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THE INFLUENCE OF CLIMATE VARIABILITY ON GRAPE RIPENING AND QUALITY IN A VINEYARD LOCATED IN MINIŞ-MĂDERAT AREA

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Abstract

Climate variability has necessitated adjustments in varietal selection and growing practices for many wine grape varieties. Simultaneously, rising temperatures and increased solar insolation have led to the accumulation of higher sugar levels in grapes, with important implications for the winemaking process. This study, conducted in a vineyard from Miniș-Măderat area, examined the influence of climate variability on the ripening time and berry sugars accumulation of several wine grape varieties. Climate data from recent years were compared to those from 2001, chosen as a benchmark year. Climate resources were analyzed based on the vine's requirements, with key climate indices calculated. Additionally, the evolution of grape ripening and the optimal harvest time were monitored, and differences were compared with the reference year. The results revealed that the majority of varieties ripened 20–30 days earlier, depending on the year and variety. A significant increase in must sugar content was also observed. These findings highlight the need for adaptive strategies in viticulture to address the challenges posed by climate variability.

Key words: *climate indices, grape, quality, ripening.*

INTRODUCTION

Climate plays a crucial role in shaping grape cultivation, influencing the geographic distribution of vineyards, varietal assortments, and the specific techniques employed in grape production (Jones et al., 2005; van Leeuwen & Darriet, 2016). Over recent years, significant climatic disturbances have increasingly impacted viticulture, affecting not only cultivation practices but also grape quality, winemaking processes, and the overall typology of wines (Hannah et al., 2013). These climatic changes present both challenges and opportunities for wine producers as they adapt to a shifting environmental landscape (Dobrei et al., 2023). One of the most notable consequences of changing climatic conditions is the rise in useful temperatures and real insolation, which has led to a substantial increase in sugar accumulation across all cultivated grape varieties (Sadras & Moran, 2012). This enhanced sugar content directly affects the ripening process, resulting in technological maturity occurring much earlier than in previous years (Palliotti et al., 2014). While this acceleration of grape maturity may seem advantageous, it poses significant challenges for winemakers (Bucur & Dejeu 2024). Increased sugar levels translate into higher potential alcohol content, necessitating earlier harvests to maintain the balance and quality of the resulting wines (De Orduña, 2010). This adjustment, however, influences other critical must and wine parameters, requiring modifications to both vineyard management and winemaking practices (Poni et al., 2018). The impact of these climatic shifts extends beyond sugar accumulation and harvest timing (Costea et al., 2023). Aromatic grape varieties are particularly vulnerable to elevated temperatures during the harvest period, which can lead to the degradation or loss of volatile aromatic compounds (Stroe & Budescu, 2023). In response, winegrowers are adopting innovative strategies to preserve aromatic profiles, such as harvesting at night or relocating vineyards to cooler, more northern regions (Filimon et al., 2023). Additionally, many wineries are revising their varietal assortments to better align with the new climatic realities, selecting grape varieties that are more resilient to increased temperatures and earlier ripening (van Leeuwen & Destrac-Irvine, 2017; Mustea et al., 2011).

Given these profound and ongoing changes, understanding the relationship between climatic factors and grape quality is essential for future-proofing viticultural practices. This study aims to investigate how environmental variables—particularly temperature and insolation—affect key grape ripening parameters such as sugar accumulation and technological maturity across multiple grape varieties. The findings will contribute to a broader understanding of the adaptive strategies required to maintain grape and wine quality in the face of a rapidly changing climate.

MATERIALS AND METHODS

Study Area and Experimental Design

The research was conducted in the Miniș-Măderat Vineyard (Romania) over four consecutive years, from 2021 to 2024, focusing on three wine grape varieties: 'Fetească Regală', 'Pinot Noir', and 'Cabernet Sauvignon'. This vineyard is characterized by temperate-continental climatic conditions, making it suitable for studying the impact of climate variability on grape ripening and quality. The climatic conditions during the study period were compared with those of the year 2001, which was used as a reference year to assess long-term climatic changes and their effects on grape development.

Climatic Data Collection and Analysis

Meteorological data were collected throughout each growing season (April to October) from the local weather station situated within the vineyard. The climatic parameters recorded included air temperature, precipitation, and sunlight duration. These data were used to calculate key viticultural climatic indices that characterize the heliothermal and water resources critical to grapevine development. The indices calculated were: global heat balance (Σt°g) - (total sum of daily temperatures above 0°C during the growing season); active heat balance (Σt°a) - (sum of daily temperatures exceeding 10°C during the growing season); useful heat balance (Σt°u) - (sum of daily temperatures above 10°C, excluding non-vegetative periods); hydrothermal coefficient (CH) - (reflects the ratio between precipitation and temperature, indicating drought stress); Martonne aridity index (I-ar-DM) - (evaluates aridity based on temperature and precipitation levels); real heliothermal index (IHr) - (measures actual solar heat availability for vine development); viticultural bioclimatic index (Ibcv) - (integrates thermal and hydric variables to assess vine suitability); oenoclimatic aptitude index (IAOe) - (describes the suitability of the climatic conditions for wine production) and Huglin heliothermal index (IH) - (indicates the cumulative effect of temperature on grapevine phenology). These indices were calculated following established methodologies (Huglin, 1978; Tonietto & Carbonneau, 2004) to evaluate the interaction of biotope factors and their collective impact on grapevine growth and fruit composition.

