Scientific Papers. Series B, Horticulture. Vol. LXX, No. 1, 2026
Print ISSN 2285-5653, CD-ROM ISSN 2285-5661, Online ISSN 2286-1580, ISSN-L 2285-5653

CLIMATE INFLUENCE ON QUALITY PARAMETERS OF GRAPES, WINE, AND ECONOMIC PERFORMANCE IN FETEASCĂ NEAGRĂ

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Abstract

The consistent production of high-quality wines, characterized by typicality and authenticity, is fundamental to market competitiveness. Achieving this trait requires the ongoing adaptation of agronomic techniques to harmonize the biological needs of the cultivar with the prevailing climatic variables of each growing season. The research was conducted between 2022 and 2024 in the Miniș-Măderat vineyard, focusing on Feteasc neagră, widely regarded by specialists and consumers as Romania's most valuable grape cultivar. The climatic conditions over the four-year period were analyzed in detail, with particular attention to their influence on both grape and wine quality parameters, as well as key economic indicators. The quality parameters assessed for grapes and wine included sugar content, protein content, macro- and microelement concentrations, vitamins, and tannins. Economic indicators considered were production costs, unit costs, production value, and profit. Correlations and regression analyses were subsequently performed to evaluate the relationships between selected climatic variables and the measured quality and economic parameters. Significant variations were observed in several indicators across the four years, highlighting the impact of climatic fluctuations on grapevine performance and wine quality.

Key words*: grapes, economic performance, quality, wine.*

INTRODUCTION

Viticulture is one of the agricultural sectors highly sensitive to climatic variability, as vine development, productivity, and the quality of the raw material intended for winemaking are strongly influenced by environmental factors (Dobrei et al., 2023). Air temperature, precipitation regime, solar radiation, and thermal amplitudes during the vegetation period determine the dynamics of the physiological processes of the vine, the accumulation of biochemical compounds in grape berries, and consequently the organoleptic and technological characteristics of the resulting wines (Bucur & Dejeu, 2022). In recent decades, increasing climatic variability has intensified the need to analyze the relationships between meteorological conditions during the growing season and the quality parameters of grapes and wines, making this topic particularly relevant from both a viticultural and economic perspective (Filimon et al., 2024).

The quality of grapes intended for winemaking is determined by a series of physicochemical and technological indicators, including sugar content, total acidity, pH, phenolic composition, and the balance of aromatic compounds (Dobrei et al., 2021). These parameters result from the interaction between the genetic potential of the variety, the pedoclimatic conditions of the vineyard area, and the applied cultivation technology (Frîncu et al., 2024). Among these factors, annual climatic conditions play a decisive role, influencing vine phenology and the processes of accumulation and transformation of compounds in grape berries during ripening (Dominguez et al., 2024).

The Feteasc Neagră cultivar, one of the most valuable native grape varieties for red wine production in Romania, is distinguished by its high oenological potential and its capacity to

reflect the climatic particularities and terroir of the cultivation area (Constantinescu et al., 2024). Wines obtained from this variety are appreciated for their intense color, complex phenolic structure, and distinctive aromatic profile (Cichi et al. 2024). However, the expression of these qualitative characteristics may vary significantly from one vintage to another, depending on the thermal, hydric, and radiation regimes during the vegetation period (Bocăneală et al., 2025).

In addition to its impact on product quality, climatic variability also affects the economic performance of wine farms through its influence on production levels, production costs, market value of wines, and overall production efficiency (Costea et al., 2025). Therefore, correlating agrobiological and oenological indicators with economic indicators allows for an integrated analysis of the viticultural system, providing valuable information to support technological and managerial decision-making (Stroe et al., 2025).

The objective of this study was to evaluate the relationships between climatic variability and the main quality indicators of grapes and wines obtained from the Fetească Neagră variety in the Miniș wine-growing center over the period 2021-2024. The study aims to identify the influence of bioclimatic factors on the physicochemical characteristics of grapes and to highlight the correlations between climatic conditions and oenological parameters using multivariate statistical approaches.

MATERIALS AND METHODS

Study area and experimental design. The research was conducted during the 2022-2024 growing seasons in the Miniș–Măderat vineyard, located in western Romania within the Crișana wine region, one of the traditional viticultural areas recognized for the production of high-quality red wines. The study focused on the Romanian autochthonous grape cultivar Fetească Neagră, which is well adapted to the pedoclimatic conditions of the region and is known for its high oenological potential.

