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Canopy Management Strategies Under Climate Change: Responses of *Vitis vinifera* L. cv. Saperavi to Pre-Flowering Defoliation in Kakheti

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Abstract

This study investigates the effects of early basal leaf removal (ELR) on vine physiology, berry composition, and wine quality in *Vitis vinifera* cv. Saperavi, cultivated in Georgia's Kakheti region, in Akura village (Telavi district, Kakheti, Eastern Georgia) on moderately fertile alluvial–calcareous loamy soils typical for the Alazani Valley viticultural area. Akura is characterised by a moderately continental climate with warm summers and mild to moderately cold winters. The vines were 21 years old.

Three defoliation intensities: intensive (8 basal leaves removed), moderate (4 leaves removed), and control (no leaves were removed) were applied prior to flowering. Intensive ELR moderately reduced yield via smaller berry and cluster size but significantly enhanced technological and phenolic maturity.

Observed improvements included higher soluble solids, reduced malic acid, elevated phenolic content, lower disease incidence, and increased extract levels in the resulting wine.

Importantly, this study represents the first systematic, data-driven investigation of ELR in Georgian Saperavi vineyards, providing modern viticultural guidance under the current climate context.

In light of climate change, ELR is presented as a practical strategy for achieving uniform ripening and improving fruit and wine quality.

Keywords

Grapevine, Saperavi, ELR, climate, sunburn.

Introduction

Grapevine cultivation is among the oldest agricultural practices known to humankind. Genetic and archaeological evidence indicate that the domestication of *Vitis vinifera* originated in Georgia (Yang Dong *et al.*, 2023). Today, grapevine is one of the most widely cultivated perennial crops, contributing economically through wine production, table grapes, and raisins (Alston & Sambucci, 2019). Viticulture and winemaking are strongly influenced by climate, which affects growth, yield, and berry composition (Fraga *et al.*, 2013), making the sector vulnerable to climate change (Ferrer-Galeco, 2024).

Observations show rising temperatures in wine regions worldwide (IPCC, 2022), and projections indicate significant shifts in temperature and

Submitted/accepted for publication: 19 November, 2025 / 30 March, 2026

precipitation that could affect grape physiology and wine quality (Arias *et al.*, 2022).

Although grapevines can adapt to environmental stress, rapid climate change requires short and long - term strategies (Ferrandino & Lovisolo, 2014; Van Leeuwen & Destrac - Irvine, 2017).

Optimising canopy management, particularly through targeted green pruning techniques such as leaf removal, has emerged as a key tool to mitigate climatic stress (Smart & Robinson, 2008; Tessarin *et al.*, 2022). By modifying the microclimate around clusters, these practices enhance light exposure, reduce humidity, and improve airflow, influencing berry development and composition (Caravia *et al.*, 2016).

For example, previous research on Cabernet Sauvignon has shown that basal leaf removal around veraison can enhance both sugar accumulation and anthocyanin content at harvest.

Specifically, defoliation performed at the onset of veraison significantly increased the concentration of key anthocyanins such as malvidin – 3 – O - glucoside and peonidin – 3 - O - glucoside (Yue *et al.*, 2020).

Studies have demonstrated that early-season basal leaf removal is an effective technique for reducing the concentration of 3 – isobutyl – 2 - methoxypyrazine (IBMP) in grape berries, a compound associated with green, vegetal aromas.

In particular, defoliation carried out before flowering was found to significantly decrease IBMP levels, confirming its utility as a canopy management strategy to improve aromatic quality (Lei *et al.*, 2022).

For example, Intrieri *et al.* (2017) found that removing 30 - 40% of the vine's total leaf area led to higher anthocyanin levels in Sangiovese grapes, especially when the harvest was postponed by 7 - 8 days. With climate change and modern viticultural challenges reshaping growing conditions, effective canopy management is essential for fruit quality and vineyard sustainability.

While Georgia is one of the world's oldest viticulture centres (McGovern *et al.*, 2017), modern research on green pruning and fruit quality in local varieties is limited. Studies elsewhere show early defoliation can enhance wine composition (Reynolds, 2010).

In Georgia, despite its rich winemaking heritage, research on local grape varieties' response to such techniques is limited.

Materials and Methods

Plant Material - The first - year field study was conducted in 2024 in the Saperavi vineyard of Winery Pi, situated in Akura village, Telavi, within the Kakheti region, one of Georgia's premier wine - growing areas, encompassing the majority of the country's Protected Designations of Origin (PDOs) (IPCG,2025).

The vineyard is situated at an elevation of 450 meters, on a southwestern - facing slope (latitude 41°53'43.1" N, longitude 45°40'18.9"E).

The Saperavi variety (*Vitis vinifera* ssp. *sativa*) was planted in 2004 on the 5BB rootstock.

Its identity was confirmed using ampelographic descriptors (OIV, UPOV), in accordance with the "National Catalogue of Agricultural Plant Species Permitted for Distribution in the Territory of Georgia."

The vineyard spans approximately 1 hectare and includes 30 rows of 130 meters each, three rows of 90 meters, and one row of 50 meters, with a

vine spacing of 1.5 meters, totalling around 2,700 vines.

The vines are trained using a bilateral Guyot system at a height of 80 cm above ground. Key phenological growth stages were recorded according to the BBCH scale (Meyer, 2001).

Leaf Removal: The vineyard was managed according to standard viticultural practices, including routine phytosanitary treatments. Green pruning operations were implemented as part of canopy management and included leaf removal on May 19 (BBCH 57) and top hedging on June 22 (BBCH 75) and August 20 (post - veraison, BBCH 85).

The leaf removal experiment within this study involved the application of three distinct defoliation techniques. For this purpose, three consecutive rows within a uniform block of the vineyard were selected for treatment and observation: Rows 30, 33, and 34.

