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EVOLUTION OF PHYSICOCHEMICAL PARAMETERS AND PHENOLIC CONTENT DURING THE RIPENING OF FETEASCĂ NEAGRĂ VAR. GRAPES IN THE TERASELE DUNĂRII VITICULTURAL AREA

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Abstract

The ripening process of Fetească Neagră grapes is a critical determinant of wine quality, particularly in regions with varying climatic conditions. This study evaluates the technological and phenolic maturity of Fetească Neagră grapes over three consecutive years (2021-2023) in the Terasele Dunării wine-growing region. The analysis focused on sugar accumulation, total acidity, pH, nitrogen availability, anthocyanin content, and the Total Polyphenol Index (TPI), alongside the implications of different harvest strategies and maceration techniques.

The results indicate significant variations among the three vintages, largely driven by climatic factors. 2021 presented favourable conditions, allowing for extended ripening and balanced phenolic development, while 2022 exhibited an accelerated maturation due to water deficits, necessitating early harvests. 2023, marked by extreme drought, led to a compressed ripening window and lower anthocyanin accumulation, influencing wine color stability and requiring an advanced maceration strategy. Additionally, nitrogen availability fluctuated significantly between years, potentially affecting fermentation dynamics and having multiple technological and sensory implications.

These findings underscore the importance of adaptive harvesting decisions and enological interventions in maintaining wine quality under varying climatic conditions. The study highlights the need for real-time monitoring of grape maturation and the application of targeted maceration techniques to optimize phenolic extraction and balance wine composition.

***Key words**: Fetească Neagră, technological maturity, phenolic maturity, harvest strategies, maceration, climatic influence, nitrogen management.*

INTRODUCTION

The selection of the optimal harvest date is a crucial aspect of winemaking, as it directly impacts grape composition, wine quality, and overall style. The decision is influenced by multiple factors, including climatic conditions, technological and phenolic maturity, but also economic and strategic considerations (Țârdea et al., 2000; Ribéreau-Gayon et al., 2006).

The timing of harvest plays a key role in defining the balance between sugar accumulation, acidity reduction, and phenolic development (Bell and Henschke, 2005; Gutiérrez-Gamboa et al., 2021). In red winemaking, an optimal balance between sugar content, acidity, and phenolic maturity is necessary to ensure both color stability and structured tannins (Ortega-Regules et al., 2008). Harvesting too early may result in wines with high acidity and green tannins, whereas excessive delays can lead to high alcohol content and potential loss of aromatic freshness (Ribéreau-Gayon et al., 2006; van Leeuwen et al., 2022).

For rosé wines, the timing of harvest is even more critical, as higher acidity and lower phenolic content are desirable to maintain freshness and fruit-forward aromatic expression. Late harvests can lead to increased alcohol content and excessive phenolic extraction, making the wines unbalanced (Allegro et al., 2021; van Leeuwen et al., 2022). Therefore, the decision to harvest for rosé production is generally made at an earlier stage of ripening than for red wines, often at a lower sugar-to-acid ratio (Le Menn et al., 2019). However, it should be noted that, where varietal characteristics and vintage-specific climatic conditions allow, grapes may be harvested at different ripening stages depending on the intended wine style - earlier for dry wines, and later for sweet wines with higher sugar and aromatic complexity (Gil et al., 2019; van Leeuwen et al., 2022).

Phenolic maturity is also important for wine quality, affecting its color stability, structure, and aging potential. Unlike technological maturity, which focuses on sugar-acid balance, phenolic maturity evaluates the extractability of pigments and tannins from grape skins and seeds (Garrido & Borges, 2013; Gutiérrez-Escobar et al., 2021; Ortega-Regules et al., 2008). Evaluating phenolic maturity was essential for assessing the quality of grapes used in winemaking, with significant implications in defining the aromatic, chromatic, and structural profile of the final wines.