The experimental vineyard was located in the Miniș viticultural center (Arad County, Romania), at approximately 46°05′ N latitude and 21°37′ E longitude, at altitudes ranging between 120 and 300 m above sea level. The area is characterized by a moderate continental climate with Mediterranean influences, which provides favorable thermal conditions for grapevine development and the accumulation of sugars and phenolic compounds in grape berries. The soils in the experimental plot are predominantly well-drained brown soils and cambisols with moderate fertility, typical of the Miniș-Măderat vineyard. The vineyard is situated on gently sloping terrain (5-12%) with predominantly southern and south-western exposure, ensuring good solar radiation during the growing season and creating favorable microclimatic conditions for grape ripening. The Fetească Neagră cultivar vines were trained using a single Guyot training system, with a planting density of approximately 4,000 vines per hectare. Vineyard management practices followed the principles of integrated viticultural management, including canopy management, soil maintenance, and phytosanitary treatments.

The experimental design covered three consecutive wine-growing years (2022-2024), each year representing a distinct climatic scenario. The experiment was organized using a randomized sampling design with three replicates. Each replicate consisted of 10-15 vines of the Fetească Neagră cultivar, selected to ensure uniformity in vigor and productivity.

Climatic data and bioclimatic indices. To characterize the climatic conditions specific to each growing year (2022-2024), the main meteorological parameters relevant for grapevine development were analyzed during the vegetation period (April-October). The climatic data included (AT) average air temperature (°C), average (ST) soil temperature (°C), total (PP) precipitation (mm), air hygroscopicity (%) (AH), and solar radiation expressed as sunshine duration (hours) (SR).

The average air temperature (AT) represents one of the most important factors influencing vine phenology, berry development, and the accumulation of sugars and phenolic compounds in grapes. Soil temperature (ST) plays a significant role in root activity, nutrient uptake, and overall plant metabolism. The precipitation (PP) regime (mm) determines the water availability during the vegetation period and strongly influences vegetative growth, berry size, and grape composition. The air

hygroscopicity (%) (AH), reflecting atmospheric humidity conditions, contributes to the regulation of plant transpiration processes and may also influence the incidence of fungal diseases during the growing season. Additionally, sunshine duration (hours) (SR) represents a key parameter controlling photosynthetic activity, which directly affects carbohydrate accumulation and grape maturation. Based on these meteorological parameters, several bioclimatic indices commonly used in viticultural research were calculated, including the global thermal balance (Σtog), active thermal balance (Σtoa), useful thermal balance (Σtou), hydrothermal coefficient (CH), drought index (I-ar-DM), heliothermal index (Ihr), viticultural bioclimatic index (Ibcv), oenoclimatic aptitude index (IAOe), and Huglin heliothermal index (IH). These indices allowed the characterization of the climatic potential of each growing season and facilitated the evaluation of the relationships between climatic variability and grape quality indicators.

Biological material. Grape sampling was performed at technological maturity, determined based on the stabilization of sugar accumulation and the balance between sugars and acidity in the must. For each replicate, approximately 3-5 kg of grape clusters were randomly collected from different parts of the canopy, ensuring representative sampling. Immediately after harvest, the grape samples were transported to the laboratory, where they were subjected to physicochemical and biochemical analyses to determine the main quality parameters. In parallel, part of the harvested grapes was used for micro-vinification, carried out under controlled conditions, in order to obtain wines representative of each study year.

To evaluate the quality of the raw material, several chemical composition parameters were determined in the grape samples. The following indicators were analyzed: sugar content (g/L must), protein content (g/100 g), phosphorus (mg/100 g), copper (mg/100 g), potassium (mg/100 g), magnesium (mg/100 g), iron (mg/100 g), calcium (mg/100 g), sodium (mg/100 g) vitamin C (total ascorbic acid, mg/100 g), vitamin B6 (mg/100 g), vitamin E (α-tocopherol, mg/100 g) and tannin content (g/100 g).

Physicochemical and biochemical analyses. The sugar content of the grape must was determined using a refractometric method, expressed as grams of sugar per liter of must (g/L). The analyses were performed on freshly pressed grape juice obtained from representative berry samples. Measurements were carried out using a digital refractometer (Atago PAL-1, Atago Co., Ltd., Tokyo, Japan), calibrated with distilled water before each series of determinations.

