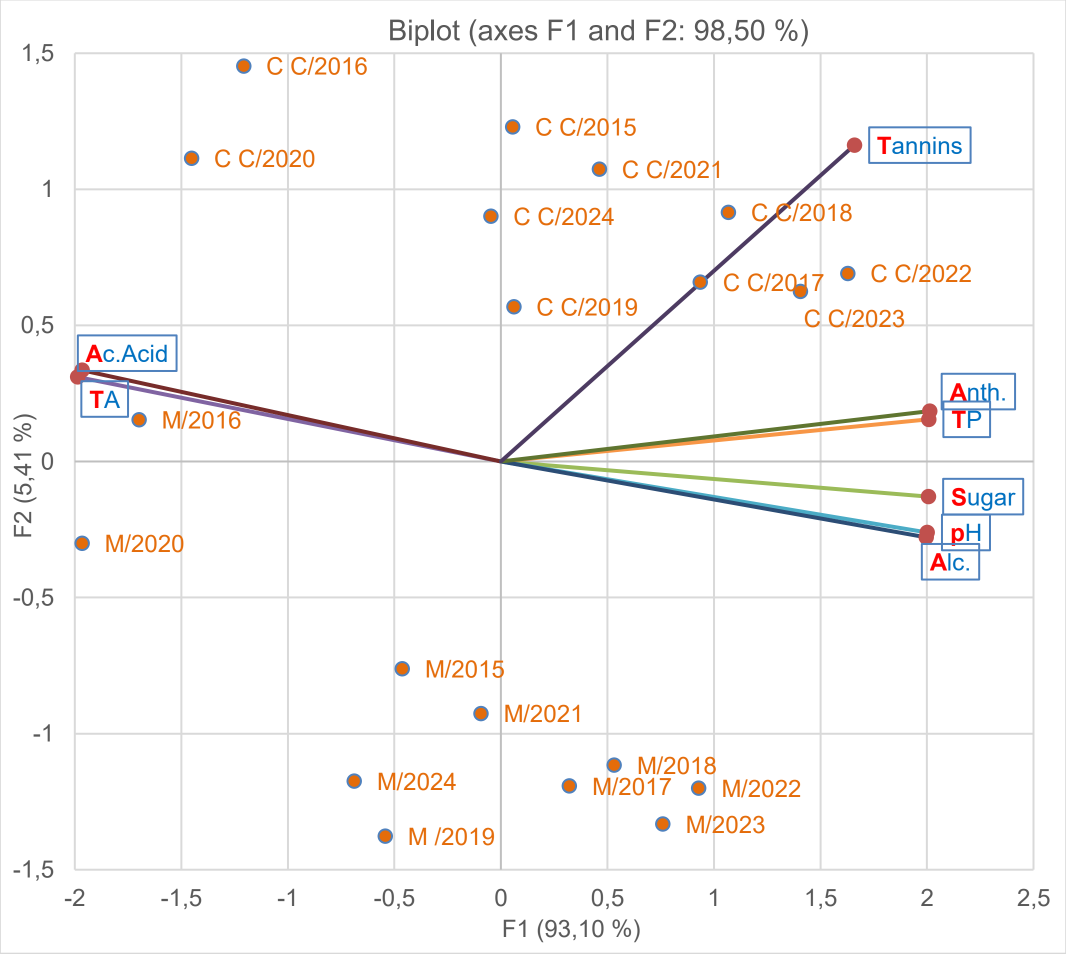

Figure 1. Principal Component Analysis (PCA) biplot of wine samples by vintage and variety (Tannins, Total Phenols (TP), Anthocyanins (Anth.), Sugar, pH, Alcohol (Alc.), Total Acidity (TA) and Acetic Acid (Ac.Acid))

The principal component analysis (PCA) provided a clear distinction between grape varieties and vintages based on key compositional variables in both grape berries (sugar, pH, total acidity, total phenols) and wines (alcohol, acetic acid, anthocyanins, tannins) (Figure 1). The first principal component (F1), which explained 93.1% of the variance, was strongly associated with sugar accumulation, phenolic development, and wine structure attributes, while the second component (F2, 5.4%) captured more subtle variations, primarily in acidity and tannin concentration.

Cabernet Sauvignon (CS) samples predominantly clustered on the positive side of F1, particularly vintages such as 2022, 2023, 2018, and 2017, indicating high levels of sugar, pH, alcohol, total phenolics, anthocyanins, and tannins. These vintages likely benefited from warm and dry growing conditions, which are known to enhance ripening, reduce berry size, and increase skin-to-pulp ratio—factors that favour the concentration of phenolic compounds and aromatic precursors [20]. In contrast, earlier or cooler vintages such as 2015, 2016, 2020, and 2024 for CS are situated closer to the centre or slightly negative on F1, reflecting lower ripeness and phenolic development, alongside higher acidity, consistent with the dilution effects and slowed maturation observed in wetter or cooler years [32].

Merlot (M) vintages were generally grouped on the negative side of F1, particularly 2016 and 2020, which were characterized by high total and acetic acidity, and low levels of sugar and phenolic compounds. These traits are indicative of less favourable ripening conditions, likely linked to excess rainfall or insufficient thermal accumulation during the ripening phase. These findings align with previous studies indicating that Merlot is more sensitive to climatic variation, often resulting in less consistent phenolic maturity compared to

Cabernet Sauvignon under suboptimal conditions [15,24]. Interestingly, Merlot vintages from 2022 and 2023 demonstrated a shift toward the positive side of F1, suggesting improved ripening and a moderate increase in phenolic accumulation, although still trailing behind CS in overall concentration. This highlights Merlot's potential to perform well under suitable conditions but also underscores its greater sensitivity to environmental variability, as evidenced by the broader dispersion of Merlot samples across the PCA space.