Grape ripening monitoring

Grape ripening was monitored throughout each growing season to assess the dynamics of sugar accumulation and acidity levels. The technological maturity of grapes was determined by measuring the following parameters at regular intervals from veraison until harvest: must sugar (g/L) - determined using a refractometer (expressed as g/L); total acidity (g/L tartaric acid) - measured through titration with sodium hydroxide and expressed in g/L of tartaric acid; berry weight (g) - calculated as the mean weight of 100 randomly selected berries collected from multiple points across the vineyard. The date of technological maturity was established when the sugar content and acidity levels reached optimal values for each variety based on standard viticultural practices. All measurements were conducted in triplicate to ensure the accuracy and reproducibility of results.

Statistical Analysis

Statistical analyses were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) and XLSTAT Cloud (Addinsoft, Paris, France). Descriptive statistics were calculated to summarize the climatic indices (Σt°g, Σt°a, Σt°u, CH, I-ar-DM, IHr, Ibcv, IAOe, and IH) and grape ripening parameters (sugar content, total acidity, and berry weight). Comparative analyses between the study years (2021-2024) and the reference year (2001) were conducted using one-way ANOVA, followed by Tukey's HSD post-hoc test to identify significant differences ($p < 0.05$). Pearson's correlation coefficients were calculated to assess relationships between climatic indices and grape ripening parameters. Additionally, Principal Component Analysis (PCA) was performed to identify the most influential climatic factors affecting grape maturity. All analyses were performed in triplicate for reproducibility, and statistical significance was set at $\alpha = 0.05$. Outputs from Microsoft Excel and XLSTAT Cloud were cross-validated to ensure consistency.

RESULTS AND DISCUSSIONS

Climatic resources play a pivotal role in determining varietal assortment, cultivation techniques, grape quality, and the economic performance of vineyards. In our study, significant changes were observed in all analyzed climatic elements during the research years (2021-2024) compared to 2001 and the 1991-2000 averages (Table 1). Throughout the study period, both average and maximum air temperatures exceeded those recorded in 2001. Notably, 2024 experienced the highest average temperature, surpassing 2021 by over 6°C. This substantial increase aligns with global observations, where viticultural regions have reported growing season mean temperature rises of approximately 1.3°C between 1950 and 1999, and 1.7°C from 1950 to 2004 (Santos et al., 2020). Elevated temperatures can significantly impact grapevine physiology, affecting phenology, berry composition, and overall wine quality. Studies have shown that higher temperatures can lead to advanced phenological stages, reduced acidity, and altered aromatic profiles in grapes (van Leeuwen & Darriet, 2016). Additionally, increased temperatures may exacerbate water deficits, further influencing grape development and vineyard management practices.

Similar trends have been observed in other wine-producing regions. For instance, research indicates that warmer growing seasons have led to challenges in achieving balance in fruit composition, resulting in higher alcohol levels and lower acidity in wines (Dobrei et al., 2021). Furthermore, studies have documented that rising temperatures and decreased water availability have affected grapevine physiology and biochemistry, impacting berry quality (Arias-Pérez et al., 2021).

Table 1. The main climatic parameters in the Miniș-Măderat vineyard from 2021 to 2024 period

Year	The mean air temperature (°C)			The mean of soil temperature (°C)	Precipitations (mm)	Hygroscopicity (%)	Insolation (hours)
	Mean	Maximum	Minimum				
2021	12.4	40.0	-12.0	13.6	970.5	74.0	2440
2022	13.4	41.4	-12.0	13.9	560.3	73.0	2130
2023	14.62	38,6	-7.8	14.7	924.9	76.3	2380
2024	15.24	41.7	-8.4	15.3	619.2	72.6	2562
Mean 2021-2024	13.95	40.4	-10	14,3	768.7	73,9	2378
Mean 1991-2000	11.2	36.5	-13.5	12.3	670.0	79.3	1834.9
2001 (C)	9.2	37.9	-13.3	10.7	826.0	81	1913.7

In terms of minimum temperatures recorded across the research period, all years exhibited higher minimum values compared to those recorded in 2021. With regard to the average soil temperature, significant changes are evident when compared to the reference year of 2001. In all four research years, the average soil temperature was 3-6°C higher than in 2001.

The average annual precipitation, however, displayed a contrasting pattern. The years 2022 and 2024 experienced lower precipitation levels than the reference year (2001), while the years 2021 and 2023 recorded significantly higher values. In terms of hygroscopicity, all research years had values lower than those of the reference year. Conversely, all four research years recorded higher values for sunshine hours, with 2024 surpassing the 2001 values by more than 600 hours.