The primary purpose of this study was to perform a comparative analysis of the technological and phenolic maturity during the ripening of the grapes of the Fetească Neagră variety for three consecutive years (2021, 2022, 2023) in one of the driest wine-growing regions of the country. The aim was to identify the key parameters defining the technological maturity (sugar level, total acidity, pH, mass of 100 berries) and phenolic maturity (content of anthocyanins and total polyphenols) for this variety, under these specific conditions of the mentioned area. At the same time, the variation of recorded parameters was monitored according to the conditions specified for each year.

MATERIALS AND METHODS

Grapes

The experiment was carried out on grapes *Vitis vinifera* subsp. *vinifera*, var. Fetească Neagră from the wine-growing area "Terasele Dunării" during three consecutive harvest years (2021-2023) provided by a local producer.

Sampling of grapes

At the beginning of grape maturation, the samples are collected at five-day intervals, and as the ripening process progresses, the interval was reduced to three days. Vines are selected randomly but uniformly, avoiding the edges of the plots and keeping the choice of sampling rows and time of day constant.

From each plot area, berries are harvested from 10-20 vines, located at different points, ensuring a balanced distribution between the grapes in the middle of the line, those on the sunny side, and those inside the vine. Sampling involves the use of scissors, detaching small portions of bunches, each with 3-5 berries, until a sample with a minimum mass of 1 kg was obtained, equivalent to approximately 500-700 berries. Samples were placed in plastic bags with details of the variety, harvest date, plantation location, etc., and transported to the laboratory under controlled conditions. They were analyzed the same day.

Determination of the technological maturity of grape berries

Technological maturity of grapes involves the analysis of fundamental parameters, such as the mass of the 100 grape berries, sugar content, total acidity, and pH.

Determination of the mass of 100 berries

The previously prepared berries were counted and weighed accurately using a technical laboratory balance, determining the mass of 100 berries according to the following formula:

$$\text{Mass of 100 berries (g)} = \frac{\text{Total weight of the berries}}{\text{Total number of weighted berries}} \cdot 100$$

Determination of sugar level

Grape must was obtained by manually pressing the berries, then transferred into Erlenmeyer flasks and refrigerated for 2–3 hours to allow clarification. Sugar content was subsequently determined using the refractometric method (SR 6182 – 25:2009).

Determination of total acidity

Total acidity was determined according to the OIV-MA-AS313-01: R2015 method, by titration of the sample with a 0.1 N NaOH, in the presence of bromothymol blue as an indicator, and was expressed in g tartaric acid equivalents/L.

Determination of pH

The pH values were measured by a pH meter (Mettler Toledo, Spain) calibrated before each measurement.

Determination of phenolic maturity of grape berries

This includes the quantification of anthocyanins and the estimation of total phenolic content through the Total Polyphenol Index (TPI), both contributing to wine color intensity, stability, and astringency.

Determination of anthocyanins
The determination of anthocyanins was carried out using the Puissant-Léon method. Briefly, 50 berries were randomly selected, and the skins were separated, quickly washed, and air-dried for 30 minutes. After drying, the skins were shredded and then collected in an Erlenmeyer flask, and a volume of 50 mL HCl 1% was added. The mixture was kept for 24 hours at room temperature. The extraction was repeated 2-3 times until the skins reached a light pink coloration.
The absorbance was recorded at wavelengths of 520 nm with a Libra S22 UV-VIS spectrophotometer (Biochrom, Cambridge, UK). The content of anthocyanins (mg/kg) was calculated with the formula:

$$\text{Anthocyanins (mg/Kg)} = \frac{A_{520nm}\ .\ 22,76\ .\ 0,4}{M} . 1000$$

where: A_{520nm} - optical density at λ = 520 nm; M - the mass of 100 berries; 22.76 and 0.4 are coefficients.
Determination of total polyphenols index
The total Polyphenol Index (TPI) was performed by measuring optical absorption at the wavelength of 280 nm (Ribéreau-Gayon et al., 1983; Vivas et al., 2003). The method is based on maceration of 200 crushed berries in a solution of ethanol and hydrochloric acid, for one hour. After obtaining the clear solution by maceration and filtration, a preliminary dilution of 1/100 with distilled water was carried out. The samples are then read using the Libra S22 UV-VIS spectrophotometer (Biochrom, Cambridge, UK) at a wavelength of 280 nm. TPI was calculated according to the formula:

$$IPT = A_{280nm} \cdot 100$$

where: A_{280nm} represents the optical density at λ = 280 nm.