The total protein content was determined using the Kjeldahl method. The digestion and distillation processes were carried out using a Kjeldahl digestion and distillation system (Kjeltec™ 8400 Analyzer, Foss Analytical, Denmark). The mineral composition of the samples, including phosphorus (P), copper (Cu), potassium (K), magnesium (Mg), iron (Fe), calcium (Ca), and sodium (Na), was determined after wet mineralization of the samples using a mixture of nitric and perchloric acids. The concentrations of the elements were measured using atomic absorption spectrometry (AAS) with a PerkinElmer AAnalyst 400 spectrometer (PerkinElmer Inc., USA). Phosphorus was determined spectrophotometrically using a UV-Vis spectrophotometer (Shimadzu UV-1800, Kyoto, Japan). The vitamin C (ascorbic acid) content was determined by spectrophotometric titration based on its reducing capacity using 2,6-dichlorophenolindophenol, with measurements performed using a UV-Vis spectrophotometer (Shimadzu UV-1800). The concentrations of vitamin B6 (pyridoxine) and vitamin E (α-tocopherol) were determined using high-performance liquid chromatography (HPLC). The analyses were performed using an HPLC system (Agilent 1260 Infinity II, Agilent Technologies, USA) equipped with a UV detector and appropriate chromatographic columns for vitamin separation. The tannin content was determined using the Folin-Ciocalteu spectrophotometric method, which allows the quantification of total phenolic compounds present in grape berries. Absorbance measurements were performed using a UV-Vis spectrophotometer (Shimadzu UV-1800), and the results were expressed as grams per 100 g of fresh sample (g/100 g). All analyses were performed in triplicate to ensure the accuracy and reproducibility of the experimental data.

Statistical analysis. The experimental data obtained for the climatic indices and grape quality indicators were statistically processed to evaluate the relationships between climatic conditions, grape, and wine composition. Descriptive statistics (mean and standard deviation) were calculated for all variables. Differences between the studied years were assessed using analysis of variance (ANOVA) at a significance level of $p \leq 0.05$. To explore the relationships between bioclimatic parameters and grape quality indicators, Principal Component Analysis (PCA) was applied. This multivariate method allowed the reduction of data dimensionality and the identification of the main factors explaining the variability between the studied years. All statistical analyses and graphical representations were performed using IBM SPSS Statistics (Version 26.0, IBM Corp., USA) and XLSTAT 2023 (Addinsoft, France).

RESULTS AND DISCUSSIONS

The comparative analysis of the climatic indicators (Table 1) shows that the 2022-2024 growing seasons were characterized by warmer and sunnier conditions than the multi-year average, while the precipitation remained within limits close to the vine's ecological optimum. These climatic conditions favored vegetative growth, the physiological ripening of grapes, and the accumulation of quality compounds, indicating high viticultural potential in the studied area and favorable conditions for producing high-quality wines. The hydrothermal coefficient (CH) averaged 1.13, suggesting a relative balance between thermal conditions and total rainfall, while the real heliothermal index (Ihr) indicates a high potential for solar radiation in combination with available thermal resources.

Table 1. Values of the main climatic indicators in the Miniș-Măderat vineyard (2022-2024)

Parameter	2022	2023	2024	Mean 2022-2024	Mean 1971-2020
Average air temperature (°C)	13.40	14.37	14.57	14.11	11.70
Average soil temperature (°C)	13.90	14.48	14.70	14.36	12.90
Precipitation (mm)	560.30	693.85	631.10	628.41	646.40
Hygroscopicity (%)	73.00	68.23	69.23	70.15	78.80
Sunshine duration (hours)	2130.0	2258.6	2905.0	2431.2	1982.8
Σ toa* (total active temperatures, °C)	4423.4	3896.8	4605.6	4308.6	3949.3
Σ tou* (useful active temperatures, °C)	2152.4	1994.9	2435.6	2194.3	1750.0
Hydrothermal coefficient (CH)*	1.30	1.10	1.00	1.13	1.10
Real heliothermal index (Ihr)*	2.60	2.80	3.70	3.03	2.20
Heliothermal index (IH)*	2507.4	2523.5	2937.2	2656.03	5753.1

*Σ toa = sum of active temperatures (all temperatures above 10 °C); Σ tou = sum of useful temperatures (temperatures for vine development, typically above 10 °C but adjusted for phenology); CH, Ihr, IH are standard viticultural climatic indices.