Each row was subjected to a different leaf removal strategy, as follows:

- Row 30: Prior to flowering, 8 basal leaves were removed from the main shoot, including those directly adjacent to the fruit zone. No lateral leaf removal was performed. Top hedging was conducted twice, at BBCH 75 and 85.
- Row 33: Before flowering, 4 basal leaves were removed. No lateral leaf removal was performed. Top hedging was conducted twice, at BBCH 75 and 85.
- Row 34: No defoliation was carried out in the fruit zone at any stage during the growing season. Lateral shoots were not removed, and top hedging was performed twice, at BBCH 75 and 85.

collection was carried out from mid - veraison (BBCH 83) through to harvest (BBCH 89) following internationally accepted viticultural sampling protocols and methodological standards developed by various researchers.

The sampling was conducted during the morning hours on three dates: August 11, September 1, and September 14 at intervals of approximately 15 to 20 days.

The final harvest took place on September 22. Sampling focused on a designated block of rows 30, 33, and 34, each containing 40 - 60 vines.

To ensure representative sampling, every fifth vine was marked, and 20% of vines per row were selected. From each vine, 40 - 50 berries were collected from clusters on both sides of the canopy and from upper, middle, and lower positions; within each cluster, berries were sampled from apical, median, and basal sections. Cluster number per vine was recorded, yielding an average of 24 clusters per vine.

For cluster morphology, three clusters per row were randomly selected to determine average weight, and one cluster per row was used for detailed measurements of total weight, dimensions, and stem weight (rachis and peduncle).

All samples were collected in labelled bags, weighed, stored immediately, and transported under refrigerated conditions to preserve integrity.

Analysis - Yield (kg/m²) was determined at harvest by weighing all grape clusters collected from each replicate row.

The average cluster weight (g) was calculated by weighing three representative clusters from each row. Berry weight (g) was determined based on randomly collected berry samples from each row.

Analytical samples for laboratory testing were delivered to the testing facility on the same day as collection to ensure sample integrity.

All analyses were conducted on four separate occasions by the accredited testing laboratory "Test Lab" at the Agricultural University of Georgia. On three occasions, the submitted samples consisted of grape clusters harvested from the designated experimental vineyard rows.

On the fourth occasion, the sample represented the finished wine material obtained from the harvested grapes.

All laboratory analyses were performed in accordance with standardised and validated methodologies. The analyses targeted the following parameters presented in Table 1.

Microvinification - Each vineyard row was harvested and processed separately for micro - vinification on September 22. Grapes from Row 30 (26 °Brix, 124 kg), Row 33 (24.4 °Brix, 130 kg), and Row 34 (23.5 °Brix, 140 kg) were destemmed, crushed, and placed into individual 150 L fermentation tanks.

Alcoholic fermentation, carried out with indigenous, wild yeasts, lasted 20 days at 18 – 26 °C. Wines were separated from pomace, transferred to 150 L stainless steel tanks and underwent natural malolactic fermentation. After malolactic fermentation, the wines were racked off the lees and sulfites (5 g/100 L) were added, and on November 8, transferred into glass demijohns. Bottling occurred on December 8, 2024, with 18 labelled bottles per row, stored at 12 - 16 °C.

Comprehensive chemical analyses were performed on December 25, 2024, at "Test Lab" following standard enological procedures (Table units 10 - 11).

Preliminary organoleptic evaluation was conducted via blind tasting on August 15, 2025, using the OIV scoring sheet, including descriptive notes on sensory attributes.

Results

Analytical description of the data collected during field research:

Table 2. Results of Soil Analyses Conducted at the Laboratory of Ecological Agriculture and Nature Protection of the Georgian Agricultural University.

Climatological Data - Climate data for 2023 – 2024 (May - October) were obtained from the Hydrogeological Department of the LEPL National Environmental Agency of Georgia and the nearest Telavi meteorological station, supplemented by the GECSA application (Georgian Environmental and Climate Smart Agriculture), a national system for real-time agrometeorological monitoring and analysis. Historical phenological data from 2022 – 2023 contextualized local environmental effects. Monthly precipitation averages revealed notable variability during flowering and berry ripening (Table 2).

In May 2024, elevated temperatures advanced flowering, while intermittent rainfall extended the phase. Post-flowering development was faster than in previous years.

Drought in 2022 and excess precipitation in 2023 delayed veraison, whereas balanced 2024 precipitation supported uninterrupted vine growth, with veraison completed by mid - August and an earlier harvest (Table 3)

(IPCC, 2022; Fraga *et al.*, 2013).

The general flowering period commenced on May 23 (BBCH 61) and concluded on June 12

(BBCH 69).

This phenological stage coincided with unseasonably cool weather conditions, which likely influenced its duration.

Approximately 60 days following the onset of flowering, between July 20 and 25, the onset of veraison was observed, corresponding to BBCH 81, with the first signs of berry coloration.

By August 7, veraison had progressed to approximately 80% of the berries, corresponding to BBCH 85.

By September 20, 120 days had elapsed since the beginning of flowering, indicating advanced berry ripening. The harvest was conducted on September 22, corresponding to BBCH 89.

The BBCH stage 57, corresponding to pre-flowering canopy management, included leaf removal prior to flowering. This practice was conducted on 15 May 2022, 22 May 2023, and 19 May 2024, respectively.

Discussion

Yield Components and Cluster Morphology

The influence of early leaf removal (ELR) on yield structure and cluster morphology was significant across the studied rows.

Row 30, which underwent the most intensive defoliation (eight basal leaves removed before flowering), consistently demonstrated the lowest cluster, berry, and stem weights compared to both Row 33 (four leaves removed) and the control, Row 34.

The progression of average cluster weight across the four sampling dates shows a consistent downward trend in all treatments.

Row 30 decreased from 192 g on 11 August to 131 g at harvest, representing a reduction of 31.8%, row 33 from 215g to 135 g, corresponding to a 37.2% decrease, and the control Row 34 from 320g to 145g, equivalent to a 54.7% reduction. The sharpest declines occurred between 1 – 14 September in rows 30, with a percentage of 22.3% and 33 - 18.2%, while Row 34 showed the greatest decline between 14 – 22 September, with a reduction of 33.2%.