Since the precipitation regime is particularly significant for viticulture, both in terms of production quality and cultivation technology, it is well established that precipitation levels influence the intensity of disease and pest outbreaks, thereby affecting the phytosanitary treatment schedule (see Table 2). For this reason, a detailed analysis of the precipitation regime according to the Hellmann Criterion was deemed necessary. The research years varied considerably, both in terms of total precipitation amounts and seasonal distribution. Applying the Hellmann Criterion, the years ranged from extremely rainy in 2021 to normal in 2024. Although no research year was considered overall as deficient in precipitation, all four research years recorded lower precipitation levels during the grapevine growing season when compared to the reference year, 2001. Notably, the year 2024, classified as normal according to the Hellmann Criterion in terms of total annual precipitation, recorded the lowest precipitation during the grapevine growing season.

The climatic changes observed in the Miniș-Măderat vineyard align with broader trends in viticulture, particularly regarding rising temperatures and variable precipitation. Studies by Costa et al. (2023) and Duchêne et al. (2010) confirm increased soil and minimum temperatures, influencing vine development. Variations in precipitation, as noted by Williamson et al. (2024), highlight how rainfall patterns impact vine health and yield, with lower rainfall during critical periods potentially increasing pest and disease risks. Additionally, higher sunshine hours, as seen in 2024, may improve grape quality, compensating for water deficits. These findings emphasize the need for adaptive viticulture strategies to maintain productivity under changing climatic conditions.

Table 2. Precipitation trends and characterisation of the years 2021-2024 in the Miniș-Măderat vineyard

Year	Precipitation, L/m^2		The rainfall rating of the year according to the Hellmann criterion	Mean deviation (%)
	Total/year	Growing season		
2021	970.5	431.0	Extremely rainy	55,75
2022	560.3	461.2	Normal	-10,08
2023	924,95	415,7	Very rainy	48,44
2024	619,2	391,9	Normal	-0,63
2001 (C)	826.0	569.9	Slightly rainy	17.8

The rainfall classification of the year according to the Hellmann criterion/Deviation from the multi-year mean (%) (Extremely dry < -50%; Very dry -31% to -50%; Dry -21% to -30%; Slightly dry -11% to -20%; Normal -10% to 10%; Slightly rainy 11% to 20%; Rainy 21% to 30%; Very rainy 31% to 50%; Extremely rainy > 50%).

To more accurately assess the suitability of the Miniș-Măderat wine-growing area for viticulture based on its climatic resources, several climatic indices were calculated. Regarding temperature resources, it was observed that in all four years of the research, both the global heat balance values and the active and useful heat balance values exhibited a consistent increase. This trend clearly reflects the global warming phenomenon.

The warmest year in the entire research cycle was 2024, with its heat balance values showing significant positive deviations when compared to both the reference year (2001) and the multiannual average. Furthermore, the average values of the global active and useful heat balance over the four research years were notably higher than those of the reference year and the multiannual average. These findings suggest that in the Miniș-Măderat area, there has been a slight excess of temperature in recent years, which has considerable implications for the accumulation of sugars and the timing of the grape harvest.

The rise in temperature resources in the Miniș-Măderat region aligns with global warming trends affecting viticulture. Studies by Jones et al. (2024) and Dominguez et al. (2022) highlight increased temperatures, earlier grape harvests, and higher sugar content, impacting grape composition and wine quality. Similarly, Fraga et al. (2023) note that rising heat balances can alter grape acidity and flavour. These trends are consistent across Mediterranean and European regions, including the Miniș-Măderat area, suggesting climate change's significant impact on viticulture. The warming influences sugar accumulation, harvest timing, and potentially wine characteristics.

Table 3. The main bioclimatic indicators values in the Miniș-Măderat vineyard from 2021 to 2024

Year	Σ t°g	Σ t°a	Σ t°u	CH	I-ar-DM	Ihr	Ibcv	IAOe	IH
2021	4586.0	3917.0	1913.5	1.2	43.3	2.9	6.1	4911.0	2247.9
2022	4943.7	4423.4	2152.4	1.3	23.9	2.6	4.9	4762.5	2507.4
2023	5276.7	4621.2	2353.5	2.0	37.57	5.6	7.4	6835.5	2523.5
2024	5739.6	5077.1	2577.2	1.2	24.53	6.6	10.9	5874.1	2937.2
Mean 2021-2024	5136.5	4509.6	2249.1	1.4	32.32	4.4	7.32	5595.7	2554.0
Mean 1991-2000	4361.5	3831.4	1756.1	1.2	31.8	2.1	6.1	4470.1	2142.0
2001(C)	4141.4	3636.4	1536.4	1.9	43.0	1.7	3.2	3972.7	1701.9
Mean 2001-2020	4724.6	4214.1	1971.7	0.9	26.2	2.6	9.6	4952.1	2362.8

Global heat balance (Σt°g); active heat balance (Σt°a); useful heat balance (Σt°u); hydrothermal coefficient (CH); Martonne aridity index (I-ar-DM); real heliothermal index (IHr); viticultural bioclimatic index (Ibcv); oenoclimatic aptitude index (IAOe); Huglin heliothermal index (IH); C-control.

