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From vine to wine I: ripening dynamics of Divico, a new disease-resistant variety with high oenological potential

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ABSTRACT

The susceptibility of *Vitis vinifera* grape varieties to fungal diseases has initiated the development of resistant cultivars. Divico, a fungus-resistant variety, demonstrates high resistance to downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and grey mould (*Botrytis cinerea*). Evidence from empirical vinification demonstrates that Divico can produce red wine with a high anthocyanin content and promising sensory qualities. However, no published data currently describe its berry ripening dynamics, despite the importance of this parameter for wine quality. This study investigates the ripening dynamics of Divico grapes over four vintages (2019 – 2022) in two Swiss vineyards located in Leytron and Pully. The focus is on the temporal evolution of key berry composition parameters, including sugars, organic acids, pH, and phenolic compounds (total polyphenol index and anthocyanin concentration). Climatic variability between vintages was taken into account. The results confirmed that Divico berries accumulated high anthocyanin concentrations (> 3000 mg/kg) and exhibited stable sugar levels at the ripening plateau. At full maturity, the pH values of Divico berries remained stable regardless of vintage, with values of 3.3 at Leytron and 3.1 at Pully, demonstrating a consistent response across varying climatic conditions. These findings highlight the potential of Divico grapes for sustainable viticulture, offering high-quality potential grapes with resilience to fungal diseases and flexibility in harvest timing.

KEYWORDS: robust variety, fungus resistant grapevine varieties, grape maturity monitoring, Divico, modelling

INTRODUCTION

The susceptibility of *Vitis vinifera* grape varieties to fungal diseases requires the use of pesticides that are harmful to the environment and human health. Societal demand for more sustainable viticulture has prompted researchers in various countries to set up breeding programs to obtain fungus-resistant grape varieties (FRV) that are more tolerant to the main fungal diseases of the vine, such as downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*). Divico is a red grape variety resulting from a 1997 cross between Gamaret (Agroscope's intraspecific cross strain, Gamay × Reichensteiner) and Bronner. It inherited multiple quantitative trait loci for fungus resistance: *Rpv*10, *Rpv*3.3 for downy mildew, *Ren*3, *Ren*9 for powdery mildew, and *Rgb*1 for black rot (*Guignardia bidwellii),* and has a low sensitivity to grey rot (*Botrytis cinerea*) (Spring *et al*., 2013).

The data presented in Spring *et al*. (2013) were based on a trial conducted on Divico since 2003, focusing on its resistance to downy and powdery mildew, productivity, phenology, and must quality potential. Divico's resistance to downy mildew was shown to be based on its ability to rapidly synthesise pterostilbene, a compound involved in defence mechanisms to combat the fungal diseases on both leaves and bunches. Furthermore, the structure and composition of the waxes covering the surface of the vine's green parts appear to contribute to resistance to powdery mildew. In Divico, the surface is highly cross-linked with a granular crystallisation pattern, which may explain its good resistance to powdery mildew. The authors also demonstrated that the tangential layer of the Divico berry skins is strong (comparable to that of Gamaret), thus contributing to Divico's very good resistance to Botrytis. Productivity of Divico is satisfactory, with a yield ranging from 0.6 kg/m^2 to 1 kg/m^2 depending on planting density (Spring *et al*., 2013). Regarding phenology, its budbreak is considered early, similar to Pinot noir. Its ripening is classified in the first period according to the ampelographic classification of Pulliat, which places it in the same group as Chasselas, Pinot noir, and Gamaret (Pulliat, 1888; Spring, 2014). Compared to Pinot noir, which is susceptible to grey rot, Divico benefits from a later harvest, which enhances the structure, tannin quality, and complexity of the wines. However, no monitoring of ripening was performed in this first study. Currently in Switzerland, resistant grape varieties account for 3.7 % of the total vineyard area (Blackford *et al*., 2026). Approved in 2013, Divico is the leading disease-resistant grape variety in Switzerland by planted area (OFAG, 2025). With 104 ha recorded in 2024, Divico accounts for over a third of all disease-resistant red grapes planted in the country. Winegrowers are showing a growing interest in cultivating Divico. Their observations have raised new questions about this grape variety, which require scientific answers based on solid data, particularly regarding the monitoring of its ripening from both a technological and phenolic standpoint, as well as winemaking methods adapted for Divico.

The quality of a red wine is intrinsically linked to the composition of the grape berries at the time of harvest. During ripening, the berries undergo a complex evolution of their metabolites, both primary (sugars and acids) and secondary (phenolic compounds, flavour precursors, and aromas), which directly influence the organoleptic characteristics of the wine. The accumulation of sugars is key in the maturation process. They are transported via the phloem to the berry, where their concentration increases until they reach a plateau (Conde *et al*., 2007; Coombe & McCarthy, 2000; Ollat *et al*., 2002; van Leeuwen *et al*., 2022), which marks the end of active sugar loading. Any subsequent increase in sugar content is then solely due to dehydration of the berry (Conde *et al*., 2007). Organic acids, mainly tartaric acid and malic acid, also play crucial roles. In general, their concentrations increase before veraison and decline afterwards. Tartaric acid decreases through dilution, linked to an increase in berry volume (Ollat *et al*., 2002) or the enhanced precipitation of potassium hydrogen tartrate inside the berry (Rösti *et al*., 2018). In contrast, malic acid concentration gradually decreases after veraison, as it is metabolised during cell respiration (Ollat *et al*., 2002; Rienth *et al*., 2016; Rösti *et al*., 2018).

Secondary metabolites, such as polyphenols, contribute to the complexity and typicity of wine. After decreasing at veraison, total polyphenols measured by the Folin–Ciocalteu method stabilise at the end of ripening (Conde *et al*., 2007; Holt *et al*., 2010). Anthocyanins, the pigments responsible for red colour, increase after veraison, reaching a maximum that varies according to vintage and grape variety (Allegro *et al*., 2021; Bautista-Ortín *et al*., 2006; Conde *et al*., 2007; Fournand *et al*., 2006; Holt *et al*., 2010). Once the peak anthocyanin accumulation is reached, the anthocyanin concentration decreases, resulting in an inverted U-shaped curve that illustrates the changes in anthocyanin levels during ripening (De Montmollin *et al*., 2004; De Montmollin *et al*., 2007; Ortega-Regules *et al*., 2008). Swiss researchers De Montmollin *et al*. (2004) confirmed that Gamaret wines made from grapes harvested one to two weeks after the peak of anthocyanin accumulation exhibited significantly higher quality in terms of aromas and roundness in the mouth compared to those harvested at other stages of ripeness. Since this study, anthocyanin accumulation in Switzerland has been monitored to help producers determine the optimal harvest date for several red grape varieties, notably Gamaret, Cabernet-Sauvignon, Gamay, and Syrah. However, the study conducted by this same group of researchers did not identify a relevant criterion to aid in the decision to harvest Pinot noir, as the anthocyanin accumulation curve for this grape variety lacked a distinct accumulation peak, showing instead a continuous progression unlike the clear patterns observed in the other varieties mentioned above (Dupraz *et al*., 2008). Moreover, ripening is a crucial stage in the development of aromas and aroma precursors, which are essential for defining a wine's quality and typicity (van Leeuwen *et al*., 2022). Therefore, assessing ripeness requires more than just measuring sugar concentration (Conde *et al*., 2007); other parameters must

also be considered. van Leeuwen *et al*. (2022) summarised the different types of ripeness: technological ripeness (assessed based on the sugar/acid ratio); phenolic ripeness, which takes into account anthocyanin content (maximum at maturity), and extractable tannin quality (a modulator of the sensory quality of the wine); and aromatic ripeness.

