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Agronomic and Physiological Responses of 'Chardonnay' Grapevines to Management Strategies with Late Pruning and Late Cane Tying

Gábor Sándor Vértes [1], István Fazekas [1,*], Márta Ladányi [2], György Lukácsy [1], Marianna Mile [1] and Diána Ágnes Nyitrainé Sárdy [1]

[1] Institute of Viticulture and Enology, Hungarian University of Agriculture and Life Sciences, Ménesi Str. 45, 1118 Budapest, Hungary; vertes.gabor.sandor@phd.uni-mate.hu (G.S.V.); lukacsy.gyorgy@uni-mate.hu (G.L.); mile.marianna@uni-mate.hu (M.M.); nyitraine.sardy.diana.agnes@uni-mate.hu (D.Á.N.S.)

[2] Department of Applied Statistics, Institute of Mathematics and Basic Science, Hungarian University of Agriculture and Life Sciences, Villányi Rd. 29–43, 1118 Budapest, Hungary; ladanyi.marta@uni-mate.hu

* Correspondence: fazekas.istvan@uni-mate.hu

Highlights

What are the main findings?

- Late cane tying was associated with higher yield and average bunch weight in umbrella-trained 'Chardonnay' vines, without the yield penalties associated with late pruning under cordon training.
- In contrast to late pruning in cordon-trained vines, late cane tying in umbrella-trained vines maintains stable canopy growth dynamics, demonstrating no significant impact on the leaf area index, porosity, or clumping index.

What are the implications of the main findings?

- This research suggests that late cane tying may represent a distinct management strategy for umbrella-trained vines that potentially supports productivity.
- Late cane tying has potential as a non-invasive viticultural tool for managing productivity in the umbrella trellis system while maintaining vine canopy structure.

Abstract

To mitigate the potential drawbacks of late pruning, this study evaluated an alternative approach utilising the anatomical features of the umbrella trellis system, cane pruning, and apical dominance. Vine canes were tied at four distinct phenological stages: before budburst, at the 3-leaf, 5-leaf, and 7-leaf stages (BBCH 00, 13, 15, and 17, respectively). We hypothesised that exploiting apical dominance would allow distal buds to burst first; subsequent arching and tying of the cane would then trigger the burst of the remaining basal buds with a temporal delay. The effects of these treatments were evaluated based on leaf area index (LAI), canopy porosity and structure, fertility coefficients, and yield components, supplemented by must composition analysis at harvest and compared alongside a traditional late-pruned cordon-system evaluated under identical phenological timings. Our findings indicated that delayed tying treatments on umbrella-trained vines did not affect canopy structure, resulted in higher yields, greater average bunch weights, without inducing the negative side effects reported for late pruning cordon-trained vines. Regarding final must composition, the treatments produced minor and inconsistent variations, with no significant differences across most measured parameters at harvest.

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1. Introduction

Global climate change has significantly altered grapevine phenology over the past decade, resulting in particularly early budburst, flowering, and ripening. These temperature anomalies and earlier phenological phases increase the risk of spring frosts and heat stress. They can also lead to issues such as excessive sugar accumulation and low acidity in the must [1–16].

Late pruning is one of the most effective adaptation strategies employed worldwide to mitigate these challenges. The technique involves pruning after budburst, thereby shifting shoot development, flowering, and ripening to a later stage in the growing season [1,8,10,13,16–18].

Numerous studies have demonstrated that late pruning can enhance the aromatic complexity of the berries, maintain fruit acidity, and delay the harvest date without significantly reducing yield [2,3,8,16,19–22].

This practice is considered a particularly promising solution in wine regions with Mediterranean and continental climates, where high summer temperatures accelerate grapevine ripening and must sugar levels are often excessive. However, the effectiveness of this method also depends on cultivar-specific characteristics, the precise timing of pruning, and environmental conditions [1,6,7,9,15,16,23].

Overall, late pruning is a phenological control tool that can help growers mitigate the adverse effects of climate change and optimise quality parameters by altering the timing of grapevine growth and ripening. To date, research in this area has primarily focused on investigating the applicability of this method across different wine regions and varieties, as well as understanding the underlying mechanisms of late pruning.

However, numerous studies have indicated that its practical application is questionable, as this drastic intervention can lead to a significant reduction in yield [2,6,8,17,20,22,24–27]. Furthermore, fruit maturity can become heterogeneous—with immature, mature, and overripe bunches coexisting on the vines—and its long-term effects remain unknown. To address these issues, this study evaluated the potential of the umbrella trellis system. We hypothesised that by exploiting the inhibition of basal buds—driven by acrotony, apical dominance, and the hormone auxin [28–32]—a similar phenological delay could be induced. In this approach, it is hypothesised that the distal buds of the unbent cane burst first; subsequently, at the target phenological stage, this apical dominance is thought to be weakened by arching and tying the cane, potentially allowing the remaining buds to initiate budburst. Standard late pruning removes biomass, depleting carbohydrate reserves and potentially reducing vine vigour. In contrast, our proposed method seeks to achieve similar phenological shifts without these negative consequences.

To evaluate the physiological impact of this approach on the vine, fertility coefficients, yield, and the average bunch and berry weight were quantified. Furthermore, fruit quality was assessed by analysing the final must composition, specifically sugar content, titratable acidity (TA), and the organic acid profile.

Because training architecture, pruning type, and bud load operate as integrated systems in commercial viticulture, this approach was evaluated alongside a standard pruned cordon system subjected to late pruning. The two systems were evaluated as distinct Combined Management Strategies (CMS: cordon training with late pruning [cordon (LP)] vs. umbrella training with late cane tying [umbrella (LCT)]) to determine how timing interventions modulate vegetative growth, productivity, and fruit maturity within each respective framework. This study focuses on 'Chardonnay', a foundational cultivar essential for sparkling wine production.

2. Materials and Methods

2.1. Growing Seasons

Measurements were intended to cover three consecutive growing seasons (2023, 2024, and 2025). However, the 2024 vintage was characterised by extreme heat and severe drought in Hungary, which significantly impacted the experimental vineyard. Specifically, the cordon-trained vines suffered powdery mildew (*Erysiphe necator*) damage approaching 100%, resulting in total crop loss. While umbrella-trained vines experienced lower infection rates, the remaining healthy berries suffered severe shrivelling and desiccation prior to harvest. Because the harvestable crop was either destroyed by powdery mildew or severely desiccated across all variants, fruit sampling and yield measurements could not be conducted in 2024. This exclusion decision was made in the field prior to any data collection or statistical analysis.

2.1.1. Vintage 2023

The spring of 2023 was characterised by significant temperature fluctuations but averaged near the long-term norm, concluding only 0.2 °C cooler than the 1991–2020 climate average. This resulted from a warm March followed by a notably cold April. Following a wet winter trend, seasonal precipitation reached 117% of the average, with a nationwide rainfall surplus across all three months [33].

Summer 2023 followed the general warming trend, with a national mean temperature of 21.6 °C (+0.8 °C anomaly), making it the 12th warmest summer since 1901. While temperatures in June were average, July (+1.2 °C) and August (+1.0 °C) were marked by intense heatwaves, with a seasonal maximum of 39.5 °C on 27 August in Dévaványa, and a minimum of 0.9 °C on 4 June in Zabar [33].

In contrast to the severe droughts of 2021–2022, summer precipitation reached 220.6 mm (109% of the norm). June was 10% wetter, July 8% drier, and August 26% wetter than average. Significant spatial variations were observed: western and northern regions were notably wet, while southern areas remained dry. The highest seasonal total was 486.9 mm (Parád/Kékestető), whereas the lowest was 83.3 mm (Szarvas). A maximum 24 h rainfall of 122.0 mm was recorded on 6 June at Kékestető during severe storm events [33].

2.1.2. Vintage 2025

The spring of 2025 was marked by sharp monthly fluctuations, finishing slightly warmer than average with a nationwide mean temperature of 11.6 °C (+0.5 °C anomaly). Both March (+2.2 °C) and April (+1.3 °C) were characterised by unseasonal warmth, whereas May was significantly colder (−2.0 °C) than normal. Total seasonal precipitation was 143.2 mm (103% of the norm), although its distribution was highly uneven [33].

The summer of 2025 aligned with the global warming trend, with a nationwide seasonal mean temperature of 22.1 °C (+1.2 °C anomaly), ranking as the 7th warmest summer since 1901. Every month exceeded the average temperature: June was exceptionally hot (+2.5 °C anomaly, the 2nd-warmest June on record), while July and August recorded anomalies of +0.7 °C and +0.5 °C, respectively. Peak temperatures exceeded 40 °C during prolonged heatwaves in July. Concurrently, the season was marked by severe drought; the national precipitation total was only 121.6 mm (60% of the norm), making it the 10th driest summer since 1901. June was the driest since 1901, with an 83% rainfall deficit, while July (−15%) and August (−23%) provided no significant recovery. Spatial disparities were drastic: while severe convective storms occurred in northern border areas, the central and southern regions remained critically dry, with seasonal totals falling below 80 mm (and under 50 mm in several locations), resulting in a seasonal nationwide minimum of 39.6 mm [33].

2.2. Experimental Site Description

The experimental vineyard is situated in the Tóra district on the periphery of Etyek, Hungary (47.439365° N, 18.696895° E; Figure 1). The cordon-trained plot is located within the smaller area demarcated by a yellow rectangle in Figure 1, while the umbrella-trained plot occupies the larger area highlighted in red.

Figure 1. The experimental vineyard (source: https://www.google.com/maps, accessed 20 November 2023). Yellow frame: the cordon-trained plot. Red frame: the umbrella-trained plot.

The dominant parent material is loess, and the primary soil types are forest-residual chernozem and chernozem brown forest soil. Due to decades of intensive viticultural use, the original genetic soil profiles are no longer recognisable, and the area is now characterised by anthropogenic soil. The soil is slightly alkaline and contains high levels of carbonates from the surface downward. The active (finely distributed) lime content is also high. The humus layer extends to a depth of 75 cm; its vertical distribution was influenced by deep-soil inversion (trenching) before planting, as the organic matter content does not follow the standard decreasing trend with depth. The organic matter (humus) content is classified as medium, and the soil contains no detectable levels of water-soluble salts. The vineyard is situated on a 0–5% south-eastern (SE) slope.

The experiment was conducted at the Vértes Birtok Winery in Etyek. The 'Chardonnay' cultivar is cultivated across two adjacent blocks.

The plot designated for the late pruning trial covers 0.26 ha and consists of five rows. These vines are trained to a cordon system, with a trunk height of approximately 70 cm, 3.0 m inter-row spacing, and 0.9 m intra-row spacing.

For the late cane tying study, a larger 0.7 ha block established in 2006 was utilised, comprising ten rows trained to the umbrella trellis system. The planting density is identical to the first plot (3.0 m inter-row × 0.9 m intra-row). In both blocks, the scion was grafted onto Teleki 5C rootstock.

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The trellis infrastructure consists of Voestalpine Leova 60/40 steel line posts spaced every six vines. The system includes a fruiting wire at 70 cm and three pairs of foliage wires at heights of 110 cm, 150 cm, and 190 cm for canopy management. Mechanical topping is routinely performed 20 cm above the uppermost wire pair. The vineyard floor is managed with native vegetation, maintained using tractor-drawn flail mowers in the inter-row spaces and string trimmers within the vine rows (intra-row zones).

