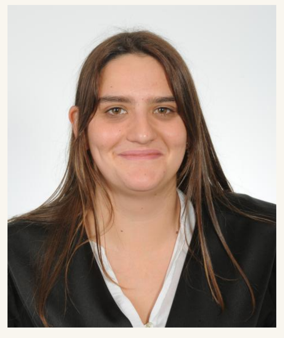

ANALYTICAL CHARACTERIZATION OF GRAPES AT DIFFERENT STAGES OF RIPENING FOR THE VALORISATION OF BY-PRODUCTS

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Introduction

Grape ripening is a multivariate process involving sugars, acids, phenolics, and volatiles, whose combined evolution defines grape and wine quality [1]. Climate change increasingly disrupts these dynamics, creating mismatches between technological, phenolic, and aromatic maturity [2]. At the same time, grape by-products (skins, seeds, must) are valuable sources of bioactive compounds, but their valorisation depends on harvest timing and compositional monitoring [3]. Chemometric tools such as PCA, ASCA, and PLS provide powerful means to unravel the effects of ripening stage, variety, and vineyard microclimate, enabling a more precise understanding of grape development and supporting sustainable strategies for valorisation.

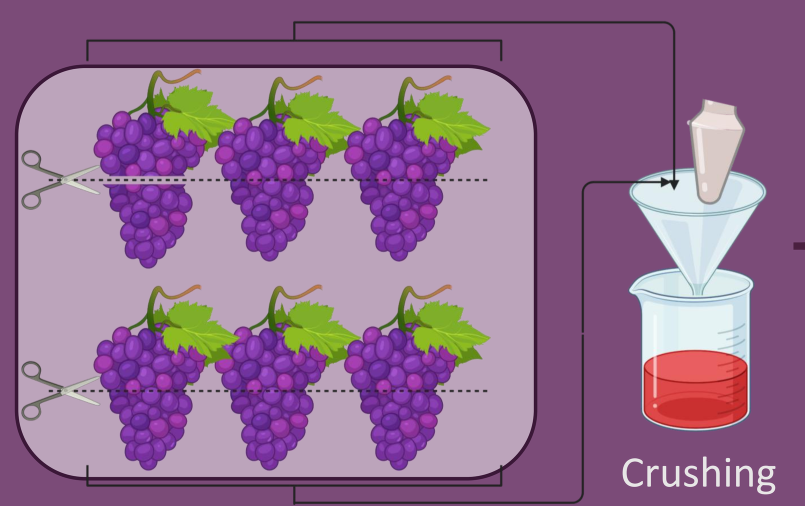
Aim of study

Grape ripening drives biochemical changes that shape wine quality and by-product potential. Garnatxa Negra (Grenache) and Cabernet Sauvignon were selected as the grape varieties due to their differences in maturity. Both of them were studied across ripening stages and orientations using physicochemical, volatile, and MIR analyses combined with ASCA

» To establish a chemometric framework to monitor ripening dynamics and guide the sustainable valorisation of grape by-products under climate variability

Materials and Methods

- Cabernet Sauvignon
  Grenache
- 6 or 7 maturity points around the optimum harvest point
- Two orientations considered: northeast and southwest



Must →
- Maturity control (TSS and pH)
- Polyphenol content
- Volatile compounds

Skin →
- Polyphenol content
- MIR

Seeds →
- Polyphenol content
- MIR

ANOVA – Simultaneous Component Analysis (ASCA)

Characterize grape by-products at different stages of ripeness in order to enhance their value and improve grape industry profits

Results

Must

Table 1: ASCA on must volatile composition

Factor	Effect (%) Cabernet Sauvignon	Effect (%) Grenache
Harvest time	45.25*	48.94*
Grape Position	4.30*	9.14*
Harvest Time x Grape position	24.34*	24.38*
Residuals	26.11	17.55

*Statistically significant effects (p value < 0.05)

Skins

Table 2: ASCA on grape skin MIR spectra

Factor	Effect (%) Cabernet Sauvignon	Effect (%) Grenache
Harvest time	20.55*	13.18*
Grape Position	3.14*	4.77*
Harvest Time x Grape position	21.83*	5.40*
Residuals	54.48	75.94

*Statistically significant effects (p value < 0.05)