Given this multifaceted evolution of primary and secondary metabolites, relying on simple observational data is often insufficient to capture the full dynamics of ripening. Consequently, several researchers have developed mathematical models to describe ripening curves, particularly for sugar accumulation. These models allow for precise comparisons between grape varieties and enable the assessment of how environmental and agronomic factors such as nitrogen status or rainfall influence ripening dynamics (de Rességuier *et al*., 2024; Plantevin *et al*., 2024; Suter *et al*., 2021).

Although the maturity of *Vitis vinifera* cultivars has been extensively studied, less information is available regarding newer varieties, particularly those resistant to fungal diseases. This raised a critical question: do FRVs like Divico follow maturation trajectories similar to established varieties, or do they exhibit distinct kinetic patterns? To address this issue, the present study monitored primary metabolites during the ripening of Divico berries and compared their kinetics with those of Pinot noir, a reference variety selected due to its shared classification in the first group of Pulliat's ampelographic classification and its prevalence in Swiss and international vineyards. Subsequently, the evolution of phenolic maturity and secondary metabolites was analysed to understand Divico's specific ripening patterns better. To this end, the analysis integrated both established models from the literature and novel kinetic models developed specifically for this study.

MATERIALS AND METHODS

1. Grapes

The Divico grapes studied in this article came from two Agroscope experimental vineyards in Leytron (46°10' N, 7°12' E; 485 m asl), Valais, and Pully (46°30' N, 6°39' E; 465 m asl), Vaud, Switzerland. The vines were not irrigated at any point during the trial, in either Pully or Leytron. The experimental site in Leytron was on very stony (PEYROSOL > 60 % coarse elements, namely stones, blocks, and gravel) and deep soil (> 2.5 m vine root depth) with a water-holding capacity estimated at 150 mm. The experimental site in Pully was on deep, clayey (> 15 %) sandy soil without stones. The water-holding capacity was estimated at 200 mm. Divico planted in 2010 in Leytron and in 2016 in Pully were grafted onto rootstock 3309C and were trained using a single Guyot training system (200 × 90 cm for Leytron and 200 × 85 cm for Pully). The Pinot noir (clone RAC 12) planted in 2012 in Leytron and 2011 in Pully were grafted onto rootstock 3309C and were trained using a single Guyot training system (180 × 90 cm for Leytron and 190 × 90 cm for Pully).

2. Ripeness monitoring

After veraison, berry sampling was conducted randomly on a row of 52 vines, ensuring representation from both upper and lower bunch zones and both sides of the row. To avoid bias, only one berry was harvested per bunch. Samples were split into two subsets: 300 berries for technological ripeness and 200 for phenolic ripeness. Technological ripeness was measured across four vintages (2019–2022). Berries were weighed, crushed, and the resulting juice was centrifuged (2224 rcf for 15 min at 20 °C). pH and total acidity (titrated with NaOH to pH 7.00) were determined, while sugar content (°Brix) was measured by a refractometer (ATAGO CO., LTD, Japan). Tartaric acid, malic acid, and assimilable nitrogen were quantified using a WineScan™ (FOSS, Hillerød, Denmark).

Phenolic ripeness was assessed in Divico over three vintages (2019, 2020, and 2022) using the Institut Français de la Vigne et du Vin (IFV) method (Cayla *et al*., 2002; Fragoso *et al*., 2011; Vinsonneau *et al*., 2008). The 200 berries were crushed, and a 50 g sample was macerated in an acid hydroalcoholic solution (85 mL of HCl 0.1 % *v/v* and 15 mL of ethanol 96 %) in a 250 mL flask for 1 h under gentle agitation on a stirring plate (30 rpm). The macerate was then centrifuged, and the supernatant was analysed to measure the Total Polyphenol Index (TPI) at 280 nm, and the extractable anthocyanin concentration was quantified via the Puissant–Léon method at 520 nm (Puissant & Léon, 1967). Both measures were carried out using an Agilent Cary 60 spectrophotometer (Agilent Technologies), and all analyses were performed in duplicate.

3. Climatic conditions

Monthly precipitation and mean and maximum air temperature data from 1 April to 31 October during the study period (2019–2022) were retrieved from MétéoSuisse (www.meteosuisse.admin.ch), from the Sion station for Leytron and the Pully station for Pully. Supplementary Figure 1 presents a comparison of meteorological conditions from April to October across four vintages at the Leytron and Pully sites, relative to the 1991–2020 averages.

4. Ripening data modelling

The choice of the modelling approach for each trait was based on the typical shape of its temporal evolution during berry ripening. Variables showing a progressive accumulation towards a plateau (sugar) were modelled using a logistic function, variables characterised by a rapid decline approaching a minimum asymptote (total acidity and malic acid) were described using exponential decay models, variables exhibiting approximately linear trends during the observation period (tartaric acid and pH) were fitted with linear regressions, and variables showing a transient peak accumulation (anthocyanins) were modelled using a Gaussian function.

4.1. Sugar

Sugar accumulation modelling was performed using previously described 3-parameter logistic function (de Rességuier *et al*., 2024; Suter *et al*., 2021) [Equation 1]:

$$S(DOY) = \frac{Smax}{1+0.005.e^{(-4.k_{sugar}.\left(\frac{DOY-DOY95\%_{sugar}}{Smax}\right))}} \quad \text{(Equation 1)}$$

where Smax is the estimated maximum sugar concentration (°Brix), DOY is the day of the year, $DOY95\%_{sugar}$ is the DOY when 95 % of the maximum sugar has accumulated, and k_{sugar} is the estimated maximum rate of accumulation (°Brix per day). The sugar concentration (Brix) at $DOY_{95\%}$ (Plateau 95 %), and the number of days between $DOY_{95\%}$ and veraison ($Dur_{95\%\text{-}Ver}$) were also calculated and used as agronomic indicators of grape ripening.