2.3. Experimental Design and Vine Selection

The field experiment was arranged in a randomised complete block design (RCBD) with three replicates (blocks) within each respective management block. Each block contained all four phenological stage levels of treatments, with five vines per level (15 vines per treatment; 60 vines per management strategy; 120 vines total). By partitioning the experimental plot into homogeneous blocks perpendicular to the primary environmental gradient, intra-block variance was minimised, ensuring that each treatment schedule was evaluated under statistically comparable baseline conditions. To eliminate edge effects and boundary artefacts, data collection was strictly restricted to the inner experimental vines, with the outer rows and terminal vines serving as buffers.

2.4. Experimental Treatments

2.4.1. Umbrella Training with Late Cane Tying (LCT)

The treatments were implemented at four predefined phenological stages: BBCH 00 (dormancy), BBCH 13 (3-leaf stage), BBCH 15 (5-leaf stage), and BBCH 17 (7-leaf stage) [34].

The specific treatments were as follows: 1. control (BBCH 00): Pruning and tying performed during dormancy, before sap flow (bleeding); 2. BBCH 13: Pruning performed during dormancy; canes remained vertical and were tied at the 3-leaf stage; 3. BBCH 15: Pruning performed during dormancy; canes remained vertical and were tied at the 5-leaf stage; 4. BBCH 17: Pruning performed during dormancy; canes remained vertical and were tied at the 7-leaf stage.

Pruning was conducted uniformly across all treatments, leaving two canes per vine with 12 buds each, resulting in a total bud load of 24 buds per vine. Tying was performed by arching the canes and securing them to the fruiting wire using a metal binder. Table 1 shows the timeline and calendar dates of the treatments.

Table 1. Timeline and calendar dates of pruning, late cane tying, and harvest operations for 'Chardonnay' grapevines in the 2023 and 2025 experimental years.

Treatment Schedule	Year	Pruning Date	Late Pruning or Tying Date	Harvest Date
control	2023	16 February	11 March	26 September
	2025	21 February	8 March	11 September
BBCH 13	2023	16 February	26 April	26 September
	2025	21 February	21 April	11 September
BBCH 15	2023	16 February	2 May	26 September
	2025	21 February	29 April	11 September
BBCH 17	2023	16 February	11 May	26 September
	2025	21 February	7 May	11 September

2.4.2. Cordon Training with Late Pruning (LP)

The late pruning treatments were likewise carried out at the same four phenological stages (BBCH 00, 13, 15, and 17) [34].

The treatments consisted of: 1. control (BBCH 00): Final pruning performed during dormancy; 2. BBCH 13: Pre-pruning during dormancy, final pruning at the 3-leaf stage;

3. BBCH 15: Pre-pruning during dormancy; final pruning at the 5-leaf stage; 4. BBCH 17: Pre-pruning during dormancy; final pruning at the 7-leaf stage.

Control vines (BBCH 00) were pruned before the onset of sap flow on 16 February 2023 and 21 February 2025. To simulate a commercially viable application of this technique, vines of the remaining treatment schedule levels were pre-pruned during dormancy at the height of the middle wire pair on the same dates. This was designed to mimic mechanical pre-pruning at a distance of approximately 50 cm from the cordon wire, leaving 8–9 buds on all canes. During the final pruning of these treated vines, they were cut back to 2-bud spurs, resulting in a total bud load of 10 buds per vine. Table 1 shows the timeline and calendar dates of the treatments.

Phytosanitary management of the experimental vines followed standard commercial practices used in the rest of the vineyard. Following initial vine assessments, trunk suckering was performed. Manual shoot positioning was carried out in June, followed by mechanical canopy hedging (topping) in July.

2.5. Canopy Structure Studies

Canopy structure was evaluated using the VitiCanopy Ver.1.0.2. mobile application [35]. Measurements were taken from 15 vines per treatment (5 vines per block replicate) at four distinct time points throughout the growing season. The application uses image-analysis algorithms to process canopy gap-fraction data, enabling instantaneous field-level calculation of the leaf area index (LAI), clumping index (CI), and canopy porosity.

2.5.1. Leaf Area Index (LAI)

LAI is a dimensionless parameter and a primary indicator of plant canopy structure. It is defined as the total one-sided green leaf area per unit of ground surface area (m^2/m^2). In viticulture, LAI is a critical metric for assessing vine vigour, potential photosynthetic capacity, and vegetative growth.

2.5.2. Clumping Index (CI)

The clumping index is a dimensionless structural parameter that quantifies the spatial distribution and grouping of leaves within the canopy. It describes how much leaf positioning deviates from a theoretical random distribution. CI values typically range between 0 and 1; a value of 1 indicates a perfectly random leaf distribution, while values significantly below 1 indicate that foliage is clustered or “clumped”.

2.5.3. Canopy Porosity

Canopy porosity is an architectural parameter defined as the ratio of open gaps (voids) to the total volume or projected area of the plant canopy (expressed as a percentage, %). It quantifies the degree of “openness” of the vine foliage, which is essential for assessing light penetration and spray efficacy.

2.6. Fertility Coefficients

Fertility coefficients were determined following the Csepregi sampling method [36,37]. The absolute fertility coefficient is defined as the ratio of the total number of bunches to the total number of fertile shoots. The relative fertility coefficient is the ratio of the total number of bunches to the total number of all shoots (both fertile and infertile). For this assessment, all shoots from 15 vines per treatment (5 vines per block) were sampled, and the number of bunches per shoot was recorded.

2.7. Yield and Yield Components

Manual harvesting was performed simultaneously for all treatments on 26 September 2023 and 11 September 2025. Because our measurements were conducted in a commercial production vineyard under strict harvest logistics, total yield per vine was determined on a representative subset of three vines per treatment per year (one vine per block replicate; n = 3, total *N* = 24 per year combined across both years, *N* = 48). To prevent selection bias and ensure representative sampling across blocks, candidate vines were selected prior to veraison using predefined criteria: (1) exclusion of outer buffer vines to eliminate edge effects; (2) exclusion of vines exhibiting trunk disease symptoms or missing cordons/canes; and (3) exclusion of vines displaying extreme outlier vigour. From the remaining uniform pool, one target vine per block was randomly selected using a random number generator and permanently tagged for harvest yield recording.

To evaluate individual yield components while accounting for natural biological and intra-plot variability, a spatially distributed sampling protocol was implemented within the randomised complete block design (RCBD). Average bunch weight was determined from a subset of 30 bunches per treatment (10 bunches per plot; from which 2 bunches sampled symmetrically per vine across 5 designated vines, 1 bunch per cane/cordon arm), totalling 240 measured bunches across the experiment per year. For average berry weight, 30 individual berries per treatment (10 per plot) were sampled from different bunches, totalling 240 berries per year. All mass measurements were recorded using a VWR SE-622 analytical balance. To account for the hierarchical sampling structure and avoid pseudoreplication, subsamples of berries and bunches collected within each plot were averaged prior to statistical modelling, establishing the plot-level mean as the independent experimental unit (n = 3 true biological replicates per treatment combination; total *N* = 48, Denominator DF = 32 across all univariate models).

2.8. Must Analysis

Must was extracted from the berries via manual pressing, followed by filtration through a stainless-steel mesh to ensure sample homogeneity. Fresh must samples were analysed using a Foss WineScan™ instrument (FOSS, Hillerød, Denmark). This instrument employs Fourier Transform Infrared (FTIR) technology to determine multiple parameters simultaneously. All analyses were performed in triplicate per treatment group (n = 3 analytical replicates per treatment, *N* = 24 per year).

2.9. Statistical Methods

All statistical analyses were conducted in R (v4.5.2, R Core Team, 2025), utilising the packages dplyr [38] and tidyr [39] for data handling, nlme [40] for model estimation, emmeans [41] for estimated marginal means, and multcomp [42] for pairwise comparisons.

This study evaluated the temporal impacts of viticultural practices on grapevine performance across four distinct structural datasets. Because the late pruning practice was applied exclusively to pruned cordon vines and late cane tying was applied exclusively to cane-pruned umbrella vines in adjacent vineyard sections, training system, pruning method, target bud load, and plot area are structurally confounded. Consequently, these systems are formally defined and evaluated as two separate Combined Management Strategies (CMS): Cordon with Late Pruning (cordon (LP)) and Umbrella with Late Cane Tying (umbrella (LCT)).

All experiments utilised a crossed factorial structure defined by three primary factors: Year (2023 and 2025), Combined Management Strategy (CMS: cordon with LP, umbrella with LCT), and Phenological Stage (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17). Statistical inferences are primarily focused on evaluating the effects of treatment timing (phenological stage) within each CMS. Direct comparisons between the two CMS groups reflect the combined integrated package rather than isolated training system or pruning effects.

The four datasets were structured as follows: 1. Fertility: Total number of bunches, absolute fertility coefficient, and relative fertility coefficient. 2. Canopy structure: Leaf area index (LAI), canopy porosity, and clumping index (CI). These were measured at four consecutive time points per season to capture temporal canopy progression (Dates: 22 May, 5 June, 21 June, and 5 July in 2023; 20 May, 1 June, 16 June, and 4 July in 2025). 3. Yield and yield components: Total yield per vine, average bunch weight and average berry weight. 4. Final must composition: Sugar content (TSS), titratable acidity (TA), pH, and malic and tartaric acid concentrations.

The hierarchical nesting varied across datasets depending on whether individual vines were tracked repeatedly. For the first two datasets, 120 unique vines were tracked across both years, rendering Year a within-subject factor. In the second dataset (Canopy Structure), measurements were recorded at four consecutive time points, resulting in a hierarchical structure where the measurement dates were nested within Year, which in turn was nested within Vine ID. In the third and fourth datasets, individual vines were not tracked repeatedly across years; thus, these were treated as crossed factorial structures of independent spatial observations [43].

To analyse multiple joint variables simultaneously and control for Type I error rates, global Multivariate Joint Models were implemented. For Datasets 1 and 2, Multivariate Linear Mixed Models (MLMM) were executed using the nlme package [40]. For the first dataset, the fixed-effects structure included Year, Combined Management Strategy (CMS: cordon with LP, umbrella with LCT), and Phenological Stage, along with their two- and three-way interactions. For the second dataset, the fixed effects were Year, CMS, Phenological Stage, and Measurement Time Point, including all two-, three-, and four-way interactions.

Within-vine and within-year covariances among the response variables were captured using random-effects terms. For Datasets 3 and 4, where no subject-level random grouping factor existed, Multivariate Generalised Least Squares (GLS) models were fitted with Year, CMS, Phenological Stage, and their interactions as fixed effects. Degrees of freedom were adjusted to reflect the true biological replication, preventing pseudo-replication inflations in F-statistics and p-values. To account for scale differences across response variables, heteroscedasticity was modelled using the varIdent function in the nlme package.

Follow-up univariate models were fitted separately for each dependent variable. For Datasets 1 and 2, univariate linear mixed-effects models were executed with Vine ID and Year as random structures. To account for the temporal autocorrelation of consecutive measurements in Dataset 2, a first-order autoregressive (AR1) correlation structure was incorporated.

For Datasets 3 and 4 (yield and yield components), individual subsamples of berries and clusters within each plot were averaged prior to modelling to account for the hierarchical sampling design and eliminate pseudoreplication. Thus, the plot-level mean was established as the independent biological replicate (n = 3 replicates per treatment combination; total $N = 48$, Denominator DF = 32). Three-way factorial univariate Generalised Least Squares (GLS) models [44] were fitted for each response variable using the nlme package. To account for and resolve extensive heteroscedasticity across the subgroups, group-specific residual variance weights were incorporated using the varIdent function.