Statistical analysis
The results are expressed as mean values made in triplicate ± standard deviation.

RESULTS AND DISCUSSIONS

Technological maturity of Fetească Neagră grapes
Determination of 100 berries' weight
The evolution of 100-berry weight for the Fetească Neagră variety is presented in Figure 1. In 2021, berry mass increased from 145 g (August 15) to 194 g (September 14), with a sustained growth especially between August 25 and September 11. This trend reflects a year with generally favorable climatic conditions and moderate water deficit, which did not significantly hinder biomass accumulation. The growth rate remained relatively constant, with slight stabilization toward the end of the period, indicating physiological maturity.

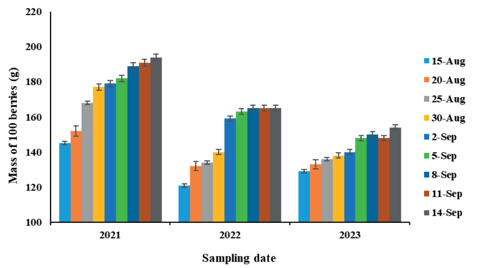

Figure 1. The evolution of the mass of 100 grape berries during ripening

In contrast, 2022 showed a more pronounced impact of drought. Initial values were lower (121 g on August 15), and the accumulation was slower, reaching only 165 g by September 14. A brief increase occurred between August 30 and September 5, coinciding with rainfall, yet the final values remained below those from 2021. These differences can be attributed to limited soil moisture, which constrained water and sugar accumulation, and thus berry development.
In 2023, under significant water stress, berries recorded the lowest weights of the three years, increasing from 129 g (August 15) to just 154 g (September 14). Notably, the final phase showed minimal gain, suggesting inhibited accumulation of reserves due to severe drought.
Overall, a clear relationship can be observed between water availability and berry mass: 2021, with better climatic conditions, yielded the highest values (194 g), while 2022 and 2023 - marked by drought - saw significantly reduced weights (165 g and 154 g, respectively).
The mass of 100 berries remains a parameter essentially related to the variety and subject to the influences of the macro- and microclimatic conditions. The variations can be large, which has been shown by numerous studies and by the practical experience of all producers, the

main reason being related to the weather conditions of each harvest year (Jones & Davis, 2000; Ortega-Regules et al., 2008). Moreover, in addition to climatic and agro-technical factors, a recent study carried out in China also shows the impact that soil type has on the weight of grapes, through its ability to retain not only water, but also heat (Wang et al., 2025).
A comparative reference can be made to two other wine-growing regions in Romania. In the Ștefănești vineyard (Argeș County), the Fetească Neagră 6St clonal selection reached a mass of 157 g per 100 berries at harvest in 2017, with the harvest occurring on September 23 (Onache, 2017). In Dealu Mare - Valea Călugărească, a 2022 study investigating the effect of viral infections on Fetească Neagră grapevines reported a mass of 158 g per 100 berries for the uninfected control group (Barbu et al., 2022). Infected vines showed reductions in berry mass ranging from 4% to 14%, depending on the severity of symptoms. Although not focused on climatic variation, these values offer a useful benchmark from another important viticultural area of Romania. The reported values are lower than those observed in 2021 (194 g) and 2022 (165 g), but slightly exceed the 2023 value of 154 g. These external data points underscore the combined influence of environmental conditions and plant health status on berry development.

Determination of sugar content

The evolution of sugar concentration during the ripening period in the three harvest years (2021-2023) is presented in Figure 2. As shown, the values differ significantly between years, primarily due to climatic variability. In 2021, sugar content started at 146.20 g/L and increased steadily to 227.01 g/L by September 14, reflecting a consistent accumulation pattern without notable fluctuations. Between August 15 and 25, the increase was moderate (approximately 31 g/L in 10 days), followed by a similarly constant rise between August 25 and September 5, reaching 205.77 g/L - an additional 28 g/L over 11 days. From September 5 to 14, the accumulation slowed, with only a 21 g/L increase in 9 days, indicating a typical deceleration in vine metabolism toward the end of ripening. Taken together with other observations in this study, these dynamics suggest that in 2021, the grapes may have reached or even slightly exceeded optimal ripeness.

