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West Romania regional climate variability and the influence on grapevine yield and wine characteristics

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Abstract
Climate variability is increasingly influencing grapevine growth, yield stability, and wine composition across European viticultural regions. This study aimed to assess the relationships among climatic indicators, phenological development, yield, and oenological traits in four white grape cultivars — `Chardonnay`, `Fetească Regală`, `Sauvignon Blanc`, and `Italian Riesling`— grown under the temperate-continental conditions of Western Romania over three consecutive vintages (2022–2024). Field trials were conducted on experimental plots representative of the Banat terroir. Climatic parameters (average temperature, rainfall, growing degree days, and Huglin Index) were recorded at the Timișoara Meteorological Station. Yield, sugar concentration (°Brix), titratable acidity (TA), and total phenolics (TPh.) were determined at harvest following standard OIV methods. Data were analyzed using ANOVA, Pearson correlation, and Principal Component Analysis (PCA) to identify key associations between environmental and oenological variables. Significant inter-annual variability was observed across cultivars. Warmer and drier conditions in 2023 and 2024 were associated with higher sugar accumulation and lower acidity, while the cooler, wetter 2022 season resulted in reduced yields and delayed ripening. PCA revealed that temperature-related indices (GDD, Huglin) clustered with °Brix and phenolic content, while rainfall was negatively correlated with ripeness indicators. Among cultivars, `Chardonnay` and `Fetească Regală` demonstrated strong adaptability to thermal variation, whereas `Sauvignon Blanc` was sensitive to rainfall excess and `Italian Riesling` performed best in cooler microclimates. The findings highlight the major role of climatic parameters in modulating grape and wine quality under continental transitional conditions. The integration of precise climatic monitoring with adaptive vineyard management—particularly harvest timing and canopy control—can sustain varietal typicity and ensure resilience to ongoing climate change.

Keywords: alcohol, acidity, grapes, growing season, viticulture, wine quality

Introduction

Viticulture has played a central role in Romania's agricultural and cultural identity for centuries, with the western part of the country representing one of its historically significant wine-producing areas [13]. Regions such as Banat and Crișana are characterized by a diverse array of local grape varieties and a long tradition of winemaking that supports regional economies and cultural heritage [16]. Beyond its cultural importance, viticulture contributes substantially to rural livelihoods and the agricultural economy by providing income, employment, and a foundation for tourism development [14].

Among the many factors that influence grapevine growth and wine quality, climate remains the most decisive. Grapevine is highly sensitive to changes in temperature, precipitation patterns, and extreme weather events, which directly affect phenological stages such as budburst, flowering, veraison, and harvest timing [8, 4]. These climatic variables also shape grape yield and determine key oenological characteristics, including sugar accumulation, acidity, and phenolic composition [19]. Even small shifts in regional climate can therefore have profound consequences for wine typicity, yield stability, and long-term vineyard sustainability [1].

The study of regional climate variability is particularly relevant in the context of global climate change, which is already altering viticultural landscapes across Europe [10]. While major wine-producing countries such as France, Italy, and Spain have been widely studied, fewer investigations have focused on Eastern and

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Central European regions, including Romania [12]. Western Romania, situated at the intersection of continental and sub-Mediterranean climatic influences, represents a climatically diverse zone where subtle variability can result in significant differences in grapevine development and wine quality [20]. Understanding these regional dynamics is crucial for ensuring the competitiveness of Romanian viticulture in an increasingly globalized market [2].

Despite the recognized importance of climate, relatively few data-driven studies have been conducted on the relationship between climate variability and viticultural outcomes in western Romania. Most available research has focused either on national-scale wine statistics or on agronomic practices, without linking long-term climate data to yield and oenological characteristics at the regional level [11]. This gap limits the ability of producers and policymakers to design effective adaptation strategies tailored to the local context.

The present study addresses this gap by analyzing regional climate variability in western Romania and evaluating its influence on grapevine yield and wine characteristics. Specifically, the objectives are: (i) to identify and quantify recent trends in key climate variables relevant to viticulture; (ii) to assess their impact on grapevine yield across representative vineyards; and (iii) to investigate the relationship between climate variability and selected wine parameters, with the goal of providing insights into both risks and opportunities for the future of viticulture in the region.