4.2. Total acidity and malic acid

Total acidity and malic acid generally decrease rapidly after veraison before approaching a minimum residual concentration at maturity. An exponential decay model with an asymptote was therefore selected to capture this behaviour (Equation 2 and Equation 3):

$$TA = a.e^{(k_{TA}.DOYcentered)} + TA_{asymp} \quad \text{(Equation 2)}$$

$$Mal_ac = a.e^{(k_{Mal_ac}.DOYcentered)} + Mal_ac_{asymp} \quad \text{(Equation 3)}$$

where a, k, and asymptotic concentration (TA_{asymp} and Mal_ac_{asymp}) are the parameters estimated for each variable, total acidity (g of tartaric acid/L) and malic acid concentration (g/L), by nonlinear regression (nls function in R). To improve the numerical stability of the exponential model fit, the day of the year (DOY) was centred on the first measurement point for each year-cultivar combination, so that DOYcentred = 0 corresponds to the start of the monitoring period for each Grape Variety/Location/Year. Parameters k_{TA} and k_{Mal_ac} represent the speed at which total acidity and malic acid concentration, respectively, decrease during berry ripening, and are expressed in units of inverse days (day^{-1}). TA_{asymp} and Mal_ac_{asymp} represent the minimum asymptotic value of total acidity or malic acid concentration. $DOY95\%_{TA}$ was calculated and corresponds to the day of the year when total acidity reaches 95 % of its final asymptotic value, estimated by the exponential model. It thus reflects the total acidity at the end of maturation.

4.3. Tartaric acid and pH

Preliminary inspection of the data indicated approximately linear trends over the monitored ripening period. Consequently, linear models were used to describe the evolution of tartaric acid concentration and pH (Equation 4 and Equation 5):

$$Tart_ac = k_{Tart_{ac}} \cdot DOY + b_{Tart_ac} \quad \text{(Equation 4)}$$

$$pH = k_{pH}.DOY + b_{pH} \quad \text{(Equation 5)}$$

where the slopes k_{Tart_ac} and k_{pH} and the y-intercepts (estimated initial values) b_{Tart_ac} and b_{pH} were estimated by linear regression (function lm in R). The slopes were used as agronomic indicators.

4.4. Anthocyanin

Anthocyanin accumulation is characterised by an increase during ripening followed by stabilisation or decline near harvest, resulting in a bell-shaped temporal pattern. A Gaussian model was therefore used to estimate the timing and magnitude of peak anthocyanin accumulation and was fitted separately for each domain–vintage combination. The model adopted follows the form (Equation 6):

$$Anthocyanin = Max_{antho}.e^{(-\frac{(DOY-DOY_{peak})^2}{2\sigma^2})} \quad \text{(Equation 6)}$$

where Max_{antho} represents the maximum amplitude of anthocyanins, DOY_{peak} the day of the year (DOY) corresponding to the peak accumulation, and σ the peak width, reflecting the rate of accumulation and degradation. The parameters were estimated by nonlinear regression (nls function in R). The number of days between DOY_{peak} and mid-veraison date ($Dur_{Peak\text{-}Ver}$) was also calculated and used as agronomic indicators.

5. Statistical analyses

5.1. Model performance assessment

The adequacy of the models was assessed using the coefficient of determination (R^2), the Pearson correlation coefficient (r) and the root mean square error (RMSE). R^2 quantifies the proportion of the variance in the response variable explained by the "model r" reflects the strength of the linear association between observed and predicted values; and RMSE measures the average prediction error, calculated as the square root of the mean of the squares of the residuals (differences between observed and predicted values).

5.2. Inferential statistical analyses

The influence of grape variety, location, and vintage on agronomic indicators ($DOY95\%_{sugar}$, Plateau95%, $Dur_{95\%\text{-}Ver}$, k_{sugar}, k_{TA}, TA_{asymp}, $DOY95\%_{TA}$, k_{Mal_ac}, Mal_ac_{asymp}, $DOY95\%_{Mal_ac}$, k_{Tart_ac}, and k_{pH}) was studied using a mixed linear model (lmer function from the lme4 package; Bates *et al*., 2015). Grape variety and location were treated as fixed effects to quantify their average effects on the response variable, while vintage was included as a random effect on the intercept in order to model the interannual variability not captured by the fixed effects. To assess model performance, we calculated both the marginal R^2 (variance explained by fixed effects only) and the conditional R^2 (variance explained by both fixed and random effects), following the method of Nakagawa and Schielzeth (2013). This distinction allows quantifying the specific contribution of climatic variability (vintage) to the total variance. Interactions between fixed effects (grape variety × location) were also taken into account. When the linear mixed-effects model including vintage as a random effect failed to converge, typically

due to a limited number of observations per vintage or low interannual variability, a classical linear model including grape variety, location, and their interaction as fixed effects was fitted instead. For the anthocyanin, due to the low number of replicates per group, only simple linear models (lm in R) were used to assess the effect of location and vintage on each anthocyanin parameter (Max_{antho}, DOY_{peak}, σ, and $Dur_{Peak\text{-}Ver}$) separately.

For each parameter, the model coefficients, their standard errors, *t*-values, and *p*-values were calculated to assess the statistical significance of each predictor. All model coefficients were estimated relative to the reference group, Pinot noir, harvested in Leytron during the 2019 vintage.

An analysis of variance (ANOVA) was then performed on the adjusted model to test the overall significance of the fixed effects (car package; Fox & Weisberg, 2019). The normality of the residuals was assessed using the Shapiro-Wilk test, and homoscedasticity was visually verified from the graph of the residuals as a function of the fitted values. In cases where the normality of the residuals was not met, a non-parametric approach was adopted: a Kruskal–Wallis test was applied to assess the overall differences between the levels of the fixed factors, followed by a Dunn test for pairwise comparisons, with Bonferroni correction for multiple comparisons, using the rstatix package (Kassambara, 2025).

RESULTS AND DISCUSSION

1. Ripening modelling

As described in Materials and Methods, different models were used to describe temporal dynamics and assess the influence of grape variety, vineyard location, and vintage. As shown in Table 1, for each parameter, the model chosen showed good to excellent fit, as indicated by low RMSE, high R^2 (> 0.88), and strong Pearson correlation between observed and predicted values (> 0.94). These results confirm that the models accurately captured the temporal dynamics of all parameters.

TABLE 1. Performance metrics of the ripening model for the different response variables.

