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Effects of Leaf Removal Application in Different Phenological Stages on Yield and Quality Parameters in Karaerik Grape Variety

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HIGHLIGHTS

- Leaf removal timing significantly affected yield, berry traits, and chemical composition.
- Flowering-stage defoliation reduced yield but improved cluster looseness and berry size.
- Early to mid-stage leaf removal increased TSS, maturity index, and phenolics.
- Fruit set and pea-size stages were optimal for quality improvement with less yield loss.

Abstract

This two-year study evaluated the effects of basal leaf removal applied at five phenological stages (pre-flowering, full flowering, fruit set, pea-size berry, and veraison) on yield, cluster structure, berry morphology, and chemical composition of the 'Karaerik' grape cultivar under the ecological conditions of Erzincan. The study aimed to determine the optimal timing of leaf removal as a cultural practice to improve quality in large-berried, compact-cluster table grapes. Leaf removal treatments were applied at the specified growth stages, and yield per vine, cluster characteristics, berry traits, cracking incidence, and chemical and phenolic properties were assessed over two consecutive seasons. The results indicated that leaf removal significantly affected both yield and quality parameters. Yield per vine decreased compared with the control, particularly when leaf removal was performed at the flowering stage, where yield declined from 11.93 kg vine^{-1} to 9.70 kg vine^{-1}. In contrast, several morphological traits improved following leaf removal. Berry weight increased from 4.69 g in the control to 5.72 g with pre-flowering applications, accompanied by increases in berry size and reductions in cluster compactness. All leaf removal treatments reduced the number of cracked berries relative to the control. Chemical composition was also influenced by treatment timing. Total soluble solids increased from 17.05 °Brix in the control to 18.64 °Brix with leaf removal at full flowering, while titratable acidity decreased and the maturity index increased. In addition, early and mid-season leaf removal enhanced bioactive compounds, with the highest total phenolic (508.70 mg L^{-1} GAE) and total flavonoid (102.90 mg g^{-1} CE) contents recorded at the fruit set stage. In conclusion, leaf removal was an effective practice for improving grape quality; however, its effects strongly depended on phenological timing. Applications at flowering reduced yield, whereas treatments at fruit set and pea-size berry stages provided a more favorable balance between yield and quality in 'Karaerik' grapes.

Keywords: Leaf removal; Phenological stage; Table grape; Berry quality; Phenolic compounds; *Vitis vinifera*

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1. Introduction

The Grapevine (*Vitis vinifera* L.) is one of the most economically important fruit crops worldwide and is extensively cultivated for both table and wine grape production. In table grape cultivation, the primary objectives include achieving high yield in combination with large berry size, well-developed and uniform clusters, superior visual quality, and reduced susceptibility to diseases. The attainment of these objectives depends not only on cultivar-specific genetic characteristics but also on environmental conditions and the cultural practices applied throughout the growing season. Canopy management practices such as leaf removal, lateral shoot removal, shoot tipping, and hedging improve air circulation within the canopy and enhance light penetration into the cluster zone, thereby promoting photosynthetic efficiency and uniform ripening (Çelik et al. 1998; Poni et al. 2006; Korkutal et al. 2018).

Leaf removal is a widely adopted canopy management practice that involves the removal of basal leaves surrounding the fruiting zone at specific phenological stages. This practice modifies the cluster microclimate by increasing air movement, regulating solar radiation interception, and moderating berry temperature (Poni et al. 2017). It is particularly effective in cool and humid regions, where it contributes to the suppression of fungal diseases, while also improving commercially important traits such as berry size, coloration, and overall visual quality in table grape cultivars (English et al. 1989; Smart et al. 1990; Li and Feng 2025; Celik and Akural 2026). Moreover, leaf removal enhances berry skin development, sugar accumulation, and color uniformity, thereby increasing the commercial value of grapes (Hunter et al. 1991; Staff et al. 1997; Poni et al. 2006). Consequently, leaf removal is regarded as a key cultural practice that supports both quality improvement and product safety in table grape production (Sivilotti et al. 2016).

The Karaerik grape cultivar, widely grown in Erzincan and surrounding regions, plays a significant role in regional table grape production and the local economy. This cultivar is characterized by large berries, a crisp texture, dark purple–black skin color, and a pronounced aroma, making it highly valued in domestic markets. Because external appearance and physical quality attributes largely determine market acceptance in table grapes, the timing and intensity of cultural practices directly influence commercial success. Increasing production costs and rising consumer expectations have further emphasized the need to optimize quality-oriented vineyard management strategies.