Model assumptions were verified using the residuals of the univariate models. Normality was assessed on the normalised residuals by examining skewness and kurtosis, with acceptable ranges defined as [−2, +2] and [−4, +4], respectively. The normality assumption was satisfied in all cases. Homoscedasticity was evaluated by calculating the ratio of the maximum to minimum group variance across subgroups for both raw and normalised residuals. In all instances, raw variance ratios remained below 3.0, except for the leaf area index (LAI), which reached 8.88. Although this exceeds the conventional threshold of 3.0, it remains below the critical threshold for Hartley's F_{max} test under k = 64 groups and df = 14 (N = 15), where ratios up to 10.0 can occur due to sampling noise alone. Furthermore, any underlying heteroscedasticity was explicitly addressed during model fitting using varIdent group weights, ensuring that all standard errors and post hoc comparisons were statistically valid. Post-correction normalised residual variance ratios confirmed that heteroscedasticity was successfully neutralised within the model space [43].

Post hoc comparisons were performed using the emmeans package [41]. Differences between phenological stages were evaluated pairwise within each combination of Year, CMS, and measurement time point (where applicable). CMS comparisons were evaluated pairwise within each combination of Year, phenological stage, and measurement time point. Year-to-year comparisons were conducted within each combination of CMS, phenological stage, and measurement time point. Comparisons between measurement time points were evaluated pairwise within each combination of CMS, phenological stage, and year using. The Šidák adjustment was applied in all cases to stabilise the Type I error rate.

To resolve numerical instability and failures in Satterthwaite approximation calculations caused by extreme differences in variance among subgroups in GLS models, degrees of freedom were calculated using the robust residual mode. This approach utilises the standard model residual degrees of freedom while preserving the accuracy of estimated marginal means and adjusted standard errors [41].

3. Results and Discussion

3.1. Results of the Canopy Structure

In the overall multivariate model, the three-way multivariate interactions (CMS × Phenophase × Measurement Time Point and Year × Phenophase × Measurement Time Point were both highly significant ($F(9, 2464) = 3.95$, $p < 0.001$; $F(9, 2464) = 2.16$, $p < 0.05$, respectively). These results indicate that joint canopy growth trajectories across consecutive time points varied significantly by year, CMS, and phenological stage.

3.1.1. Leaf Area Index

For LAI, all four fixed effects were highly significant in the univariate model (Year: $F(1, 112) = 67.21$; CMS: $F(1, 112) = 63.48$; Measurement Time Point: $F(3, 112) = 841.72$; Phenophase: $F(3, 112) = 26.18$, all with $p < 0.001$) together with their all two-, three- and four-way interactions ($p < 0.05$).

The values observed in the late-pruned cordon-trained vines (Table 2) are consistent with previous findings, showing that the leaf area index (LAI) decreases proportionally with later final pruning. In the first experimental year (2023), this pattern persisted across all four measurement dates. In contrast, during 2025, the late-pruned (cordon) vines reached parity with the control vines between the third and fourth sampling events [1,2,4,6,10,20,22,31]. No such reduction in LAI was observed with the umbrella + late cane tying strategy (Table 2); the values remained statistically comparable across all phenological stages. Furthermore, the temporal development of the foliage followed a similar pattern across all treatment groups, confirming that the timing of cane tying exerted no significant influence on canopy expansion during the study period.

Table 2. Mean ± standard deviation and post hoc pairwise comparisons for leaf area index (LAI), analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17). Measurements are presented at four consecutive time points (Dates: 22 May 2023, 5 June 2023, 21 June 2023, 5 July 2023, 20 May 2025, 1 June 2025, 16 June 2025, 4 July 2025). Lowercase letters denote significant differences among phenological stages within the same year, CMS, and time point (Šidák, $p < 0.05$). Uppercase letters denote significant differences among measurement time points (Šidák, $p < 0.05$). An asterisk (*) indicates that a CMS has a significantly higher value compared to the other CMS within that specific year, phenological stage, and time point ($p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within the same CMS, phenological stage, and time point ($p < 0.05$).

Leaf Area Index										
			Date 1		Date 2		Date 3		Date 4	
CMS	Phenophase	Year	Mean ± SD	Post Hoc	Mean ± SD	Post Hoc	Mean ± SD	Post Hoc	Mean ± SD	Post Hoc
cordon (LP)	control	2023	1.05 * ± 0.30	Ac	**2.60** * ± 0.43	Bc	**3.04** * ± 0.64	BCb	**3.18** * ± 0.71	Cb
cordon (LP)	BBCH 13	2023	0.63 ± 0.27	Ab	**2.07** * ± 0.62	Bbc	2.45 * ± 0.55	Cab	**2.90** * ± 0.58	Dab
cordon (LP)	BBCH 15	2023	0.50 ± 0.26	Aab	**1.59** ± 0.50	Bb	2.38 * ± 0.78	Cab	**2.58** * ± 0.40	Cab
cordon (LP)	BBCH 17	2023	0.35 ± 0.14	Aa	0.99 ± 0.42	Ba	2.06 ± 0.75	Ca	2.37 * ± 0.69	Ca
cordon (LP)	control	2025	1.02 * ± 0.65	Ab	1.40 * ± 0.64	Bb	2.44 * ± 0.62	Cb	2.20 * ± 0.38	Ca
cordon (LP)	BBCH 13	2025	**0.97** * ± 0.68	Ab	1.49 * ± 1.01	Bab	2.10 * ± 0.78	Cab	2.22 * ± 0.66	Ca
cordon (LP)	BBCH 15	2025	**0.94** * ± 0.70	Ab	1.13 ± 0.81	Aab	1.89 * ± 0.37	Ba	2.08 * ± 0.57	Ba
cordon (LP)	BBCH 17	2025	**0.47** ± 0.19	Aa	0.88 ± 0.49	Ba	1.88 ± 0.56	Cab	2.14 * ± 0.40	Ca
umbrella (LCT)	control	2023	0.52 ± 0.18	Aa	**1.23** ± 0.22	Ba	1.49 ± 0.26	Ca	**1.73** ± 0.38	Da
umbrella (LCT)	BBCH 13	2023	0.55 ± 0.19	Aa	**1.30** ± 0.50	Ba	1.48 ± 0.43	Ca	**1.61** ± 0.46	Ca
umbrella (LCT)	BBCH 15	2023	0.55 ± 0.17	Aa	**1.33** ± 0.39	Ba	1.52 ± 0.39	Ca	1.58 ± 0.40	Ca
umbrella (LCT)	BBCH 17	2023	0.69 * ± 0.26	Aa	**1.44** * ± 0.41	Ba	1.69 ± 0.48	Ca	**1.81** ± 0.43	Ca
umbrella (LCT)	control	2025	0.51 ± 0.15	Aa	0.78 ± 0.19	Ba	1.33 ± 0.35	Ca	1.33 ± 0.28	Ca
umbrella (LCT)	BBCH 13	2025	0.59 ± 0.25	Aa	0.86 ± 0.33	Ba	1.41 ± 0.57	Ca	1.24 ± 0.34	Ca
umbrella (LCT)	BBCH 15	2025	0.55 ± 0.24	Aa	0.86 ± 0.35	Ba	1.46 ± 0.44	Ca	1.49 ± 0.63	Ca
umbrella (LCT)	BBCH 17	2025	0.57 ± 0.21	Aa	0.94 ± 0.27	Ba	1.61 ± 0.48	Ca	1.38 ± 0.45	Ca

3.1.2. Results of the Canopy Porosity

All four fixed effects were highly significant for canopy porosity (Year: $F(1, 112) = 48.58$; CMS: $F(1, 112) = 254.22$; Measurement Time Point: $F(3, 112) = 362.58$; Phenophase: $F(3, 112) = 15.42$, all with $p < 0.001$), together with significant two-way interactions CMS × Phenophase, Year × Measurement Time Point, CMS × Measurement Time Point, and Phenophase × Measurement Time Point ($p < 0.01$). However, no three-way interactions were significant ($p > 0.05$).

To the best of our knowledge, the literature regarding the effects of late pruning or late cane tying on canopy porosity is currently unavailable; therefore, these findings provide novel insights into this architectural characteristic.

Regarding the late-pruned cordon-trained vines (Table 3), canopy porosity generally decreased with increasing leaf area index, although the reduction was not strictly proportional. In the first experimental year (2023), significant differences were observed at every measurement date, whereas in the second year (2025), differences among phenological stages were detected only at the first sampling event. During the first trial year, the reduction in canopy porosity was slower in the late-pruned vines compared to the control; the control vines reached their final porosity level by the second measurement date, while the treated vines attained this level only by the third or fourth sampling dates. In the second year, this trend was not observed, and the rate of change in porosity remained consistent across all treatments.

Table 3. Mean ± standard deviation and post hoc pairwise comparisons for canopy porosity, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17). Measurements are presented at four consecutive time points (Dates: 22 May 2023, 5 June 2023, 21 June 2023, 5 July 2023, 20 May 2025, 1 June 2025, 16 June 2025, 4 July 2025). Lowercase letters denote significant differences among phenological stages within the same year, CM, and time point (Šidák, $p < 0.05$). Uppercase letters denote significant differences among measurement time points (Šidák, $p < 0.05$). An asterisk (*) indicates that a CMS has a significantly higher value compared to the other CMS within that specific year, phenological stage, and time point ($p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within the same CMS, phenological stage, and time point ($p < 0.05$).

Canopy Porosity										
			Date 1		Date 2		Date 3		Date 4	
CMS	**Phenophase**	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
cordon (LP)	control	2023	0.27 ± 0.07	Ba	0.14 ± 0.03	Aa	0.12 ± 0.05	Aa	0.11 ± 0.05	Aa
cordon (LP)	BBCH 13	2023	0.39 ± 0.14	Cb	0.18 ± 0.06	Bab	0.16 ± 0.04	Bab	0.12 ± 0.03	Aa
cordon (LP)	BBCH 15	2023	0.39 ± 0.10	Cb	0.21 ± 0.06	Bb	0.17 ± 0.06	ABab	0.14 ± 0.03	Aab
cordon (LP)	BBCH 17	2023	0.41 * ± 0.05	Cb	0.27 * ± 0.06	Bc	0.18 ± 0.05	Ab	0.15 ± 0.05	Ab
cordon (LP)	control	2025	0.30 ± 0.10	Ba	**0.24** ± 0.06	Ba	**0.16** ± 0.05	Aa	**0.18** ± 0.05	Aa
cordon (LP)	BBCH 13	2025	0.31 ± 0.10	Ba	**0.26** ± 0.12	Ba	0.17 ± 0.05	Aa	**0.18** ± 0.05	Aa
cordon (LP)	BBCH 15	2025	0.31 ± 0.11	Bab	**0.29** ± 0.10	Ba	0.18 ± 0.04	Aa	**0.19** ± 0.05	Aa
cordon (LP)	BBCH 17	2025	0.39 * ± 0.07	Cb	0.28 ± 0.10	Ba	0.19 ± 0.05	Aa	0.18 ± 0.04	Aa
umbrella (LCT)	control	2023	0.33 * ± 0.06	Ca	0.24 * ± 0.04	Ba	0.22 * ± 0.03	Ba	0.19 * ± 0.04	Aa
umbrella (LCT)	BBCH 13	2023	0.33 ± 0.06	Ba	0.23 * ± 0.05	Aa	0.23 * ± 0.06	Aa	0.21 * ± 0.06	Aa
umbrella (LCT)	BBCH 15	2023	0.34 ± 0.04	Ba	0.24 ± 0.05	Aa	0.22 * ± 0.05	Aa	0.21 * ± 0.05	Aa
umbrella (LCT)	BBCH 17	2023	0.33 ± 0.06	Ca	0.23 ± 0.04	Ba	0.20 ± 0.04	Aa	0.18 ± 0.05	Aa
umbrella (LCT)	control	2025	0.35 ± 0.07	Ba	**0.31** * ± 0.05	Ba	0.24 * ± 0.05	Aa	0.22 * ± 0.04	Aa
umbrella (LCT)	BBCH 13	2025	0.35 ± 0.06	Ca	**0.30** ± 0.06	Ba	0.24 * ± 0.06	Aa	**0.24** * ± 0.05	Aa
umbrella (LCT)	BBCH 15	2025	0.36 ± 0.08	Ba	**0.35** ± 0.11	Ba	0.23 * ± 0.07	Aa	0.23 * ± 0.06	Aa
umbrella (LCT)	BBCH 17	2025	0.32 ± 0.09	Ba	**0.32** ± 0.05	Ba	0.22 ± 0.04	Aa	**0.23** * ± 0.05	Aa

In the umbrella + late cane tying trial (Table 3), no significant differences in canopy porosity were found among phenological stages at any of the measurement dates. The reduction in canopy porosity followed a consistent pattern across all treatment groups. The only exception occurred in the first year, when the control vines and those tied at the BBCH 17 stage reached their final canopy porosity by the second and third measurement dates; however, this difference was not statistically significant and was not replicated in the second year.