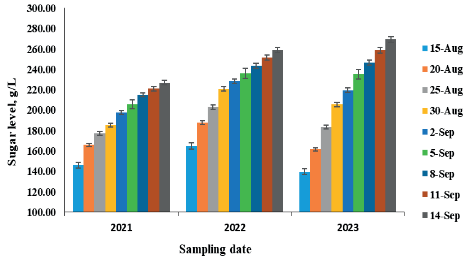

Figure 2. Sugar accumulation (g/L) in the grapes throughout the ripening period

The 2022 growing season was marked by a drier climate than 2021, with reduced rainfall and elevated temperatures that accelerated sugar accumulation in the grapes. This more rapid progression suggests an adaptive vine response to environmental stress. Between August 25 and 30, sugar content reached 220.73 g/L, corresponding to an advanced ripening stage. By September 5, levels rose to 236.09 g/L - 30.32 g/L higher than in the same period of 2021 - indicating proximity to technological maturity, when the flow of sugars to the berries begins to decrease. Compared to the 2021 harvest year, the value recorded on September 5 is 30.32 g/L higher than the one on the same date. The faster accumulation, particularly in the early ripening phase, was likely driven by moderate drought conditions that concentrated soluble solids in the must. However, prolonged water deficit subsequently reduced accumulation rates, as the vine redirected metabolic resources to preserve vital functions at the expense of berry development. These dynamics reflect an accelerated ripening process with implications for sugar–acid balance, optimal harvest timing, and the sensory profile of the resulting wine.
The year 2023 was marked by significantly drier climatic conditions than previous years, which had a major impact on grape ripening. The extreme drought influenced the dynamics of sugar accumulation, a delay was noted in the process, followed by a continuous acceleration in the second part of ripening. On September 14 a value of 269.31 g/L sugar was recorded.

These values align with and, in some cases, surpass those reported in recent literature for Fetească Neagră. For example, Barbu et al. (2022) reported a sugar concentration of 255.67 g/L in healthy control vines of Fetească Neagră from the Valea Călugărească vineyard, according to the data presented in their study, while Stoica et al. (2024) reported sugar concentrations of 245 g/L and 234.6 g/L in Fetească Neagră grapes from Banu Mărăcine (Dolj), corresponding to two consecutive vintages (2022 and 2023) - both regions known for their high ripening potential. In contrast, Constantinescu et al. (2024) reported lower average sugar levels for the 2022 harvest across five Romanian vineyards, with Dealu Mare reaching 228 g/L, Recaș 224 g/L, and Sarica Niculitel 220 g/L. Northern and cooler sites such as Iași and Blaj showed significantly lower values (189-187 g/L), highlighting strong regional variability.

Determination of total acidity

After sugars, organic acids are the most important components of grapes, contributing to the freshness of taste, the extraction of phenolic and aromatic compounds from the skins of the berries, and the activity of yeasts during alcoholic fermentation. Therefore, acidity is an essential parameter of the quality of must and wine, influencing both sensory balance and microbiological and chemical stability of the final wine (Chidi et al., 2018; Cui et al. 2024; Ju et al. 2023).

As can be seen in Figure 3, for the 2021 harvest year the acidity on August 15 started at the highest level 13.40 g/L of TA and decreased up to 6.70 on September 14. The initial higher decrease, due to the degradation of malic acid and the subsequent "gradual" decrease specific to the evolution of tartaric acid represent a typical trend of acidity (Țârdea et al., 2000).

The year 2022 started with lower values since the beginning of the monitoring period, with total acidity values of 9.65 g/L recorded on August 15. Finally, on September 14, it reached the value of 6.01 g/L, slightly lower than in the previous year on the same date.