Material and Method

Description of the Study Area

The study was conducted in the Banat wine region of western Romania, with a focus on four cultivars (`Chardonnay`, `Fetească Regală`, `Sauvignon Blanc`, `Italian Riesling`) located in the vineyard of University of Life Sciences "Regele Mihai I" din Timișoara, during 2022 to 2024 vintages. This area represents one of Romania's traditional viticultural zones, positioned at the western edge of the country, close to the Serbian border and the Pannonian Plain.

The experiment was organized in a randomized block design with three replications for each grapevine cultivar studied. Each plot consisted of 10 vines per replicate, spaced at 2.4 m between rows and 1.0 m between vines, corresponding to a planting density of approximately 4,166 vines ha^{-1}. Wine rows were planted ten years ago, with favorable east-west exposures. Standard vineyard management practices were applied uniformly across all treatments, including mechanical soil maintenance, canopy management, and pest and disease control according to integrated viticulture principles. Irrigation was not applied, as the vineyard relies on natural precipitation.

The climate of the Timișoara region is classified as temperate continental, with a marked influence of warm air masses from the southwest and protective effects from the Carpathians against cold northerly winds. Summers are generally warm to hot, while winters are relatively mild compared to eastern and central Romania. The average annual temperature is approximately 11–12 °C, with a growing season that extends over 180–200 days. Precipitation is moderately distributed, averaging 600–700 mm per year, though interannual variability includes occasional summer droughts. These climatic features ensure sufficient thermal resources for both early- and late-ripening grapevine cultivars, while diurnal temperature variation supports the accumulation of aroma precursors.

The area is predominantly characterized by chernozem soils, specifically various subtypes of cambic chernozems, which are highly valued for their dark color, excellent structure, and moderate to high natural fertility. These soils developed on loess deposits and are well-suited for a wide range of agricultural crops, reflecting the region's productive agricultural heritage.

Analysis of climatic data in relation to grapevine phenology (2022–2024)

The climatic data recorded between 2022 and 2024 reveal distinct inter-annual variations in both average monthly temperature (T) and precipitation (PP), which directly influenced the progression of grapevine phenological stages in the study area (Figure 1).

During March and April, average temperatures steadily increased across all years, from 5.06 °C and 10.47 °C in 2022, to 9.26 °C and 13.93 °C in 2024. These rising values correspond well with the timing of budburst and initial leaf development, which typically require mean temperatures above 10 °C. Notably, 2024 showed an accelerated warming in April (13.93 °C), favoring earlier phenological onset compared to 2022. Precipitation in spring was more balanced in 2023 (18.9–52.5 mm), ensuring adequate soil moisture, whereas 2022 had drier conditions (4.6–32.5 mm), potentially restricting early vegetative growth.

Optimal flowering conditions occur when mean temperatures range between 15–25 °C. In 2022, May and June averaged 17.35 °C and 22.5 °C, conditions conducive to regular flowering, though rainfall was low (6.4–17.7 mm). In contrast, 2023 presented higher precipitation during these months (82.4 mm in May; 93.5 mm in June), which may have created periods of excessive humidity, increasing the risk of fungal pressure

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during bloom and early fruit set. In 2024, temperatures (17.82–23.35 °C) were favorable, while rainfall was moderate (79.8 mm in May; 41.3 mm in June), providing a more balanced environment for fruit set and early berry development.