	Model type	RMSE	R^2	Pearson r
Sugar [°Brix]	Ascending sigmoid	0.43	0.981	0.990
Total acidity1 [g/L]	Decreasing exponential	0.45	0.988	0.994
Malic acid [g/L]	Decreasing exponential	0.22	0.995	0.997
Tartaric acid [g/L]	Linear	0.54	0.933	0.966
pH	Linear	0.06	0.924	0.954
Anthocyanin [mg/kg]	Gaussian	80	0.886	0.941

[1] Expressed in tartaric acid.

2. Sugar accumulation

Observed values and modelled values of sugar accumulation of Pinot noir and Divico grapes are presented in Figure 1, while ANOVA and Kruskal–Wallis results for the accumulation parameters are detailed in Table 2 and Table 3, respectively. The models demonstrated a strong fit for sugar accumulation (RMSE = 0.43 °Brix, R^2 = 0.981; Table 1), accurately capturing the sigmoidal trajectory typical of grape ripening.

The Kruskal–Wallis test revealed a significant difference in sugar concentration at the end of ripening (Plateau95%) between the two varieties. The Dunn test for pairwise comparisons revealed that Divico berries showed a value approximately 2 °Brix lower (–1.995) than that of Pinot noir (Table 3). Furthermore, the linear model for sugar accumulation rate (k_{sugar}) indicated a tendency toward a slower accumulation in Divico compared to Pinot noir (–0.20 °Brix/day, p = 0.093) (Table 2). Notably, no significant effect of location or the variety × location interaction was detected for these parameters, suggesting that the varietal trajectory of Divico remains consistent across the studied terroirs. This trajectory distinctly attained a plateau at the end of ripening, indicating a stabilisation of sugar levels consistent with similar patterns observed in other varieties such as Shiraz or Petit Verdot (Coombe & McCarthy, 2000; Suter *et al*., 2021). The minimal increase in sugar concentration during late ripening suggests a low rate of berry dehydration. A similar observation was recorded for Gamaret, one of Divico's parent varieties, as well as in other powdery and downy mildew-resistant grape varieties, which showed a nearly stable sugar content at the end of ripening (Bigard *et al*., 2019; De Montmollin *et al*., 2004; De Montmollin & Dupraz, 2003). This stabilisation could be attributed to the particularly robust skin structure of Divico, comparable to that of Gamaret, which limits water permeability and delays dehydration (Spring *et al*., 2013). However, this hypothesis remains to be verified.

While varietal genetics set the baseline potential, the vintage effect emerged as the primary driver of ripening timing (DOY95%). The mixed linear model revealed that fixed effects (grape varieties and location) accounted for only 16.4 % of the variability (marginal R^2), whereas including the random vintage effect increased the explained variance to 56.0 % (conditional R^2). This substantial increase underscores the profound influence of interannual climatic fluctuations on the phenology of Divico, indicating that year-to-year climate variations explain more than half of the observed variability in maturity dates.

This climatic dependency is illustrated in Figure 1. Compared with the 1991–2020 reference period, 2019 was characterised by a warmer-than-average growing season, despite cooler temperatures during spring (April–May). Summer temperatures were high, and precipitation remained close to normal, except for particularly dry conditions in September, especially at Pully. In 2020, a warm spring was followed by summer temperatures close to the long-term

TABLE 2. ANOVA results for fixed (grape variety and location and their interaction) and random effects of vintage on maturity parameters.

	Explained variable	Fixed effect	Estimate	Std. error	F value	Pr(>F) *p*-value		Random effect	Std. Dev.	R^2conditional	R^2 marginal
Sugar accumulation	$DOY95\%_{sugar}$	Intercept	252.45	11.54				Vintage	15.88	56.0 %	16.4 %
		Grape variety	3.05	11.84	1.658	0.230	ns	Residual	16.74		
		Location	22.96	11.84	1.193	0.303	ns				
		Grape variety × Location	–27.65	16.74	2.728	0.133	ns				
	k_{sugar}	Intercept	0.54	0.06				Vintage	-		33.0 %
		Grape variety	–0.20	0.08	3.336	0.093	°	Residual	-		
		Location	–0.07	0.08	0.113	0.743	ns				
		Grape variety × Location	0.19	0.12	2.503	0.140	ns				
Total acidity	k_{TA}	Intercept	–0.09	0.01				Vintage	0.016	71.10 %	31.40 %
		Grape variety	0.03	0.01	16.120	0.003	**	Residual	0.014		
		Location	0.004	0.01	0.088	0.774	ns				
		Grape variety × Location	–0.004	0.01	0.087	0.775	ns				
	TA_{asymp}	Intercept	4.56	0.29				Vintage	0.39	71.50 %	46.40 %
		Grape variety	0.57	0.30	20.936	0.001	**	Residual	0.42		
		Location	–0.44	0.30	0.053	0.824	ns				
		Grape variety × Location	0.77	0.42	3.420	0.097	°				
Malic acid concentration	k_{Mal_ac}	Intercept	–0.12	0.02				Vintage	0.03	69.90 %	65.90 %
		Grape variety	0.03	0.02	5.103	0.065	°	Residual	0.02		
		Location	0.01	0.03	0.026	0.877	ns				
		Grape variety × Location	–0.02	0.02	0.695	0.436	ns				
	Mal_ac_{asymp}	Intercept	2.08	0.19				Vintage	0.28	77.30 %	52.10 %
		Grape variety	–0.33	0.19	26.104	0.001	***	Residual	0.27		
		Location	0.21	0.19	1.266	0.290	ns				
		Grape variety × Location	–0.71	0.27	7.096	0.026	*				
Tartaric acid	k_{Tart_ac}	Intercept	–0.15	0.01				Vintage	0.02	87.30 %	39.50 %
		Grape variety	0.05	0.01	22.685	0.003	**	Residual	0.01		
		Location	0.01	0.01	0.030	0.868	ns				
		Grape variety × Location	–0.02	0.01	3.226	0.123	ns				
pH	k_{pH}	Intercept	0.02	1.87×10^{-3}				Vintage	-		74.9 %
		Grape variety	–0.01	2.65×10^{-3}	42.995	2.70×10^{-5}	***	Residual	-		
		Location	1.50×10^{-3}	2.65×10^{-3}	0.116	0.739	ns				
		Grape variety × Location	-2.70×10^{-3}	3.75×10^{-3}	0.581	0.461	ns				

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05 '°' 0.1; Intercept (Pinot noir × Leytron × 2019); Linear mixed model: X ~ Grape variety * Location + (1|Vintage); Linear model: X ~ Grape variety * Location.

TABLE 3. Kruskal–Wallis results for fixed (grape variety and location and their interaction) on maturity parameters.

