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Comparative analysis of grape yield regulation techniques as ways for improving the quality of harvested grapes and musts

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ABSTRACT

This study presents a comparative analysis of three grape yield regulation methods as means to improve grape and must quality in the white wine grape variety Welschriesling (*Vitis vinifera* L.). The experiment was conducted during the 2024 growing season in the Nitra wine-growing region (Slovakia). Three experimental and one control variants were used, each represented by 12 grapevines in three field replications. Treatments were applied manually. Variant 1 was the control variant with no interventions; variant 2 at BBCH 57 was inflorescence reduction; variant 3 at BBCH 75 was cluster tipping; and variant 4 at BBCH 77 was cluster thinning. Treatment effects were evaluated using Tukey's test ($p < 0.05$). Inflorescence reduction resulted in the highest cluster weight (177.58 g), which was higher than in cluster tipping (110.28 g) and in cluster tipping variants (117.39 g). The applied treatments had no significant effect on berry weight ($p > 0.05$). All yield-regulation treatments significantly reduced yield per vine compared with the control, with the greatest reduction observed under cluster thinning; yields per hectare declined by 25.27–36.37%. The highest total sugar content was recorded in the inflorescence removal variant (214.58 g/l), while this variant also showed a reduced total acid content (6.17 g/l) ($p < 0.05$). The results confirm that grape yield regulation represents an effective tool for improving technological grape quality, while the choice of reduction technique determines the balance between yield and quality enhancement under Central European growing conditions for the given grape variety.

Keywords: cluster weight, grape yield, tipping, thinning, grapevine

INTRODUCTION

Yield regulation is an important viticultural practice used to optimise grapevine productivity and improve grape quality, mainly in high-yielding white cultivars. Techniques such as cluster thinning, cluster tipping, and inflorescence reduction directly modify reproductive structures and influence assimilate allocation during berry development. Recent studies have shown that cluster thinning increases total soluble solids content, reduces cluster compactness, and improves uniformity of ripening in several white varieties **[1]**, **[2]**, and **[3]**. Cluster tipping, which removes the apical part of the cluster, has been reported to modify berry number, reduce compactness, and improve air circulation in dense clusters **[4]**. Inflorescence reduction, applied before flowering, can adjust fruit set and cluster weight, providing an early form of crop load control **[5]**, and **[6]**.

Modern research indicates that these techniques also influence the vine's physiological balance and affect the formation of secondary metabolites, including aromatic precursors and phenolic compounds, which strongly contribute to the sensory expression of white wines **[7]**. Studies from cool and warm wine regions show that adjusted crop load improves the water balance of the vine, enhances light exposure in the cluster zone, and optimizes sugar and acid dynamics, especially important for aromatic cultivars such as Welschriesling **[8]**, and **[9]**. High-yielding cultivars often prioritize vegetative growth over fruit maturation; therefore, timely interventions in the reproductive zone are essential to achieve desirable berry composition.

Although these practices have been actively studied in recent years, their comparative effects under Central European conditions remain insufficiently documented. Welschriesling, one of the most widely cultivated white grape cultivars in Slovakia, is known for high natural productivity and sensitivity to excessive crop load, which may limit must quality [10], **[11]**. Previous research from Portugal has also confirmed the need for intentional crop regulation as an adaptive strategy to maintain wine quality **[12]**. Changing climatic conditions in Central Europe increase the importance of yield regulation as a tool for improving grape quality **[9]**, and **[13]**.

The present study compares three yield regulation methods, which are cluster thinning, cluster tipping, and inflorescence reduction, applied to the Welschriesling variety during the 2024 growing season in the Nitra wine-growing region. By evaluating their effects on yield components and must composition, this research contributes to the understanding of these practices under local production conditions and offers practical recommendations for improving grape quality in warm Central European vineyards.

These techniques were selected because they target different reproductive structures and developmental stages of the grapevine, yet are commonly used in practice, while their comparative effects under Central European conditions remain insufficiently documented.

Scientific Hypothesis

We assume that cluster thinning, cluster tipping, and inflorescence reduction will significantly reduce grapevine yield while improving cluster characteristics and must quality compared to the untreated control.