The hydrothermal coefficient (CH) is a key indicator that reflects the water resources of a wine-growing area in relation to its thermal resources. The values of this coefficient in the Miniș-Măderat area throughout the four years of research indicate that the region offers very favourable conditions for producing quantitatively and qualitatively balanced yields. It is generally accepted that the most favourable values for grapevine cultivation fall between 1.1 and 2, and based on this range, the Miniș-Măderat region can be considered stable for viticulture (Table 3).

The real heliothermal index and the Huglin heliothermal index jointly describe the light and temperature resources available to a wine-growing area. The real heliothermal index in the Miniș-Măderat vineyard showed an upward trend compared to the reference year (2001). Throughout the four years of research, the heliothermal resources of the area proved to be favourable for grapevine cultivation, with the 2024 values suggesting a slight excess in light and heat, approaching the upper limit of favourability. While 2021 and 2022 values exceeded those of the reference year, they remained close to the multiannual average for the region. The Huglin heliothermal index (IH) demonstrated a similar dynamic to the real heliothermal index (IHr). Based on this index, 2024 again stands out as a year with a slight excess of light and temperature, approaching the maximum threshold for optimal grapevine growth. The bioclimatic viticultural index (Ibcv), which integrates the effects of temperature, light, and insolation, reflects the overall conditions for grapevine cultivation. Values between 5 and 15 are considered favourable, and in all four years of research, the values of this index were higher than those of the reference year, which was notably rainy. These values were also close to the multiannual average, indicating stable conditions for viticulture without significant imbalances in temperature, light, and humidity.

The only exception was the reference year of 2001, which, due to being one of the rainiest years in recent history, saw values of the bioclimatic viticultural index fall outside the optimal range for grapevine cultivation. Given that the Miniș-Măderat Vineyard is renowned for its red wines, the oenoclimatic aptitude index (OAI) was calculated to assess the region's potential for producing red wines. A vineyard is considered to have medium favourability for red wine production when OAI values exceed 4300, and high favourability when the values exceed 4600. In all four years of the study, the OAI values for Miniș-Măderat were well above 4300, demonstrating that the region is highly favourable for red wine production.

These values were consistently superior to both the reference year of 2001 and the multiannual average. These findings emphasize the importance of heliothermal indices in predicting vine performance. The hydrothermal coefficient, as discussed by Fraga et al. (2023), also highlights favourable conditions for grapevine cultivation in regions with a coefficient between 1.1 and 2. The results from Miniș-Măderat suggest a stable and high-quality grape production environment, particularly for red wines. These findings are consistent with those from other wine-producing regions.

Table 4. The evolution of grape maturation in the 'Fetească Regală' variety in the Miniș-Măderat vineyard from 2021 to 2024

Year	Variables	Date of observations												
		July	August						September					
		25-31	1-5	6-10	11-15	16-21	22-26	27-31	1-5	6-10	11-15	16-21	22-26	27-30
2021	Sugar (g/l)				131	135	139		157	189	200			
	Total acidity (g/l Tartaric acid)				18.2	12.2	10		9.3	7.5	6.2			
	100 berry weight (g)				83	87	110		135	155	162			
2022	Sugar (g/l)			136	137		140	164	196	204				
	Total acidity (g/l Tartaric acid)			15.4	14.9		11.1	10.9	8.8	6.9				
	100 berry weight (g)			100	118		148	154	164	170				
2023	Sugar (g/l)			158		175	189	196		204	207			
	Total acidity (g/l Tartaric acid)			15.8		13.2	12.1	9.7		8.6	6.2			
	100 berry weight (g)			122		138	144	156		165	172			
2024	Sugar (g/l)	149	161		173	187	204		212					
	Total acidity (g/l Tartaric acid)	14.8	13.5		13.1	9.5	8.4		6.1					
	100 berry weight (g)	128	129		131	138	139		142					
2001 (Mt)	Sugar (g/l)							128	132		144	179	187	192
	Total acidity (g/l Tartaric acid)							19.3	14.9		10.1	8.7	7.4	6.9
	100 berry weight (g)							116	129		141	147	159	165

Regarding the evolution of grape ripening in the 'Fetească Regală' variety, it was observed that in all four years of research, the grapes reached maturity and accumulated significantly higher amounts of sugar compared to the reference year 2001.