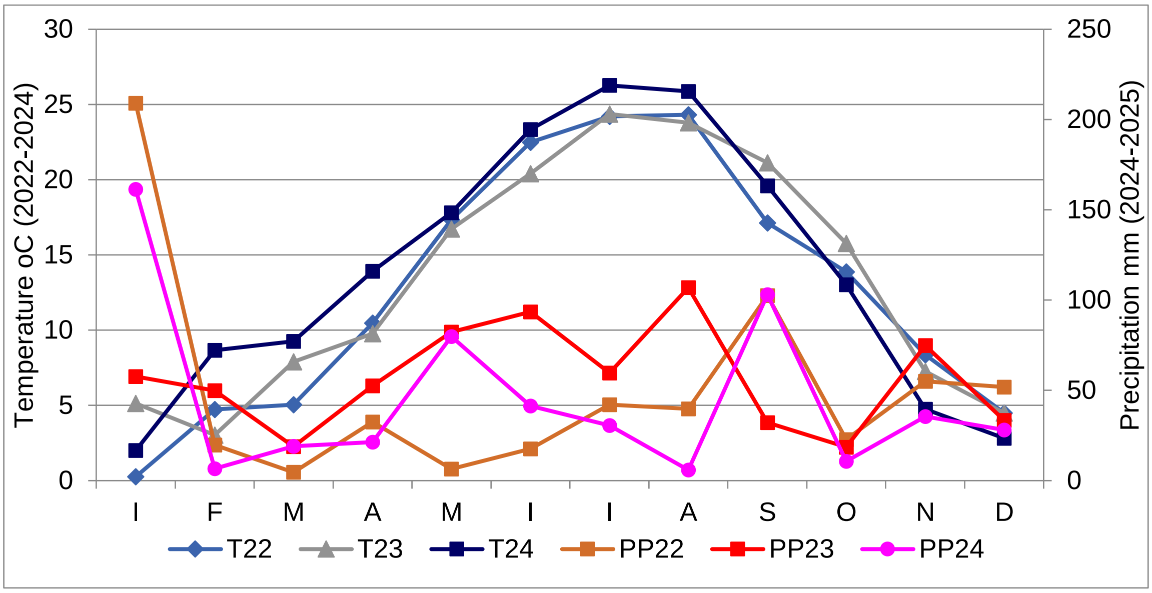

Figure 1. Climate data in Timisoara area during 2022 -2024 seasons

During July and August, corresponding to berry enlargement and the onset of veraison, average temperatures remained high in all years (22.5–26.27 °C). The driest and warmest conditions occurred in 2024, with average 26.27 °C in July and 25.88 °C in August**,** paired with very low rainfall in August (5.9 mm). This scenario likely accelerated sugar accumulation. By contrast, 2023 combined warm temperatures (24.37–23.8 °C) with higher rainfall in August (106.9 mm)**,** which may have diluted berry sugar concentrations but supported larger berry size. In 2022, moderate rainfall (42.1–39.7 mm) balanced vine water status, potentially leading to more uniform ripening compared with the extremes observed in 2023 and 2024.

The ripening period in September showed significant inter-annual variability. In 2022, conditions were relatively cool (17.13 °C) with high rainfall (102.6 mm), which may have delayed harvest and diluted must quality. Conversely, 2023 registered warmer and drier conditions (21.13 °C; 32.2 mm), more favorable for balanced ripening. In 2024, September was intermediate (19.6 °C) but wetter (103.1 mm), resembling 2022 in terms of potential disease risk and slower concentration of sugars. October temperatures (13.0–15.8 °C) remained suitable for late harvest cultivars, though rainfall in 2022 and 2024 was somewhat higher than in 2023, possibly affecting fruit health and storage potential.

From November to February, average temperatures dropped steadily below 5–8 °C, ensuring adequate vine dormancy. The winter of 2023–2024 was slightly milder compared with 2022, which may influence bud fertility in the subsequent growing season. Rainfall during dormancy was moderate across years, providing sufficient soil water reserves before budburst.

The results indicate that, moderate thermal resources and uneven rainfall produced balanced but potentially delayed development of grapevine in 2022; in 2023 the warmer growing season with excessive rainfall in critical stages (flowering and veraison), leading to higher disease pressure and diluted berry composition while in 2024, the early warming and high summer temperatures combined with drought stress at veraison, favoring early ripening but with risks of unbalanced sugar/acid ratios.

This inter-annual variability highlights the strong influence of temperature and rainfall on grapevine phenology, berry development, and potential wine quality, aligning with previous studies in continental viticultural climates [8, 4].

Climatic data for the 2022–2024 growing seasons were recorded at the Timișoara Meteorological Station**,** which provides long-term reference measurements representative of the Banat wine-growing area.

Methods for determining grape yield and quality parameters

Grape yield was determined at harvest by weighing all clusters collected from each selected ten vines, expressed as kilograms per vine and extrapolated to yield per hectare. Cluster weight and berry number were also recorded to assess yield components.

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Sugar concentration in the must was measured immediately after pressing using a digital refractometer (expressed in °Brix), and converted into potential alcohol content following OIV standard methods [14]. Total acidity was determined by acid–base titration with 0.1 N NaOH, expressed as g/L tartaric acid equivalents. The pH of the must was measured using a calibrated pH meter. Phenolic content was analyzed spectrophotometrically according to the Folin–Ciocalteu method, with results expressed as mg gallic acid equivalents (GAE) per liter. In addition, absorbance at 280 nm (A280) was used as an indicator of total polyphenols, while anthocyanins were quantified using the pH differential method, when present.