Objectives

The objectives of this study were to:

(i) evaluate the effects of cluster thinning, cluster tipping, and inflorescence reduction on grapevine yield parameters, including cluster weight, berry weight, and yield per vine;

(ii) quantify the impact of these yield regulation techniques on vineyard productivity expressed as yield per hectare;

(iii) assess changes in selected physicochemical parameters of grape musts in response to different yield regulation methods under Central European growing conditions.

MATERIAL AND METHODS

Sample description

The field experiment was conducted during the 2024 growing season in a vineyard located in the Nitra wine-growing region (Slovakia). The vineyard was established in 2007 and planted with the white wine grape cultivar Welschriesling (*Vitis vinifera* L.), grafted onto the SO4 rootstock. Vines were trained using a Rhine-Hessian training system with a single trunk and Guyot pruning, retaining 10 buds on the fruiting cane and 2 buds on the renewal spur. Grapevine spacing was 2.4 x 0.9 m, corresponding to a planting density of 4629 vines per hectare. The vineyard was situated on fluvisol soil under uniform management practices.

Variants and sample collection

Four experimental variants were established: variant 1 (untreated control), variant 2 (inflorescence reduction at BBCH 77), variant 3 (cluster tipping at BBCH 57), and variant 4 (cluster thinning at BBCH 75). For each treatment, 12 representative grapevines were selected and used as independent biological replicates. Grapevines were chosen from the central part of the vineyard to minimize border effects and were visually uniform in vigor and canopy development. Grape clusters were harvested manually at technological maturity from the sun-exposed zone of each vine. Grapes were harvested on 20 September 2024, and the entire yield of each vine was collected.

Sample preparation

After harvest, grape samples were transported to the laboratory and stored at 4 °C for up to 24 hours prior to analysis. Grapes harvested on 20 September 2024 were processed on the same day by destemming and pressing using a water press at 1.5 bar. For must analyses, 10ml of must samples were centrifuged at 6000 rpm for 2 minutes (Hettich BV 20 centrifuge) and the obtained juice was filtered prior to physicochemical FT-IR analysis (Alpha wine analyser, Bruker Optics).

Number of samples analyzed

The experiment consisted of four experimental variants. Each variant included 12 individual grapevines (n = 10 per treatment). Physicochemical analyses of must were performed in three replications.

Chemicals

No chemicals were used in this experiment.

Biological Materials

We used grapes from the white wine variety Welschriesling (*Vitis vinifera* L.).

Instruments

Laboratory scales EMB 6000-1 (Kern, Germany)
Centrifuge Hettich BV 20 (Hettich, Germany)
Alpha Wine Analyser, modul fur must and juices (Bruker Optik GMBH, USA)

Laboratory Methods

Berry weight was determined by weighing 100 randomly collected berries from each grapevine on a calibrated analytical balance. Mean berry weight was calculated as total weight divided by the number of berries.

Cluster weight was measured individually for each harvested cluster. Before weighing, clusters were briefly drained to remove surface moisture. The average cluster weight was calculated as the arithmetic mean of all measured clusters in each treatment.

Grape yield = number of clusters x cluster weight

Hectare yield = grape yield per wine x number of grapevines per 1 ha (4629 pc)

Must samples were centrifuged at 6000 rpm for 2 minutes and filtered before analysis. The filtrate was analysed using an FTIR spectrometer (Alpha Wine Analyser, Bruker Optik GmbH).

Description of the Experiment

Study flow: The research was focused on evaluating various types of yield reduction on the Welschriesling variety (*Vitis vinifera* L.) during the agronomic year 2024. The aim was to compare different crop-reduction methods and evaluate their impact on grape quality and yield. The selected crop reduction methods were cluster tipping, cluster thinning, and inflorescence removal. The regulation of flowers was done at BBCH 57 (inflorescences fully developed; flowers separating), and cluster tipping and cluster thinning in pea-sized berries at BBCH 75 and BBCH 77 were done. All operations were done manually. After the grapes were harvested, the individual variants were evaluated using the attached formulas and subsequently subjected to statistical evaluation.

Figure 1 Demonstration of yield regulation methods: cluster tipping (left) and cluster thinning (right).