Numerous studies on wine grape cultivars have demonstrated that cluster-zone leaf removal reduces fungal disease incidence by improving canopy aeration and enhances berry color, flavor, and phenolic compound accumulation through increased sunlight exposure (Poni et al. 2009; Tardaguila et al. 2010; Lee and Skinkis 2013). However, information regarding the effects of leaf removal on table grape cultivars, particularly those with compact clusters and large berries such as Karaerik, remains limited. Given the morphological and physiological differences between wine and table grapes, findings obtained from wine grape cultivars may not be directly transferable.

Excessively compact clusters in table grapes negatively affect fruit quality during both postharvest handling and fresh consumption. Therefore, leaf removal strategies that promote looser and more uniform clusters are of particular importance. Adjustments in the leaf-to-fruit ratio influence the allocation of photosynthates, resulting in significant changes in yield, cluster architecture, berry development, soluble solid accumulation, and carbohydrate reserves (Koblet et al. 1994; Bennett et al. 2005; Intrieri et al. 2008; Zenoni et al. 2017). Nevertheless, excessive or improperly timed leaf removal may lead to adverse effects such as reduced fruit set, yield losses, smaller berries, and delayed ripening (Kliewer and Bledsoe 1986; Chorti et al. 2016), highlighting the importance of phenological timing.

Leaf removal also affects the biochemical composition of grapes. Phenolic compounds play a critical role in determining color, flavor, and aroma, which are essential quality attributes in both table and wine grapes (Bal et al. 2011; Tahmaz et al. 2022). Increased cluster light exposure resulting from leaf removal stimulates phenolic biosynthesis, thereby enhancing organoleptic quality and marketability.

Despite its potential benefits, comprehensive studies evaluating the effects of leaf removal applied at different phenological stages on the Karaerik grape cultivar are scarce. Therefore, the objective of this study is to investigate the effects of leaf removal applied at pre-flowering, full flowering, fruit set, pea-size berry, and veraison stages on yield, berry characteristics, and quality parameters of the Karaerik grape grown under Erzincan ecological conditions, in comparison with an untreated control.

2. Materials and Methods

2.1. Plant Material

The experiment was conducted in a commercial vineyard consisting of own-rooted grapevines, which was established in 2007, and managed under uniform cultural and agronomic practices. The vines used in the study were at full bearing capacity and had a mean trunk height of approximately 1 m. Vines were trained using a bilateral permanent cordon system supported by a double T trellis structure. The vineyard was established at a spacing of 2 m × 2 m between and within rows, corresponding to standard regional production practices.

2.2. Experimental Design and Treatments

The study was conducted according to a randomized complete block design with three replications, and each replication consisted of three vines. During winter pruning, four spurs were retained on each cordon of every vine, and 3–4 buds were left per spur, resulting in a standardized total of 30 buds per vine. Fourteen days after bud break, shoot and cluster numbers were counted and standardized to 24 shoots per vine to ensure uniform crop load. Throughout the growing season, all vines, including the control, received identical canopy management practices, including shoot thinning, removal of water sprouts, lateral shoot removal, and shoot topping.

Leaf removal treatments were applied according to the phenological scale described by Lorenz et al. (1995). Treatments consisted of manually removing the first five basal leaves from each shoot at the following phenological stages: pre-flowering (PF), full flowering (FF), fruit set (FS), pea-size berry (PS), and veraison (V) (Figure 1; Figure 2). Vines without leaf removal served as the control treatment. The experiment was carried out during the 2022 and 2023 growing seasons, and all measurements were recorded separately for each year.

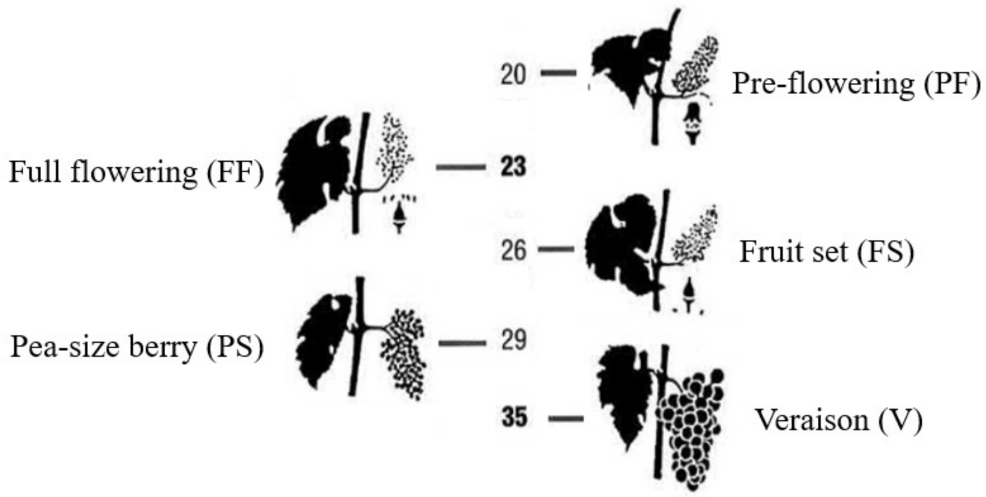

Figure 1. Leaf removal periods according to the phenological scale stages (Lorenz et al., 1995)