This latter drop coincided with the veraison-to-harvest ripening period, when berry dehydration and shrivelling can contribute to weight loss.

Berry weight followed the same pattern, decreasing by 21.8% in row 30, 23.4% in row 33, and 25.5% in row 34 between 11 August and 14 September.

While all rows showed weight reduction over time, the more intensive early leaf removal in row 30 appears to have produced smaller clusters from the outset, potentially mitigating the extent of subsequent shrinkage compared to the control (Table units 6 and 7).

Despite these size reductions, yield per vine remained relatively stable across treatments. Row 30 yielded 3.16 kg per vine, row 33 yielded 3.25 kg, and row 34 yielded 3.50 kg.

When extrapolated to a vineyard density of 2.700 vines per hectare, this corresponds to 8.53 tons/ha for row 30, 8.78 tons/ha for row 33, and 9.45 tons/ha for row 34. Thus, row 30 yielded 2.85% less than row 33 and 9.7% less than row 34, representing a reduction of 0.92 tons/ha compared to the control, while row 33 yielded 7.1% less than row 34, corresponding to a difference of 0.67 tons/ha.

This slight decrease in yield from ELR-treated rows reflects lower berry and cluster weight but is associated with structural and quality advantages, including looser clusters, reduced

disease pressure, and more favourable ripening conditions (Gatti et al., 2015; Poni et al., 2015).

Additionally, ELR appeared to alter internal resource allocation within the cluster. Stems in Row 30 were on average 9.15% lighter than those in Rows 33 and 34, indicating reduced allocation to structural mass and potentially more efficient distribution toward berry development.

These findings are consistent with Smart and Smith (1986) and Smith et al. (1988), who reported that early defoliation leads to looser clusters and reduced Botrytis incidence due to improved air circulation and light penetration.

Berry Weight

Differences in berry weight among treatments can be explained by alterations in the source sink balance. Optimal ripening requires an adequate leaf area-to-fruit ratio of approximately 1 m²/kg (Petrie et al., 2000; Kliewer and Dokoozlian, 2005); reductions in leaf area limit photosynthate supply and constrain berry growth (Ollat and Gaudillere, 1998; Scholefield et al., 1977).

Pre-flowering defoliation reduces fruit set and pericarp cell expansion, resulting in lower berry weight and yield (Scholefield et al., 1977; Ollat and Gaudillere, 1998; Tittmann et al., 2016). Decreased leaf area may also reduce transpiration and water uptake, further limiting berry enlargement (McElrone, 2013).

Smaller berries typically exhibit higher skin-to-pulp ratios, promoting concentration of sugars, phenolics, and color compounds (Matthews and Anderson, 1988; Clingeleffer et al., 1996; Picard et al., 2017).

In the present study, the most intensive defoliation treatment showed the highest concentrations of phenolics, color compounds, dry matter, sugars, and tannins, likely due to reduced sink competition and altered assimilate partitioning (Lebon et al., 2006).

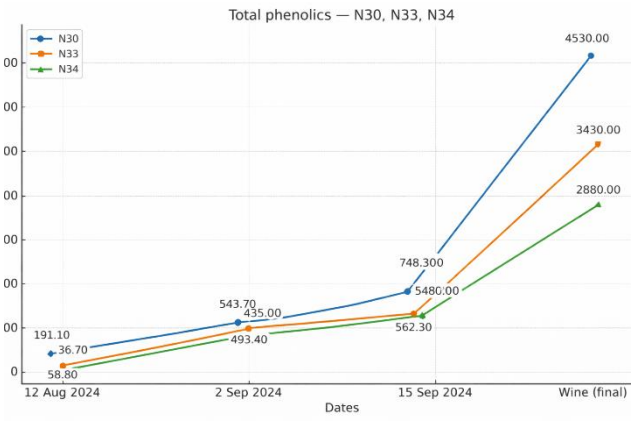
Early leaf removal can additionally decrease cluster compactness through reduced fruit set and increased light and UV-B exposure (Gatti et al., 2015; Sampson and Cane, 1999).

Enhanced radiation modifies hormonal regulation, reducing auxin and gibberellin levels while increasing abscisic acid, thereby promoting secondary metabolite accumulation (Pontin et al., 2010; Miao et al., 2021; Alonso et al., 2016; Teixeira et al., 2013).

Light-dependent upregulation of flavonoid pathway genes, including FLS1 and UFGT, further explains the elevated anthocyanin and proanthocyanidin levels observed under intensive defoliation (Martínez-Lüscher et al., 2014; Blancquaert et al., 2019; Koyama et al., 2012).

Phenolic and Color Development

Figure 1. Dynamics of Total Phenolic Accumulation (mg/L) in Grape Juice and Their Subsequent Transformation during Wine-making.



Pre-flowering ELR strongly influenced phenolic compounds and color development in both

grapes and wines. Row 30, with the most intensive defoliation, showed the highest values across all parameters.

By mid-September, total phenolics in Row 30 grapes reached (748.3 mg/L), 33% higher than Row 33 and 36% above the control Row 34; in wines, Row 30 reached (4530 mg/L), 57.3% higher than Row 34 and 32,07% higher than Row 33, while Row 33 still exceeded the control by 19,1 %. Tannins followed the same trend: Row 30 grapes (1.35 mg/L) were 27% higher than Row 33 and 17% higher than Row 34. Wines followed the same trend, and Row 30 wines (2320 mg/L) contained 46% more tannins than Row 34 and 37% more than Row 33.

In contrast, Row 33 wines showed only a modest 7% increase over the control, confirming that intensive pre-flowering leaf removal provided the greatest enhancement. (Table 11, Figure 1). These findings mirror results in Cabernet-Sauvignon and Probus (Ivanišević *et al.*, 2020), where early defoliation enhanced monomeric anthocyanin and tannin concentrations. The physiological mechanism behind this response lies in the light-dependence of the flavonoid biosynthetic pathway, particularly during early berry development stages.