Seeds

Table 3: ASCA on seed MIR spectra

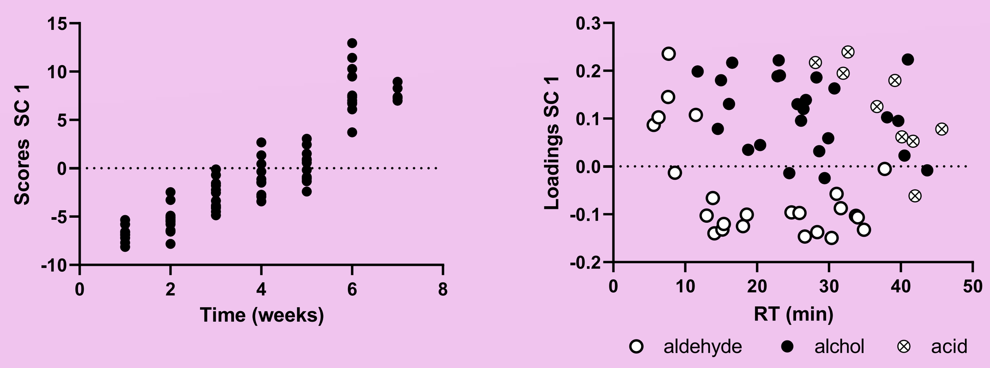
Factor	Effect (%) Cabernet Sauvignon	Effect (%) Grenache
Harvest time	14.04*	16.92*
Grape Position	0.58	1.01
Harvest Time x Grape position	8.42*	9.01*
Residuals	79.96	73.03

*Statistically significant effects (p value < 0.05)

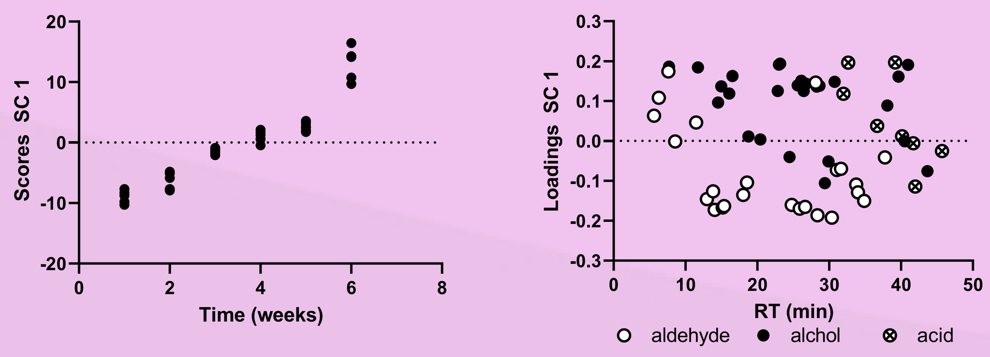
ASCA analysis confirms harvest season as the dominant source of variability. While grape position significantly influences must and skins, this effect is negligible in seeds, where score distributions cluster around harvest, indicating less pronounced changes.