Figure 2. Grapevine without leaf removal (A) and with leaf removal (B)

2.3. Evaluated Characteristics

Pomological characteristics of the Karaerik grape cultivar were determined, including fresh grape yield (kg vine^{-1}), cluster weight (g), number of berries per cluster (number cluster^{-1}), cluster width and length (cm), cluster compactness degree (1–9 scale), single berry weight (g), berry width and length (mm), and number of cracked berries (number per 100 berries). In addition, chemical characteristics including total soluble solids (TSS, %), titratable acidity (TA, %), pH, and maturity index (TSS TA^{-1}) were determined.

For the analysis of phenolic compounds, 0.5 kg grape samples were collected from each experimental plot one day before harvest on 19 September 2022 and 25 September 2023. Total phenolic content was determined according to Singleton and Rossi (1965) and expressed as mg L^{-1} gallic acid equivalents (GAE), while total flavonoid content was measured following the method of Zhishen et al. (1999) and expressed as mg g^{-1} catechin equivalents (CE).

2.4. Statistical Analysis

Statistical analyses were performed using JMP® Pro 17.0.0 software (JMP Statistical Discovery LLC, United Kingdom). The experiment was designed according to a factorial arrangement within a randomized complete block design. The data were analyzed using a two-way ANOVA including year, leaf removal treatments, and their interaction (Year × Treatment). Blocks were included in the statistical model; however, block effects were not statistically significant and therefore are not presented in the tables. Mean comparisons were performed using the LSD (least significant difference) test due to its higher sensitivity in detecting differences among treatments. Statistical significance was evaluated at the $p<0.05$ and $p<0.01$ levels.

3. Results and Discussion

3.1. Effect of Leaf Removal at Different Phenological Stages on Yield

In this study, analysis of the effects of leaf removal treatments on yield per vine revealed that both the Year Main Effect (YME) and the Period Main Effect (PME) were statistically significant, while the YME × PME interaction was not significant (Table 1). Block effects were not statistically significant for the evaluated traits and therefore are not presented in the tables. Assessment of the YME showed that the 2022 growing season, under leaf removal applied at various phenological stages, was placed within the first significance group. In terms of the PME, the control treatment numerically exhibited the highest yield (11.93 kg vine^{-1}), while leaf removal applied during the flowering stage resulted in the lowest yield; moreover, the pea-size berry and veraison stages were grouped within the same statistical category.

Previous investigations have clearly indicated that defoliation implemented at the flowering stage leads to a substantial reduction in fruit set across both red- and white-fruited grapevine cultivars (Poni et al., 2009; Tardaguila et al., 2010; Sabbatini and Howell, 2010; Acimovic et al., 2016). The carbon deficit created by leaf removal at this phenological phase disrupts meiotic activity during anthesis, limits hexose allocation, and ultimately lowers flower fertility (Lebon et al., 2004). The intensity of leaf removal conducted either prior to or following flowering not only alters developmental dynamics during berry maturation but also exerts a substantial impact on fruit set. In a study by Bogicevic et al. (2015), early basal leaf removal was implemented on shoots of the Vranac local cultivar and Cabernet Sauvignon, revealing a more pronounced yield response in Cabernet Sauvignon. Across both cultivars, defoliation resulted in yield reductions ranging from 23% to 36% relative to the untreated control.

Table 1. The Effects of leaf removal at different phenological stages on fresh grape yield per vine during the 2022 and 2023 growing seasons

Observations	Years	Periods						
		PF	FF	FS	PS	V	C	YME
Fresh grape yield (kg vine^{-1})	2022	11.19±0.46 ^{ns}	10.89±0.34	10.94±0.30	12.62±0.27	12.42±0.15	12.75±0.72	11.79±0.87 *A**
	2023	8.72±0.09	8.89±0.34	8.47±0.27	9.73±0.51	10.25±0.94	11.10±0.44	9.52±1.02 *B*
	PME	9.96±1.26 *C**	9.89±1.03 *C*	9.70±1.25 *C*	11.17±1.48 *B*	11.33±1.22 *B*	11.93±0.96 *A*	

Values are presented as mean ± standard deviation (M±SD).
PF: Pre-flowering, FF: Full flowering, FS: Fruit set, PS: Pea-size berry, V: Veraison, C: Control; PME: Period Main Effect, YME: Year Main Effect.
Different lowercase letters within the same row and uppercase letters within the same column indicate statistically significant differences based on the LSD post hoc test *$p<0.01$. ns: indicates non-significant differences ($p>0.05$).