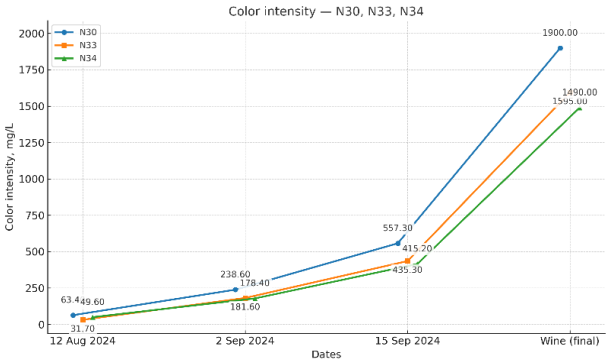
Increased sunlight exposure, achieved by reducing canopy density, activates gene expression related to anthocyanin and flavonol synthesis (Puccioni *et al.*, 2019).

Pigment Concentration also increased notably under ELR. Row 30 grapes (557.3 mg/L) were 34% higher than Row 34 and 28% higher than Row 33, while Row 33 showed only a 5% gain over the control.

The wines reflected the same pattern: Row 30 (1900 mg/L) exceeded Row 34 by 28% and Row 33 by 20%, whereas Row 33 improved just 7% over Row 34.

These results confirm that intensive ELR (30) produced wines with markedly greater phenolic density, structural tannins, and color expression, whereas partial removal (33) led to only modest improvements over the untreated control in row 34 (Tab.11, Figure 2).

Figure 2. Dynamics of Pigment Accumulation (mg/L) in Grape Must and Their Subsequent Transformation during Winemaking.

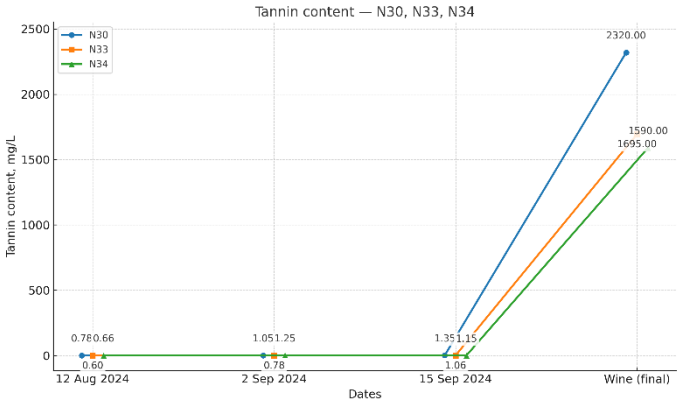


This enhancement is especially important for Saperavi, a teinturier variety, where high anthocyanin and extract levels contribute significantly to both visual appeal and mouthfeel. Similar improvements in pigment intensity and flavour expression have been observed in white cultivars such as Sauvignon Blanc and Chardonnay under ELR regimes (Smart *et al.*, 1985; Intrieri *et al.*, 2008).

Overall, the data confirm that early leaf removal enhances phenolic and color development by increasing light interception in the fruit zone. The resulting enrichment in flavonoid compounds, extract, and dry matter not only improves sensory characteristics but also confers greater oxidative and microbial stability to the wine.

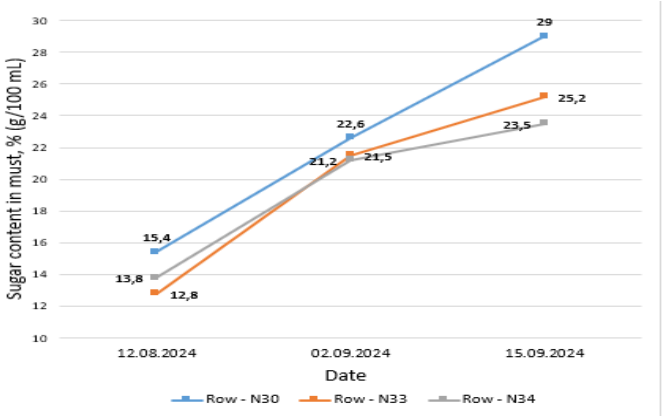
For varieties like Saperavi, this practice offers a targeted strategy to elevate wine quality. (Tab.11, Figure 3).

Figure 3. Dynamics of Tannin Accumulation



(mg/L) in Grape Must and Wine

Figure 4. Dynamics of Sugar Accumulation during Grape Ripening



A major indicator of berry maturity is sugar concentration, expressed as °Brix. Defoliated vines in Row 30 exhibited markedly higher sugar accumulation. On 14 September, sugar content reached 29% versus 23.5% in Row 34. At harvest, Brix was 26° in Row 30, 9.62 % higher than 34 (23,5°) and 6,15 % higher than 33 (24,4°).

Row 33 exceeded 34 by 3.69%. Despite smaller berries, this striking difference is primarily due to higher light exposure in the fruit zone, which enhances photosynthesis and directs assimilates to the berries. The mechanism is well documented: early defoliation shifts the source-sink balance by reducing fruit set and stimulating photosynthetic compensation in upper canopy leaves, leading to more concentrated sugar accumulation per berry (Tardaguila et al., 2010; Poni and Bernizzoni, 2010).

This finding supports the hypothesis that increased fruit exposure enhances sugar concentration.

This effect is likely associated with improved allocation of photosynthates to the berries and reduced fruit set, which lowers crop load and increases the leaf-to-fruit ratio (Kliewer and Dokoozlian, 2005).