3.1.3. Clumping Index

Regarding the clumping index, fixed effects CMS, Phenophase and Measurement Time Point were highly significant (CMS: $F(1, 112) = 31.85$, $p < 0.001$; Measurement Time Point: $F(3, 112) = 67.78$, $p < 0.001$; Phenophase: $F(3, 112) = 3.86$, $p < 0.05$), though, Year was only marginally significant (Year: $F(1, 112) = 2.87$, $p = 0.09$). However, two-way interactions CMS × Phenophase, Year × Measurement Time Point, CMS × Measurement Time Point, and Phenophase × Measurement Time Point were all significant ($p < 0.01$), together with significant three-way interactions Year × Phenophase × Measurement Time Point, Year × CMS × Measurement Time Point and CMS × Phenophase × Measurement Time Point ($p < 0.05$).

Similarly to canopy porosity, the impact of late pruning on the clumping index has previously remained undocumented. For the cordon + late pruning treatment (Table 4), comparable values were observed across all treatments on the first measurement date. Significant differences between phenological stages emerged from the second measurement date in both years. In the first year, vines pruned at the 3-leaf and 5-leaf stages required more time to reach a canopy structure similar to the control, whereas the canopy of vines pruned at the 7-leaf stage remained more clumped even at the final (fourth) measurement date. A very similar pattern was observed in the second year; however, in 2025, the clumping index converged toward similar values across all treatment groups by the fourth sampling date.

Table 4. Mean ± standard deviation and post hoc pairwise comparisons for clumping index, analysed across two years (2023 vs. 2025), two Combined Management Strategy (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17). Measurements are presented at four consecutive time points (Dates: 22 May 2023, 5 June 2023, 21 June 2023, 5 July 2023, 20 May 2025, 1 June 2025, 16 June 2025, 4 July 2025). Lowercase letters denote significant differences among phenological stages within the same year, CMS, and time point (Šidák, $p < 0.05$). Uppercase letters denote significant differences among measurement time points (Šidák, $p < 0.05$). An asterisk (*) indicates that a CMS has a significantly higher value compared to the other CMS within that specific year, phenological stage, and time point ($p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within the same CMS, phenological stage, and time point ($p < 0.05$).

Clumping Index										
			Date 1		Date 2		Date 3		Date 4	
CMS	**Phenophase**	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
cordon (LP)	control	2023	0.70 ± 0.05	Aa	**0.88** * ± 0.10	Bb	0.93 * ± 0.09	Bb	0.94 * ± 0.09	Bb
cordon (LP)	BBCH 13	2023	0.71 ± 0.04	Aa	0.82 * ± 0.08	Bb	0.88 * ± 0.10	BCab	0.92 * ± 0.13	Cab
cordon (LP)	BBCH 15	2023	0.72 ± 0.06	Aa	0.74 ± 0.07	Aa	**0.85** * ± 0.09	Bab	0.89 * ± 0.11	Bab
cordon (LP)	BBCH 17	2023	0.72 ± 0.04	Aa	0.70 ± 0.05	Aa	0.81 ± 0.11	Ba	0.83 * ± 0.11	Ba
cordon (LP)	control	2025	0.73 ± 0.05	Aa	0.75 ± 0.08	Aab	0.87 * ± 0.08	Bb	0.87 * ± 0.10	Ba
cordon (LP)	BBCH 13	2025	0.74 ± 0.09	Aa	0.79 * ± 0.12	ABb	0.83 * ± 0.16	ABab	0.85 * ± 0.10	Ba
cordon (LP)	BBCH 15	2025	0.73 ± 0.06	Aa	0.76 ± 0.11	ABab	0.77 ± 0.08	Aa	0.84 * ± 0.10	Ba
cordon (LP)	BBCH 17	2025	0.72 * ± 0.04	ABa	0.71 ± 0.03	Aa	0.77 ± 0.09	BCa	0.82 * ± 0.07	Ca
umbrella (LCT)	control	2023	0.68 ± 0.06	Aa	0.72 ± 0.05	ABa	0.74 ± 0.06	Ba	0.73 ± 0.06	ABa
umbrella (LCT)	BBCH 13	2023	0.69 ± 0.05	Aa	0.72 ± 0.08	ABa	0.75 ± 0.09	Ba	0.74 ± 0.10	ABa
umbrella (LCT)	BBCH 15	2023	0.70 ± 0.04	Aa	0.73 ± 0.04	Ba	0.74 ± 0.07	ABa	0.73 ± 0.05	ABa
umbrella (LCT)	BBCH 17	2023	0.71 ± 0.03	Aa	0.74 * ± 0.05	Aa	0.75 ± 0.09	Aa	0.74 ± 0.11	Aa
umbrella (LCT)	control	2025	0.70 ± 0.06	Aa	0.71 ± 0.06	Aa	0.74 ± 0.05	Aa	0.70 ± 0.06	Aa
umbrella (LCT)	BBCH 13	2025	0.71 ± 0.04	Aa	0.72 ± 0.07	ABa	0.75 ± 0.04	Ba	0.72 ± 0.06	ABa
umbrella (LCT)	BBCH 15	2025	0.71 ± 0.04	Aa	0.75 ± 0.06	Aa	0.74 ± 0.06	Aa	0.75 ± 0.08	Aa
umbrella (LCT)	BBCH 17	2025	0.68 ± 0.07	Aa	0.75 * ± 0.05	Ba	0.77 ± 0.09	Ba	0.73 ± 0.06	ABa

In the umbrella + late cane tying trial (Table 4), no such trends were detected. Foliage distribution remained consistent across all treatment groups at every measurement date, and the rate of temporal change was lower than that observed in the cordon-trained (late-pruned) vines.

3.2. Productivity

To evaluate the vegetative–reproductive balance of the vines, fertility coefficients were determined. These indices provide valuable insights into the equilibrium between growth and crop load, as they account for all shoots, including those arising from older wood.

The global multivariate model demonstrated a highly significant three-way interaction, Year × CMS × Phenophase ($F(3, 560) = 4.367$, $p < 0.01$), indicating that metrics varied significantly across years, CMSs, and phenophases.

3.2.1. Absolute Fertility Coefficient

For absolute fertility coefficient, Year ($F(1, 112) = 4.12$ $p < 0.05$), CMS ($F(1, 112) = 19.28$, $p < 0.001$), and Phenophase ($F(3, 112) = 6.62$, $p < 0.0001$) were highly significant together with CMS × Phenophase ($F(3, 112) = 9.30$, $p < 0.001$) and Year × Phenophase ($F(3, 112) = 2.80$, $p < 0.001$). Pairwise comparison results are shown in Table 5.

Table 5. Mean ± standard deviation and post hoc pairwise comparisons for the absolute fertility coefficient, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: (cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17). Lowercase letters denote significant differences among phenological stages within the same year and CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenological stage (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within the same CMS and phenological stage ($p < 0.05$).

Absolute Fertility Coefficient					
		Cordon (LP)		**Umbrella (LCT)**	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	1.37 ± 0.17	Ab	1.32 ± 0.26	Aa
BBCH 13	2023	1.35 ± 0.17	Ab	1.39 ± 0.20	Aa
BBCH 15	2023	1.18 ± 0.18	Aa	1.48 ± 0.22	Ba
BBCH 17	2023	1.14 ± 0.18	Aa	1.41 ± 0.14	Ba
control	2025	**1.50** ± 0.14	Bb	1.34 ± 0.26	Aa
BBCH 13	2025	1.30 ± 0.19	Aa	1.43 ± 0.13	Ba
BBCH 15	2025	1.20 ± 0.14	Aa	1.39 ± 0.19	Ba
BBCH 17	2025	1.13 ± 0.21	Aa	1.46 ± 0.19	Ba

In the cordon + late pruning trial (Table 5), the control vines exhibited the highest absolute fertility coefficient in both study years (2023: 1.37; 2025: 1.50). In the first year, vines pruned at the BBCH 13 stage yielded a similar value (1.35); however, in the second year, all cordon + late-pruned treatments exhibited lower values than the control. Although a numerical decline in the means was observed as pruning was further delayed, these differences were not statistically significant. This indicates that while late pruning affects the absolute fertility coefficient of cordon-trained vines, progressively delaying pruning from the 3-leaf to the 7-leaf stage does not yield a further significant reduction.

Among the umbrella-trained vines subjected to late cane tying (Table 5), no significant differences were observed across the phenological stages. While the control vines for both CMSs showed comparable absolute fertility in both years, a higher number of bunches per fertile shoot was recorded in the late cane-tied (umbrella trained) treatments compared to the late-pruned (cordon trained) treatments across all phenological stages.

3.2.2. Relative Fertility Coefficient

CMS × Phenophase ($F(3, 112) = 15.15$, $p < 0.001$) and Year × Phenophase ($F(3, 112) = 10.95$, $p < 0.001$) were highly significant also in case of RTE, with the significant main effects of

Year (F(1, 112) = 5.10, $p < 0.05$), CMS (F(1, 112) = 35.87, $p < 0.001$), and Phenophase (F(3, 112) = 8.28, $p < 0.0001$). In the cordon + late pruning trial (Table 6), delaying the pruning date resulted in a downward trend in the relative fertility coefficient (the number of bunches per total shoot). The highest values were observed in the control treatment in both study years (2023: 0.75; 2025: 1.19), whereas the lowest values were recorded for vines pruned at the BBCH 17 stage (2023: 0.41; 2025: 0.37). This finding aligns with previous studies, which reported that late pruning of cordon-trained vines significantly reduces the relative fertility coefficient [2,24,45]. In the umbrella + late cane-tying trial (Table 6), although the treated vines exhibited a slightly higher bunch-to-total-shoot ratio than the control in the first study year, this pattern was not replicated in 2025. No statistically significant differences were found, despite the higher average values observed in the treatments compared with the control. These results highlight a distinct physiological response to late cane tying on umbrella-trained vines compared to traditional late pruning on cordon-trained vines.

Table 6. Mean ± standard deviation and post hoc pairwise comparisons for relative fertility coefficient, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17). Lowercase letters denote significant differences among phenological stages within the same year and CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenological stage (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within the same CMS and phenological stage ($p < 0.05$).