3.2. Effect of Leaf Removal at Different Phenological Stages on Cluster Structure

When leaf removal treatments applied at different phenological stages were evaluated in terms of cluster structure, statistically significant differences were observed among both treatments and years. Examination of the effects of leaf removal applied during the flowering period on cluster structure parameters indicated that, although leaf removal negatively affected cluster weight and the number of berries per cluster at all application stages, it resulted in a marked reduction in cluster compactness. Analysis of the data presented in Table 2 showed that the Year Main Effect (YME) and Period Main Effect (PME) were statistically significant for cluster weight, number of berries per cluster, cluster length, and cluster compactness degree, whereas the YME × PME interaction was not statistically significant. The block factor did not exert a significant influence on any of the evaluated cluster traits and was therefore excluded from tabular presentation. With respect to the year effect, the 2022 growing season was predominantly classified within the first significance group following leaf removal applications at different phenological stages. Regarding the PME, the highest cluster weight was recorded in the control treatment (476.28 g), while the lowest values were obtained from leaf removal treatments applied during the flowering-related stages (PF, FF, and FS).

Consistent with the present findings, Acimovic et al. (2016) evaluated the response of the Pinot noir (*Vitis vinifera* L.) cultivar to the removal of 4, 6, 8, and 10 basal leaves per shoot and reported that the removal of six or eight leaves effectively enhanced fruit quality while causing only a limited reduction in fruit set. Similarly, Bogicevic et al. (2015) applied early basal leaf removal to the local Vranac and Cabernet Sauvignon cultivars and observed reductions in yield, cluster weight, and number of berries per cluster in both cultivars, accompanied by an increase in berry weight. These findings are consistent with Alatzas et al. (2023), who reported that defoliation treatments reduced key yield components such as berry size, cluster weight, and yield per vine. This agreement suggests that the reductions observed in the present study may be attributed to source limitation induced by leaf removal, despite its potential benefits for fruit composition. Recent studies further support these results, indicating that early leaf removal reduces cluster compactness and berry number primarily through carbon limitation and altered canopy microclimate, while simultaneously improving cluster uniformity (Celik and Akural 2026). In addition, it has been reported that the timing and intensity of defoliation are critical factors determining the balance between yield reduction and structural improvement in clusters (Cincotta et. al. 2021; Gambacorta et. al. 2022).

Leaf removal applications performed at different phenological stages did not result in pronounced changes in cluster width or length compared with the control. However, the reduction in fruit set induced by the treatments indirectly affected cluster structure. A decrease in the number of berries per cluster provided a favorable basis for improvements in fruit quality. As shown in Table 2, leaf removal reduced cluster compactness and contributed to the formation of a more balanced cluster architecture. In particular, leaf removal applied during the flowering period resulted in looser clusters compared with the control treatment.

Table 2. The Effect of leaf removal at different phenological stages on cluster structure during the 2022 and 2023 growing seasons.