Explained variable	Factor	H statistic	*p*-value	
Plateau95%	Grape variety	3.982	0.046	*
	Location	0.397	0.529	ns
	Grape variety × Location	4.654	0.199	ns
$Dur_{95\%\text{-}Ver}$	Grape variety	0.176	0.674	ns
	Location	0.276	0.600	ns
	Grape variety × Location	0.993	0.803	ns
$DOY95\%_{TA}$	Grape variety	0.000	1.000	ns
	Location	0.397	0.529	ns
	Grape variety × Location	1.103	0.776	ns
$DOY95\%_{Mal_ac}$	Grape variety	0.000	1.000	ns
	Location	0.540	0.462	ns
	Grape variety × Location	1.081	0.782	ns

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05 '°' 0.1.

average, combined with below-average precipitation in July and August (Figure S1). In 2022, warm temperatures combined with low precipitation resulted in the earliest sugar accumulation patterns observed, consistent with an advanced ripening timeline. These conditions were associated with an earlier onset of sugar accumulation, as reflected in earlier monitoring dates and a leftward shift of the curves (Figure 1). Accordingly, the 2020 and 2022 vintages display lower DOY95% values. Finally, the 2021 season was characterised by below-average temperatures and abundant rainfall throughout the growing season. Correspondingly, berries exhibited slower ripening dynamics, consistent with a cooler and wetter vintage.

Although vintage strongly influenced the timing of ripening, its effect on final sugar concentration appeared less pronounced in Divico than in Pinot noir. Visual inspection of the ripening curves (Figure 1) suggests that Divico maintained a relatively stable sugar plateau across vintages, whereas Pinot noir exhibited greater variation in final sugar concentration between warm (2022) and cool (2021) years. Although this observation was not formally tested through a significant variety × vintage interaction, it may indicate the presence of physiological or morphological mechanisms that buffer sugar accumulation under contrasting climatic conditions. Reduced berry dehydration, consistent with the plateau observed during late ripening, represents one possible explanation. If confirmed, such traits could help limit excessive sugar accumulation and associated increases in potential alcohol content under future climate warming scenarios.

With regard to the duration between veraison and the 95 % sugar accumulation stage ($Dur_{95\%\text{-}Ver}$), no significant effect of grape variety, location or the grape variety × location interaction was observed (Table 3). The vintage effect could not be included in the full model due to a lack of convergence; therefore, a simple linear model was retained, explaining 33 % of the variance and suggesting that other unmodeled factors may influence this parameter.

Overall, the results indicate that climatic conditions substantially affect the rate and timing of Divico berry maturation, as observed in traditional grape varieties (Holt *et al*., 2010). Warm and dry vintages, such as 2020 and 2022, accelerated ripening and allowed berries to reach their final sugar concentrations earlier in the season. However, this did not result in excessive sugar accumulation, thereby limiting potential alcohol levels. Conversely, cooler and wetter vintages, such as 2021, delayed the maturation of the grapes.

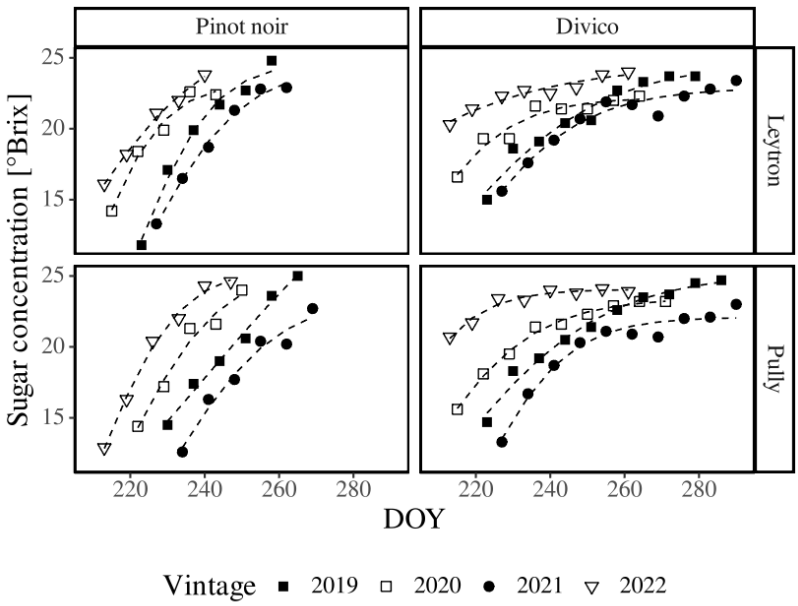


FIGURE 1. Sugar accumulation during ripening of Pinot noir and Divico grapes: observed values (points) and modelled values (dashed lines).

3. Evolution of Acidity and Organic Acid Concentrations

3.1. Total acidity

The modelling of total acidity was performed using an exponential decay model with an asymptote, and curves are shown in Figure 2A. Analysis of k_{TA} values, the speed at which total acidity decreased during berry ripening, revealed a significant grape variety effect ($p < 0.01$) (Table 2). The positive coefficient for Divico (+ 0.03) indicated that the decrease in acidity was significantly smaller for this grape variety than for Pinot noir. This can largely be explained by the initial lower TA of Divico (Figure 2A). Although the interaction between grape variety and location was not statistically significant at the 5 % level ($p = 0.097$), post-hoc comparisons suggested that the variety effect was larger in Pully (–1.346; $p < 0.01$) than in Leytron (–0.571; $p = 0.516$) (Table S1). Moreover, for the asymptotic total acidity value (TA_{asymp}), a significant effect of grape variety was observed, with higher values for Divico than for Pinot noir at the end of ripening (+ 0.57 g/L, $p < 0.01$). The location effect and the grape variety × location interactions did not reach the significance threshold. The fixed effects explained 31.4 % of the variability of k_{TA} and 46.40 % of the variability of TA_{asymp}. Upon inclusion of the random vintage effect, the explained variance increased to over 71 %, demonstrating the significant impact of vintage on acid metabolism. This finding aligns with the sugar accumulation dynamics previously described, where specific climatic signatures dictated ripening precocity. The warm spring followed by a dry summer in 2020, and the combined heat and low precipitation in 2022, which drove the earliest sugar accumulation patterns, similarly precipitated an earlier onset of acid degradation. Consequently, the decline in total acidity for both 2020 and 2022 was temporally shifted earlier in the season compared to the cooler, wetter 2021 vintage and the 2019 season, which, despite a warm summer, experienced a cooler spring. The analysis of $DOY95\%_{TA}$ showed no effect of either grape variety or location (Table 3).