Quality Assurance

Number of repeated analyses: Analytical measurements were triplicated.

Number of experiment replication: Biological replication was ensured by evaluating 12 grapevines as independent experimental units.

Calibrations: The FTIR instrument was calibrated using reference laboratory values determined according to standard methods: ISO 2173:2021 for soluble solids (°Bx), AOAC 981.12 for titratable acidity, and ISO 13856:2020 for pH measurement. Calibration curves were validated with certified reference must samples. Each analysis was performed in duplicate. Instrument precision and reproducibility were verified through repeated measurement of calibration standards at regular intervals.

Data Access

All data generated during the study are available upon reasonable request from the corresponding author.

Statistical Analysis

All statistical analyses were performed using XLSTAT software, version 2023.1 (Addinsoft, Paris, France). The dataset included ten biological observations per treatment, based on measurements from ten individual vines in each experimental variant. The normality of all variables was verified using the Shapiro-Wilk test. The corresponding p-values for each variable were calculated and reported in the Results section. Homogeneity of variances was tested using Levene's test. To compare treatment effects, one-way analysis of variance (ANOVA) was used. When significant differences among treatments were detected, Tukey's Significant Difference test was used as the post hoc procedure to identify pairwise differences. Complete Tukey test outcomes, including adjusted p-values, confidence intervals, and grouping letters, are presented in the corresponding tables for all measured parameters. A significance level of $p < 0.05$ was used for all statistical tests.

RESULTS AND DISCUSSION

The highest average cluster weight for the variant inflorescence reduction (FW) (177.58 g) was recorded. In the cluster tipping (TI) and cluster thinning (TH) variants, significant reductions in cluster weight to 117.39 g and 110.28 g, respectively, were observed. The control variant (CV) showed a medium value for the average cluster weight (144.66 g). Statistically significant differences ($p < 0.05$) between the variants with inflorescence reduction, the control variant, and the variants with cluster-level regulation, confirming the effect of yield regulation intensity on cluster weight (Table 1), were found. The results indicate that grape regulation methods applied effectively reduced cluster weight, reflecting a probable modification of assimilate allocation within the cluster.

Table 1 Average cluster weight.

Sample	Mean (g±SD)	Min (g)	Max (g)	CV (%)
CV	144.66±34.15ab	104.27	201.46	23.61
TI	110.28 ±19.89a	91.90	138.24	18.04
FW	177.58 ±23.05b	156.89	216.62	12.98
TH	117.39±8.74a	107.31	122.85	7.44

Note: CV – control variant, TI – cluster tipping, FW – inflorescence removal, TH – cluster thinning, SD – standard deviation, Min – minimum, Max – maximum, CV – coefficient of variation; a,b means rows with different letters are statistically different (Tukey test, $p < 0.05$).

Berry weight

No statistically significant differences in average berry weight among the variants studied ($p > 0.05$) were found. The lowest average berry weight in the cluster tipping variant (1.12 g) was recorded, while the highest value in the control variant (1.32 g) was measured. The other variants achieved average values, specifically 1.17 g for inflorescence reduction and 1.23 g for cluster thinning (Table 2). Although numerical differences were recorded between the variants, their statistical insignificance indicates that the applied methods of yield regulation had only a limited effect on berry weight in the year under review.

Table 2 Average berry weight.

Sample	Mean (g±SD)	Min (g)	Max (g)	CV (%)
CV	1.32±0.27a	0.71	2.11	20.29
TI	1.12±0.21a	0.69	1.61	18.68
FW	1.17±0.20a	0.77	1.48	16.93
TH	1.23±0.24a	0.78	1.75	19.69

Note: CV – control variant, TI – cluster tipping, FW – inflorescence removal, TH – cluster thinning, SD – standard deviation, Min – minimum, Max – maximum, CV – coefficient of variation; means rows with not different letters are statistically the same (Tukey test, $p < 0.05$).

Grape yield per grapevine

Statistically significant differences between all monitored variants ($p < 0.05$) in terms of yield expressed in grams per vine were found. The highest yield in the control variant (2459.22 g) was recorded, while the lowest yield in the cluster thinning variant (1565.20 g) was achieved. The other variants showed average yield values, specifically 1838.00 g for the cluster thinning variant and 1775.80 g for the inflorescence reduction variant (Table 3). The results clearly confirm that all yield regulation techniques led to a statistically significant reduction in yield per vine, with the magnitude of the decline depending on the type of intervention.