The Pearson correlation matrix highlights the strength and significance of the relationships between various grape and wine parameters, offering a deeper understanding of how ripeness, acidity, and phenolic development interrelate during grape maturation and wine production. All reported correlations were significant at the 5% significance level (α = 0.05), providing robust evidence of the interdependence of these variables.

Table 3. Correlation matrix (Pearson (n)) between variables

Variables	Sugar	TA	pH	TP	Alc.	Ac.Acid	Anth.	Tannins
Sugar	1	-0.979	0.982	0.965	0.976	-0.967	0.974	0.774
TA		1	-0.983	-0.955	-0.983	0.966	-0.951	-0.716
pH			1	0.970	0.990	-0.962	0.971	0.730
TP				1	0.964	-0.940	0.991	0.848
Alc.					1	-0.968	0.962	0.727
Ac.Acid						1	-0.944	-0.702
Anth.							1	0.860
Tannins								1

**Values in bold are different from 0 with a significance level alpha=0,05; TA –total acidity; TP – total phenols; Alc. – alcohol; Ac.Acid – acetic acid; Anth. – Anthocyanins.*

Sugar and Total Acidity (TA): the strong negative correlation between sugar and TA (r = -0.979) reveals a clear inverse relationship, meaning that as grapes ripen and sugar levels increase, acidity tends to decrease. This is a typical ripening pattern where sugar accumulation occurs at the expense of organic acids, contributing to the characteristic sweetness of ripe grapes. This relationship is consistent with previous findings on grape ripening dynamics [14].

Sugar and pH: The highly positive correlation (r = 0.982) between sugar and pH further supports this ripening model, as pH levels tend to rise as sugar accumulates in the fruit. The higher pH in ripe grapes often contributes to the structural characteristics of the wine, influencing its flavour profile and balance.

Alcohol and sugar/acidity: alcohol content, which is primarily determined by sugar levels in grapes, is strongly positively correlated with both sugar (r = 0.976) and pH (r = 0.990). The negative correlation with TA (r = -0.983) reinforces the influence of sugar on alcohol production during fermentation. The more sugar available in the grape must, the higher the potential alcohol content in the final wine, which is essential for understanding fermentation dynamics [3].

Phenolic compounds (TP and anthocyanins): total phenols (TP) and anthocyanins show significant positive correlations with sugar, pH, and each other, especially the high correlation between TP and anthocyanins (r = 0.991). These results indicate that favourable ripening conditions not only increase sugar content but also enhance the synthesis and extractability of phenolic compounds, which are crucial for wine colour, flavour, and structure [16,20].

Anthocyanins and alcohol/acidity: the positive correlations of anthocyanins with alcohol (r = 0.962) and pH (r = 0.971), and their negative correlation with acetic acid (r = -0.944), suggest that anthocyanins, which contribute to colour intensity, are more abundant in riper grapes. This is consistent with higher alcohol production during fermentation and the influence of grape ripeness on wine colour [9].

Tannins and ripening: while tannins show somewhat weaker, but still significant, correlations with sugar (r = 0.774), pH (r = 0.730), and anthocyanins (r = 0.860), their negative correlation with TA (r = -0.716) points to their development being partially influenced by ripening. However, tannin content is also significantly affected by environmental factors like temperature and sunlight, which influence the rate of phenolic extraction [22].

Acetic acid and stress conditions: acetic acid, which is associated with stress or microbial contamination, consistently shows strong negative correlations with sugar (r = -0.967), pH (r = -0.962), TP (r = -0.940), and alcohol (r = -0.968), while its positive correlation with TA (r = 0.966) highlights the increased acidity that often accompanies acetic acid production. These findings imply that high levels of acetic acid are typical in cooler or more stressed growing conditions where grape maturation is limited [4]. The regression analysis corroborates the idea that warm, well-ripened vintages are associated with higher levels of sugar, pH, alcohol, and phenolic compounds, while cooler, less favourable vintages show higher acidity and elevated acetic acid levels. These correlations align well with established literature on grape ripening and wine chemistry [22,26] and reinforce the insights gained from the varietal and vintage trends observed in this study.

Conclusions

Cabernet Sauvignon generally exhibits higher alcohol, anthocyanin, and tannin levels than Merlot, resulting in wines with greater intensity, structure, and colour depth. In contrast, Merlot tends to produce softer, fruitier wines with lower tannin and acidity. Both varieties have shown increased levels of anthocyanins and tannins from 2017 to 2022, likely due to improvements in vineyard management and winemaking practices. Colour intensity in both varieties is strongly influenced by climate, with warmer years promoting higher anthocyanin concentrations and deeper colour. Acetic acid levels serve as an indicator of fermentation stress, showing higher concentrations in cooler years with less colour intensity. Additionally, alcohol content correlates with colour, as higher sugar levels in warmer years contribute to both higher alcohol and deeper colour. PCA analysis reveals that Cabernet Sauvignon is more consistent across vintages, performing better in warmer, drier conditions, while Merlot shows greater variability, particularly in cooler vintages. This suggests that Cabernet Sauvignon is more resilient to climatic variations, whereas Merlot's expression is more influenced by environmental conditions.

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