The year 2024 was particularly notable, as the ripening process began at the end of July, with the grapes reaching technological maturity in the first days of September (Table 4). For the 'Pinot Noir' variety (Table 5), the evolution of grape ripening throughout the research cycle followed a similar pattern to that observed in the 'Fetească Regală' variety. For this variety as well, 2024 was the year with the earliest grape ripening and the highest sugar accumulation, while 2021 had the latest ripening and the lowest sugar levels. Compared to 2001, grape ripening in the 'Pinot Noir' variety occurred earlier, and sugar accumulation was higher in all four research years. Similar findings have been reported in other wine-growing regions. Jones et al. (2024) observed that rising temperatures across European vineyards have led to earlier grape ripening and increased sugar accumulation, particularly in early-ripening varieties like 'Pinot Noir'. Additionally, a study by van Leeuwen and Darriet (2016) in the Bordeaux region confirmed that warmer growing seasons accelerate phenological stages, leading to earlier harvests and higher sugar content, which directly influences wine quality and alcohol levels.

Table 5. The evolution of grape maturation in the 'Pinot noir' variety in the Miniș-Măderat vineyard from 2021 to 2024

Year	Variables	Date of observations												
		July	August						September					
		25-31	1-5	6-10	11-15	16-21	22-26	27-31	1-5	6-10	11-15	16-21	22-26	27-30
2021	Sugar (g/l)				94	108	125		153	185	202			
	Total acidity (g/l Tartaric acid)				17.8	15.3	11.1		8.9	6.7	5.9			
	100 berry weight (g)				72	83	113		124	138	140			
2022	Sugar (g/l)			108	125		153	185	192		210			
	Total acidity (g/l Tartaric acid)			15.2	14.9		13.3	9	6.4		5.9			
	100 berry weight (g)			107	125		127	130	132		138			
2023	Sugar (g/l)			172		180	196	212		220	238			
	Total acidity (g/l Tartaric acid)			16.3		14.7	13.2	11.4		8.3	6.1			
	100 berry weight (g)			107		116	125	132		139	142			
2024	Sugar (g/l)	140	163		172	197	212		230					
	Total acidity (g/l Tartaric acid)	18,3	16,2		13.9	12.9	8.1		6.3					
	100 berry weight (g)	112	115		120	127	140		147					
2001 (C)	Sugar (g/l)							89	105	124	173	184	191	196
	Total acidity (g/l Tartaric acid)							18.9	16.3	14.7	10.2	8.4	7.8	6.9
	100 berry weight (g)							110	116	121	129	136	139	141

These studies align with the results from the Miniș-Măderat vineyard, where the increased heat accumulation in recent years has advanced the ripening process and enhanced sugar levels in both 'Pinot Noir' and 'Fetească Regală' varieties.

For the 'Cabernet Sauvignon' variety (Table 6), it was observed that in all four years of research, the gap in reaching maturity between this variety and the other two was significantly smaller compared to 2001. Additionally, the date of technological maturity for the 'Cabernet Sauvignon' variety occurred earlier in all four research years than in the control year 2001. The highest sugar accumulations were recorded in 2024 and 2023, with all four research years showing superior sugar levels compared to the control year.

Table 6. The evolution of grape maturation in the 'Cabernet Sauvignon' variety in the Miniș-Măderat vineyard from 2021 to 2024

Year	Variables	Date of observations													
		July	August						September						October
		25-31	1-5	6-10	11-15	16-21	22-26	27-31	1-5	6-10	11-15	16-21	22-26	27-30	1-5
2021	Sugar (g/l)					71	83		110	155		180	185		
	Total acidity (g/l Tartaric acid)					19.1	16.7		14.8	11.5		9.6	7.3		
	100 berry weight (g)					61	85		100	107		120	129		
2022	Sugar (g/l)			96	115		144	157	169		183	190			
	Total acidity (g/l Tartaric acid)			21.8	20.4		18.3	12.7	9.5		7.2	7.0			
	100 berry weight (g)			96	102		116	119	125		129	131			
2023	Sugar (g/l)			155	170		182	199		207	210	214			
	Total acidity (g/l Tartaric acid)			19.7	17.5		13.2	10.9		8.6	7.4	6.9			
	100 berry weight (g)			90	105		114	121		129	132	133			
2024	Sugar (g/l)	121	156		160	189	210	221	223						
	Total acidity (g/l Tartaric acid)	21	17.9		13.7	11.8	7.8	6.9	6.6						
	100 berry weight (g)	87	91		94	95	102	109	112						
2001 (Mt)	Sugar (g/l)								75	87	118	145	169	180	183
	Total acidity (g/l Tartaric acid)								19.7	18.5	16.9	10.6	9.7	7.9	7.6
	100 berry weight (g)								75	83	89	102	114	123	126

Similar results have been reported in other wine-growing regions. According to Duchêne et al. (2010), rising temperatures in Bordeaux have led to earlier ripening and increased sugar accumulation in late-ripening varieties like 'Cabernet Sauvignon'. Likewise, a study by