Observations	Years	Periods						
		PF	FF	FS	PS	V	C	YME
Cluster weight (g)	2022	466.16±19.31 *ns*	453.55±14.32	455.78±12.34	525.70±11.18	514.90±9.62	497.11±40.15	485.53±33.16 *A**
	2023	363.46±3.73	370.62±14.21	352.95±11.20	405.48±21.01	426.96±39.30	455.46±11.21	395.82±40.36 *B*
	PME	414.80±52.59 *B**	412.08±43.07 *B*	404.36±52.31 *B*	465.58±61.66 *A*	470.93±49.79 *A*	476.28±31.83 *A*	
Number of berries per cluster (number cluster^{-1})	2022	82.00±8.72 *ns*	83.17±2.52	78.17±2.36	88.50±4.27	94.83±3.18	100.50±12.53	87.86±9.49 *A**
	2023	63.00±3.04	65.50±16.48	63.67±12.50	69.50±10.50	79.17±9.29	105.00±8.72	74.30±17.22 *B*
	PME	70.91±10.89 *C**	72.50±13.07 *C*	74.33±10.32 *C*	79.00±11.54 *BC*	87.00±9.67 *B*	102.75±9.10 *A*	
Cluster width (cm)	2022	11.51±1.03 *abc**	11.95±1.39 *ab*	12.03±0.61 *ab*	11.04±0.59 *bc*	13.05±1.11 *a*	10.26±0.54 *c*	11.64±1.15 *ns*
	2023	11.58±1.46 *abc*	10.00±1.00 *bc*	10.58±0.88 *bc*	11.50±1.00 *abc*	11.50±1.00 *abc*	12.67±0.38 *a*	11.39±1.09
	PME	11.54±1.03 *ns*	11.22±1.22	11.30±0.95	11.27±0.71	12.27±1.16	11.46±1.26	
Cluster length (cm)	2022	16.79±0.44 *ns*	15.43±0.17	16.46±0.27	15.30±1.07	16.52±1.53	16.72±0.67	17.53±0.91 *A**
	2023	18.83±1.26	16.67±0.38	17.00±0.90	16.67±0.88	18.75±1.00	17.25±0.25	16.20±1.15 *B*
	PME	17.81±1.28 *A**	16.05±0.67 *C*	16.73±0.61 *BC*	15.98±1.05 *C*	17.63±1.54 *A*	16.99±0.49 *AB*	
Cluster compactness degree (OIV-204)	2022	4.57±0.20 *ns*	4.65±0.25	4.63±0.11	5.85±0.36	6.95±0.48	6.93±0.30	5.60±1.07 *ns*
	2023	4.85±0.35	4.82±0.34	5.12±0.34	5.99±0.22	6.93±0.21	6.91±0.40	5.77±0.94
	PME	4.71±0.27 *C**	4.73±0.25 *C*	4.87±0.32 *C*	5.92±0.25 *B*	6.94±0.30 *A*	6.92±0.29 *A*	

Values are presented as mean ± standard deviation (M±SD).
PF: Pre-flowering, FF: Full flowering, FS: Fruit set, PS: Pea-size berry, V: Veraison, C: Control; PME: Period Main Effect, YME: Year Main Effect. OIV-204: 1 = very loose, 3 = loose, 5 = medium, 7 = compact, 9 = very compact (OIV, 2019)
Different lowercase letters within the same row and uppercase letters within the same column indicate statistically significant differences based on the LSD post hoc test *p<0.01. ns: indicates non-significant differences (p>0.05).

Numerous studies have reported that leaf removal practices significantly influence cluster structure (Mosetti et al. 2016; Frioni et al. 2017; Riesterer-Loper et al. 2019; Verdenal et al. 2019; Lopes et al. 2020). These effects have been associated with the removal of approximately 15–40% of carbohydrate sources (leaves) during periods of intensive vegetative growth, which reduces carbon allocation to reproductive organs and negatively affects fruit set (Frioni et al. 2018). Furthermore, the linear relationship between the proportion of leaf area removed and the corresponding decrease in yield supports this interpretation (Frioni et al. 2019). Chalfant and Dami (2021) reported that early defoliation decreased cluster compactness in the Chambourcin cultivar, while no significant effects were observed on berry cracking or the severity of Botrytis bunch rot. In contrast, Kök (2014) found that early and late leaf removal combined with cluster thinning increased cluster width and length in the Muscat Hamburg cultivar, whereas changes in cluster compactness were not statistically significant. Overall, the results of the present study are in close agreement with those reported in previous research (Poni et al. 2006; Hed et al. 2009; Diago et al. 2010; Palliotti et al. 2011; Tardaguila et al. 2010; Komm and Moyer 2015; Verdenal et al. 2019).

3.3. Effect of Leaf Removal at Different Phenological Stages on Berry Structure

Leaf removal applied to the basal portion of shoots at different phenological stages alters the cluster microclimate and consequently influences the morpho-anatomical and biochemical characteristics of berry structure. In the present study, analysis of the effects of leaf removal on single berry weight, number of cracked berries, and berry width and length indicated that the Year Main Effect (YME) and Period Main Effect (PME) were statistically significant, whereas the YME × PME interaction was statistically significant for all traits except the number of cracked berries (Table 3). The block effect was not found to be significant for any of the berry structure parameters examined and was therefore omitted from further presentation. With respect to the year effect, leaf removal treatments applied at different phenological stages were generally classified within the first significance group in 2022. Regarding phenological timing, vines subjected to leaf removal at the pre-flowering stage produced the highest individual berry weight (5.72 g), whereas the lowest berry weight (4.69 g) was recorded in the untreated control.