The data summarized in Table 2 illustrate the dynamics of the main biochemical and nutritional parameters of the analyzed grapes during the 2022-2024 period, offering a comprehensive view of how composition responds to year-to-year climatic variation. The primary quality indicators, including sugars, acids, phenolic content, and antioxidant activity, showed a high degree of stability, with only moderate fluctuations between vintages. This relative consistency aligns with findings from other multi-year investigations, which also report vintage-dependent variability in grape composition driven by climatic factors such as temperature, precipitation, and growing degree days. For example, long-term studies have demonstrated that climatic conditions during key phenological stages can significantly influence sugar accumulation, acidity decline, and phenolic profiles, with warmer and drier years often associated with increased sugar content and altered secondary metabolite levels in grapes and wine (van Leeuwen et al., 2016; Bai et al., 2025). Other multi-year field experiments have similarly highlighted the effects of annual climate variability on phenolic composition and technological maturity across different grape cultivars, reinforcing the notion that environmental conditions - though variable - often exert a predictable influence on biochemical traits (Romero et al., 2016).

Table 2. Grape quality parameters (Mini's vineyard during 2022-2024 growing seasons)

Parameter	Year			
	2022 / (± SD)	2023 / (± SD)	2024 / (± SD)	Mean
Sugar content (g/L)	206.00 ± 9.50	225 ± 9.50	218 ± 9.50	216.33
Protein content (g/100 g)	5.621 ± 0.039	5.698 ± 0.039	5.675 ± 0.039	5.66
Phosphorus (mg/100 g)	91.175 ± 0.076	91.326 ± 0.076	91.238 ± 0.076	91.246
Copper (mg/100 g)	0.604 ± 0.021	0.645 ± 0.021	0.629 ± 0.021	0.626
Potassium (mg/100 g)	270.87 ± 0.44	271.72 ± 0.44	271.53 ± 0.44	271.37
Magnesium (mg/100 g)	29.87 ± 0.22	30.31 ± 0.22	30.26 ± 0.22	30.14
Iron (mg/100 g)	2.59 ± 0.08	2.74 ± 0.08	2.68 ± 0.08	2.67
Calcium (mg/100 g)	362.17 ± 1.66	365.43 ± 1.66	364.11 ± 1.66	363.90
Sodium (mg/100 g)	9.31 ± 0.015	9.34 ± 0.015	9.33 ± 0.015	9.32
Vitamin C, total ascorbic acid (mg/100 g)	11.511 ± 0.005	11.521 ± 0.005	11.519 ± 0.005	11.517
Vitamin B6 (mg/100 g)	0.439 ± 0.018	0.473 ± 0.018	0.467 ± 0.018	0.459
Vitamin E (alpha-tocopherol) (mg/100 g)	2.218 ± 0.18	2.265 ± 0.18	2.549 ± 0.18	2.344
Tannins (g/100 g)	0.48 ± 0.22	0.91 ± 0.22	0.79 ± 0.22	0.72

Regarding sugar content, an increase was observed in 2023, likely reflecting favorable climatic conditions for photosynthesis and carbohydrate accumulation in the berries. Such vintage effects on sugar concentration have been reported previously, linking warmer, sunnier seasons to accelerated technological maturation (van Leeuwen et al., 2016; Rácz et al., 2026).

Protein content showed limited variability, suggesting a stable nitrogen status in the grapes, consistent with studies indicating that vine nitrogen uptake often buffers protein synthesis against inter-annual climatic variation (Camps & Ramos, 2012). Mineral composition remained largely constant. Magnesium ranged from 29.87-30.31 mg/100 g, while phosphorus showed high stability. Iron and copper exhibited moderate fluctuations, likely influenced by soil composition and element bioavailability (Pradubsuk & Davenport, 2011). Bioactive compounds showed mostly stable levels: vitamin C remained constant, supporting antioxidant potential, while vitamin B6 varied slightly. Notably, α-tocopherol (vitamin E) increased in 2024, reflecting ecological influences on antioxidant metabolism (Şeker et al., 2012). Tannin content varied among years, reflecting the effect of climate on phenolic biosynthesis and maturation, in agreement with previous observations on vintage effects in grapes (Echave et al., 2025).