Webb et al. (2023) in Australian vineyards found that climate warming shortens the ripening period and advances harvest dates across multiple grape varieties. These findings align with the results from the Miniș-Măderat vineyard, where the 'Cabernet Sauvignon' variety reached technological maturity earlier and exhibited higher sugar accumulation in all four research years compared to the control year. From the summary table (Table 7), it was observed that all varieties recorded higher sugar content values at technological maturity during the research years compared to the reference year. The year with the highest sugar accumulation potential was 2024 for the 'Fetească Regală' and 'Cabernet Sauvignon' varieties, and 2023 for the 'Pinot Noir' variety. The differences recorded relative to the control were significant, approximately 40 grams of sugar per liter, corresponding to an increase in the must's alcoholic potential of over 2.0-2.5% vol. alc. Among the all varieties, the lowest sugar accumulation values compared to the control year were recorded in 2021, which was characterized by exceptionally high rainfall. Regarding the achievement of technological maturity, substantial differences between the research years and the reference year (2001) were evident for all varieties. While technological
maturity was reached at the end of September and the beginning of October in the reference year, in 2024, it occurred in the first days of September. This indicates an advancement of 26-29 days compared to the control, depending on the variety. The results indicate a clear trend of increased sugar accumulation in all studied varieties during the research years compared to the reference year. Similar studies have shown that climatic variations, particularly temperature increases and reduced rainfall during the ripening period, contribute to higher sugar concentrations in grapes (Costea et al., 2023). The significant differences observed, particularly in 2024 for 'Fetească Regală' and 'Cabernet Sauvignon' and in 2023 for 'Pinot Noir', align with previous research highlighting the influence of warmer growing seasons on sugar accumulation and earlier maturation (Cichi et al., 2024). The advancement of technological maturity by 26-29 days compared to the control year reflects the impact of climate change on grapevine phenology, as supported by similar findings in other viticultural regions (Bucur & Dejeu, 2022). The lower sugar accumulation recorded in 2021, an exceptionally rainy year, confirms the negative effect of excessive precipitation on grape ripening. These findings emphasize the increasing variability in grape development and the potential need for adaptive vineyard management strategies to maintain grape quality in the face of changing climatic conditions (Stroe, 2021).

Table 7. Results on must sugar concentration and the achievement of technological maturity in the varieties from the Miniș-Măderat vineyard during the 2021-2024 period

Year	Variety	Sugar concentration of the must at technological maturity (g/l)	Difference to control (C)	Date of reaching technological maturity	Difference compared to C, for technological maturity (days)
2021	'Feteasca regala' (FR21)	200	8	16.09	-12
	'Pinot noir' (PN21)	202	6	17.09	-12
	'Cabernet Sauvignon' (CS21)	185	2	23.09	-11
2022	'Feteasca regala' (FR22)	204	12	12.09	-16
	'Pinot noir' (PN22)	210	14	13.09	-16
	'Cabernet Sauvignon' (CS22)	190	7	17.09	-17
2023	'Feteasca regala' (FR23)	207	15	14.09	-14
	'Pinot noir' (PN23)	238	42	15.09	-14
	'Cabernet Sauvignon' (CS23)	214	31	16.9	-18
2024	'Feteasca regala' (FR24)	212	20	02.09	-26
	'Pinot noir' (PN24)	230	34	02.09	-27
	'Cabernet Sauvignon' (CS24)	223	40	05.09	-29
Mean 2021-2024	Feteasca regala (FR-M)	205.7	13.7	-	-
	Pinot noir' (PN-M)	220	24	-	-
	Cabernet Sauvignon' (CS-M)	203	20	-	-
2001 (C)	Feteasca regala' (FR-C)	192	-	28.09	-
	Pinot noir' (PN-C)	196	-	29.09	
	Cabernet Sauvignon' (CS-C)	183	-	04.10	

Principal Component Analysis (PCA) revealed that the first principal component (F1) accounted for 67.72% of the total variance, while the second principal component (F2) explained 14.45% (Figure 1). The position of the 'Cabernet Sauvignon' control sample (CS-C) indicates delayed technological maturity and lower sugar accumulation under control treatment. The samples from 2021 (CS21) and 2022 (CS22) demonstrated a moderate response to environmental factors, although sugar accumulation remained below the levels observed in more favourable years. In contrast, the 2023 (CS23) and 2024 (CS24) samples suggest a substantial increase in sugar accumulation, coupled with higher levels of sunlight exposure and elevated temperatures. This positioning indicates that 'Cabernet Sauvignon' exhibited a strong positive response to favourable environmental conditions during these years. The position of the 'Cabernet Sauvignon' (CS-M) across the 2021-2024 period reflects an average response across all growing seasons and experimental conditions.