In 2023, the driest year, acidity started at 12.80 g/L on August 15 and dropped to 9.72 g/L by August 25. Between August 30 and September 14, total acidity stabilized between 6.56 and 7.60 g/L, a range that may reflect both the onset of water stress and the approach to technological maturity.

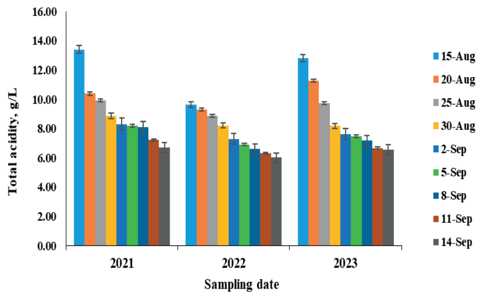

Figure 3. Evolution of total acidity (g/L tartaric acid) throughout the ripening period

A comparable acid degradation trend was reported by Onache (2017) for Fetească Neagră in the Ștefănești region, where titratable acidity decreased steadily from 22.00 g/L on August 15 to 7.13 g/L at harvest (September 23). The linear decline, marked by a sharp initial drop, aligns with the typical degradation of malic acid followed by the slower reduction of tartaric acid.

Determination of the Gluco-Acidimetric Index

The balance between sugar accumulation and acidity reduction during grape ripening plays a crucial role in defining the final wine composition (Jones & Davis, 2000; Leolini et al., 2019). The gluco-acidimetric index (S/A), calculated as the ratio between sugar concentration and total acidity, is widely used to assess the technological maturity of grapes and determine the optimal harvest time (Segade et al., 2008; van Leeuwen et al., 2022). This index provides a comprehensive measure of grape ripeness, integrating both sugar accumulation and acid degradation processes.

As shown in Figure 4, the S/A index exhibited different evolutionary trends over the three analyzed years (2021-2023), highlighting the significant impact of climatic conditions.

In 2021, the index showed a steady increase from 10.91 (August 15) to 33.88 (September 14). The gradual rise reflected a balanced ripening process, with no extreme drought conditions affecting grape development. The threshold for full maturity was reached between September 2-5, when the S/A index ranged between 23.81 and 25.12, corresponding to approximately 35-45 in sulfuric acid equivalents (Țârdea et al., 2000).

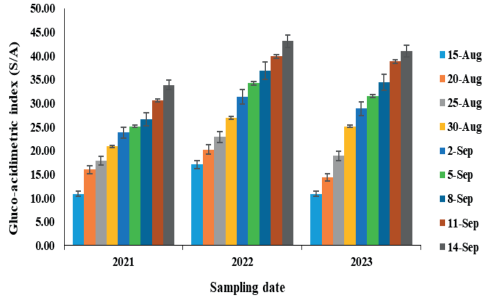

Figure 4. Evolution of the sugar-acid ratio of the grapes throughout the ripening period

In contrast, 2022 exhibited a more accelerated increase, from 17.08 (mid-August) to 43.12 (September 14). This rapid rise was indicative of high temperatures and low precipitation, which enhanced sugar accumulation and acid degradation. The technological maturity threshold was reached earlier than in 2021, between August 25-30 (values of 22.88-26.92). By September 5, the index had already exceeded 31, suggesting advanced ripeness and potential over-maturation. The faster decrease in acidity and intensified sugar concentration indicate that 2022 produced wines with higher alcohol content but lower acidity, impacting their sensory balance.

The year 2023, characterized by the most extreme drought conditions, displayed an initial slow progression (10.92 on August 15) followed by a rapid increase in late August and early September. By September 14, the S/A index had reached 41.05, confirming an advanced ripening phase. Compared to 2022, the maturation curve in 2023 was steeper, likely due to severe water stress, which intensified sugar accumulation while significantly reducing acidity. The early threshold of 25.14 (August 30) suggested a compressed ripening period, raising concerns about wine stability due to potential over-concentration effects.

Comparing these results with the Ștefănești viticultural region (Onache, 2017), where Z/A values ranged from 4.68 (August 15) to 27.20 (September 23), a significant delay in grape maturation was observed. The slower accumulation of sugars and prolonged retention of acidity confirm the influence of regional climatic differences, emphasizing the need for adapted harvest strategies based on local conditions.