The Principal Component Analysis (PCA) biplot illustrates the relationships between the analyzed biochemical parameters and climatic variables during 2022–2024 vintages. The first principal component (F1) explains 74.79% of the total variance, while the second component (F2) explains 25.21%, indicating that the two axes together capture the overall variability of the dataset and provide a reliable representation of the multivariate relationships among variables. The F1 axis is mainly associated with variables related to grape biochemical composition, including sugars, tannins, vitamin C, vitamin B6, and protein content, which show positive loadings. The grouping of variables on the positive side of the axis indicates a strong positive correlation among them. In contrast, CH located on the negative side of F1, suggesting a relationship with the biochemical variables associated with grape maturation.

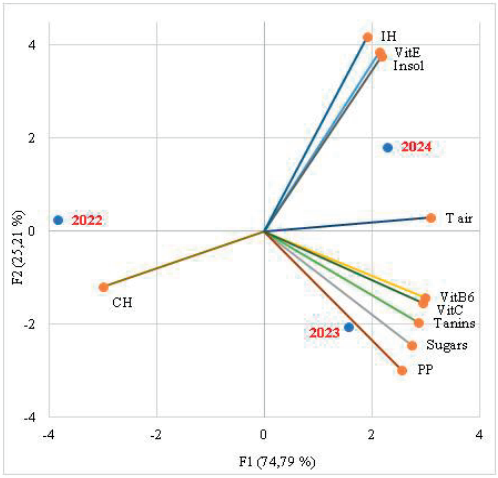

Figure 1. Principal Component Analysis (PCA) biplot showing the relationships between grape berry quality parameters and climate variables during the 2022-2024 vintages

Similar correlations between sugar accumulation and phenolic compounds during grape ripening have been reported in other grape quality studies (Ramos et al., 2024; Rouxinol et al., 2023). The F2 axis is mainly influenced by variables such as vitamin E, insoluble components, and the heliothermal index (IH). Their proximity indicates a positive association, suggesting that increased thermal and solar conditions may favor the synthesis of antioxidant compounds in grapes. Previous research has shown that environmental factors such as temperature, sunlight, and water availability strongly influence the biosynthesis of antioxidants and phenolic compounds in grape berries (van Leeuwen & Darriet, 2016; Kok et al., 2025; Crupi et al., 2023). Samples from the 2023 growing season are closely associated with higher levels of sugars, tannins, vitamin C, vitamin B6, and proteins, suggesting favorable climatic conditions for grape maturation and the accumulation of primary and secondary metabolites. Similar relationships between climatic conditions and the accumulation of sugars and phenolic compounds in grapes have been reported in previous studies (Rouxinol et al., 2023; Cataldo et al., 2023). In contrast, samples from the 2024 growing season show stronger associations with vitamin E, insoluble components, and the heliothermal index, indicating that environmental conditions during that year may have favored the biosynthesis and accumulation of antioxidant compounds. Temperature and solar radiation are known to influence the production of antioxidant molecules in grape berries (van Leeuwen et al., 2024; Ramos et al., 2024). The 2022 growing season, however, appears less strongly associated with the main biochemical variables, suggesting comparatively lower concentrations of these compounds. Such inter-annual variability is commonly attributed to differences in climatic conditions during berry development and ripening, which significantly influence grape composition and metabolic processes (Shahab et al., 2023).

The evolution of the main biochemical and nutritional parameters during the 2022-2024 vintages (Table 3) indicates a generally stable composition of the wine, with moderate variations associated with the specific conditions of each growing season. The low variability of protein content suggests a relatively stable nitrogen fraction, which is important for the colloidal and physicochemical stability of wine. The slight increase observed in 2023 may be related to fermentation conditions and the composition of the initial must. Nitrogen compounds are known to influence fermentation dynamics and wine stability (Christofi et al., 2022).

Macroelements showed a relatively uniform distribution during the analyzed period. Potassium remained stable, confirming its key role in the ionic balance of wine and in tartaric stabilization processes (Han et al., 2023). Calcium and phosphorus also presented relatively constant values, contributing significantly to the mineral composition of the wine, while sodium remained at low levels typical of quality wines. Moderate variations in iron and copper may be associated with both the characteristics of the raw material and the influence of technological equipment during the winemaking process (Wang et al., 2023).

The analysis indicates relatively stable levels of vitamin C, suggesting a consistent antioxidant potential of the wine across years. Phenolic compounds, particularly tannins, play a key role in determining the antioxidant capacity and sensory characteristics of wine. The observed variation in tannin content reflects the influence of grape ripening conditions and phenolic extraction during fermentation (Baris et al., 2026).