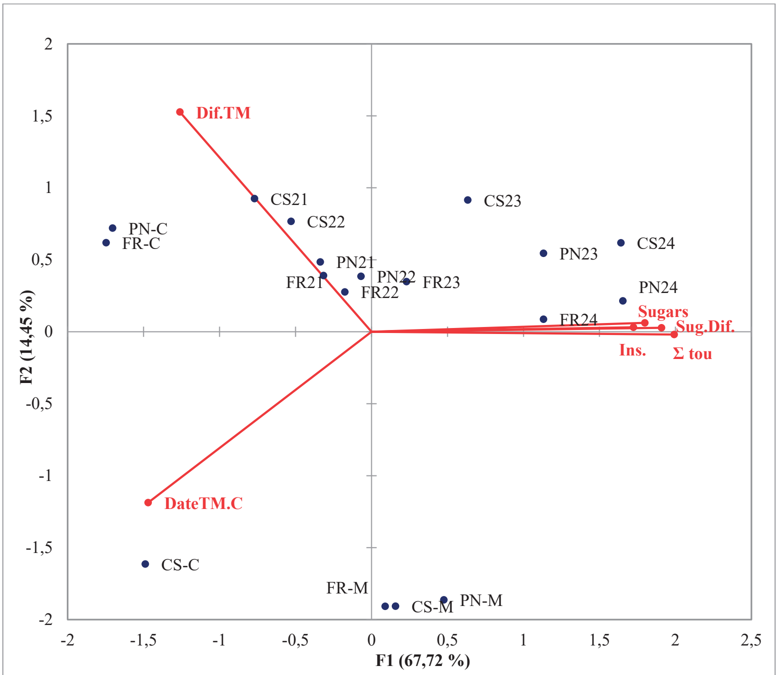

Figure 1. The PCA biplot for the relationships among variables and treatments (2021-2024)
Fr – Feteasca Regala; PN – Pinot Noir; CS – Cabernet Sauvignon; FR-M - Feteasca Regala Mean; PN-M = Pinot Noir Mean; CS-M = Cabernet Sauvignon Mean; FR-C - Feteasca Regala Control; PN-C = Pinot Noir Control; CS-C = Cabernet Sauvignon Control; SugDif = sugars difference to control; DataTM – Technological Maturity Date; Ins – insolation; Σ t°u – temperature amount

Among the three varieties, 'Cabernet Sauvignon' displayed the most pronounced response to environmental factors, particularly in 2023 and 2024, when sugar accumulation and associated variables reached their highest levels. The control sample of 'Pinot Noir' (PN-C), similar to the 'Fetească Regală' control (FR-C), suggests reduced sugar accumulation and delayed technological maturity under control conditions. The 2021 (PN21) and 2022 (PN22) samples indicate moderate improvements in sugar accumulation and other growth-related parameters compared to the control. The 2023 (PN23) and 2024 (PN24) samples reflect higher sugar accumulation and improved exposure to environmental factors. The position of the Pinot Noir' (PN-M) over the 2021–2024 period suggests an average performance across all years and conditions. Overall, 'Pinot Noir' showed progressive improvements over time, with 2023 and 2024 demonstrating increased sugar accumulation and a more pronounced influence of environmental factors. The 'Fetească Regală' control sample (FR-C), similar to PN-C, indicates lower sugar accumulation and a limited response to environmental variables. The 2021 (FR21) and 2022 (FR22) samples showed slight improvements in sugar content and environmental influences compared to the control group. However, the 2023 (FR23) and 2024 (FR24) samples remained positioned behind 'Cabernet Sauvignon' and 'Pinot Noir' along the F1 axis. Notably, FR24 is closer to the positive side of F1, suggesting increased sugar accumulation and more favourable environmental conditions in this year. The position of FR-M (mean for 2021-2024) indicates a weaker response across all growing seasons compared to the other two varieties. 'Fetească Regală' exhibited the weakest response to environmental factors. Nevertheless, the more favourable position of FR24 indicates some improvement in sugar accumulation in 2024 compared to previous years. These results emphasize the strong influence of environmental conditions - particularly temperature and sunlight exposure - on sugar accumulation and grape maturity, with 'Cabernet Sauvignon' being the most responsive and 'Fetească Regală' the least.