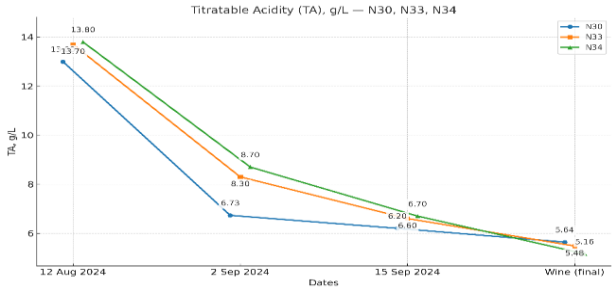
Similar patterns were reported in Sangiovese (Puccioni et al., 2019), where early leaf removal under drought conditions improved sugar content by approximately 2 °Brix. Figure 4. Patterns of Sugar Accumulation (%) during the Grape Ripening Period.

Moreover, Row 30 grapes showed a faster ripening curve, reaching optimal sugar levels earlier in the season than the other treatments. This is consistent with previous results in Cabernet-Sauvignon and Probus by Ivanišević et al. (2020), where ELR accelerated sugar accumulation and increased total soluble solids (TSS).

In warm climates or late-ripening varieties like Saperavi, this accelerated maturity is advantageous for achieving harvest before fall rains, which often increase disease pressure.

Acid Balance

Figure 5. Titratable Acidity (g/L) of Grape Must and Wine



Achieving a favourable balance between sugar and acid is crucial for must and wine quality (Gatti et al., 2015; Paolo Sabbatini et al., 2014). While early leaf removal (ELR) can increase sugar accumulation rates, they often result in a relatively low TA at harvest, especially in warm climates. (Gatti et al., 2015).

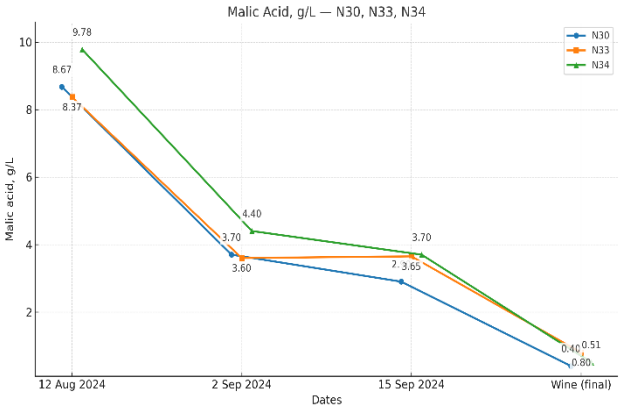
Acidity declined across all treatments, but Row 30 achieved the most favourable balance between sugar and acid at harvest. Titratable acidity (TA) in Row 30 dropped from 13.0 g/L in August to 6.2 g/L by mid-September, a reduction of about 52%. Row 33 showed a similar decrease, from 13.7 g/L to 6.6 g/L (–52%), while Row 34 declined from 13.8 g/L to 6.7 g/L (–51%).

Although the percentage reductions were comparable, the final values highlight a key difference: Row 30 produced grapes with a more balanced acid level in relation to sugar concentration. (Tab11, Figure 5) This trend was also reflected in the wines. Row 30 retained the highest acidity at 5.64 g/L, while Row 33 and Row 34 measured slightly lower at 5.48 g/L (–2.8%) and 5.16 g/L (–8.5%), respectively. At first glance, this appears contradictory, since the grapes from Rows 33 and 34 had slightly higher acidity at harvest.

However, this can be explained by the role of malic acid. Wine from Row 33 in particular retained more residual malic acid (0.8 g/L) compared to wine from Row 30 (0.4 g/L), which influenced the acid profile of the final wine. Consequently, basal leaf removal might be pivotal to decreasing the levels of organic acids. (Paolo Sabbatini et al., 2014) Malic acid declined in all rows, starting from veraison, with the sharpest reduction in Row 30 (– 66%), moderate loss in Row 33 (–56%), and intermediate decline in Row 34 (–62%). The faster depletion in Row 30 reflects higher light and temperature from early leaf removal, which accelerates respiration and malic breakdown. In contrast, Row 34 retained more malic acid under shaded canopy conditions, showing the cooling effect of less exposure.

The more exposed berries in Row 30 likely experienced higher diurnal temperature ranges, accelerating malic acid respiration while preserving tartaric acid, a pattern corroborated in trials by Smith et al. (1988) and Paolo Sabbatini et al. (2014).

Figure 6. Transformation of Malic Acid (g/L) from Grapes to Wine.



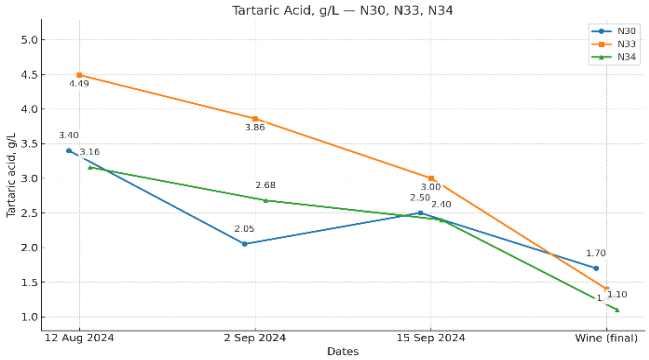
Malic acid degradation was most complete in Wines Row 30 and Row 34, with final concentrations of 0.4 g/L and 0.5 g/L, respectively, whereas Wine Row 33 retained higher residual malic acid at 0.8 g/L. Correspondingly, lactic acid concentrations reached 2.0 g/L in Row 30, 1.2 g/L in Row 33, and 2.3 g/L in Row 34, indicating effective malolactic fermentation and improved microbiological stability.

The lower malic acid concentration observed in the highly defoliated treatment is likely associated with increased berry exposure to solar radiation and elevated temperatures due to reduced canopy shading.

High temperatures suppress phosphoenolpyruvate (PEP) carboxylase activity, reducing malic acid synthesis, while enhancing the activity and thermal stability of malic enzyme, thereby promoting malate degradation (Lakso & Kliewer, 1975).

This temperature-driven enzymatic imbalance accelerates malic acid loss in grape berries (Lakso & Kliewer, 1975).