Several studies have reported that leaf removal applied particularly during the flowering period reduces fruit set but redirects photosynthetic activity toward younger leaves, resulting in increased berry size, a higher pulp-to-skin ratio, and enhanced phenolic accumulation (Bledsoe et al. 1988; Keller et al. 2005; Intrieri et al. 2008). Evaluation of the effects of leaf removal applied at different phenological stages on the incidence of cracked berries per cluster (Table 3) showed that all defoliation treatments reduced berry cracking compared with the control, indicating a beneficial effect. The highest number of cracked berries was observed in the control treatment (4.58 berries per 100), whereas lower values were recorded at all leaf removal stages, including pre-flowering, full flowering, fruit set, pea-size berry, and veraison.

These findings are generally consistent with previous reports. Palliotti et al. (2012) indicated that early leaf removal improves berry resistance by regulating cluster microclimate, while Intrieri et al. (2008) reported that leaf removal applied at flowering strengthens berry structure. Tardaguila et al. (2010) and Diago et al. (2012) emphasized that although leaf removal enhances fruit quality, excessive defoliation may limit photosynthetic capacity. Thus, the present results corroborate earlier findings and further clarify the phenology-dependent effects of leaf removal. Recent studies further support these interpretations, indicating that early defoliation enhances berry skin development and structural integrity through improved light exposure and altered microclimatic conditions (Celik and Akural 2026). In addition, it has been reported that optimized leaf removal can reduce physiological disorders such as berry cracking while promoting more uniform berry growth, although excessive exposure may induce stress depending on environmental conditions (Li and Feng 2025).

When berry width and length were evaluated, the YME and YME × PME interaction were statistically significant at $p \leq 0.01$, whereas the PME was significant at $p \leq 0.05$ for berry length but not for berry width (Table 3). In terms of years, 2022 was included in the highest significance group for both traits. Across phenological stages, leaf removal increased berry length by 0.20 mm at the fruit set stage and by up to 1.01 mm at the pre-flowering stage. These results indicate that leaf removal directly influences berry development, resulting in significant differences in berry dimensions. Leaf removal applied at the flowering and fruit set stages promoted berry enlargement primarily by limiting berry number, whereas treatments at the pea-size berry and veraison stages improved light penetration and air circulation within the cluster zone, thereby favoring berry growth under specific conditions. Comparable results have been reported by Poni et al. (2006), Intrieri and Filippetti (2000), and Tardaguila et al. (2008). In contrast, Kılıç (2019) reported no significant effects of summer pruning on berry width or length in the Red Globe cultivar, suggesting that cultivar-specific traits and differences in phenological timing may account for these inconsistencies.

Table 3. The effects of leaf removal at different phenological stages on berry structure during the 2022 and 2023 growing seasons

Observations	Years	Periods						
		PF	FF	FS	PS	V	C	YME
Single berry weight (g)	2022	5.65±0.15 *ab***	5.47±0.14 *abc*	5.84±0.24 *a*	5.75±0.22 *ab*	5.36±0.15 *bc*	5.13±0.14 *c*	5.53±0.30 *A**
	2023	5.80±0.17 *a*	5.47±0.32 *abc*	5.39±0.11 *bc*	5.56±0.34 *ab*	5.12±0.43 *c*	4.25±0.13 *d*	5.26±0.71 *B*
	PME	5.72±0.22 *A**	5.46±0.58 *AB*	5.62±0.65 *A*	5.65±0.26 *A*	5.24±0.29 *B*	4.69±0.45 *C*	
Number of cracked berries (number 100-1)	2022	1.50±0.10^{ns}	0.67±0.76	1.50±0.50	0.83±0.58	1.33±1.04	4.17±0.58	2.39±1.28 *A**
	2023	1.67±1.61	2.00±2.00	1.00±1.32	2.17±0.58	2.50±1.32	5.00±1.80	1.67±1.86 *B*
	PME	1.58±0.93 *B**	1.33±1.40 *B*	1.25±0.85 *B*	1.50±1.32 *B*	1.91±1.13 *B*	4.58±1.17 *A*	
Berry width (mm)	2022	21.12±0.26 *ab**	20.54±0.35 *bc*	21.01±0.36 *ab*	21.22±0.04 *ab*	22.37±0.52 *a*	22.34±0.32 *a*	21.43±0.74 *A**
	2023	19.71±1.08 *bcd*	19.00±2.08 *cd*	19.09±1.04 *cd*	19.70±1.37 *bcd*	18.89±0.62 *d*	17.30±0.24 *e*	18.95±1.28 *B*
	PME	20.41±0.96^{ns}	19.77±1.44	20.05±1.15	20.46±1.10	20.63±1.80	19.82±2.53	
Berry length (mm)	2022	23.20±0.54 *bc**	22.74±0.31 *cd*	23.64±0.31 *abc*	24.13±0.39 *abc*	24.22±0.21 *ab*	25.05±0.07 *a*	23.83±0.80 *A**
	2023	22.81±0.56 *bcd*	21.50±1.19 *de*	20.74±1.61 *e*	23.54±1.37 *bc*	20.53±1.35 *e*	18.93±0.21 *f*	21.34±2.00 *B*
	PME	23.00±0.49 *AB***	22.12±1.80 *B*	22.19±1.73 *B*	23.83±0.87 *A*	22.37±2.01 *B*	21.99±3.06 *B*	