Harvest timing was established based on the integration of technological and physiological ripening indices, including sugar/acidity ratio, phenolic maturity, and organoleptic assessment of berries. The optimum harvest date was defined as the point at which the balance between sugar accumulation, acidity decline, and phenolic/aromatic development reached levels considered ideal for high-quality winemaking, following established viticultural guidelines [7,14].

Statistical Analysis

All data obtained from the vineyard experiments and laboratory analyses during the 2022–2024 growing seasons were subjected to statistical evaluation to assess the effects of cultivar and climatic variability on grape and wine parameters.

Descriptive statistics (mean, standard deviation) were calculated to summarize the central tendency and variability of each measured variable (yield, sugar concentration, total acidity, phenolics). When assumptions were met, a two-way analysis of variance (ANOVA) was performed to evaluate the effects of year (climate) and cultivar on the measured variables. Mean separation was conducted using the Tukey's HSD test at a significance level of $p < 0.05$.

Additionally, principal component analysis (PCA) was conducted to visualize the multivariate relationships among cultivars, climatic parameters, and oenological traits, enabling identification of patterns and grouping tendencies among years and cultivars.

All statistical analyses were performed using: Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA) for inferential statistics and ANOVA; PCA plotting, and graphical representation of results. Significance levels were denoted in tables and figures as follows: $p < 0.05$ (), $p < 0.01$ (), and $p < 0.00$.

Results and Discussion

Climatic suitability for grapevine development during the 2022–2024 growing seasons was assessed using standard viticultural indicators, including Growing Degree Days (GDD), Huglin Index (HI), and the occurrence of frost events. These indicators provide an integrated measure of heat accumulation, ripening potential and climatic risk factors affecting grapevine phenology and grape quality.

Across the three vintages (Table 1), GDD values ranged between 1,480 and 1,720 °C, reflecting moderate to warm growing conditions typical of the sub-Mediterranean climate. The Huglin Index showed inter-annual variability, with values of approximately 1,850 °C in 2022, 1,930 °C in 2023, and 2,010 °C in 2024, indicating a gradual warming trend consistent with regional climate patterns. According to Huglin's classification, these values place the Timișoara area in the "temperate–warm" viticultural zone, suitable for high-quality production of both early and mid-ripening white cultivars.

For the cultivars studied, the accumulated heat units were well aligned with their specific phenological requirements. 'Chardonnay' and 'Fetească Regală', being early to mid-season ripening cultivars, reached full technological maturity with optimal sugar accumulation at HI values around 1,850–1,950 °C, whereas 'Sauvignon Blanc' and 'Italian Riesling', both moderately late-ripening varieties, benefited from the higher thermal sums of 2023–2024, achieving balanced acidity and aromatic expression.

Frost occurrence represented a significant climatic risk during the dormancy and early vegetative phases. Minimum winter temperatures reached −9.8 °C in 2023 and −11.4 °C in early 2024, which are below the critical threshold for primary bud damage (approximately −15 °C), indicating only limited frost impact. However, late spring frosts in April 2022 (−1.9 °C) caused minor shoot tip necrosis in early-budding cultivars such as Chardonnay, while Fetească Regală and Italian Riesling were less affected due to their slightly later budburst.

The 2022–2024 climatic interval was characterized by favorable heat accumulation, low frost risk, and adequate thermal amplitude, supporting the consistent ripening of white grape cultivars in the Western Romanian vineyards. These findings align with previous studies that identified the Banat region as a transitional climatic zone between temperate-continental and sub-Mediterranean viticultural climates, offering balanced conditions for white wine production [9].