The evolution of the gluco-acidimetric index across these three years demonstrates the strong influence of climatic factors on grape ripening.

pH Evolution During Grape Ripening

Another crucial parameter in assessing grape maturity is pH, as it directly influences the chemical stability, microbial resistance, and overall sensory profile of the resulting wine (Babincev et al., 2016; Leolini et al., 2019). Unlike total acidity, which measures all acid fractions, pH reflects the actual concentration of hydronium ions (H_3O^+), providing a more precise insight into must reactivity and fermentation conditions (Figure 5) (Chidi et al., 2018; Khalafyan et al., 2023).

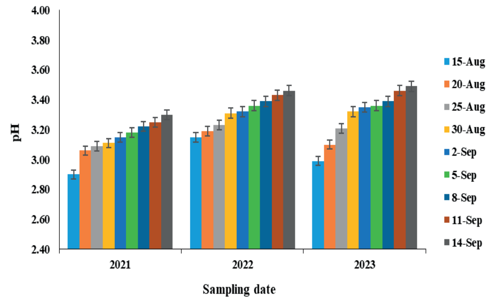

Figure 5. pH evolution in the grapes throughout the ripening period

In 2021, the pH increased gradually from 2.90 (August 15) to 3.30 (September 14), indicating a balanced ripening process. The steady progression suggests a well-regulated degradation of malic acid and accumulation of potassium ions, maintaining a stable acidity profile. This pH evolution, combined with moderate sugar accumulation (227.01 g/L) and a controlled decline in total acidity (13.40 g/L to 6.70 g/L), indicates a vintage suitable for producing fresh, well-structured wines with good aging potential.

The year 2022 exhibited a faster pH increase, starting at 3.15 (August 15) and reaching 3.46 (September 14). The accelerated decline in acidity (from 9.65 g/L to 6.01 g/L) and higher sugar accumulation (259.13 g/L) suggest a more intense ripening process, likely due to higher temperatures and reduced water availability. The elevated pH levels highlight

potential risks related to microbial stability, requiring careful sulfite management during winemaking.
In 2023, the pH evolution was even more pronounced, rising from 2.99 (August 15) to 3.49 (September 14), mirroring the effects of extreme drought conditions. Despite a slower acidity decline (12.80 g/L to 6.56 g/L), the significant increase in sugar content (269.31 g/L) suggests a rapid maturation period with concentrated must composition. Elevated pH values beyond 3.45 can compromise wine longevity and color stability, necessitating strict enological interventions to maintain freshness and structural balance (Chidi et al., 2018; Vicente et al., 2022).
Comparing these results with data from the Ștefănești region (Onache, 2017), where Fetească Neagră was harvested at a pH of 3.31 (September 23), it becomes evident that climatic conditions significantly impact pH evolution. The earlier pH increase observed in the Terasele Dunării region emphasizes the influence of temperature and water availability on acid degradation dynamics.
Additional insights come from Barbu et al. (2022), who reported a pH of 3.65 at harvest for healthy Fetească Neagră vines grown in Valea Călugărească (Dealu Mare). An interesting observation from the same study is that viral infections appeared to influence pH levels. Infected samples showed slightly lower pH values (ranging from 3.37 to 3.55) compared to the healthy control. pH can therefore serve not only as an indicator of wine stability but also as a potential marker of grapevine health.

Phenolic Maturity of the grapes

The two key indicators used in this study were anthocyanin content and the total polyphenol index (TPI).

Anthocyanins Content

Anthocyanins are the primary pigments responsible for the color of red grapes and wines. Their accumulation follows a characteristic pattern during ripening, influenced by genetic factors, climatic conditions, and vineyard management (Garrido & Borges, 2013; Río Segade et al., 2008). As shown in Figure 6, anthocyanin levels varied significantly between years.

In 2021, anthocyanin content increased steadily from 461 mg/kg (August 15) to 776 mg/kg (September 14), reflecting a balanced ripening process. The accumulation rate was highest between August 15-30, followed by a plateau in early September, indicating optimal color development.