Figure 7. Transformation of Tartaric Acid (g/L) from Grapes to Wine.



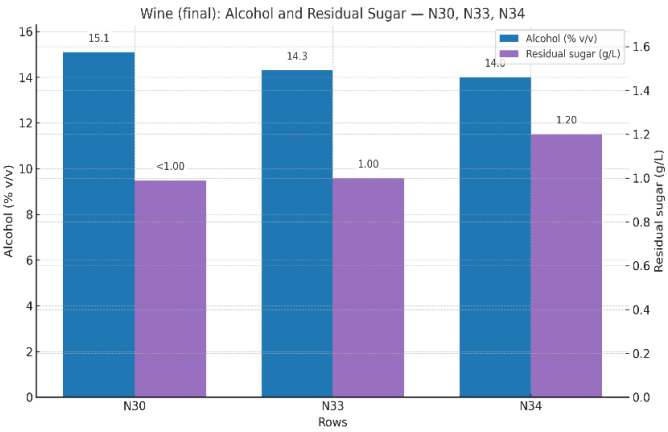
Row 30 exhibited a near equilibrium between malic and tartaric acids at harvest, with concentrations of 2.9 g/L and 2.5 g/L, respectively. Such balance is uncommon, as tartaric acid typically predominates due to its greater stability, while malic acid declines during ripening (Gatti et al.). These results suggest that early leaf removal accelerated malic degradation without complete depletion, resulting in a more balanced acid profile. This equilibrium is desirable in premium red wines, as tartaric acid contributes to pH stability, while residual malic acid supports freshness and facilitates controlled malolactic fermentation. Accordingly, Row 30 achieved a more harmonized acid composition, which may enhance phenolic integration and aging potential (Kalajdžić et al., 2020; van Leeuwen, 2016).

pH increased gradually across treatments, with Row 30 reaching the highest final value (3.8). The reduction in malic acid, together with a slight decrease in tartaric acid, likely contributed to this shift. These findings confirm that canopy management influences not only total acidity but also acid composition and pH dynamics, with important implications for wine stability and ageing.

In Saperavi, where acidity retention can remain high under conventional canopy conditions, early leaf removal appears to moderate acid levels without prolonging hang time, thereby improving balance and reducing the need for post-fermentation corrections.

Aromatic Characteristics

Diagram 1. Alcohol (%) and Residual Sugar Content (g/L) in Experimental Wines.



Although volatile aroma compounds were not directly measured, results suggest that early leaf removal (ELR) in Row 30 enhanced aroma potential. Grapes from Row 30 had the highest

dry matter (31.2%), ~13% more than Row 33 (27.7%) and 22% more than Row 34 (25.6%), reflected in higher wine extract (27.9 g/L vs. 27.0 and 25.8 g/L) and alcohol (15.1% vs. 14.3% and 14.0%), indicating greater sugar and soluble compound accumulation linked to aroma precursors.

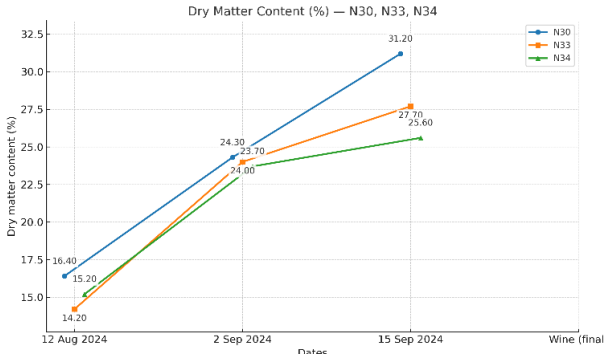
ELR's role in aroma formation is well-documented: early defoliation increases TDN in Riesling (Schüttler *et al.*, 2015) and enhances carotenoid, polyphenol, and aroma compound biosynthesis, particularly under UV-B exposure (Joubert *et al.*, 2016).

Norisoprenoids such as β-damascenone, β-ionone, vitispirane, and TDN are derived from the oxidative degradation of carotenoids and may occur in glycosidically bound forms that are released during fermentation and wine aging (Mendes-Pinto, 2009).

Cluster light exposure increases volatile terpenes by 30% in Traminette (Skinkis *et al.*, 2010) and linalool under higher sunlight (Zhang *et al.*, 2017).

Moderate early-season defoliation optimizes carotenoid and flavonoid accumulation, while excessive heat can degrade these compounds (Gambetta *et al.*, 2021).

Figure 8. Dynamics of Dry Matter Accumulation during Grape Ripening (%).



Taken together, the results suggest that early defoliation not only improves berry composition through enhanced sugar and phenolic accumulation but also creates favorable microclimatic conditions for the synthesis and preservation of key aroma precursors. These benefits underscore the importance of precise canopy management strategies to optimize grape and wine quality.

Wine Quality and Sensory Evaluation

The wines from the three canopy management treatments exhibited distinct sensory profiles consistent with reported effects of early leaf removal (ELR) and cluster-zone modification (Verdenal et al., 2025; Kalajdžić et al., 2020). Row 34 (94 points) produced a medium-ruby, fruit-forward wine of moderate complexity with elevated alcohol and a warm finish.

Lower phenolic extraction and higher approachability are consistent with shaded, non-defoliated canopies favouring early-drinking styles (Verdenal et al., 2019).

Row 33 (84 points) showed a deeper ruby–violet color and pronounced dark fruit aromatics; however, elevated residual malic acid and a short finish resulted in reduced balance, reflecting compositional instability often associated with intermediate defoliation intensity (Kalajdžić et al., 2020).

Row 30 (94 points) exhibited the greatest color intensity, concentrated dark fruit expression, and persistent yet integrated tannins with strong mid-palate structure.

Despite slight alcoholic volatility, the wine maintained balance and ageing potential. These attributes reflect increased skin-to-pulp ratio and enhanced phenolic concentration under pre-flowering ELR (Ivanišević et al., 2020;

Verdenal et al., 2025).