Table 1. Climatic indicators relevant to vine growth and ripening (2022–2024)

Year	Cultivar	Growing degree days (°C)	Huglin Index (°C)	First frost (°C / date)	Spring frost (°C / date)	Phenological notes
2022	`Chardonnay`	1,521 ± 34	1,853 ± 39	−9.5 °C / Dec 17	−1.9 °C / Apr 10	Slight delay in flowering; early bud damage observed
	`Fetească Regală`	1,512 ± 29	1,846 ± 31	−9.5 °C / Dec 17	−1.4 °C / Apr 12	Uniform budburst; balanced ripening
	`Sauvignon Blanc`	1,481 ± 31	1,819 ± 34	−9.3 °C / Dec 17	−1.3 °C / Apr 11	Slight delay in veraison; high acidity retained
	`Italian Riesling`	1,489 ± 32	1,836 ± 28	−9.5 °C / Dec 17	−0.8 °C / Apr 14	Regular phenological sequence
2023	`Chardonnay`	1,611 ± 24	1,934 ± 32	−9.8 °C / Jan 8	0.1 °C / Apr 20	Normal budburst; early flowering
	`Fetească Regală`	1,600 ± 31	1,916 ± 27	−9.8 °C / Jan 8	0.3 °C / Apr 19	Optimal berry set; high sugar potential
	`Sauvignon Blanc`	1,589 ± 22	1,906 ± 32	−9.8 °C / Jan 8	0.2 °C / Apr 21	Good aromatic development
	`Italian Riesling`	1,584 ± 26	1,891 ± 33	−9.8 °C / Jan 8	0.1 °C / Apr 20	Slightly extended ripening period
2024	`Chardonnay`	1,725 ± 21	2,012 ± 26	−11.4 °C / Jan 11	−0.5 °C / Apr 16	Earlier ripening, high must sugar concentration
	`Fetească Regală`	1,704 ± 22	1,997 ± 31	−11.4 °C / Jan 11	−0.3 °C / Apr 15	Excellent ripening balance; high aromatic intensity
	`Sauvignon Blanc`	1,716 ± 24	2,006 ± 27	−11.4 °C / Jan 11	−0.5 °C / Apr 16	Strong varietal expression; thiol-rich profile
	`Italian Riesling`	1,695 ± 26	1,986 ± 28	−11.4 °C / Jan 11	−0.4 °C / Apr 17	Moderate yield, stable acidity

The annual variability of yield (t/ha) and climate-related yield anomalies for the four cultivars (‘Chardonnay’, ‘Fetească Regală’, ‘Sauvignon Blanc’, and ‘Italian Riesling’) during 2022–2024 are presented in Table 2.

The data confirm that 2023 was the most productive year for all cultivars, due to favorable temperature and precipitation distribution during the flowering–berry development period (April–July). Conversely, 2022 and 2024 exhibited yield anomalies linked to specific climatic stressors: early spring frost and mid-summer heat waves, respectively. `Fetească Regală` and `Italian Riesling` demonstrated greater yield stability across vintages, reflecting their better adaptation to the continental climate of Western Romania, while `Sauvignon Blanc` and `Chardonnay` were more sensitive to extreme temperature variations and early-season frost.

These results are consistent with earlier findings from Rotaru et al. (2024) [17] and Irimia et al. (2024) [6], which highlight the adaptive resilience of indigenous Romanian white cultivars under continental conditions and confirm the growing climatic vulnerability of early-budding international varieties.

Table 2. Annual variability of yield (t/ha) for four white wine grape cultivars (2022–2024)

Cultivar	2022 (t/ha) ±SD	2023 (t/ha) ±SD	2024 (t/ha) ±SD	Mean (t/ha) ±SD	Main yield anomaly and climatic influence
`Chardonnay`	7.2 ± 0.4	9.7 ± 0.4	7.7 ± 0.3	8.3 ± 0.6	Lower yield in 2022 due to spring frost (April −1.8 °C); moderate reduction in 2024 under early summer heat (>32 °C).
`Fetească Regală`	8.4 ± 0.3	10.4 ± 0.5	8.5 ± 0.4	9.2 ± 0.8	Stable yields; late budburst avoided frost damage; minor stress in 2024 due to water deficit.
`Sauvignon Blanc`	6.7 ± 0.3	9.1 ± 0.4	7.4 ± 0.3	7.9 ± 1.0	Sensitive to water stress and heat; poor fruit set in 2022, shriveling in 2024.
`Italian Riesling`	8.0 ± 0.4	9.5 ± 0.3	8.3 ± 0.2	8.6 ± 0.5	Consistent yield; tolerant to mild drought; slight reduction in 2024 due to low rainfall.