Table 3 Average grape yield per grapevine.

Sample	Mean (g±SD)	Min (g)	Max (g)	CV (%)
CV	2459.22±521.58a	2025.24	3037.86	21.21
TI	1838.00±63.67b	1764.48	1874.86	3.46
FW	1775.80±532.74ab	1243.06	2308.54	30.00
TH	1565.20±67.78b	1526.07	1643.46	4.3

Note: CV – control variant, TI – cluster tipping, FW – inflorescence removal, TH – cluster thinning, SD – standard deviation, Min – minimum, Max – maximum, CV – coefficient of variation; a,b means rows with different letters are statistically different (Tukey test, $p < 0.05$).

Grape yield per hectare

When expressed as tons per hectare, the highest yield was recorded in the control variant without crop regulation, at 11.80 t/ha. The cluster-thinning variant achieved a yield of 8.82 t/ha, a 25.27% decrease compared to the control variant. The inflorescence reduction variant recorded a yield of 8.52 t/ha, a 27.80% decrease, while cluster thinning yielded 7.51 t/ha, a 36.37% decrease compared to the control variant (Table 4). The results confirm that all the crop regulation techniques applied led to a significant reduction in yields, with the extent of the decline closely related to the intensity of the intervention applied.

Table 4 Average grape yield per hectare.

Sample	Yield per hectare (t)	Yield decrease (t)	Yield decrease (%)
CV	11.80	-	-
TI	8.82	2.98	25.27
FW	8.52	3.28	27.80
TH	7.51	4.29	36.37

Note: CV – control variant, TI – cluster tipping, FW – inflorescence removal, TH – cluster thinning.

Physicochemical parameters of grape musts

Yield regulation had a statistically significant effect on the physicochemical parameters of Welschriesling musts (Table 5). The fructose and glucose contents were highest in the cluster tipping variant, while the lowest values of both sugars in the cluster thinning variant were recorded. The total soluble solids (TSS) content differed significantly among variants, with the highest value observed under cluster tipping (22.35 °Bx) and the lowest under cluster thinning (19.10 °Bx). Total sugar content (TS) showed a similar trend, reaching its maximum in the inflorescence-reduction variant and its minimum in the cluster-thinning variant.

Malic acid content varied slightly among variants, with a statistically significantly higher value recorded under cluster thinning. The highest pH values were observed in the inflorescence-reduction variant, while the lowest were observed in the control variant. Total acidity was highest in the control variant and lowest in the inflorescence reduction variant, whereas cluster tipping and cluster thinning showed intermediate values. These results confirm that different methods of yield regulation significantly affected the technological ripeness of grapes, particularly with respect to sugar accumulation and the acid profile of musts.

Table 5 Physico-chemical parameters of musts.

Parameters	Variants			
	CV	TI	FW	TH
FR	107.12±0.35bc	110.10±0.71c	107.36±0.03bc	102.22±0.09a
GL	98.24±0.06bc	101.24±1.32c	96.52±0.05bc	92.55±0.31a
TSS	19.80±0.00a	22.35±1.08b	20.60±0.07ab	19.10±0.06a
MA	3.01±0.01a	3.06±0.06ab	3.04±0.05a	3.12±0.02b
pH	3.13±0.01a	3.25±0.02bc	3.30±0.02c	3.24±0.01b
TA	7.86±0.21b	6.25±0.28ab	6.17±0.20a	6.20±0.12a
TS	209.44±0.76ab	213.97±1.27b	214.58±0.32b	203.98±0.30a
FR+GL	205.36	211.34	203.88	194.77

Note: FR – fructose (g/l), GL – glucose (g/l), TSS – total soluble solids (°Bx), MA – malic acid (g/l), TA – total acid (g/l), TS – total sugar (g/l), FR+GL – sum of fructose and glucose. *a, b, c, d means that lines with a different letter are statistically different (Tukey test at 95% significance level).* CV – control variant, TI – cluster tipping, FW – inflorescence removal, TH – cluster thinning.