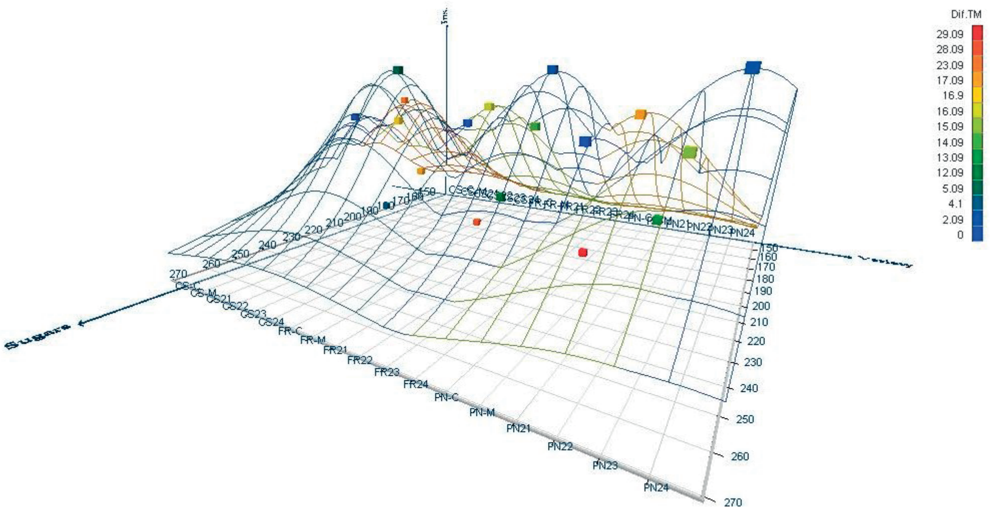

Figure 2. Variation in sugar content, insolation hours, and grape varieties in the Miniș-Măderat Vineyard (2021-2024)
Sugar content (Sugars) – X-axis; Insolation (Ins.) – measured in hours – Y-axis; Grape varieties across different years (Variety) – Z-axis.
The color gradient represents Delta TMC (Temperature Mean Change), with values ranging from 0 (red, indicating no temperature change) to -29 (dark blue, indicating a significant decrease)

The 3D surface plot illustrates the relationship among three variables: sugar content (X-axis), insolation measured in hours (Y-axis), and grape varieties across different years (Z-axis) (Figure 2). Additionally, the colour gradient represents Delta TMC (Temperature Mean Change), with values ranging from 0 (red, indicating no temperature change) to -29 (dark blue, indicating a significant decrease). The analysis of sugar content across grape varieties ('Cabernet Sauvignon' - CS, 'Fetească Regală' - FR, and 'Pinot Noir' - PN) from 2021 to 2024 reveals a wide range of sugar accumulation. In general, later years (particularly 2023 and 2024) exhibit higher sugar content, as reflected by the rightward shift of data points along the X-axis. Notably, the CS24 ('Cabernet Sauvignon', 2024) and PN24 ('Pinot Noir', 2024) samples demonstrate the highest sugar accumulation, suggesting favourable environmental conditions for sugar synthesis. Increased insolation positively correlates with sugar content across most varieties. Samples from 2024 (CS24, PN24, FR24) display the highest insolation hours, reinforcing the role of increased sunlight in enhancing sugar accumulation. 'Cabernet Sauvignon' shows the most pronounced increase in sugar content and insolation between 2021 and 2024, suggesting a heightened sensitivity to environmental changes. 'Pinot Noir' demonstrates a progressive increase in sugar accumulation, with a marked improvement in 2023 and 2024. In contrast, 'Fetească Regală' consistently shows the lowest sugar accumulation, although a slight increase is observed in 2024. Overall, the plot reveals a positive correlation between sugar content and insolation hours across all grape varieties, with 2023 and 2024 being the most favourable years for sugar accumulation. 'Cabernet Sauvignon' exhibits the strongest response to environmental variations, while 'Fetească Regală' remains the least responsive. Despite minor temperature fluctuations indicated by insolation emerges as the primary factor influencing sugar content throughout the study period.

CONCLUSIONS

The climatic resources of the Miniș-Măderat wine-growing region have undergone significant changes over the four years of research compared to both the reference year 2001 and the multiyear averages. Solar radiation during all research years was considerably higher than in the reference year, with 2024 standing out, as solar radiation exceeded the reference by more than 600 hours. In terms of precipitation, the research years were extremely variable, ranging from the exceptionally rainy year of 2021 to a normal year in 2024, according to Hellmann's criterion. This irregularity was also evident in the amount of rainfall during the growing season, where all years recorded values lower than the reference. The synthetic bioclimatic indicators calculated based on climatic resources show that, despite recent changes, the Miniș-Măderat wine-growing region continues to offer favourable and highly favourable conditions for viticulture. The Oenoclimatic Aptitude Index (IAOe) indicates that, in recent years, the Miniș-Măderat region provides very favourable conditions for cultivating red grape varieties, despite the clear evidence of global warming as shown by the active and useful thermal balance. The Viticultural Bioclimatic Index (Ibcv), which integrates the effects of three climatic factors (temperature, sunlight, and radiation), reveals that while climatic disturbances are evident, these three factors remain in balance within the Miniș-Măderat region. As a result, the area continues to provide some of the most favourable conditions for grapevine cultivation in Romania. As a consequence of the evident climatic changes compared to the reference year 2001, both the grape ripening dynamics and the qualitative parameters at technological maturity have changed significantly. For all varieties, there was a clear increase in must sugar content, sometimes exceeding 40 grams per litre, resulting in an increase in the alcoholic potential of the must by up to 2.0-2.5% vol alc. Due to the new climatic reality, significant differences were also observed regarding the time of reaching technological maturity. In all four research years, especially in 2024, grape varieties reached technological maturity much earlier, at the beginning of September, recording an advancement of 26 to 29 days compared to the reference year 2001.

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