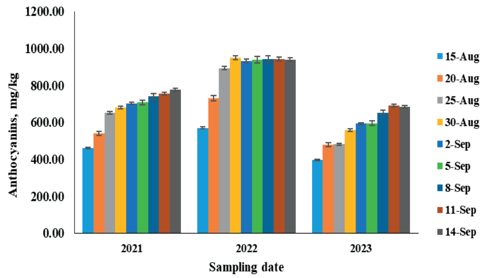

Figure 6. Evolution of anthocyanin accumulation in the grapes throughout the ripening period

The year 2022 exhibited a more rapid accumulation, with anthocyanin levels reaching 950 mg/kg by August 30. The plateau was reached earlier than in 2021, suggesting an accelerated ripening process driven by higher temperatures and moderate drought conditions. This rapid accumulation required careful harvest timing to prevent anthocyanin degradation through oxidation.
In contrast, year 2023 displayed the lowest anthocyanin levels, with a slower accumulation rate and a final value of 692 mg/kg. Severe water stress likely hindered pigment biosynthesis, leading to reduced color potential in the resulting wines. The combination of high temperatures and desiccation effects may have suppressed anthocyanin formation despite high sugar concentrations.
In Ștefănești vineyard (Dealurile Munteniei), Fetească Neagră grapes accumulated only 508 mg/kg of anthocyanins at harvest (Onache, 2017), significantly lower than values recorded in the Terasele Dunării region. Similarly, Cabernet Sauvignon in Ștefănești contained 521 mg/kg, a much lower amount than the 1367 mg/kg reported in the warmer Miniș vineyard (Țârdea et al., 2000). In contrast, in the Drăgășani region, anthocyanin content in Fetească Neagră varied between 1208-1346 mg/kg, while Cabernet Sauvignon accumulated 1461-1570 mg/kg (Tutulescu & Popa, 2020).

These variations highlight the strong influence of local climatic conditions on phenolic maturity.

Total Polyphenol Index (TPI) Determination

The Total Polyphenol Index (TPI) is a crucial parameter in assessing the phenolic maturity of grapes, directly impacting the quality of red wines. Alongside anthocyanins, grapes contain a variety of phenolic compounds, including tannins and flavonoids, which significantly influence wine structure, astringency, aromatic complexity, stability, and aging potential (Garrido & Borges, 2013; Gil et al., 2019; Ortega-Regules et al., 2008). Monitoring the accumulation of these compounds during grape ripening provides valuable insights for determining the optimal harvest time and adjusting vinification processes accordingly (Ghanem et al., 2014; Gutiérrez-Escobar et al., 2021; Martínez-Moreno et al., 2021).

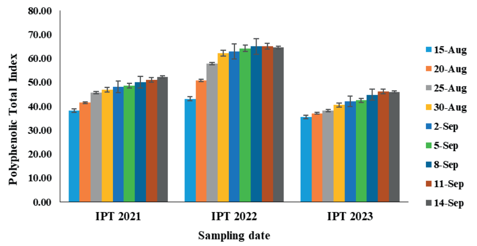

Figure 7. Evolution of the Total Polyphenol Index (TPI) in the grapes throughout the ripening period

The TPI estimation method, based on absorbance measurements at 280 nm, was chosen for its rapidity and practicality, making it a widely used tool in wineries for quick evaluations of grape phenolic potential. This method relies on the ability of polyphenols to absorb ultraviolet light due to their conjugated aromatic structures (Aleixandre-Tudo et al., 2017; Ribéreau-Gayon et al., 1983; Terblanche, 2019). While it does not allow for a detailed characterization of individual phenolic classes, it provides a reliable global assessment of total polyphenol content, serving as an essential indicator for technological decisions.

The TPI evolution during the three consecutive vintages (2021-2023) is presented in Figure 7. In 2021, TPI showed a steady increase from 38.20 on August 15 to 52.30 on September 14, indicating a balanced ripening process with progressive phenolic accumulation. Unlike anthocyanins, which exhibited more pronounced increases in the latter part of maturation, TPI followed a more uniform trend, confirming that, in addition to anthocyanins, other polyphenols (tannins, flavonoids, phenolic acids) contributed significantly to the overall phenolic composition.