Relative Fertility Coefficient					
		Cordon (LP)		**Umbrella (LCT)**	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	0.75 ± 0.27	Ac	0.60 ± 0.27	Aa
BBCH 13	2023	0.65 ± 0.27	Abc	0.74 ± 0.26	Aab
BBCH 15	2023	0.48 ± 0.28	Aab	0.94 ± 0.27	Bb
BBCH 17	2023	0.41 ± 0.24	Aa	0.80 ± 0.21	Bab
control	2025	**1.19** ± 0.28	Bd	0.70 ± 0.44	Aa
BBCH 13	2025	**0.82** ± 0.24	Ac	**1.02** ± 0.32	Aa
BBCH 15	2025	0.57 ± 0.21	Ab	1.02 ± 0.30	Ba
BBCH 17	2025	0.37 ± 0.22	Aa	0.92 ± 0.37	Ba

3.2.3. Number of Bunches

In the univariate model of number of bunches, the main effects of Year (F(1, 112) = 34.36, $p < 0.001$), CMS (F(1, 112) = 8.69, $p < 0.01$), and Phenophase (F(3, 112) = 11.70, $p < 0.0001$) were highly significant, along with the two-way interactions CMS × Phenophase (F(3, 112) = 15.73, $p < 0.001$) and CMS × Year (F(1, 112) = 5.14, $p < 0.05$).

Consistent with previous findings [2,6,8,20,22,25–27,31,46], delaying the pruning date of cordon-trained vines led to a gradual, stepwise reduction in the number of bunches per vine (Table 7). While the control vines produced an average of 24.07 bunches in 2023 and 23.53 bunches in 2025, the lowest values in both years were recorded for vines pruned at the BBCH 17 stage; these averaged 8.73 bunches per vine in 2023 (a 63.73% reduction) and 6.20 bunches per vine in 2025, representing a 73.65% reduction compared to the control.

Table 7. Mean ± standard deviation and post hoc pairwise comparisons for number of bunches, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17). Lowercase letters denote significant differences among phenological stages within the same year and CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenological stage (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within the same CMS and phenological stage ($p < 0.05$).

Number of Bunches					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	24.07 ± 10.52	Bc	**16.00** ± 9.47	Aa
BBCH 13	2023	19.20 ± 9.31	Abc	**18.80** ± 7.69	Aa
BBCH 15	2023	12.40 ± 7.84	Aab	**22.13** ± 11.65	Ba
BBCH 17	2023	**8.73** ± 5.55	Aa	**21.53** ± 8.30	Ba
control	2025	23.53 ± 8.18	Bc	11.20 ± 8.63	Aa
BBCH 13	2025	14.40 ± 5.22	Ab	12.60 ± 5.94	Aa
BBCH 15	2025	11.33 ± 4.88	Ab	14.60 ± 6.28	Aa
BBCH 17	2025	6.20 ± 3.80	Aa	13.13 ± 7.22	Ba

In the late cane-tying trial, although the treated vines exhibited higher average values than the control vines, no statistically significant differences were detected in either year.

3.3. Yield

The univariate generalised least squares (GLS) models fitted on pot-level means revealed that the main effect of Year was significant for both yield and berry weight ($F(1, 32) = 592.64$, $p < 0.001$; $F(1, 32) = 96.43$, $p < 0.001$, respectively). Although the main effect of Year was not significant for bunch weight ($F(3, 32) = 1.27$, $p = 0.27$), the Year × Phenophase interaction was significant ($F(3, 32) = 4.77$, $p < 0.01$), which indicates a masked significant year effect. CMS effect was significant for yield and cluster weight ($F(1, 32) = 2654.63$, $p < 0.001$; $F(1, 32) = 163.53$, $p < 0.001$, respectively) but was not significant as a main effect for berry weight ($F(1, 32) = 0.18$, $p = 0.673$). The main effect of Phenophase was significant for berry weight ($F(3, 32) = 6.01$, $p < 0.01$), and yield per vine ($F(3, 32) = 188.12$, $p < 0.001$). For bunch weight, while the main effect of Phenophase was not significant ($F(3, 32) = 2.00$, $p = 0.134$), the Training × Phenophase interaction was highly significant ($F(3, 32) = 16.47$, $p < 0.001$). The two-way Year × Phenophase interaction was significant for yield ($F(3, 32) = 4.28$, $p < 0.05$) and bunch weight ($F(3, 32) = 4.77$, $p < 0.01$) and showed a marginally significant difference for berry weight ($F(3, 32) = 2.89$, $p = 0.05$). The three-way Year × Training × Phenophase interaction was significant for yield per vine ($F(3, 32) = 3.99$, $p < 0.05$), but non-significant for berry mass ($F(3, 32) = 1.35$, $p = 0.28$) and bunch mass ($F(3, 32) = 0.31$, $p = 0.82$).

3.3.1. Yield per Vine

Our results (Table 8) align with previous studies, demonstrating a decreasing trend in yield per vine as the pruning date of cordon-trained vines was delayed [1,2,4,6,8,15,16,18,20,22,24–26]. In the first year (2023), no statistically significant differences in average yield per vine were observed between the control and vines pruned at the 3-leaf and 5-leaf stages; however, the treatments differentiated more clearly from the control in the second study year (2025). In both years, the lowest yield per vine was recorded for vines pruned at the 7-leaf stage: 592.67 g/vine in 2023 (–55.4%) and 579.33 g/vine in 2025, representing a 76.34% reduction compared to the control.

Table 8. Means and standard deviations of yield per vine analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and treatments were applied at four different phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17, n = 3). Lowercase letters denote significant differences among phenological stages within the same year and CMS (Tukey HSD, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenological stage (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in a given year compared to the other year within the same CMS and phenological stage ($p < 0.05$).

Yield Per Vine					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	Year	Mean ± SD	Post Hoc	Mean ± SD	Post Hoc
control	2023	1085.33 ± 810.15	Aab	1060.67 ± 332.00	Aa
BBCH 13	2023	1134.00 ± 157.25	Ab	1211.67 ± 41.06	Aab
BBCH 15	2023	888.33 ± 708.29	Aab	1678.67 ± 231.61	Abc
BBCH 17	2023	592.67 ± 254.32	Aa	1977.00 ± 335.24	Bc
control	2025	**2449.33** ± 65.43	Bc	**1501.33** ± 60.04	Aa
BBCH 13	2025	1053.00 ± 68.55	Ab	**1842.67** ± 60.62	Bb
BBCH 15	2025	1042.67 ± 44.02	Ab	**3045.67** ± 41.65	Bd
BBCH 17	2025	579.33 ± 59.69	Aa	**2810.67** ± 85.97	Bc

In the umbrella + late cane tying trial (Table 8), the average yield for the treated vines was numerically higher than that of the control across both years and all phenological stages. Notably, yield per vine increased as the tying date was delayed. In both study years, the lowest yield was measured in the control treatment (2023: 1060 g/vine; 2025: 1501 g/vine), whereas the highest yields were recorded in vines tied at the 5-leaf or 7-leaf stages (2023: BBCH 17 at 1977 g/vine, +86.51%; 2025: BBCH 15 at 3045 g/vine, +102.86%). The impact of the vintage was also evident in the umbrella-trained vines, with higher yields observed across all phenological stages in 2025.

The standard deviations recorded for 2025 yield per vine were markedly lower than in 2023. This reflects the strict pre-harvest vine selection protocol applied in 2025 across uniform inner vines to minimise micro-environmental outliers under extreme drought. Due to the limited sample size (n = 3 vines per treatment), yield data should be interpreted as proof-of-concept demonstrating relative treatment trajectories rather than absolute vineyard-scale tonnage.

3.3.2. Berry Weight

In the first experimental year (Table 9), among the cordon-trained late-pruned vines, the control treatment exhibited the highest average berry weight (1.67 g). In contrast, vines pruned at the BBCH 15 and BBCH 17 stages produced berries with significantly lower average weights, while the berry weight of vines pruned at the BBCH 13 stage did not differ statistically from either group. However, this trend was not replicated in 2025, when the lowest average value was recorded in the control. In the second year, treatments were differentiated into two groups based on average berry weight: the control and BBCH 13 and BBCH 15 vines formed a group with lower average values, whereas vines pruned at BBCH 17 formed a group with significantly higher berry weights. These results do not unequivocally demonstrate a consistent effect of late pruning on berry weight. In previous studies, berry weight generally exhibited a declining trend as the pruning date was delayed [2,6,8,18,20,24,46]. However, in specific cases where the baseline yield per vine was exceptionally high, such as 4.3 kg/vine [27], or 14.4 kg/vine [22], slight increases in berry weight were observed in certain years.

Table 9. Means and standard deviations of berry weight analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and treatments were applied at four different phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17; plot-aggregated n = 3). Lowercase letters denote significant differences among phenological stages within the same year and CMS (Tukey HSD, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenological stage (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in a given year compared to the other year within the same CMS and phenological stage ($p < 0.05$).

Berry Weight					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	**1.67** ± 0.33	Ab	**1.60** ± 0.42	Aab
BBCH 13	2023	**1.46** ± 0.38	Aab	**1.41** ± 0.33	Aa
BBCH 15	2023	**1.39** ± 0.41	Aa	**1.40** ± 0.25	Aa
BBCH 17	2023	1.39 ± 0.41	Aa	**1.68** ± 0.31	Bb
control	2025	1.04 ± 0.24	Aa	1.12 ± 0.25	Aab
BBCH 13	2025	1.12 ± 0.18	Aab	1.06 ± 0.26	Aa
BBCH 15	2025	1.08 ± 0.21	Aa	1.15 ± 0.24	Aab
BBCH 17	2025	1.25 ± 0.25	Ab	1.24 ± 0.24	Ab

In the late cane tying trial of umbrella-trained vines (Table 9), higher average values were observed in 2023, similar to the cordon-trained late-pruned vines. In that year, the berries of the control vines and those tied at the BBCH 17 stage exhibited higher average weights (1.60 and 1.68 g, respectively), whereas berries from the BBCH 13 and BBCH 15-scheduled treatments were significantly lighter (1.41 and 1.40 g). In this regard, the control vines were statistically comparable to both groups. Results followed a similar pattern in 2025, with the highest average (1.24 g) recorded in vines tied at the BBCH 17 stage and the lowest in the BBCH 13-scheduled treatment (1.06 g). In the second year, the control and BBCH 15 vines did not differ statistically from either the control or the vines tied at the 7-leaf stage.

3.3.3. Average Bunch Weight

Our results align closely with previous studies on late pruning [1,6,8,10,20,24,25,27,31]. In line with the delay in pruning, the average bunch weight of cordon-trained vine samples showed a progressive decline. As shown in Table 10, the BBCH 13 stage had a negligible effect on bunch weight; however, pruning at the BBCH 15 and BBCH 17 stages exerted a more pronounced impact. The lowest average bunch weights and the most substantial reductions relative to the control were recorded in 2023 for the BBCH 17-scheduled treatment (55.71 g/bunch; −31.5%) and in 2025 for the BBCH 15-scheduled treatment (55.43 g/bunch; −34.0%).

In contrast, the umbrella-trained vines subjected to late cane tying exhibited a different trend. Bunches from the treated vines generally had a higher average weight than those from the control vines. In both study years, the greatest average bunch weights were recorded in the treatment groups—specifically in vines tied at the 7-leaf stage—yielding 111.40 g/bunch in 2023 and 120.23 g/bunch in 2025. In 2025, a notably higher value was recorded for the control compared to the previous year; this result was likely attributable to the inherent vine-to-vine heterogeneity characteristic of that growing season.

Table 10. Means and standard deviations of average bunch weight analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and treatments were applied at four different phenological stages (control (BBCH 00), BBCH 13, BBCH 15, and BBCH 17; plot-aggregated n = 3). Lowercase letters denote significant differences among phenological stages within the same year and CMS (Tukey HSD, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenological stage (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in a given year compared to the other year within the same CMS and phenological stage ($p < 0.05$).