3.2. Malic acid

Malic acid evolution (Figure 2B) followed the expected catabolic trend, driven by reduced synthesis and accelerated respiration during ripening, a process known to intensify under hot conditions (Bindon *et al.*, 2014; Conde *et al.*, 2007). Statistical analysis of asymptotic values (Mal_ac_{asymp}) revealed a significant effect of grape variety ($p < 0.001$) and grape variety × location interaction ($p < 0.05$), demonstrating that the effect of grape variety depended on location (Table 2). Post-hoc comparisons showed that this difference was significant only in Pully ($p < 0.01$), where Divico had 1.04 g/L less malic acid than Pinot noir, while no significant difference was observed in Leytron ($p = 0.707$) (Table S2). With regard to the rate of decrease in malic acid, k_{mal_ac}, the model revealed a trend towards a significant effect of grape variety ($p = 0.065$), while the effect of location and the interaction between grape variety and location were not significant. Divico tended to show a slower decrease rate in malic acid during ripening, likely a consequence of its lower initial concentration (Figure 2B). Moreover, as for total acidity, the grape variety and the location did not significantly affect the $DOY95\%_{Mal_ac}$ (Table 3). Again, according to Figure 2B, the vintage effect can be seen as malic acid decreased in 2020 and 2022, both hot vintages, earlier in the season than in 2019 and 2021.

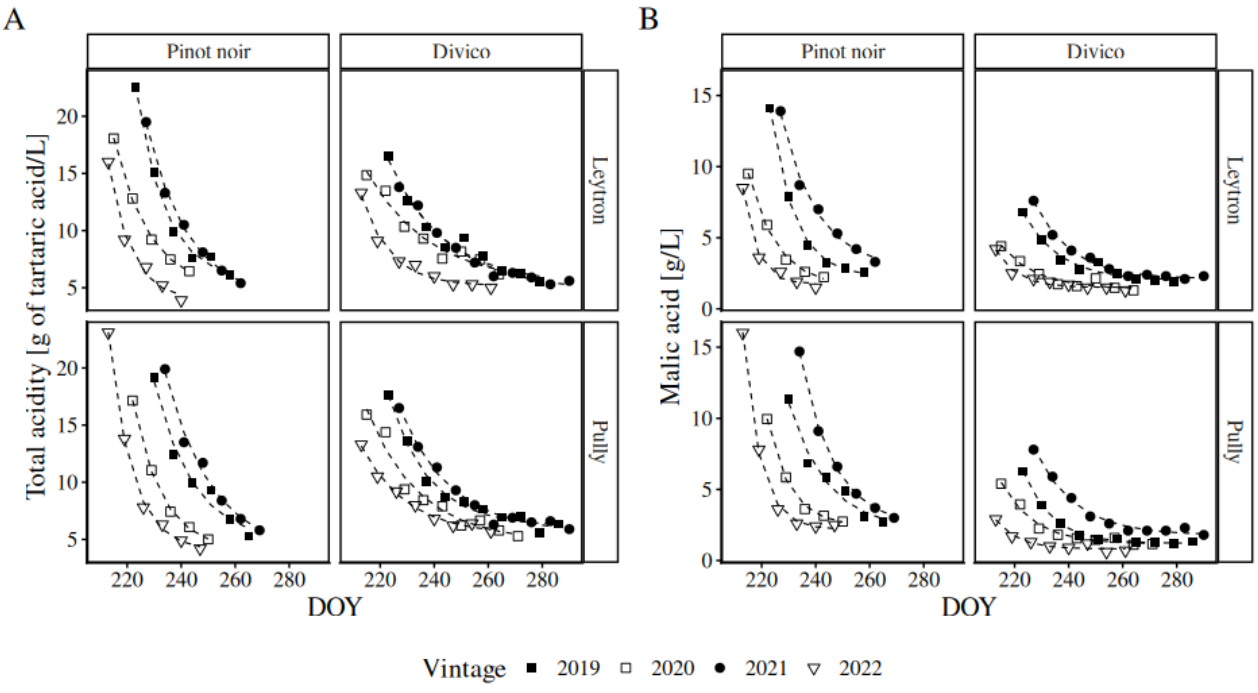


FIGURE 2. Total acidity (A) and malic acid (B) decrease during ripening: observed values (points) and modelled values (dashed lines).

3.3. Tartaric acid

The study of tartaric acid evolution, particularly the rate of decay, k_{Tart_ac}, showed a significant influence of grape variety, with higher coefficient values for Divico (+0.05, $p < 0.01$), indicating a slower decay of tartaric acid than for Pinot noir (Table 2 and Figure 3A). The location and the grape variety × location interaction did not show a significant influence on k_{Tart_ac}. The inclusion of the vintage effect drastically improved the model fit, raising the explained variance from 39.5 % (fixed effects only) to 87.3 %. This demonstrates the impact of the vintage on the rate of tartaric acid reduction. Rainfall patterns and vine water stress levels could also play a key role in annual climatic fluctuations, as higher water stress induced higher tartaric acid decrease (Rösti *et al*., 2018).

3.4. pH

With regard to pH, the slope value, k_{pH}, which indicates the rate of pH increase, was also significantly affected by the grape variety (Table 2 and Figure 3B). As expected, given the total acidity results, the coefficient for Divico was lower than that for Pinot noir, indicating a slower increase in pH in the berries during ripening (–0.01, $p < 0.001$). The vintage effect could not be included in the full model due to a lack of convergence; a simple linear model was retained, which explained 74.9 % of the variance, suggesting that the model was well-fitted to the available data, although other unaccounted variables may contribute to explaining the residual variability. Interestingly, at the end of maturation, the pH values for Divico were similar for all considered vintages, between 3.2 and 3.4 (Figure 3B), whereas Pinot noir showed higher final pH and greater variability, with values ranging from 3.3 to 3.6.

During the maturation of Divico berries, the malic acid concentration stabilised between 1.5 g/L and 2 g/L at the end of the ripening phase. This condition, together with the higher tartaric acid concentrations, particularly in the berries from Pully, ensures balanced total acidity at the end of the ripening period. This was also reflected in the pH values of the berries. At the end of ripening, the pH was relatively low and similar across all vintages (Figure 3B). This was not the case for Pinot noir, particularly with the berries from Pully, whose pH values rose sharply during a warm vintage, reaching a value over 3.5 (2020 and 2022). Rising temperatures as a result of global variations in climatic conditions are leading to an increase in pH levels in certain grape varieties and the related wines (van Leeuwen & Darriet, 2016). As wine pH is a critical factor in determining its microbiological and physicochemical stability, this trend is of particular concern. Indeed, pH exerts a significant influence on the selection of microorganisms and specific chemical reactions, in particular those impacting the efficiency of sulfur dioxide (Comuzzo & Battistutta, 2019). Consequently, the slower increase in pH in the grape berries of Divico, irrespective of the conditions present during vintage, appears to be a beneficial aspect of this variety for wine production in a changing climate (Plantevin *et al*., 2024).