Although Rows 30 and 34 achieved equal scores, their styles differed markedly: Row 34 was fruit-driven and approachable, whereas Row 30 was structured and age-worthy.

Row 33 ranked lower due to compositional imbalance. These findings agree with evidence that pre-flowering ELR enhances anthocyanin and phenolic accumulation, whereas intermediate ELR may disrupt compositional equilibrium (VanderWeide et al., 2021).

The meta-analysis by VanderWeide et al., (2021), encompassing more than 50 global studies, further identifies pre-flowering ELR as one of the most effective canopy practices for improving red wine phenolic composition, particularly under climatic constraints affecting ripening and disease pressure.

Sunburn Mitigation and Microclimate Regulation

Defoliation timing is critical for effective canopy management. Early leaf removal (ELR) promotes lateral shoot growth that partially re-covers the fruit zone before peak summer temperatures, maintaining ventilation while reducing overexposure.

In contrast, late leaf removal (LLR) removes protective foliage when berries are highly vulnerable to heat stress. Thermal imaging studies showed that LLR increased bunch temperatures by up to 0.8°C, whereas ELR maintained thermal homeostasis and reduced sunburn by 37% (Poni *et al.*, 2015).

In this study, Rows 30 and 33 benefited from natural regrowth, providing protective shading. Early-season defoliation also enhances grape acclimation to sunlight, supporting polyphenol and volatile compound biosynthesis, including carotenoids involved in photoprotection and antioxidant defence (Gambetta *et al.*, 2021; Joubert *et al.*, 2016).

Collectively, these studies emphasize that **timing of green canopy management, rather than intensity, is the key factor** in optimizing microclimate, fruit quality, and stress resilience in warm-climate viticulture (Poni *et al.*, 2015; Gambetta *et al.*, 2021; Joubert *et al.*, 2016).

Conclusion

In conclusion, pre-flowering early leaf removal (ELR) applied in Row 30 (8 basal leaves removed) reduced yield primarily through decreased cluster and berry weight, while maintaining overall productivity within an acceptable range.

At the same time, ELR improved ripening uniformity and enhanced key compositional parameters, including phenolic concentration, color intensity, and acid balance. Comparative analysis demonstrated that Row 30 consistently outperformed both Row 33 (moderate defoliation) and the control across most measured parameters.

Differences between Rows 30 and 33 were more pronounced than those between Rows 33 and 34, indicating that treatment intensity was a critical determinant of physiological and compositional responses.

These results are consistent with previous findings demonstrating that pre-flowering ELR improves fruit-zone microclimate and promotes favourable berry composition without excessive yield penalty (Poni et al., 2015; Gatti et al., 2015; Ivanišević et al., 2020; VanderWeide et al., 2021).

The data confirm that early canopy modification significantly influences yield structure, phenolic accumulation, organic acid composition, and overall wine balance. Under the climatic conditions of Kakheti, ELR represents an effective tool for optimizing fruit composition and improving wine quality potential, provided that treatment intensity is carefully managed according to site-specific conditions and production objectives.

Acknowledgement:
The authors gratefully acknowledge the Georgian Agricultural University and the Knowledge Fund for their financial support.
We thank Winery Pi for initiating and implementing the research project, for providing access to the research vineyard and winemaking facilities and conducted.
We are grateful to Gela Masurashvili for his role in managing the research vineyard and to Nikoloz Kirvalidze for assistance in preparing figures. We express our deepest gratitude to Lisa Granik MW for her exceptional contribution to the organoleptic evaluation of the wines.
Conflicts of interest: “The authors declare that they have no conflicts of interest.”

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Table 1. Physicochemical and Analytical Parameters and Standard References

#	Parameter	Methodology/Standard Reference
1	Sugar content in must, % (g/100 mL)	GOST 8756.13-87
2	Titratable acidity, g/L	GOST ISO 750-13
3	Dry matter content, %	GOST 29031-91
4	Extract, g/L	OIV-MA-AS2-03A
5	Total phenolics, mg/L	OIV-MA-AS2-10
6	Tannin content, mg/L	Methods of Technochemical Control, Simferopol, 2009
7	Color intensity (coloring substances), mg/L	OIV-MA-AS2-10
8	Density at 20/20°C	OIV-MA-AS2-01
9	pH	OIV-MA-AS313-15
10	Organic acids: malic, lactic, citric, succinic, tartaric	OIV-MA-AS313-06
	parameters for wine samples only:	
11	Ethyl alcohol content vol%	orv-MA-4s312-01B
12	Volatile acidity (g/L)	orv-MA-AS313-02
13	Residual sugar (g/L)	OTV-MA-AS3I1-OIA
14	Malvidin-3,5-O-diglucoside mg/L	orv-MA-As315-03

Table 2. Results of Soil Analyses Conducted at the Laboratory of Ecological Agriculture and Nature Protection of the Georgian Agricultural University.

Parameters	Results	Test Method
pH (H_2O)	8.30	ISO 10390:2021
$CaCO_3$, %	4.05	ISO 10693:2014
Organic matter, %	2.25	VM-01/2024
Nitrogen (N), mg/kg (plant available)	25.69	ISO 14256-1:2003
Phosphorus (P_2O_5), mg/kg (plant available)	12.67	ISO 11263:1994/2020
Potassium (K_2O), mg/kg (plant available)	101.89	ISO 22171:2023
Calcium (Ca), meq/100 g	22.14	ISO 22171:2023
Magnesium (Mg), meq/100 g	1.25	ISO 22171:2023/2024
Electrical Conductivity (EC), dS/m	0.090	ISO 11265:1994
Lime Content, %	2.46	ISO 10693:2014

Table 3. Total Atmospheric Precipitation (mm) in 2022-2024

Year/ month	V	VI	VII	VIII	IX	X
2024	279.0	45.0	40.1	125.2	105.9	28.3
2023	86.1	273.6	50.0	80.3	25.5	70.4
2022	149.5	108.3	2.7	5.1	28.4	56.5[1]

Table 4. Phenological Development of Grapevine According to the BBCH Scale (2022–2024).