Volatile compounds in the must

Grenache

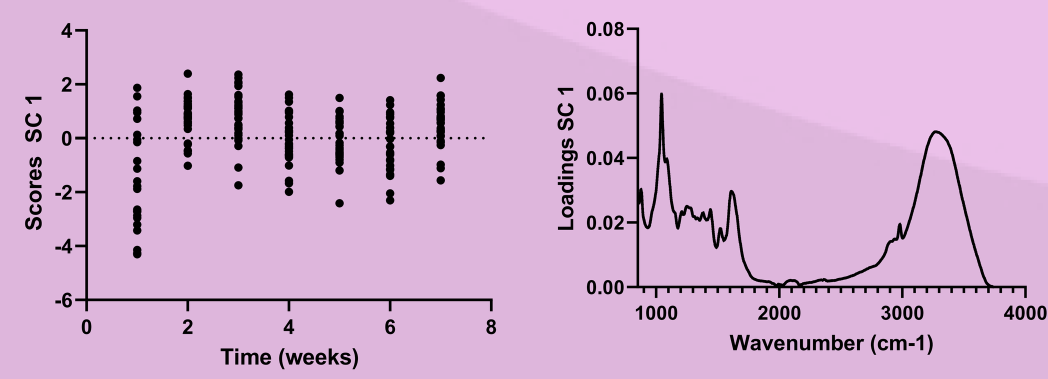


Cabernet Sauvignon

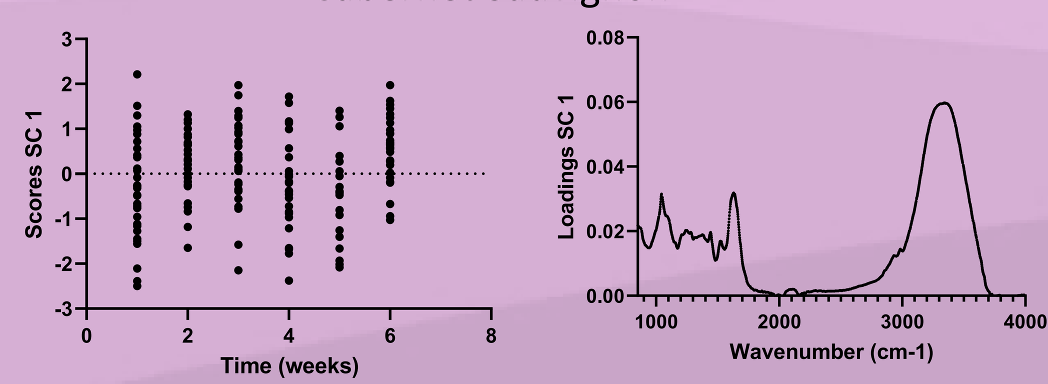


Harvest time factor separates ripening stages, with aldehydes linked to green phases, alcohols to intermediate ripening, and acids to overripe profiles.

Grenache

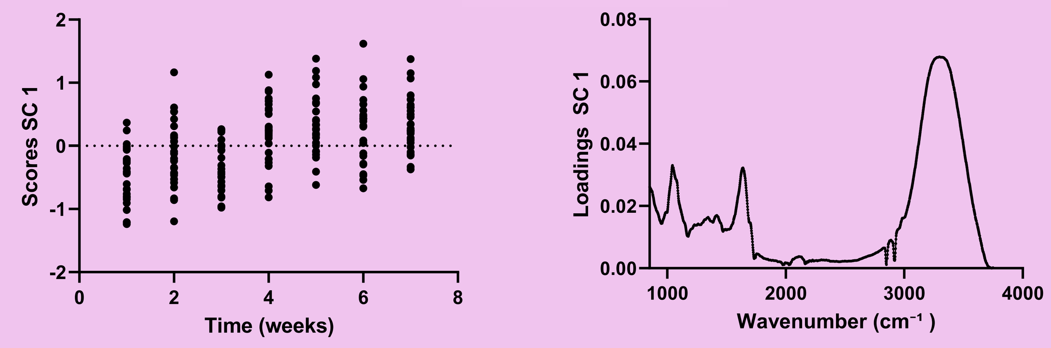


Cabernet Sauvignon

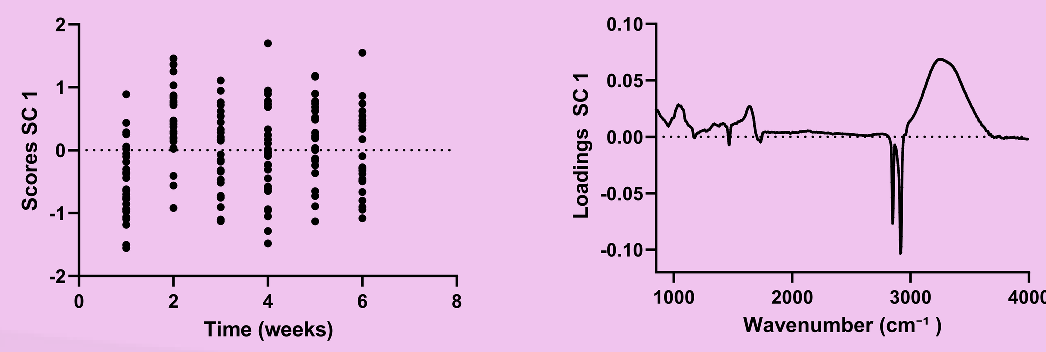


MIR spectra of grape-skins

Grenache



Cabernet Sauvignon



Harvest time factor scores track ripening in skins: phenolic-associated spectral regions (3000–3700 cm^{-1}) is the major driver, showing a progressive accumulation in Grenache and a more dynamic evolution in Cabernet Sauvignon

MIR spectra of grape-seeds

In seeds, O–H stretching associated with phenolic compounds (3000–3700 cm^{-1}) is the primary marker of ripening, displaying a steady progression in Grenache and a more dynamic trajectory in Cabernet Sauvignon. However, this evolution is less pronounced than in must and skins, as seeds had already transitioned to the lignified (woody) phase by harvest.

Conclusions

- **Must:** Volatile composition evolves markedly with ripening, discriminating green, ripe, and overripe stages. Cabernet Sauvignon retained more green-associated volatiles, whereas Grenache developed a fruitier, riper profile.
- **Skins:** Polyphenols and anthocyanins peaked around optimal harvest. MIR spectra highlighted varietal differences in phenolic accumulation and climate responses. Cluster position also influenced composition, with northeast-exposed grapes showing more advanced maturity.
- **Seeds:** Less affected by sun exposure, but still exhibited ripening-related changes. Grenache followed a linear maturation, while Cabernet Sauvignon showed a more variable trajectory.

» Chemometrics reveals varietal ripening patterns and enables sustainable valorisation of grape by-products

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