3.5. Positioning Divico based on acid dynamics

To position Divico within the framework proposed by Plantevin *et al*. (2024), αlogmal and αTar coefficients were calculated from our dataset following their methodology (Figures S2 and S3). The slope of the relationship between the tartaric acid content (µmol/berry) as a function of growing degree days (summation of mean daily temperature starting from January 1st) corresponds to the αTar coefficient.

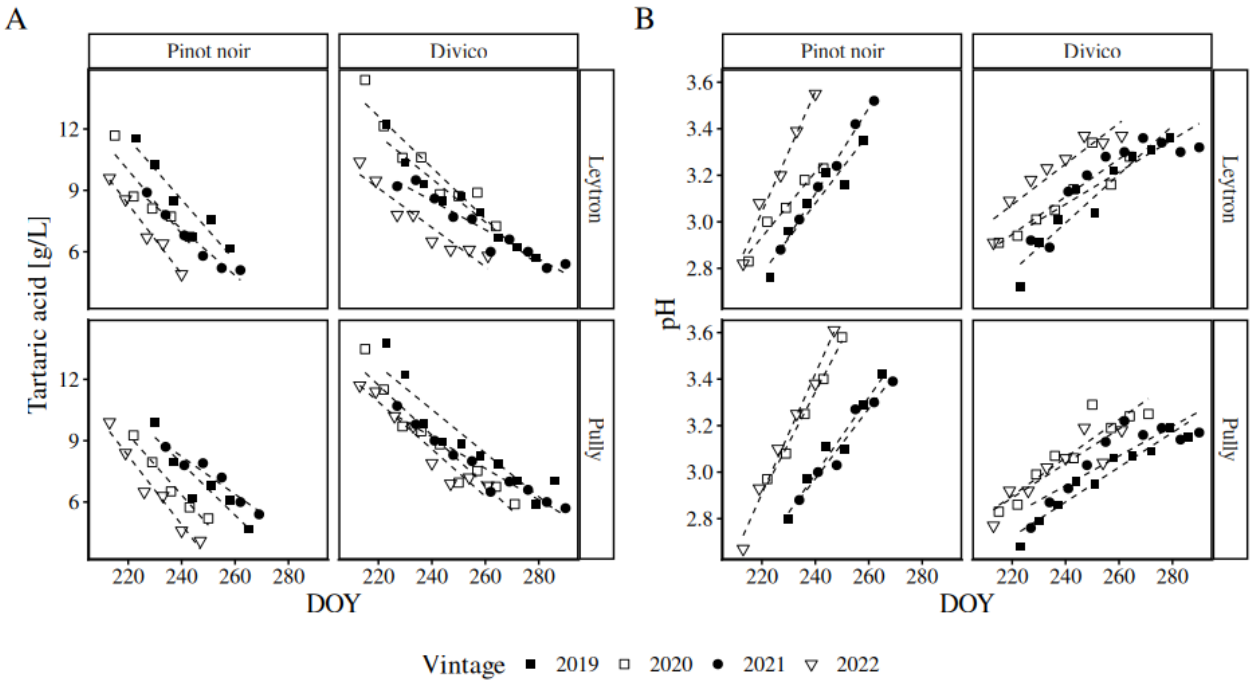


FIGURE 3. Tartaric acid (A) and pH (B) evolution during ripening: observed values (points) and modelled values (dashed lines).

More negative αTar values indicate a greater rate of tartaric acid decrease during grape ripening. The αTar values obtained in our study were within the range reported by Plantevin *et al*. (2024), who reported a value of approximately −0.025 for Pinot noir. In our dataset, αTar values for Pinot noir were −0.0314 in Leytron and −0.0408 in Pully, while Divico exhibited mean αTar values of −0.0325 and −0.0294 in Leytron and Pully, respectively. These results indicate that Divico exhibits tartaric acid degradation rates comparable to those observed in Pinot noir. Although the distributions largely overlapped, Divico tended to show slightly less negative αTar values and lower variability, suggesting a relatively stable tartaric acid pool during ripening. This might explain why a significant effect of the grape variety on tartaric acid evolution was found. The slope coefficient of the relationship between ln (malic acid content (µmol berry^{-1})) and growing degree days corresponds to the αlogmal coefficient. More negative αlogmal values indicate greater sensitivity to malic acid degradation for a given heat summation. In the study of Plantevin *et al*. (2024), αlogmal values for Pinot noir ranged from −0.0022 to −0.0007. In our study, αlogmal values for Pinot noir were −0.0023 in Leytron and −0.00215 in Pully. In contrast, Divico exhibited αlogmal values of −0.00105 and −0.00115 in Leytron and Pully, respectively. These less negative values indicate a slower rate of malic acid degradation and therefore a greater capacity to maintain acidity during ripening. Furthermore, the αlogmal values obtained for Divico fall within the range reported by Plantevin *et al*. (2024) for cultivars exhibiting relatively slow malic acid degradation. Although direct quantitative comparisons should be interpreted cautiously because the coefficients were derived from different vineyards and environmental conditions, these results suggest that Divico may possess physiological characteristics associated with improved acidity retention under warm ripening conditions.

4. Phenolic maturity

Phenolic maturity for Divico berries was monitored during the 2019, 2020, and 2022 vintages using TPI and total anthocyanin content. Equivalent monitoring was not conducted on Pinot noir in the present study.

4.1. Total phenolic index

The TPI results are presented in Figure 4A. The TPI did not change much as the Divico berries ripened. Means across the maturation period were calculated, and the influence of growing location and vintage was analysed. Although the model explained 63.6 % of the variance of the TPI variable, no significant effect was found for the location and vintage effects (Table 4).

4.2. Total anthocyanins

The evolution of anthocyanins was modelled to calculate several parameters, including Max_{antho}, the peak date (DOY_{peak}), the sigma parameter (σ) and the duration between veraison and the anthocyanin peak ($Dur_{peak\text{-}Ver}$) (Figure 4B). Among these parameters, only DOY_{peak} was significantly influenced by the vintage ($p < 0.05$), while the location showed no significant effect (Table 4). The linear model estimates for DOY_{peak} revealed that, in comparison to the reference vintage (2019), the anthocyanin peak occurred 19 days earlier in 2020 (-19, $p = 0.021$) and 22 days earlier in 2022 (-22, $p = 0.016$) (Table S3). Under the experimental conditions, the average DOY_{peak} is 265 days (± 2 days), which is approximately 22 September.

TABLE 4. ANOVA results for the effect of location and vintage on phenolic parameters during Divico ripening.