Vitamin E (α-tocopherol) showed relatively similar values (4.478-4.543 mg/100 g), with an average of 4.533 mg/100 g. This antioxidant contributes to oxidative protection and may support wine stability during maturation and storage (Akbaba et al., 2023). Overall, the results indicate a high degree of compositional stability during the 2022-2024 vintages, with only minor inter-annual variations. These findings suggest consistent quality of both the grapes and the winemaking process, resulting in a wine with a balanced biochemical profile and stable quality parameters. The comparison between grapes and wine also reflects the biochemical transformations occurring during fermentation and maturation, which contribute to the development of the mineral, antioxidant, and phenolic profile of the wine.

Table 3. Wine quality parameters (Minis vineyard during 2022-2024 growing seasons)

Parameter	2022/ (± SD)	2023/ (± SD)	2024 /(± SD)	Mean 2022-2024 /(± SD)
Protein (g/100 g)	4.707 ± 0.036	4.775 ± 0.036	4.762 ± 0.036	4.748 ± 0.036
Phosphorus (mg/100 g)	97.813 ± 0.025	97.863 ± 0.025	97.852 ± 0.025	97.842 ± 0.025
Copper (mg/100 g)	0.938 ± 0.025	0.987 ± 0.025	0.976 ± 0.025	0.967 ± 0.025
Potassium (mg/100 g)	381.56 ± 0.13	381.87 ± 0.13	381.75 ± 0.13	381.72 ± 0.13
Magnesium (mg/100 g)	47.76 ± 0.60	48.92 ± 0.60	48.81 ± 0.60	48.49 ± 0.60
Iron (mg/100 g)	3.89 ± 0.035	3.96 ± 0.035	3.93 ± 0.035	3.92 ± 0.035
Calcium (mg/100 g)	396.78 ± 0.88	398.51 ± 0.88	398.11 ± 0.88	397.80 ± 0.88
Sodium (mg/100 g)	11.69 ± 0.03	11.75 ± 0.03	11.73 ± 0.03	11.72 ± 0.03
Vitamin C (mg/100 g)	14.475 ± 0.10	14.683 ± 0.10	14.612 ± 0.10	14.59 ± 0.10
Vitamin B6 (mg/100 g)	0.649 ± 0.011	0.671 ± 0.011	0.665 ± 0.011	0.661 ± 0.011
Vitamin E (α-tocopherol, mg/100 g)	4.478 ± 0.033	4.543 ± 0.033	4.508 ± 0.033	4.533 ± 0.033
Tannins (g/100 g)	3.59 ± 0.18	3.95 ± 0.18	3.81 ± 0.18	3.78 ± 0.18

The principal component analysis (PCA) diagram illustrates the relationships between wine quality components and climatic bioindicators for the 2022-2024 vintages. The first two principal components explain 99.94% of the total variance, with PC1 accounting for 74.83% and PC2 for 25.11%. Positive PC1 values are associated with vitamin B6, vitamin C, tannins, proteins, and vitamin E, indicating that these variables strongly contribute to the compositional profile of wines produced under favorable ripening conditions. Similar relationships between phenolic compounds, vitamins, and grape maturity have been reported in previous studies, highlighting the influence of climatic conditions on the accumulation of antioxidant metabolites in wines (Varo et al., 2022; Cojocaru & Antoce, 2017).

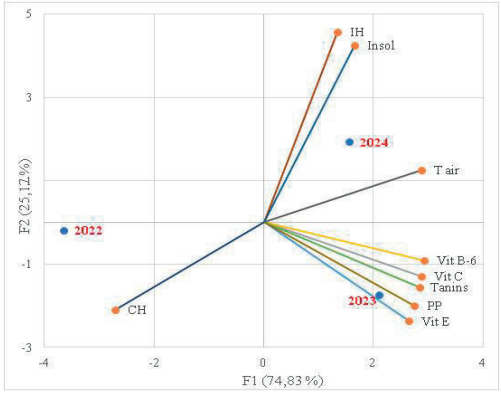

Figure 2. Principal Component Analysis (PCA) biplot showing the relationships between wine quality parameters and climate variables during the 2022-2024 vintages

The 2023 vintage shows strong correlations with higher concentrations of sugars, tannins, vitamin C, vitamin B6, proteins, and vitamin E, suggesting that the climatic conditions favored the biosynthesis and accumulation of phenolic and antioxidant compounds that contribute to wine quality and oxidative stability (Tudorache et al., 2014). The 2024 vintage is associated with vitamin E, insoluble components, air temperature (T air), and the heliothermal index (IH), indicating that higher temperatures and heliothermal conditions may have stimulated antioxidant compound production, particularly tocopherols. Environmental factors such as temperature and solar radiation are known to influence grape metabolism and antioxidant synthesis (Cataldo et al., 2023; Eder et al., 2023). In contrast, the 2022 vintage shows weaker correlations with most biochemical variables and is positioned closer to the CH climatic indicator, suggesting less favorable conditions for the accumulation of bioactive compounds. Inter-annual climatic variability is widely recognized as a major factor influencing grape composition and wine quality (Fotescu et al., 2024).