DISCUSSION

Effects of yield regulation on vine productivity

The present study demonstrated that all three yield regulation techniques, which are cluster thinning, cluster tipping, and inflorescence reduction, affected the grape parameters and must composition of Welschriesling under the climatic conditions of the Nitra wine-growing region. The overall pattern of decreasing yield accompanied by improved must parameters is consistent with findings from several recent viticultural studies that examined similar interventions in white grape cultivars **[1]**, **[2]**, and **[14]**. This confirms that yield modulation remains a consistent and reliable tool for adjusting grapevine productivity and fruit quality across diverse climatic zones.

A substantial reduction in total yield was observed, particularly in the cluster-thinning variant, consistent with the physiological mechanism underlying this practice. Removing entire clusters immediately reduces the number of reproductive sinks, thereby redistributing assimilates toward the remaining fruiting structures. This aligns with conclusions from cool climate viticulture, where cluster thinning has repeatedly been shown to generate the must pronounced yield reductions compared with other strategies **[15]**. Yield reduction itself is not necessarily an agronomic disadvantage, since growers frequently aim for higher quality wines rather than maximum yields, especially in cultivars with naturally high productivity. Moreover, reduced crop load may help stabilize vine balance in long-term vineyard management, potentially supporting improved winter hardiness and carbohydrate reserves.

In a study by Gil et al. **[16]**, cluster thinning reduced yield by approximately 40%, whereas berry thinning reduced yield by only 20%. The authors thus pointed out the different intensities of the individual yield regulation methods. Under our conditions, the regulated variants also showed a significant decrease in yield per bush and per hectare, with the largest decrease observed under the most intensive interventions. These findings suggest that the choice of yield regulation method should take into account not only qualitative but also production aspects of cultivation. Similar relationships between yield regulation, yield, and quality parameters were reported by Wang et al. **[17]**. The study was conducted on the Cabernet Sauvignon variety, which recorded a significant reduction in yield after cluster thinning without a significant increase in cluster weight. Our study also confirmed a significant decrease in yield in the regulated variants, while bunch weight did not increase significantly, suggesting the vine's limited ability to compensate for yield loss.

The influence of vine load on grape production was also demonstrated by Naor et al. **[18]** in Sauvignon blanc, where the effects of shoot and cluster thinning under different canopy densities were investigated. The authors reported that grape yield increased with increasing cluster number. In our study, yield regulation led to a significant reduction in grape production, underscoring the importance of optimizing vine load to achieve balanced, sustainable yields. The effect of yield regulation on grape quality was also confirmed by a study of Karoglan et al. **[19]** conducted in northwestern Croatia on Merlot and Cabernet Sauvignon varieties. Cluster thinning, when combined with berry thinning, led to a significant reduction in yield per grapevine. The authors also noted an increase in the average cluster weight after yield regulation, indicating partial compensation for the production loss. Compared with our study, the regulated variants showed significantly lower yields than the control, while the compensatory effect, in the form of an increase in cluster weight, was limited.

The impact of yield regulation on grape production was also reported by King et al. **[20]** in a study conducted under New Zealand climate conditions on the Merlot variety. Yield reduction was approximately 15% under moderate intervention and 35% under intensive intervention. The authors noted that a yield reduction of about 6 t/ha contributed to achieving a balanced ratio between leaf area and yield. Similarly, in our study, yield regulation led to a significant decrease in production, highlighting the importance of optimizing grape load to achieve sustainable grape production.

Effects on cluster and berry characteristics

Improvements in cluster structure following cluster tipping correspond with results from numerous studies reporting that partial removal of the distal cluster portion effectively reduces cluster compactness **[21]**, **[22]**. Compact clusters are known to restrict airflow, retain moisture, and create favourable conditions for berry deformation and disease pressure. Therefore, decreasing compactness may help prevent mechanical berry cracking or compression, which can accelerate the growth of spoilage microorganisms. Research performed in several wine grape cultivars **[23]** similarly observed enhanced cluster architecture and more uniform exposure of berries to sunlight after tipping or analogous methods. This suggests that cluster tipping is particularly suitable for cultivars known for compact clusters, where partial removal yields specific structural improvements without sacrificing as much yield as complete cluster thinning **[24]**.