	Explained variable	Effect	Estimate	Std. error	F value	Pr(>F)	*p*-value	% variance explained
TPI		(Intercept)	121.3	10.3				63.60 %
		Location	18.8	10.3	3.352	0.209	ns	
		Vintage	–3.2	12.6	0.069	0.936	ns	
Total anthocyanins (mg/kg)	Max_{antho}	(Intercept)	1192	108				53.60 %
		Location	125	108	1.3527	0.365	ns	
		Vintage	74	132	0.4792	0.676	ns	
	DOY_{peak}	(Intercept)	265	2				97.50 %
		Location	5	2	3.996	0.184	ns	
		Vintage	–19	3	36.373	0.027	*	
	σ	(Intercept)	32	3				87.70 %
		Location	7	3	4	0.184	ns	
		Vintage	13	4	5.1145	0.164	ns	
	$Dur_{Peak\text{-}Ver}$	(Intercept)	51	4				26.80 %
		Location	3	4	0.5401	0.539	ns	
		Vintage	–2	5	0.0967	0.912	ns	

Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05 '°' 0.1; Intercept (Leytron × 2019); Linear model: X ~ Grape variety + Location.

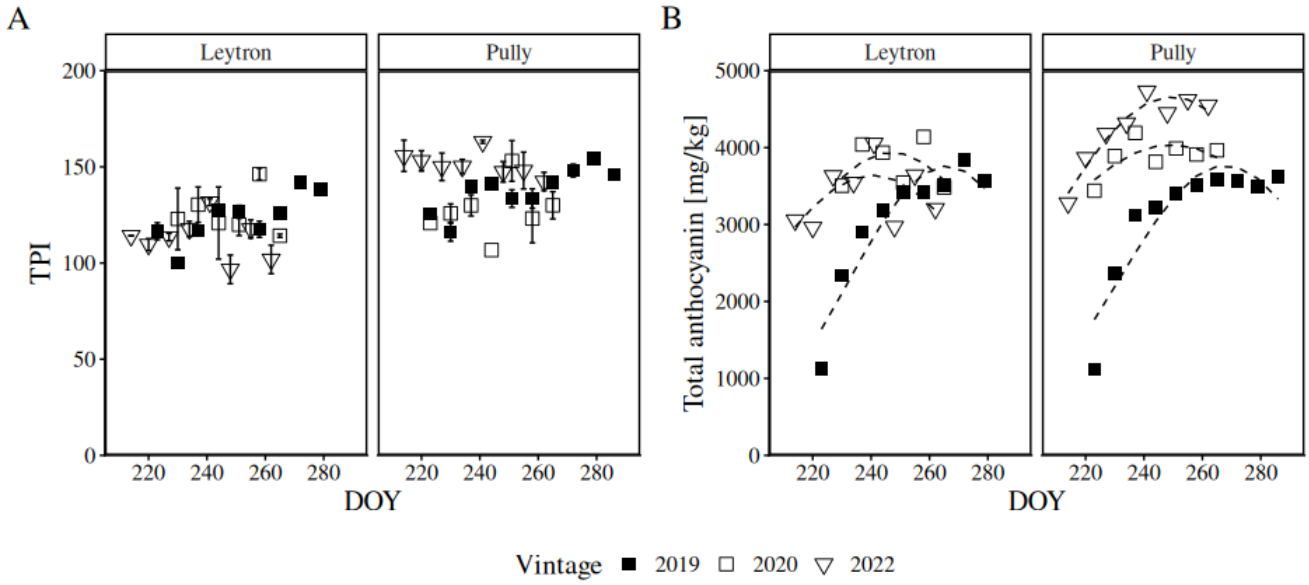


FIGURE 4. Total phenolic content (A) and anthocyanins (B) of Divico berries during ripening: observed values (points) and modelled values (dashed lines).

While direct experimental comparison was not conducted in this study, contextualising these findings with existing literature highlights the distinct profile of Divico. De Montmollin and Dupraz (2003) reported anthocyanin concentrations of approximately 900 mg/kg for Pinot noir and 2100 mg/kg for Gamaret. In contrast, Divico exhibits remarkably elevated content (> 3000 mg/kg).

In the context of traditional grape varieties, total berry colour is widely regarded as a pivotal indicator of quality. Consequently, any approach that enhances the accumulation of anthocyanins in berries stands to benefit grape growers and winemakers (Conde *et al*., 2007). In the case of Divico berries, this abundance of anthocyanins contributes to the production of wines with intense colour. The climate plays a role in anthocyanin accumulation. Warmer and drier vintages induced earlier accumulation of anthocyanins in the Divico berries sampled in 2020 and 2022, especially in Pully. One of the most interesting results of this study is the anthocyanin accumulation peak observed during ripening, which could serve as an indicator of the optimal phenolic maturity of grapes in the future, as was previously shown for Gamaret (De Montmollin & Dupraz, 2003). The high anthocyanin content observed in Divico berries suggests that maximising anthocyanin accumulation may not be a necessary goal for this variety. However, achieving both sufficient tannin quantity and appropriate quality remains essential to ensure the visual and sensory balance of Divico wines. Consequently, further investigation into tannin quality and the influence of harvest timing on the sensory properties of Divico wines is warranted.

CONCLUSIONS

The susceptibility of *Vitis vinifera* grape varieties to fungal diseases remains a major challenge for modern viticulture, driving the development of resistant grape varieties. This study provides the first in-depth characterisation of the ripening dynamics of Divico, an FRG cultivated in Switzerland. Comparative analysis of primary metabolites against the reference *Vitis vinifera* variety, Pinot noir, revealed distinct kinetic patterns in Divico berries. Notably, Divico exhibits early sugar accumulation and an earlier onset of the sugar plateau, which helps prevent excessively high sugar levels. Furthermore, it maintains consistent acidity and a relatively low pH at ripeness, regardless of the climatic conditions of the vintage. This stability, combined with its resistance to disease, positions Divico as a promising candidate for sustainable viticulture.

Moreover, Divico's high anthocyanin content is crucial for producing wines with intense colour. The peak in anthocyanin accumulation observed during ripening warrants further investigation as a potential indicator of optimal phenolic maturity. In terms of harvest management, Divico offers significant flexibility, providing a strategic advantage that allows growers to optimise both quality and yield while adapting to unforeseen climatic events. Consequently, Divico is an innovative solution capable of addressing the challenges of contemporary winegrowing by combining resilience, quality, and sustainability.

Although this study focuses specifically on the Divico grape variety, it is based on a rigorous methodology that allows for detailed monitoring of the evolution of berry ripeness. Hence, this approach provides a reproducible framework not limited to Divico, but which can be applied to other grape varieties, offering a useful tool for comparing ripening dynamics, anticipating harvest dates and assessing suitability for different terroirs across varieties.

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