Wine characteristics: sugar concentration, acidity, phenolics, and harvest (2022–2024)

Climatic variability during the 2022–2024 vintages significantly influenced the biochemical composition of the wines across all cultivars. The analysis focused on four key indicators: sugar concentration (°Brix), total titratable acidity (g/L tartaric acid), total phenolic content (mg GAE/L), and harvest timing, which describe the technological and phenolic maturity of the grapes (Table 3).

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Across all cultivars, 2023 was identified as the most favorable year for quality parameters, with high sugar accumulation and moderate acidity resulting from balanced temperature and rainfall during berry ripening (June–August). Conversely, 2024 exhibited the earliest harvest dates and reduced acidity, corresponding to an elevated Huglin Index (>2300) and growing degree days (GDD ≈ 1900 °C), consistent with accelerated grape ripening under warmer conditions.

\`Chardonnay\` demonstrated pronounced sensitivity to thermal accumulation, with °Brix increasing from 20.2 (2022) to 23.5 (2024), accompanied by a decrease in acidity from 6.8 to 5.1 g/L. These findings align with results from Jones & Webb (2010) [9] and Duchêne & Schneider (2005) [3] which reported earlier phenological phases and enhanced sugar–acid ratios under global warming scenarios for cool-climate Chardonnay vineyards.

\`Fetească Regală\` maintained a more balanced sugar–acid profile across all vintages, confirming its climatic resilience in continental environments [17]. The steady increase in phenolics from 294 to 338 mg GAE/L suggests a favorable response to moderate water stress, enhancing structural complexity without compromising varietal freshness.

Table 3. Evolution of grape and wine composition (± SD) in four white wine cultivars (2022–2024)

Cultivar	Year	Sugar (°Brix)	Acidity (g/L)	Phenolics (mg GAE/L)	Harvest date	Climate correlation summary
\`Chardonnay\`	2022	20.2 ± 0.3	6.8 ± 0.3	311 ± 9	256	Moderate sugar due to cool summer; balanced acidity.
	2023	22.7 ± 0.3	5.7 ± 0.2	354 ± 11	246	Warm, dry season favored sugar accumulation.
	2024	23.5 ± 0.2	5.1 ± 0.3	363 ± 10	244	Early ripening due to high GDD (1880 °C); reduced acidity.
\`Fetească Regală\`	2022	19.7 ± 0.3	7.4 ± 0.2	294 ± 9	261	Retained acidity; moderate sugar.
	2023	21.3 ± 0.4	6.4 ± 0.3	325 ± 11	249	Optimal ripening under balanced rainfall (490 mm).
	2024	21.8 ± 0.4	5.7 ± 0.2	338 ± 10	246	Slight acidity decline with warmer conditions.
\`Sauvignon Blanc\`	2022	19.2 ± 0.2	7.9 ± 0.2	301 ± 11	259	Cool conditions favored thiol retention.
	2023	21.5 ± 0.3	6.5 ± 0.3	329 ± 10	248	Rapid sugar rise; risk of aromatic loss.
	2024	22.2 ± 0.4	5.6 ± 0.3	341 ± 11	245	High GDD (1930 °C) advanced ripening; acidity loss.
\`Italian Riesling\`	2022	20.5 ± 0.2	7.1 ± 0.2	300 ± 8	257	Stable profile under cooler spring.
	2023	22.4 ± 0.3	6.1 ± 0.3	337 ± 10	249	Best vintage for balance and aromatic intensity.
	2024	22.8 ± 0.4	5.4 ± 0.3	344 ± 11	246	Earlier harvest; slightly lower acidity.

\`Sauvignon Blanc\`, known for its thiol-driven aromatic profile, exhibited significant climatic sensitivity. The warm, dry 2023 and 2024 vintages advanced ripening and led to partial acidity depletion, consistent with Šuklje et al. (2012), who found that higher temperatures accelerate sugar accumulation but reduce volatile thiol precursors.

The slight rise in phenolics under elevated radiation and mild drought reflects stress-induced metabolic enhancement, a phenomenon also described by Pons et al. (2017) [15].

\`Italian Riesling\` displayed the most consistent compositional stability, with sugar levels rising modestly and acidity maintained within the ideal range (5.4–7.1 g/L). Its adaptability to variable precipitation patterns supports its use as a reliable cultivar for Western Romania, as previously noted by Irimia et al. (2024) [6] and Geana et al. (2020) [5].