In contrast, 2022 exhibited the highest TPI values among the three years, starting at 43.10 on August 15 and reaching a maximum of 65.10 on September 11. This rapid increase indicates an intense accumulation of polyphenols, favored by the warm and dry climatic conditions of that year, which accelerated grape ripening (Meléndez et al., 2013; van Leeuwen et al., 2022). The correlation between high anthocyanin levels (950 mg/kg) and TPI values suggests that increased temperatures and moderate drought stimulated flavonoid biosynthesis and polyphenol accumulation. However, while a higher TPI indicates a richer phenolic composition, it also requires careful winemaking adjustments to manage tannin extraction and avoid excessive astringency in the final wines (Ortega-Regules et al., 2008; Segade et al., 2008).

The 2023 vintage, characterized by extreme drought conditions, recorded the lowest TPI values, with an initial measurement of 35.50 on August 15 and a peak of 46.20 on September 11. The slower accumulation rate compared to previous years suggests that water stress limited polyphenol biosynthesis, possibly due to structural alterations in grape skins affecting extractability. Although tannins are generally more resistant to climatic variations than anthocyanins, the severe conditions of 2023 may have reduced their extractability, influencing wine composition and sensory properties (Garrido and Borges, 2013; Ortega-Regules et al., 2008; Yamane et al., 2006).

Comparisons with other viticultural areas further highlight the influence of climatic factors on TPI evolution. In the Ștefănești region, Fetească Neagră grapes had a TPI of 33.21 at harvest (September 23, 2017), significantly lower than the values recorded in the Terasele Dunării region, particularly in 2022 (Onache, 2017). Additionally, Cabernet Sauvignon grapes in Ștefănești showed a TPI of

45.96 on September 25, 2017, higher than Fetească Neagră, emphasizing the varietal differences in tannin content (Ortega-Regules et al., 2008). In another Romanian region, Valea Călugărească (Dealu Mare), the 2022 harvest recorded a TPI of 42.00, reinforcing the notion that climatic conditions and terroir significantly influence polyphenol accumulation (Barbu et al., 2022).

The findings indicate that TPI did not fluctuate as dramatically as anthocyanins across different vintages. This stability can be attributed to the fact that certain polyphenols, such as tannins, are less susceptible to climatic variations compared to anthocyanins. While moderate climatic stress can enhance polyphenol biosynthesis, extreme drought conditions, as seen in 2023, can hinder their accumulation and extractability. These results underline the importance of precise phenolic maturity monitoring and tailored winemaking strategies to optimize polyphenol extraction and balance wine structure (Martínez-Moreno et al., 2021; Zufferey et al., 2017).

CONCLUSIONS

This study provides a comparative assessment of the ripening dynamics of Fetească Neagră grapes over three consecutive harvests (2021-2023), emphasizing the technological and phenolic maturity parameters critical to wine quality. The results revealed that climatic conditions exert a strong influence on grape ripening patterns, with 2021 allowing for extended maturation, 2022 leading to rapid sugar accumulation and early harvest decisions, and 2023 experiencing extreme drought that impacted anthocyanin synthesis and phenolic stability. Harvest timing and staggered harvesting approaches played a key role in maintaining grape and wine balance, ensuring optimal sugar-acid ratios and phenolic extraction. Maceration strategies varied across vintages, with 2021 utilizing a post-fermentative maceration approach, 2022 incorporating cold pre-fermentative maceration to control phenolic extraction, and 2023 employing a three-phase maceration process to counteract phenolic instability due to climatic stress. Additionally, nitrogen content was monitored throughout the study, revealing differences between years that could have implications for fermentation dynamics and overall enological outcomes.

The study underscores the necessity of real-time monitoring and adaptive decision-making in vineyard management, particularly in the context of climate variability. Future research should focus on integrating predictive viticultural models and enological adjustments to optimize harvest strategies, ensuring both wine stability and sensory quality under changing environmental conditions.

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