Table 4. Main economic indicators for the Fetească Neagră cultivar (EUR: 2022-2024)

Indicator	2022	2023	2024	Average
Production costs (€/ha)	1933	1987	2071	1997
Unit cost (€/kg grapes)	0.28	0.23	0.22	0.24
Winemaking cost (€/L wine)	0.39	0.39	0.42	0.40
Production value (€/ha)	2719	3432	3741	3297
Gross profit (€/ha)	787	1445	1671	1301

The analysis of production costs (Table 4) indicates a gradual increase, ranging from €1,933 ha^{-1} in 2022 to €2,071 ha^{-1} in 2024**,** with a multiannual average of €1,997 ha^{-1}**.** This trend can be attributed to the rising costs of

agricultural inputs (materials, treatments, energy, and tillage), as well as adjustments in vineyard management practices required to adapt to the climatic conditions of each growing season (Calugar et al., 2021). A relevant indicator for assessing economic efficiency is the unit cost of grapes, which decreased from €0.28 kg^{-1} in 2022 to €0.22 kg^{-1} in 2024, with an average of €0.24 kg^{-1}**.** This reduction suggests improved production efficiency, likely due to higher yields and more efficient use of technological resources. Favorable climatic conditions during the 2023 and 2024 growing seasons may have contributed to better grape development and ripening, thus improving the economic return of the vineyard (van Leeuwen et al., 2024). The winemaking cost remained relatively stable, with values between €0.39 L^{-1} and €0.42 L^{-1}**.** The slight increase observed in 2024 may be related to higher energy and processing costs associated with the transformation of grapes into wine. Nevertheless, the limited variation of this parameter indicates a relatively stable winemaking technology (Marchuk et al., 2025). A key indicator of economic performance is the production value per hectare, which increased from €2,719 ha^{-1} in 2022 to €3,741 ha^{-1} in 2024**,** with an average of €3,297 ha^{-1}. This trend reflects both higher grape yields and improvements in raw material quality, which can increase the market value of the resulting wine. Consequently**,** gross profit increased from €787 ha^{-1} in 2022 to €1,671 ha^{-1} in 2024**,** confirming the improved economic efficiency of the vineyard. These results indicate that the Fetească Neagră variety has significant economic potential under the analyzed pedoclimatic conditions.

CONCLUSIONS

This study provides an integrated evaluation of grape composition, wine quality, and economic performance of the Fetească Neagră variety cultivated in the Miniș Vineyard over the 2022-2024 vintages. The results demonstrated a generally stable biochemical profile of grapes, with moderate inter-annual variations mainly associated with climatic conditions during the growing season. Higher concentrations of sugars, tannins, and antioxidant compounds observed in the 2023 vintage indicate favorable ripening conditions, while the 2024 vintage was more strongly associated with the accumulation of vitamin E and climatic bioindicators related to temperature and the heliothermal index. The wine quality parameters showed limited variability across the studied vintages, suggesting consistent technological processing and stable raw material characteristics. The presence of phenolic compounds and antioxidant vitamins contributed to oxidative stability and the overall compositional balance of the wines. Multivariate statistical analysis (PCA) highlighted clear relationships between climatic bioindicators and wine biochemical composition, confirming the influence of annual climatic variability on metabolite accumulation and wine quality. From an economic perspective, although production costs increased slightly, the unit cost of grapes decreased, while production value and gross profit per hectare increased, indicating production efficiency and favorable economic performance. The results confirm that the Miniș vineyard provides suitable pedoclimatic conditions for the cultivation of Fetească Neagră, enabling the production of wines with stable compositional characteristics and good economic profitability. These findings highlight the importance of adapting vineyard management and winemaking practices to climatic variability in order to sustain both product quality and economic efficiency in viticultural systems.

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