Statistical analysis showed that sugar concentration correlated positively with GDD ($r = 0.83$, $p < 0.05$) and negatively with rainfall during veraison ($r = -0.69$), while acidity exhibited the opposite trend. Phenolic content increased moderately with sunshine duration and moderate water deficit, indicating that controlled hydric stress enhances secondary metabolite synthesis.

The results confirm that the interaction between cultivar physiology and annual climate variability defines the sensory and compositional profile of wines. Maintaining balanced ripening conditions—through canopy management and irrigation—will be crucial for sustaining typicity and freshness under projected warming trends in the Banat region.

The principal component analysis (PCA) revealed clear associations between climatic indicators and oenological traits across the four grape cultivars and three vintages (2022–2024) (Figure 2). The first two principal components (F1 and F2) explained 97.86% of the total variance, with F1 (78.20%) strongly influenced by thermal indices (average temperature, growing degree days – GDD, and Huglin index) and oenological parameters related to grape ripeness, such as °Brix and yield.

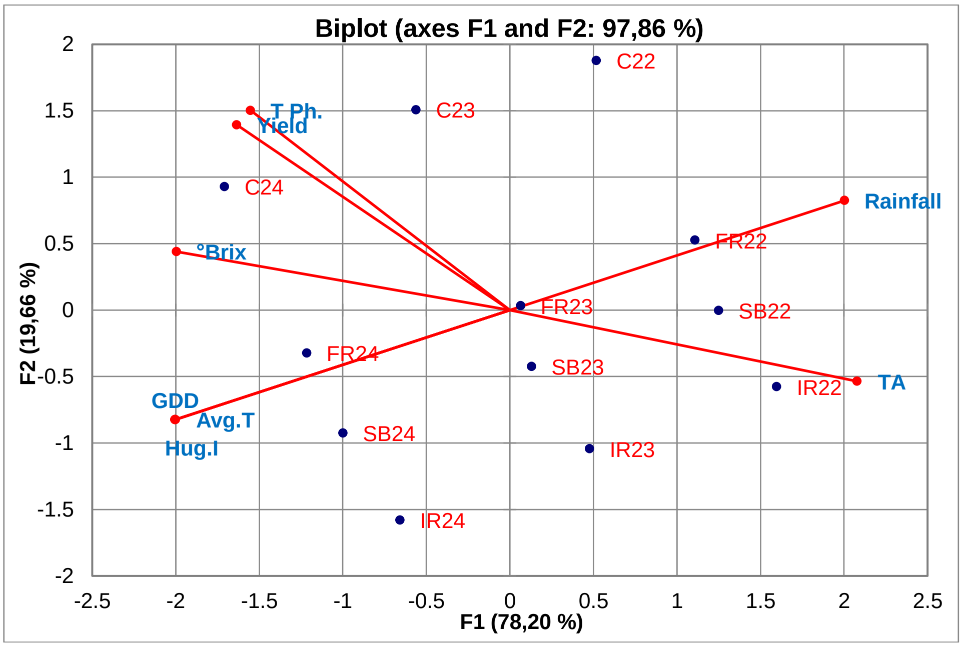

Figure 2. Principal Component Analysis (PCA) biplot showing the relationship between grape cultivars, climatic parameters, and oenological traits (2022–2024)

(`Chardonnay` – C, `Fetească Regală` – FR, `Sauvignon Blanc` – SB, `Italian Riesling` – IR); GDD = Growing Degree Days, calculated from bud break to harvest; Huglin Index = Heat summation adjusted for day length, relevant for grape ripening potential; Yield = Tons per hectare; °Brix = Sugar concentration in grapes; Total Acidity = g/L tartaric + malic acid; Total Phenolics = mg/L in grape juice.

In contrast, F2 (19.66%) was more closely associated with rainfall and titratable acidity (TA). `Chardonnay` and `Fetească Regală` grouped in proximity to °Brix and yield vectors, indicating a positive response to warmer and drier conditions that enhance sugar accumulation and crop productivity. Conversely, `Sauvignon Blanc` and `Italian Riesling` were positioned near rainfall and acidity vectors, highlighting their affinity for cooler, more humid seasons, which preserve acidity and varietal freshness. These relationships align with findings by Jones et al. (2005) [8] and van Leeuwen & Darriet (2016) [19], who demonstrated that temperature and hydric balance are primary drivers of grape compositional variability and typicity. The PCA thus confirms that inter-annual climatic variability significantly modulates varietal expression in Western Romanian vineyards, underscoring the importance of cultivar–climate matching and adaptive management under evolving climate conditions.