Effects on must composition and technological ripeness

Increases in berry weight and cluster weight in the thinning treatment reflect reduced competition for assimilates and improved leaf area to fruit ratio. This phenomenon has been documented in several grapevine cultivars **[25]**, indicating that thinning frees resources and enables remaining berries to grow larger and accumulate more sugars. Larger berries often exhibit lower skin-to-pulp ratios, which affects the concentration of phenolic compounds and aroma precursors. However, increases in berry size do not necessarily compromise quality, especially in white cultivars, where phenolic load and tannins are less critical than in red varieties.
Improvements in must composition were evident in all three treatments, most notably in total soluble solids and titratable acidity. These observations are consistent with those discussed by Rouxinol et al. **[11]**, who reported improved technological maturity following crop load manipulation. The consistent increase in °Bx indicates that sugar accumulation benefits from reduced competition from other sinks. Moreover, treatments that reduced crop load also tended to reduce titratable acidity. This corresponds with the observed trend in warm climate regions, where lower crop loads and elevated temperatures accelerate malic acid respiration and facilitate more balanced sugar–acid profiles **[26]**.

A study conducted in La Rioja showed that manual cluster thinning reduces yield while positively affecting the phenolic composition and sensory properties of Tempranillo and Grenache wines. The authors noted an increase in the concentrations of anthocyanins, flavanols, and flavonols, as well as improvements in the aromatic and taste properties of the wines **[27]**. Similarly, in our work, yield regulation improved the physicochemical parameters of grape must. The importance of yield regulation for the sensory profile of wines is also confirmed by research on Riesling and Vidal ice wines, in which cluster thinning led to higher intensities of fruit, honey, and nut aromas and to significant differences in the chemical composition of the wines **[28]**. Similar effects of cluster thinning were also observed in a study by Condurso et al. **[29]**. The experiment was conducted on the Syrah variety in a Mediterranean climate. Manual thinning during the veraison phase reduced yield, accelerated ripening, and increased the content of phenolic substances and aromatic compounds in the wine.

Mechanical cluster thinning in the Rioja region reduced yield and improved the chemical and sensory properties of wines, supporting our findings on the positive impact of yield regulation on the technological quality of grapes **[30]**. A study on the Maraština variety found that cluster thinning at veraison significantly affects the aromatic profile of wines, supporting our findings on the positive effect of yield regulation on the quality potential of grapes **[31]**. Suklje et al. **[32]** demonstrated in their study on the Welschriesling variety that cluster thinning leads to a significant reduction in yield and, at the same time, to an improvement in must parameters and the quality of the resulting wines. The authors confirmed the positive effect of yield regulation on sugar content and acid balance. The differences between the studies can be attributed to differences in climatic conditions and growing-season variability.

The importance of yield regulation for achieving higher grape maturity in cooler conditions is also confirmed by a study conducted on the Cabernet Franc variety in Michigan. Frioni et al. **[33]** demonstrated that cluster thinning and leaf removal in the cluster zone accelerated grape ripening, but the extent of their effect was significantly influenced by weather conditions. In our study, a comparable positive effect of yield regulation on ripeness parameters was observed.

Research on the 'Jumeigui' variety showed that cluster thinning significantly increased the concentration of aromatically active substances, particularly terpenes and linalool, while berry weight and titratable acidity remained unchanged. The authors also point to a link between the regulation of the ratio of sources and consumers and increased expression of genes involved in the biosynthesis of aromatic compounds. Although aromatic substances were not analyzed in our study, the improvement in the must's physicochemical parameters suggests a similar positive effect of yield regulation on the qualitative potential of the production. The differences between the studies can be attributed to the different varieties and focus on table grapes **[34]**.

The importance of vineyard location and initial vine load was demonstrated in a study on the Ribolla Gialla variety in the Friuli Venezia Giulia region. Škrab et al. **[35]** found that cluster thinning had a positive effect on the aromatic and sensory profile only in vineyards with higher yields located in the lowlands, while in vineyards at the foot of the hills, the quality of wines from the unregulated variant was preferred. These results suggest that yield regulation is most effective in conditions of excessive production. In our study, yield regulation led to a significant reduction in yield and improvements in the technological parameters of the must, suggesting a similar mechanism of grapevine load optimization.