Values are presented as mean ± standard deviation (M±SD).
PF: Pre-flowering, FF: Full flowering, FS: Fruit set, PS: Pea-size berry, V: Veraison, C: Control; PME: Period Main Effect, YME: Year Main Effect.
Different lowercase letters within the same row and uppercase letters within the same column indicate statistically significant differences based on the LSD post hoc test *$p<0.01$ and ** $p<0.05$. ns: indicates non-significant differences ($p>0.05$).

3.4. Effect of Leaf Removal at Different Phenological Stages on Certain Chemical and Phenolic Components

This section evaluated the effects of leaf removal applied at different phenological stages on selected grape chemical properties, including total soluble solids (TSS), titratable acidity (TA), pH, and maturity index, as well as phenolic-related parameters such as total phenolic and total flavonoid contents. The results indicated that variations in the timing of leaf removal treatments caused statistically significant differences in grape quality attributes. The block factor did not show a significant contribution to any of the chemical or phenolic variables assessed and was therefore not included in the data tables.

With respect to total soluble solids, the Period Main Effect (PME) was statistically significant, with the highest TSS values observed at the full flowering (18.64%) and pea-size berry (18.35%) stages, whereas the lowest values occurred in the control treatment. These findings indicate that leaf removal promotes the allocation of photosynthates to the berries, thereby enhancing sugar accumulation. The present results are consistent with several previous studies (Poni et al. 2006; Pastore et al. 2013; Zenoni et al. 2017; Mawdsley 2019; Wang et al. 2022), although contrasting results have also been reported (Rossouw et al. 2018; Valentini et al. 2019). For example, Bahar and Öner (2016) reported the highest TSS values in the control treatment of Cabernet Sauvignon vines subjected to different leaf removal regimes. In agreement with the present findings, recent studies have shown that defoliation practices can significantly increase total soluble solids by improving canopy light interception and enhancing photosynthetic efficiency (Cincotta et. al. 2021).

Titratable acidity was highest in the control treatment (0.74%), whereas significantly lower TA values were recorded in all leaf removal treatments. This reduction may be attributed to increased solar exposure, which accelerates respiratory metabolism and organic acid degradation. Similar decreases in must acidity following leaf removal have been reported by Smart and Robinson (1991) and Intrieri and Filippetti (2000). In contrast, Korkutal et al. (2022) observed increased titratable acidity following post-flowering leaf removal in the cluster zone of the Michele Palieri cultivar, a discrepancy that may be related to differences in application timing and cultivar characteristics.

pH values differed among treatments, with the highest values recorded at the pea-size berry (3.61) and veraison (3.62) stages, whereas the control and early-stage treatments (PF, FF, and FS) were grouped at lower pH levels. In terms of maturity index, the full flowering (28.12) and pea-size berry (27.84) stages showed the highest values, while the lowest maturity index was observed in the control treatment (23.07). These findings indicate that leaf removal accelerates ripening and enhances technological maturity, as previously reported by Tardáguila et al. (2008).

Table 4. The effects of leaf removal at different phenological stages on certain chemical and phenolic compounds during the 2022 and 2023 growing seasons