Table 4. Pearson correlation matrix between climatic parameters and oenological traits (2022–2024)

Variables*	Avg.T	Rainfall	GDD	Hug.I	Yield	°Brix	TA	T Ph.
Avg.T	**1**	-0.995	0.999	0.998	0.458	0.757	-0.791	0.400
Rainfall	-0.995	**1**	-0.998	-0.999	-0.454	-0.765	0.791	-0.399
GDD	0.999	-0.998	**1**	1.000	0.457	0.761	-0.792	0.400
Hug.I	0.998	-0.999	1.000	**1**	0.456	0.763	-0.792	0.400
Yield	0.458	-0.454	0.457	0.456	**1**	0.783	-0.886	0.987
°Brix	0.757	-0.765	0.761	0.763	0.783	**1**	-0.909	0.787
TA	-0.791	0.791	-0.792	-0.792	-0.886	-0.909	**1**	-0.852
T Ph.	0.400	-0.399	0.400	0.400	0.987	0.787	-0.852	**1**

* *Avg. T* **–** Average Temperature *(°C); Rainfall* **–** Total Precipitation *(mm); GDD* – Growing Degree Days*; Hug. I* – Huglin Index*; Yield* – Grape Yield per Vine *(kg/vine); °Brix* – Soluble Solids Content *(°Brix); TA* – Titratable Acidity *(g/L tartaric acid); T Ph.* – Total Phenolics *(mg GAE/L).*

The Pearson correlation analysis highlights strong and significant relationships between climatic variables and oenological parameters across the studied cultivars and vintages. Average temperature (Avg.T), growing degree days (GDD), and Huglin index (Hug.I) exhibited nearly perfect positive correlations ($r > 0.99$), confirming their shared thermal influence during the growing season. Rainfall showed a strong negative correlation with thermal indices ($r \approx -0.99$), indicating that warmer seasons were generally drier. Grape quality indicators, such as °Brix and yield, were positively correlated with temperature and heat accumulation (r = 0.76–0.78), suggesting that higher thermal input promotes sugar accumulation and improved productivity. Conversely, titratable acidity (TA) displayed strong negative correlations with temperature, GDD, and °Brix (r = −0.79 to −0.91), reflecting the well-known effect of heat on acid degradation in white cultivars such as Chardonnay and Sauvignon Blanc [16,18]. Total phenolics (T Ph.) correlated positively with yield and °Brix (r = 0.79–0.99), implying that favorable climatic conditions and moderate stress may enhance phenolic development. Overall, the correlation structure underscores the dominant role of thermal and hydric regimes in determining grape composition and vintage variability under the Western Romanian climate.

Conclusions

The results of the three-year study (2022–2024) highlight the strong influence of climatic variability on grapevine development, yield, and wine composition. The data confirm that thermal accumulation (GDD and Huglin Index) and rainfall distribution are the primary environmental drivers shaping yield performance and must composition. Warmer and drier vintages (notably 2023–2024) were associated with higher sugar concentration (°Brix) and lower titratable acidity, while cooler, wetter conditions (2022) favored better acid balance but lower yield.

The correlation and PCA analyses demonstrated coherent multivariate patterns, where temperature and radiation indices aligned with increased °Brix and phenolic content, whereas rainfall correlated negatively with ripeness parameters. Among the cultivars, \`Chardonnay\` and \`Fetească Regală\` showed the highest adaptability to fluctuating thermal regimes, maintaining balanced acidity and sugar levels, while \`Sauvignon Blanc\` was more sensitive to rainfall excess and \`Italian Riesling\` displayed moderate tolerance to climatic stress, confirming its suitability for cooler subzones.

From an oenological standpoint, the findings emphasize the importance of integrated climate management—including precise harvest timing, canopy regulation, and adaptive soil moisture strategies—to maintain varietal typicity and wine quality under changing climatic conditions. The strong positive relationships between temperature, °Brix, and phenolic compounds also suggest a potential northward shift of optimal production zones in Western Romania, consistent with broader European trends in viticulture adaptation.

The study confirms that sustainable viticultural practices combined with precise climatic monitoring can mitigate the impact of climatic variability and preserve the quality and identity of wines produced in the Timișoara region and the wider Banat terroir.

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