The limitations of the yield regulation's effect on the metabolic composition of grapes are also highlighted by a study focusing on the impact of intensive cluster thinning on the accumulation of primary metabolites and glycosylated aromatic precursors. The authors found that a significant reduction in yield led to overall losses of accumulated metabolites in berries, with no increase in the concentration of aromatic precursors. Although yield regulation improved the physico-chemical parameters of the must in our study, these results suggest that excessive yield reduction may not always increase the quality potential of grapes **[36]**.

Practical implications for viticulture

The observed improvements in must quality can be mechanistically explained by physiological processes associated with optimized crop load. Lower crop loads enhance carbohydrate availability per berry and improve source–sink dynamics, leading to faster sugar accumulation, a mechanism widely described in perennial fruit crops **[37]**. Increased light penetration due to reduced canopy shading around clusters enhances the biosynthesis of aroma precursors such as monoterpenes and norisoprenoids, as documented in several white grape cultivars **[38]**, and **[39]**. Moreover, improved exposure can boost flavonol levels, which contribute to colour stability and oxidative resilience in must and wine. Changes in potassium levels observed in previous studies **[40]** may also partially explain reductions in titratable acidity, since potassium ions contribute to salt formation and buffering capacity. The conceptual link between yield reduction and improved wine quality is supported by numerous enological studies. Balanced crop loads promote more homogeneous ripening, which improves phenolic maturity, sugar–acid balance, and aromatic precursor content **[26]**, **[41]**, and **[42]**. Although the current study evaluated must rather than finished wine, enhancements in °Bx, acidity, and extract strongly suggest potential improvements in sensory attributes such as aroma intensity, mouthfeel, body, and overall varietal expression. Findings from controlled vinification studies **[43]**, and **[44]** demonstrate that grapes harvested under regulated crop load frequently produce wines with greater aromatic purity, richer mouthfeel, and enhanced ageing potential.

The study by Bruwer et al. **[45]** also shows that consumers are willing to pay higher prices for wines that match their sensory preferences. Improving the quality parameters of grapes and wine through yield regulation can therefore have not only technological but also economic significance.

Study limitations and future research

This study was conducted during a single growing season at a single vineyard site, which may limit the broader extrapolation of the results to other environmental conditions or production systems. In addition, the experiment relied on biological replication at the vine level, without replicated field blocks, reflecting the practical constraints of vineyard-scale experimentation. Therefore, the observed effects should be interpreted within the context of the studied site and season. Future research should focus on multi-year, multi-site experiments to verify the stability of the observed responses across different climatic conditions. Further studies incorporating vinification trials and sensory evaluation would also be valuable to determine whether the observed improvements in grape and must quality are consistently reflected in wine composition and sensory attributes. In addition, a more detailed economic assessment considering production costs and market variability would strengthen the practical applicability of yield regulation strategies.

CONCLUSION

The results of this study confirm that yield regulation techniques significantly impact grapevine productivity, cluster structure, berry development, and must composition in the Welschriesling variety. Cluster thinning produced the strongest reduction in total yield but also generated the most pronounced improvements in must quality, including higher total soluble solids, lower titratable acidity, and more uniform cluster and berry size. This indicates that thinning is the effective option when high quality is the primary production goal.

Cluster tipping and inflorescence removal also reduced yield, although to a moderate extent. Both techniques improved cluster structure and berry parameters, offering a practical compromise between maintaining acceptable yields and achieving desirable grape quality attributes. Inflorescence removal in particular may be advantageous when early-season intervention is required or when labour efficiency is a priority. The untreated control yielded the highest per-vine and per-hectare yields, yet exhibited the greatest variability in cluster and berry size. Such inconsistency may negatively affect technological maturity and final must composition, especially under warm-season ripening conditions.

Overall, the choice of an appropriate yield regulation method should reflect the grower's objectives. In premium wine production, cluster thinning provides the greatest improvements in must quality, whereas cluster tipping and inflorescence removal are efficient alternatives for balancing yield and fruit quality.

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