Average Bunch Weight					
		Cordon (LP)		**Umbrella (LCT)**	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	81.36 ± 57.28	Abc	85.20 ± 51.71	Aa
BBCH 13	2023	**88.12** ± 55.21	Ac	94.80 ± 65.35	Aab
BBCH 15	2023	66.03 ± 50.60	Aab	105.08 ± 77.51	Bab
BBCH 17	2023	55.71 ± 41.31	Aa	111.40 ± 73.13	Bb
control	2025	83.97 ± 43.80	Ab	**115.07** ± 60.58	Bb
BBCH 13	2025	71.77 ± 22.84	Aab	87.93 ± 25.31	Ba
BBCH 15	2025	55.43 ± 27.99	Aa	113.60 ± 40.75	Bab
BBCH 17	2025	61.53 ± 26.39	Aab	120.23 ± 47.38	Bb

3.4. Results of the Must Analysis

The global multivariate model resulted in highly significant fixed effects of Year and Phenophase (F(1, 160) = 37.12; F(1, 160) = 10.01, respectively, both with $p < 0.001$), though just a marginally significant effect for CMS (F(1, 160) = 3.22, $p = 0.07$). However, two-way interactions Year × Phenophase and CMS × Phenophase were both highly significant ($p < 0.001$), demonstrating that the must quality parameters differed significantly across years, CMSs, and treatment phenophases.

The univariate models revealed highly significant main effects and interactive structures. The main effects of Year and Phenophase were highly significant for all five variables (Year: F(1, 32) > 24.30, $p < 0.001$; Phenophase: F(1, 32) > 26.01, $p < 0.001$). The CMS effect was significant for sugar, TA, malic and tartaric acid (F(1, 32) = 8.82, $p < 0.01$), but not for pH (F(1, 32) = 0.20, $p = 0.64$). However, the CMS × Phenophase interaction was significant for pH (F(3, 32) = 49.10, $p < 0.001$), which probably masked the main effect of CMS.

Regarding the final must sugar concentration (Table 11), late pruning cordon-trained vines at different phenological stages in the first study year (2023) did not yield statistically significant differences compared to the control (233.17 g/L), with values ranging from 225.10 g/L to 230.97 g/L. In 2025, however, sugar accumulation reached significantly higher levels at the BBCH 13 (238.63 g/L) and BBCH 15 (242.30 g/L) stages than in the samples of the same treatment phenophases in 2023 ($p < 0.05$; values in bold). Furthermore, in 2025, these two cordon + late pruning treatments resulted in significantly higher sugar concentrations not only compared to the extremely late pruning at BBCH 17 (222.23 g/L) within the same CMS but also compared to the corresponding phenological stages of the umbrella + LCT strategy.

In the umbrella-trained (late cane-tied) vines, sugar concentration was more stable across treatment stages and study years (Table 11). In 2023, no significant differences were observed among the tying dates, with sugar concentrations ranging from 213.17 g/L (control) to 226.83 g/L (BBCH 17). In 2025, the highest sugar accumulation was recorded in vines tied at the BBCH 15 stage (236.33 g/L), representing a significant increase compared to the 2023 season ($p < 0.05$, bold value) and significantly higher than the BBCH 13-scheduled treatment of the same year (220.27 g/L). Nevertheless, this peak value remained statistically comparable to both the control (234.30 g/L) and the BBCH 17-scheduled treatment (221.40 g/L).

Table 11. Mean ± standard deviation and post hoc pairwise comparisons for final must sugar content, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four treatment phenophases (control (BBCH 00), BBCH 13, BBCH 15, BBCH 17). Lowercase letters denote significant differences among phenophases within the same year, CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenophase (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within that CMS, phenophase, and time point ($p < 0.05$).

Sugar Content (g/L)					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	233.17 ± 14.62	Aa	213.17 ± 13.07	Aa
BBCH 13	2023	230.53 ± 4.32	Aa	216.53 ± 19.65	Aa
BBCH 15	2023	230.97 ± 5.88	Aa	225.10 ± 7.42	Aa
BBCH 17	2023	225.10 ± 6.39	Aa	226.83 ± 10.52	Aa
control	2025	234.00 ± 2.14	Ab	**234.30** ± 4.23	Aab
BBCH 13	2025	**238.63** ± 3.42	Bbc	220.27 ± 10.02	Aa
BBCH 15	2025	**242.30** ± 1.31	Bc	**236.33** ± 2.11	Ab
BBCH 17	2025	222.23 ± 3.04	Aa	221.40 ± 10.78	Aab

Regarding titratable acidity (Table 12), values in 2023 remained statistically stable across all phenological stages (6.33–6.77 g/L), with no significant differences observed among treatments. In 2025, however, values were significantly lower in both the control (4.80 g/L) and the BBCH 13-scheduled treatment (4.57 g/L) compared to 2023 ($p < 0.05$; values for 2023 are indicated in bold). In contrast, delaying pruning to BBCH 15 (6.07 g/L) and BBCH 17 (7.50 g/L) in 2025 resulted in significantly higher titratable acidity than at earlier phenological stages in the same year. Notably, at these later stages (BBCH 15 and BBCH 17), the cordon-trained (late-pruned) vines exhibited significantly higher acidity than the corresponding umbrella-trained (late cane-tied) ones in both study years.

In the umbrella-trained (late cane-tied) vines, titratable acidity followed a different pattern across treatments and years (Table 12). As in the cordon + LP strategy, no significant differences were observed among phenological stages in 2023, with values ranging from 5.60 g/L to 6.33 g/L. In 2025, although late cane tying at BBCH 15 (5.43 g/L) and BBCH 17 (5.60 g/L) resulted in statistically higher acidity compared to the cordon + LP strategy at BBCH 15, these values remained lower than the BBCH 17 cordon + LP treatment (7.50 g/L). Furthermore, while the control and BBCH 13-scheduled treatments in the umbrella + LCT strategy reached higher acidity in 2025 than their cordon +LP counterparts, no significant differences were detected among treatment stages within the umbrella training with LCT.

Regarding the must pH (Table 13), values in 2023 ranged between 3.34 and 3.42 across stages, with the BBCH 13-scheduled treatment showing a significantly higher value (3.42) compared to the control (3.37). In 2025, however, a clear decline in pH was observed as pruning of cordon-trained vines was delayed; values decreased from 3.37 in the control to 3.28 at BBCH 15, reaching a minimum at BBCH 17 (3.14). This represented a statistically significant difference across phenological stages. Furthermore, for both the BBCH 15 and BBCH 17-scheduled treatments, pH values in 2025 were significantly lower than those measured in 2023 ($p < 0.05$, bold values in Table 12). When comparing CMSs, the cordon system with LP exhibited a significantly higher pH in the BBCH 13-scheduled treatment in

2025 compared to the umbrella system with LCT. In contrast, the 2023 control treatment showed higher pH values for cordon + LP-trained vines.

Table 12. Mean ± standard deviation and post hoc pairwise comparisons for final must titratable acidity, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four treatment phenophases (control (BBCH 00), BBCH 13, BBCH 15, BBCH 17). Lowercase letters denote significant differences among phenophases within the same year, CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenophase (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within that CMS, phenophase, and time point ($p < 0.05$).

Titratable Acidity (g/L)					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	**6.50** ± 0.66	Aa	**6.33** ± 1.29	Aa
BBCH 13	2023	**6.33** ± 0.21	Aa	5.90 ± 0.66	Aa
BBCH 15	2023	6.60 ± 0.53	Ba	5.63 ± 0.40	Aa
BBCH 17	2023	6.77 ± 1.25	Aa	5.60 ± 0.61	Aa
control	2025	4.80 ± 0.10	Aa	5.07 ± 0.12	Ba
BBCH 13	2025	4.57 ± 0.12	Aa	5.30 ± 0.46	Bab
BBCH 15	2025	6.07 ± 0.06	Bb	5.43 ± 0.12	Ab
BBCH 17	2025	7.50 ± 0.10	Bc	5.60 ± 0.10	Ab

Table 13. Mean ± standard deviation and post hoc pairwise comparisons for final must pH value, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four treatment phenophases (control (BBCH 00), BBCH 13, BBCH 15, BBCH 17). Lowercase letters denote significant differences among phenophases within the same year, CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenophase (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within that CMS, phenophase, and time point ($p < 0.05$).

pH Value					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	3.37 ± 0.02	Ba	3.32 ± 0.03	Aa
BBCH 13	2023	3.42 ± 0.02	Ab	3.34 ± 0.07	Aab
BBCH 15	2023	**3.36** ± 0.06	Aab	**3.41** ± 0.03	Ab
BBCH 17	2023	**3.34** ± 0.10	Aab	**3.36** ± 0.05	Aab
control	2025	3.37 ± 0.04	Ac	3.34 ± 0.01	Ac
BBCH 13	2025	3.41 ± 0.02	Bc	3.28 ± 0.02	Ab
BBCH 15	2025	3.28 ± 0.01	Ab	3.31 ± 0.02	Bbc
BBCH 17	2025	3.14 ± 0.02	Aa	3.24 ± 0.01	Ba

In the umbrella-trained late cane tied vines, pH values also demonstrated treatment schedule- and vintage-dependent variations (Table 13). In 2023, pH values fluctuated between 3.32 (control) and 3.41 (BBCH 15), with the BBCH 15-scheduled treatment exhibiting a significantly higher pH than the control. In 2025, similarly to the cordon + LP strategy, delaying cane tying of umbrella-trained vines resulted in lower pH values, which decreased from 3.34 in the control to 3.24 in the BBCH 17-scheduled treatment. Significant vintage variations were also observed, as the treatments were scheduled at BBCH 15 (3.41) and BBCH 17 (3.36): in 2023, their pH values were significantly higher than the corresponding values in 2025 (3.31 and 3.24, respectively; $p < 0.05$, bold values). Across CMSs in 2025, the umbrella + late cane-tying strategy recorded a significantly higher pH at the BBCH 15 stage (3.31) than the cordon system with late pruning, whereas at the BBCH 17 stage, umbrella + LCT strategy reached a higher pH value (3.24) relative to the cordon + LP strategy (3.14).

Regarding malic acid content (Table 14), in 2023, concentrations ranged between 3.33 and 4.17 g/L across phenological stages, with no statistically significant differences observed among treatments within that year. In 2025, however, delaying pruning of the cordon-trained vines led to a strong, stage-dependent increase in malic acid content, rising progressively from 1.97 g/L in the control to 2.40 g/L at BBCH 13, 3.00 g/L at BBCH 15, and peaking at 4.33 g/L at BBCH 17. All phenological stages in 2025 differed significantly from one another. Significant vintage variation was also observed: for the control, BBCH 13, and BBCH 15-scheduled treatments, malic acid levels were significantly higher in 2023 than in 2025 ($p < 0.05$; values in bold). When comparing CMSs, the cordon system with LP recorded significantly higher malic acid content in 2025 across all late-pruned stages (BBCH 13, BBCH 15, and BBCH 17) than the umbrella system with LCT.

Table 14. Mean ± standard deviation and post hoc pairwise comparisons for final must malic acid content, analysed across two years (2023 vs. 2025), two Combined Management Strategies (cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four treatment phenophases (control (BBCH 00), BBCH 13, BBCH 15, BBCH 17). Lowercase letters denote significant differences among phenophases within the same year, CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenophase (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within that CMS, phenophase, and time point ($p < 0.05$).