BBCH Stage	Phenological Stage Description	2022	2023	2024
61	Beginning of flowering	25-May	27-May	23-May
69	End of flowering / Full bloom (cap-fall complete)	10-Jun	8-Jun	12-Jun
81	Beginning of ripening (berries softening, color change begins)	5-Aug	30-Jul	25-Jul
85	Veraison (advanced ripening; berries colored, sugar accumulation)	18-Aug	12-Aug	7-Aug
89	Physiological ripeness / Harvest readiness	4-Oct	30-Sep	22-Sep

Table 5. Number of Berries Collected per Row of Saperavi Grapevines under Different Defoliation Treatments

Date	Row 30 (g)	% Change	Row 33 (g)	% Change	Row 34 (g)	% Change
11 Aug	450 berries - 980	-	450 berries - 1040	-	450 berries - 1270	-
1 Sep	450 berries - 806	17.76%	450 berries - 844	18.85%	450 berries - 1047	17.56%
14 Sep	450 berries - 773	4.09%	450 berries - 795	5.81%	450 berries - 944	9.84%

[1] LEPL National Environmental Agency, letter N 2 1 / 7 8 00

Table 6. Mean Berry Weight (g) of *Vitis vinifera* L. cv. Saperavi

Date	Row 30 (g)	% Change	Row 33 (g)	% Change	Row 34 (g)	% Change
11 -Aug-2024	2.18	-	2.31	-	2.82	-
1-Sep-2024	1.79	17.89%	1.875	18.79%	2.33	17.38%
14-Sep-2024	1.72	3.91%	1.77	5.60%	2.10	9.48%

Table 7. Average Cluster Weight (g)

Date	Row 30 (g)	% change	Row 33 (g)	% change	Row 34 (g)	% change
11-Aug-2024	192.0	-	215.0	-	320.0	-
01-Sep-2024	173.3	9.74%	181.0	15.81%	303.0	5.31%
14-Sep-2024	134.7	22.27%	148.0	18.23%	217.0	28.38%
22-Sep-2024	131.0	2.75%	135.0	8.78%	145.0	33.18%

Table 8. Average Stems Weight (g)

Date	Row 30 (g)	% Change	Row 33 (g)	% Change	Row 34 (g)	% Change
11-Aug-2024	5.36	-	5.59	-	7.00	-
1-Sep-2024	4.86	9.33%	5.08	9.12%	6.32	9.71%
14-Sep-2024	4.42	9.05%	4.60	9.45%	5.80	8.23%
Bunch Size length/width	7CM-10 CM		8CM-12CM		20CM-15CM	

Table 9. Harvest Specification 22 September 2024

Row	Kg	% Difference vs Row 34	Per Vine (kg)	% Difference vs Row 34	°Brix	% Difference vs Row 34
30	124	11.43%	3.16	9.7%	26	9.62%
33	130	7.14%	3.25	7.14%	24,4	3.69%
34	140	-	3.50	-	23.5	-

Table 10. Physicochemical and Biochemical Composition of *Vitis vinifera* L. cv. Saperavi Berries

Parameters/ Row	Grapes 12.08.2024			Grapes 2.09.2024			Grapes 15.09.2024		
	30	33	34	30	33	34	30	33	34
Sugar content in must & wine % (g/100 mL)	15.4	12.8	13.8	22.6	21.5	21.2	29	25.2	23.5
Dry matter content, %	16.4	14.2	15.2	24.3	24	23.7	31.2	27.7	25.6
Extract, g/L	157.1	134.1	152.7	277.1	272	267.5	304.5	255.2	241.7
Total phenolics mg/L	191.1	58.8	36.7	543.7	493.4	435	748.3	562.3	548.5
Tannin content mg/L	0.78	0.6	0.66	1.05	0.78	1.25	1.35	1.06	1.15
Color intensity/color substances mg/L	63.4	31.7	49.6	238.6	181.6	178.4	557.3	435.3	415.2
Density at 20/20°C	1.070	1.062	1.067	1.097	1.092	1.091	1.12	1.106	1.098
pH	3.25	3.17	3.11	3.61	3.59	3.6	3.78	3.8	3.85
Malic acid g/L	8.67	8.37	9.78	3.7	3.6	4.4	2.9	3.65	3.7
Lactic acid g/L	0.48	0.45	0.28	0.41	0.32	0.47	0.38	0.475	0.25
Citric acid g/L	0.22	0.25	0.26	0.3	0.1	0.68	0.4	0.5	0.45
Succinic g/L	0.23	0.14	0.32	0.27	0.42	0.47	0.78	0.91	0.67
Tartaric acid g/L	3.4	4.49	3.1578	2.05	3.86	2.68	2.5	3	2.4
TA g/L	13	13.7	13.8	6.73	8.3	8.7	6.2	6.6	6.7

Table 11. Physicochemical Characteristics of Saperavi Wine

Parameters	Row 30	Row 33	Row 34	Unit / Notes
Extract	27.9	27.0	25.8	g/L
Total phenolics	4530	3430	2880	mg/L
Tannin content	2320	1695	1590	mg/L
Color intensity/color substances	1900	1595	1490	mg/L
Density (20 °C)	0.99139	0.99115	0.99014	g/mL
pH	3.80	3.85	3.90	-
Malic acid	0.40	0.80	0.51	g/L
Lactic acid	2.00	1.20	2.30	g/L
Citric acid	<0.2	<0.2	<0.2	g/L
Tartaric acid	1.7	1.4	1.1	g/L
Total acidity (TA)	5.64	5.48	5.16	g/L tartaric
Volatile acidity (VA)	0.47	0.27	0.51	g/L acetic acid
Alcohol	15.1	14.3	14.0	% v/v
Residual sugar (RS)	<1.0	1.0	1.2	g/L