Malic Acid Content (g/L)					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	**3.33** ± 0.38	Aa	**3.23** ± 0.78	Aa
BBCH 13	2023	**3.87** ± 0.31	Ba	**2.73** ± 0.06	Aa
BBCH 15	2023	**3.87** ± 0.21	Aa	**3.33** ± 0.75	Aa
BBCH 17	2023	4.17 ± 1.19	Aa	**3.03** ± 0.68	Aa
control	2025	1.97 ± 0.06	Aa	2.43 ± 0.15	Bb
BBCH 13	2025	2.40 ± 0.17	Bb	1.97 ± 0.21	Aa
BBCH 15	2025	3.00 ± 0.10	Bc	2.23 ± 0.06	Aab
BBCH 17	2025	4.33 ± 0.15	Bd	2.07 ± 0.15	Aa

In the umbrella-trained (late cane-tied) vines, malic acid content exhibited a distinct pattern across treatments and study years (Table 14). In 2023, malic acid values ranged from 2.73 g/L to 3.33 g/L, with no significant differences observed among the phenological stages. In 2025, values were lower overall, ranging between 1.97 g/L (BBCH 13) and 2.43 g/L (control), with only slight variations among treatments. Significant vintage differences were observed across most treatments, with malic acid levels at BBCH 13, BBCH 15, and BBCH 17 significantly higher in 2023 than in 2025 ($p < 0.05$; bold values). Furthermore, in 2025, the umbrella + LCT strategy recorded a significantly higher malic acid content in the control treatment compared to the cordon + LP strategy, whereas delaying cane tying to BBCH 13, BBCH 15, or BBCH 17 resulted in lower malic acid values relative to the corresponding cordon + LP treatments.

Regarding tartaric acid content (Table 15), distinct effects of CMS, and vintage were observed in the cordon-trained (late-pruned) vines. In 2023, tartaric acid values ranged from 4.77 g/L (BBCH 17) to 5.63 g/L (BBCH 13), with no statistically significant differences among treatments within that year. In 2025, however, delaying pruning of the cordon-trained vines to BBCH 15 (6.30 g/L) and BBCH 17 (6.20 g/L) resulted in significantly higher tartaric acid contents compared to both the control (5.80 g/L) and the BBCH 13-scheduled treatment (5.37 g/L). Significant vintage variation was also evident: while the BBCH 13 stage in 2023 (5.63 g/L) was significantly higher than in 2025 ($p < 0.05$, bold value), both the BBCH 15 and BBCH 17-scheduled treatments recorded significantly higher tartaric acid contents in 2025 (6.30 g/L and 6.20 g/L) compared to 2023 (5.53 g/L and 4.77 g/L; $p < 0.05$, bold values). When comparing CMSs, the cordon + LP strategy exhibited a significantly higher tartaric acid content in the control treatment in 2025 and at the BBCH 15 stage in 2023.

Table 15. Mean ± standard deviation and post hoc pairwise comparisons for final must tartaric acid content, analysed across two years (2023 vs. 2025), two Combined Management Strategies (CMS: cordon with LP = late pruning vs. umbrella with LCT = late cane tying), and four treatment phenophases (control (BBCH 00), BBCH 13, BBCH 15, BBCH 17). Lowercase letters denote significant differences among phenophases within the same year, CMS (Šidák, $p < 0.05$). Uppercase letters denote significant differences between CMSs within the same year and phenophase (Šidák, $p < 0.05$). Bold values indicate that the mean is statistically significantly higher in that year than in the other year within that CMS, phenophase, and time point ($p < 0.05$).

Tartaric Acid Content (g/L)					
		Cordon (LP)		Umbrella (LCT)	
Phenophase	**Year**	**Mean ± SD**	**Post Hoc**	**Mean ± SD**	**Post Hoc**
control	2023	5.53 ± 0.57	Aa	5.57 ± 1.07	Aa
BBCH 13	2023	**5.63** ± 0.12	Aa	5.30 ± 0.46	Aa
BBCH 15	2023	5.53 ± 0.42	Ba	4.90 ± 0.10	Aa
BBCH 17	2023	4.77 ± 0.68	Aa	5.07 ± 0.38	Aa
control	2025	**5.80** ± 0.10	Bb	5.47 ± 0.12	Aa
BBCH 13	2025	5.37 ± 0.15	Aa	**6.23** ± 0.49	Bab
BBCH 15	2025	**6.30** ± 0.20	Ac	**6.27** ± 0.12	Ab
BBCH 17	2025	**6.20** ± 0.17	Ac	**6.47** ± 0.15	Ab

In the umbrella-trained (late cane-tied) vines, tartaric acid content demonstrated a consistent upward response in 2025 (Table 15). In 2023, values ranged between 4.90 g/L (BBCH 15) and 5.57 g/L (control), with no significant differences among phenological stages. In 2025, delaying cane tying led to significantly increased tartaric acid levels across all treated stages—BBCH 13 (6.23 g/L), BBCH 15 (6.27 g/L), and BBCH 17 (6.47 g/L)—compared to the control (5.47 g/L). Furthermore, all umbrella + late cane-tying treatments (BBCH 13, BBCH 15, and BBCH 17) showed significantly higher tartaric acid contents in 2025 than in 2023 ($p < 0.05$; bold values). Across CMSs in 2025, the umbrella + LCT strategy recorded a significantly higher tartaric acid content at the BBCH 13 stage compared to the cordon + LP strategy.

In the literature on late pruning, studies frequently report reduced sugar accumulation, higher titratable acidity, and lower pH [1–3,25,46]. However, several investigations found minimal or no differences [6,8,10,14,16,20,27,31,45], while others—despite observing higher yields per vine—reported an advanced ripening stage reflected in the analytical parameters of the must [22,24]. The results of our must analysis are highly consistent with these previous research findings. However, significant differences were observed in certain cases; these were not consistently reproducible across all study years. It is presumed that because of the impact of late pruning on yield, the differences in final must composition do not fully manifest. Consequently, the impact of cordon + late pruning or umbrella + late cane tying on must composition remains inconclusive, as vineyard-specific characteristics, grape variety, regional terroir, and unpredictable seasonal climatic variations heavily modulate it.

3.5. Limitations of the Study

Several limitations should be considered when interpreting these results. Direct comparisons between late pruning and late cane-tying require cautious interpretation. These practices were evaluated under distinct training systems (cordon vs. umbrella) across adjacent but distinct vineyard blocks. All observed differences between them refer to the tested practice within the respective training system as a combined management strategy.

The evaluation of the impact of CMSs on ripening delay was constrained by the lack of a sequential analysis of ripening dynamics. Since only the final must composition was recorded at harvest, the precise kinetic shifts in sugar accumulation and organic acid degradation throughout the ripening period remain uncharacterised. It is critical to note, however, that serial ripening sampling was intentionally omitted because the removal of berries or whole bunches would have directly altered the crop load and yield-related metrics, which were the primary focuses of this evaluation. To obtain more robust and statistically reliable data regarding bunch weight, berry weight, and overall yield, a higher number of replicates would be beneficial in future investigations.

While no immediate macro-phenological anomalies were observed, a more granular approach—specifically tracking phenological stages by individual bud positions along the cane—would be necessary to comprehensively evaluate how the treatment modulates budburst uniformity and early shoot development.

Because of a data-recording omission in 2025, block-level identifiers were unavailable for yield per vine, bunch weight, and berry weight. For these specific variables, data were pooled across blocks and treated as independent in the statistical analysis, as block-level random or fixed effects could not be applied.

Because the grapevine is a perennial crop highly sensitive to cumulative stress, these findings reflect only short-term physiological responses. Evaluating consecutive vintages is essential to validate the reliability and stability of these outcomes and to assess potential long-term cumulative effects on vine carbohydrate reserves and subsequent longevity.

4. Conclusions

Delaying the pruning date of the cordon-trained vines—particularly to the BBCH 15 and BBCH 17 stages—significantly reduced the leaf area index (LAI) of the vines. This delay slowed canopy closure, resulting in a slower reduction in porosity and a more uneven, clumped canopy structure. Regarding productivity, late pruning of the cordon-trained vines significantly reduced fertility metrics, including absolute and relative fertility coefficients. It reduced the number of bunches per vine, resulting in a 63.7–73.7% drop at BBCH 17. Consequently, this delay in pruning time led to severe yield losses, with yield per vine falling 55.4–76.3% below the control in the latest treatments. Average bunch weight also fell by up to 34%, whereas berry weight showed no consistent trend across years. The impact on must composition varied by vintage; in 2023 minimal differences were found. In 2025, late pruned and cordon-trained vines had higher titratable acidity, lower pH, elevated malic and tartaric acid levels.

In contrast, delaying cane tying on umbrella-trained vines did not significantly affect canopy development or structure. Leaf area index, porosity, and clumping index remained comparable to the control, maintaining standard canopy growth dynamics. Also, the treatment did not lower bunch counts or fertility indices. Notably, late cane tying resulted in a substantial increase in the productivity of the umbrella-trained vines: yield per vine increased alongside the delay in tying, reaching up to double the control yield (+86.5% to

+102.8%) at the BBCH 15 and BBCH 17 stages. This rise was driven by a significant increase in average bunch weight (reaching 111–120 g per bunch), while bunch numbers and berry weights remained largely unaffected. Finally, delaying cane tying did not meaningfully alter must composition at harvest; its effects on sugar content, acidity, and pH were minimal and variable, demonstrating that the notable yield gain did not compromise the final must quality of the umbrella-trained vines.

According to previous studies, while late pruning in some cases may be an effective tool for delaying ripening and preserving acidity, our findings also confirmed that it entails a major trade-off: substantial losses in yield components. Late cane tying, conversely, may represent a distinct management strategy for umbrella-trained vines that potentially supports productivity.

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References

1. Palliotti, A.; Frioni, T.; Tombesi, S.; Sabbatini, P.; Cruz-Castillo, J.G.; Lanari, V.; Silvestroni, O.; Gatti, M.; Poni, S. Double-Pruning Grapevines as a Management Tool to Delay Berry Ripening and Control Yield. *Am. J. Enol. Vitic.* **2017**, *68*, 412–421. [CrossRef]
2. Gatti, M.; Pirez, F.J.; Frioni, T.; Squeri, C.; Poni, S. Calibrated, Delayed-Cane Winter Pruning Controls Yield and Significantly Postpones Berry Ripening Parameters in *Vitis vinifera* L. Cv. Pinot Noir. *Aust. J. Grape Wine Res.* **2018**, *24*, 305–316. [CrossRef]
3. Silvestroni, O.; Lanari, V.; Lattanzi, T.; Palliotti, A. Delaying Winter Pruning, after Pre-Pruning, Alters Budburst, Leaf Area, Photosynthesis, Yield and Berry Composition in Sangiovese (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.* **2018**, *24*, 478–486. [CrossRef]
4. Moran, M.; Petrie, P.; Sadras, V. Effects of Late Pruning and Elevated Temperature on Phenology, Yield Components, and Berry Traits in Shiraz. *Am. J. Enol. Vitic.* **2019**, *70*, 9–18. [CrossRef]
5. Moran, M. Late Pruning to Delay Maturity and Preserve Wine Identity in Barossa Shiraz. Doctoral Dissertation, University of Adelaide, Adelaide, Australia, 2019.
6. Allegro, G.; Pastore, C.; Valentini, G.; Filippetti, I. Effects of Delayed Winter Pruning on Vine Performance and Grape Composition in Cv. Merlot. *BIO Web Conf.* **2019**, *13*, 04003. [CrossRef]
7. Petrie, P.R.; Brooke, S.J.; Moran, M.A.; Sadras, V.O. Pruning after Budburst to Delay and Spread Grape Maturity. *Aust. J. Grape Wine Res.* **2017**, *23*, 378–389. [CrossRef]
8. Villangó, S.; Szekeres, A.; Végvári, G.; Ficzek, G.; Simon, G.; Zsófi, Z. First Experience of Late Pruning on Kékfrankos Grapevine (*Vitis vinifera* L.) in Eger Wine Region (Hungary). *Horticulturae* **2024**, *10*, 1223. [CrossRef]
9. Deloire, A.; Pellegrino, A. Late Pruning of the Vine. *IVES Tech. Rev. Vine Wine*, 22 September 2022; pp. 1–2. [CrossRef]

10. Vercesi, A.; Garavani, A.; Parisi, M.G.; Gatti, M.; Poni, S. Vine Performance and Phenology Postponement in Cane-Pruned Chardonnay Vines Grown in a Temperate Climate: The Effects of a Delayed Winter Pruning. *Aust. J. Grape Wine Res.* **2023**, *2023*, 1329802. [CrossRef]
11. Jones, G.V.; White, M.A.; Cooper, O.R.; Storchmann, K. Climate Change and Global Wine Quality. *Clim. Change* **2005**, *73*, 319–343. [CrossRef]
12. Ferretti, C.G. Topoclimate and Wine Quality: Results of Research on the Gewürztraminer Grape Variety in South Tyrol, Northern Italy. *OENO One* **2021**, *55*, 313–335. [CrossRef]
13. Persico, M.J.; Smith, D.E.; Smith, M.S.; Hopfer, H.; Centinari, M. Delaying Grapevine Budbreak to Prevent Spring Freeze Damage Impacts Lemberger Wine Flavour Compounds under Variable Weather Conditions: This Article Is Published in Cooperation with the 22nd GiESCO International Meeting, Hosted by Cornell University in Ithaca, NY, July 17–21, 2023. *OENO One* **2023**, *57*, 331–343. [CrossRef]
14. Falginella, L.; Gaiotti, F.; Belfiore, N.; Mian, G.; Lovat, L.; Tomasi, D. Effect of Early Cane Pruning on Yield Components, Grape Composition, Carbohydrates Storage and Phenology in *Vitis vinifera* L. Cv. Merlot. *OENO One* **2022**, *56*, 19–28. [CrossRef]
15. Perin, C.; Verma, P.K.; Harari, G.; Suued, Y.; Harel, M.; Ferman-Mintz, D.; Drori, E.; Netzer, Y.; Fait, A. Influence of Late Pruning Practice on Two Red Skin Grapevine Cultivars in a Semi-Desert Climate. *Front. Plant Sci.* **2023**, *14*, 1114696. [CrossRef] [PubMed]
16. Morgani, M.B.; Fanzone, M.; Peña, J.E.P.; Sari, S.; Gallo, A.E.; Tournier, M.G.; Prieto, J.A. Late Pruning Modifies Leaf to Fruit Ratio and Shifts Maturity Period, Affecting Berry and Wine Composition in *Vitis vinifera* L. Cv. 'Malbec' in Mendoza, Argentina. *Sci. Hortic.* **2023**, *313*, 111861. [CrossRef]
17. Friend, A.P.; Trought, M.C.T. Delayed Winter Spur-Pruning in New Zealand Can Alter Yield Components of Merlot Grapevines. *Aust. J. Grape Wine Res.* **2007**, *13*, 157–164. [CrossRef]
18. Gatti, M.; Frioni, T.; Garavani, A.; Biagioni, A.; Poni, S. Impact of Delayed Winter Pruning on Phenology and Ripening Kinetics of Pinot Noir Grapevines. *BIO Web Conf.* **2019**, *13*, 04002. [CrossRef]
19. Scholefield, P.B.; Nealesb, T.F. Carbon Balance of the Sultana Vine (*Vitis vinifera* L.) and the Effects of Autumn Defoliation by Harvest-Pruning. *Aust. J. Plant Physiol.* **1978**, *5*, 561–570. [CrossRef]
20. Allegro, G.; Pastore, C.; Valentini, G.; Filippetti, I. Post-Budburst Hand Finishing of Winter Spur Pruning Can Delay Technological Ripening without Altering Phenolic Maturity of Merlot Berries. *Aust. J. Grape Wine Res.* **2020**, *26*, 139–147. [CrossRef]
21. Poni, S.; Sabbatini, P.; Palliotti, A. Facing Spring Frost Damage in Grapevine: Recent Developments and the Role of Delayed Winter Pruning—A Review. *Am. J. Enol. Vitic.* **2022**, *73*, 210–225. [CrossRef]
22. Netzer, Y.; Suued, Y.; Harel, M.; Ferman-Mintz, D.; Drori, E.; Munitz, S.; Stanevsky, M.; Grünzweig, J.M.; Fait, A.; Ohana-Levi, N.; et al. Forever Young? Late Shoot Pruning Affects Phenological Development, Physiology, Yield and Wine Quality of *Vitis vinifera* Cv. Malbec. *Agriculture* **2022**, *12*, 605. [CrossRef]
23. Trought, M.C.T.; Bennett, J.S.; Boldingh, H.L. Influence of Retained Cane Number and Pruning Time on Grapevine Yield Components, Fruit Composition and Vine Phenology of Sauvignon Blanc Vines. *Aust. J. Grape Wine Res.* **2011**, *17*, 258–262. [CrossRef]
24. Buesa, I.; Yeves, A.; Sanz, F.; Chirivella, C.; Intrigliolo, D.S. Effect of Delaying Winter Pruning of Bobal and Tempranillo Grapevines on Vine Performance, Grape and Wine Composition. *Aust. J. Grape Wine Res.* **2021**, *27*, 94–105. [CrossRef]
25. Martínez-Moreno, A.; Sanz, F.; Yeves, A.; Gil-Muñoz, R.; Martínez, V.; Intrigliolo, D.S.; Buesa, I. Forcing Bud Growth by Double-Pruning as a Technique to Improve Grape Composition of *Vitis vinifera* L. Cv. Tempranillo in a Semi-Arid Mediterranean Climate. *Sci. Hortic.* **2019**, *256*, 108614. [CrossRef]
26. Frioni, T.; Tombesi, S.; Silvestroni, O.; Lanari, V.; Bellincontro, A.; Sabbatini, P.; Gatti, M.; Poni, S.; Palliotti, A. Postbudburst Spur Pruning Reduces Yield and Delays Fruit Sugar Accumulation in Sangiovese in Central Italy. *Am. J. Enol. Vitic.* **2016**, *67*, 419–425. [CrossRef]
27. Moran, M.A.; Sadras, V.O.; Petrie, P.R. Late Pruning and Carry-over Effects on Phenology, Yield Components and Berry Traits in Shiraz. *Aust. J. Grape Wine Res.* **2017**, *23*, 390–398. [CrossRef]
28. Keller, M. Phenology and Growth Cycle. In *The Science of Grapevines*; Elsevier: Cambridge, MA, USA, 2020; pp. 61–103. [CrossRef]
29. Keller, M.; Tarara, J.M.; Mills, L.J. Spring Temperatures Alter Reproductive Development in Grapevines. *Aust. J. Grape Wine Res.* **2010**, *16*, 445–454. [CrossRef]
30. Clingeleffer, P. Effect of Varying Node Number per Bearer on Yield and Juice Composition of Cabernet Sauvignon Grapevines. *Aust. J. Exp. Agric.* **1989**, *29*, 701. [CrossRef]
31. Gatti, M.; Pirez, F.J.; Chiari, G.; Tombesi, S.; Palliotti, A.; Merli, M.C.; Poni, S. Phenology, Canopy Aging and Seasonal Carbon Balance as Related to Delayed Winter Pruning of *Vitis vinifera* L. Cv. Sangiovese Grapevines. *Front. Plant Sci.* **2016**, *7*, 659. [CrossRef] [PubMed]
32. Galet, P. *Dictionnaire Encyclopédique Des Cépages*; Hachette Pratique: Paris, France, 2000.
33. HungaroMet Elmúlt Évszakok Időjárása. Available online: https://www.met.hu/eghajlat/magyarorszag_eghajlata/eghajlati_visszatekinto/elmult_evszakok_idojarasa/ (accessed on 28 May 2026).

34. Lorenz, D.H.; Eichhorn, K.W.; Bleiholder, H.; Klose, R.; Meier, U.; Weber, E. Growth Stages of the Grapevine: Phenological Growth Stages of the Grapevine (*Vitis vinifera* L. ssp. *Vinifera*)—Codes and Descriptions According to the Extended BBCH Scale. *Aust. J. Grape Wine Res.* **1995**, *1*, 100–103. [CrossRef]
35. De Bei, R.; Fuentes, S.; Gilliham, M.; Tyerman, S.; Edwards, E.; Bianchini, N.; Smith, J.; Collins, C. VitiCanopy: A Free Computer App to Estimate Canopy Vigor and Porosity for Grapevine. *Sensors* **2016**, *16*, 585. [CrossRef] [PubMed]
36. Csepregi, P. A Szőlőültetvények Fitotechnikai Mutatói. 1. Rész. A Mutatók Meghatározásához Végzett Adatfelvételezések Módszertani Fejlesztése. *Magy. Szőlő-ÉS Borgazd.* **1992**, *2*, 2–5.
37. Csepregi, P. A Szőlőültetvények Fitotechnikai Mutatói. 2. Rész. A Mutatók Számítógépes Meghatározása. *Magy. Szőlő-ÉS Borgazd.* **1992**, *2*, 2–6.
38. Wickham, H.; Francois, R.; Henry, L.; Müller, K.; Vaughan, D. *Dplyr: A Grammar of Data Manipulation*; R Package Version 1.1.2; The R Foundation: Vienna, Austria, 2023.
39. Wickham, H.; Vaughan, D.; Girlich, M. *Tidyr: Tidy Messy Data*; R Package Version 1.3.0; The R Foundation: Vienna, Austria, 2023. [CrossRef]
40. Pinheiro, J.; Bates, D.; DebRoy, S.; Sarkar, D.; R Core Team. *Nlme: Linear and Nonlinear Mixed Effects Models*; R Package Version 3.1-163; The R Foundation: Vienna, Austria, 2023.
41. Lenth, R.V. *Emmeans: Estimated Marginal Means, Aka Least-Squares Means*, R package version 1.8.5; The R Foundation: Vienna, Austria, 2023.
42. Hothorn, T.; Bretz, F.; Westfall, P. Simultaneous Inference in General Parametric Models. *Biom. J.* **2008**, *50*, 346–363. [CrossRef] [PubMed]
43. Snedecor, G.W.; Cochran, W.G. *Statistical Methods*; Iowa State University Press: Ames, IA, USA, 1989.
44. Pinheiro, J.C.; Bates, D.M. *Mixed-Effects Models in S and S-PLUS*; Springer: Berlin/Heidelberg, Germany, 2009.
45. Zheng, W.; García, J.; Balda, P.; De Toda, F.M. Effects of Late Winter Pruning at Different Phenological Stages on Vine Yield Components and Berry Composition in La Rioja, North-Central Spain. *OENO One* **2017**, *51*, 363–372. [CrossRef]
46. Frioni, T.; Pirez, F.J.; Diti, I.; Ronney, L.; Poni, S.; Gatti, M. Post-Budbreak Pruning Changes Intra-Spur Phenology Dynamics, Vine Productivity and Berry Ripening Parameters in *Vitis vinifera* L. Cv. 'Pinot Noir. *Sci. Hortic.* **2019**, *256*, 108584. [CrossRef]