Observations	Years	Periods						
		PF	FF	FS	PS	V	C	YME
Total soluble solids (TSS, %)	2022	18.16±0.57^{ns}	18.91±0.70	17.96±0.35	18.46±0.41	17.24±0.30	16.71±0.22	17.91±0.82 ^{ns}
	2023	18.18±0.16	18.36±0.22	18.07±0.04	18.24±0.16	17.19±0.47	17.38±0.44	17.90±0.51
	PME	18.17±0.34 *B**	18.64±0.50 *A*	18.01±0.21 *B*	18.35±0.28 *AB*	17.22±0.32 *C*	17.05±0.44 *C*	
Titratable acidity (%)	2022	0.66±0.02 *c***	0.66±0.01 *cd*	0.68±0.01 *c*	0.66±0.01 *cd*	0.63±0.02 *d*	0.76±0.02 *a*	0.68±0.04 ^{ns}
	2023	0.66±0.02 *cd*	0.67±0.01 *c*	0.68±0.03 *c*	0.66±0.03 *cd*	0.69±0.02 *c*	0.72±0.02 *b*	0.68±0.03
	PME	0.66±0.02 *B**	0.66±0.01 *B*	0.68±0.02 *B*	0.66±0.02 *B*	0.66±0.03 *B*	0.74±0.02 *A*	
pH	2022	3.52±0.09 *cd**	3.59±0.04 *bc*	3.51±0.03 *de*	3.61±0.02 *ab*	3.56±0.06 *bcd*	3.62±0.04 *ab*	3.57±0.07 *A**
	2023	3.43±0.02 *e*	3.54±0.04 *bcd*	3.53±0.02 *cd*	3.61±0.04 *ab*	3.68±0.03 *a*	3.34±0.06 *f*	3.52±0.11 *B*
	PME	3.48±0.07 *C**	3.57±0.04 *AB*	3.51±0.02 *BC*	3.61±0.02 *A*	3.62±0.09 *A*	3.48±0.14 *C*	
Maturity index (%)	2022	27.27±0.18 *bcd**	28.71±0.61 *a*	26.29±0.49 *d*	28.12±0.51 *ab*	27.30±0.36 *bcd*	22.09±0.45 *f*	26.63±2.20 ^{ns}
	2023	27.70±0.63 *abc*	27.52±0.89 *bc*	26.73±1.06 *cd*	27.56±1.28 *bc*	25.08±0.20 *e*	24.05±0.08 *e*	26.44±1.54
	PME	27.48±0.43 *A**	28.12±0.86 *A*	26.51±0.71 *B*	27.84±0.84 *A*	26.19±1.23 *B*	23.07±1.02 *C*	
Total phenolic content (mg L^{-1})	2022	461.89±12.45 ^{ns}	467.86±14.42	465.71±22.61	412.84±26.10	357.01±30.58	332.64±21.38	416.32±58.16 *B**
	2023	554.13±17.00	540.60±25.08	551.70±20.68	507.01±20.38	466.61±50.22	442.17±35.05	510.37±49.65 *A*
	PME	508.00±47.69 *A**	504.23±43.90 *A*	508.70±46.49 *A*	459.92±50.82 *B*	411.81±64.46 *C*	387.41±59.68 *D*	
Total flavonoid content (mg g^{-1})	2022	81.06±6.05 ^{ns}	82.95±9.43	88.75±11.86	80.31±6.67	73.15±2.34	63.22±6.70	78.24±10.30 *B**
	2023	118.28±6.95	120.09±12.75	117.04±13.10	107.25±8.48	94.62±10.84	93.41±10.75	108.45±14.04 *A*
	PME	99.67±19.35 *A**	101.52±20.70 *A*	102.90±17.44 *A*	93.78±14.84 *AB*	83.88±12.50 *BC*	78.31±16.77 *C*	

Values are presented as mean ± standard deviation (M±SD).

PF: Pre-flowering, FF: Full flowering, FS: Fruit set, PS: Pea-size berry, V: Veraison, C: Control; PME: Period Main Effect, YME: Year Main Effect.

Different lowercase letters within the same row and uppercase letters within the same column indicate statistically significant differences based on the LSD post hoc test *$p<0.01$ and ** $p<0.05$. ns: indicates non-significant differences ($p>0.05$).

Total phenolic content was highest at the pre-flowering (508.00 mg L^{-1}), full flowering (504.23 mg L^{-1}), and fruit set (508.70 mg L^{-1}) stages, whereas the lowest value was measured in the control treatment (387.41 mg L^{-1}). The increase in phenolic accumulation associated with leaf removal can be attributed to improved light exposure in the cluster zone and stimulation of the phenylpropanoid pathway. Similar trends were reported by Ristic et al. (2007) and Pastore et al. (2013), and Quartacci et al. (2022) further demonstrated that leaf removal increases phenolic acids and flavanols in grape berries. Recent literature further confirms that leaf removal enhances phenolic biosynthesis by upregulating key enzymes in the phenylpropanoid pathway and improving berry skin exposure to light (Celik and Akural 2026).

A comparable response was observed for total flavonoid content, with the highest values recorded at the pre-flowering (99.67 mg g^{-1}), full flowering (101.52 mg g^{-1}), and fruit set (102.90 mg g^{-1}) stages. In contrast, lower flavonoid contents were observed at veraison (83.88 mg g^{-1}) and in the control treatment (78.31 mg g^{-1}). These results indicate that leaf removal, particularly when applied at early and mid-phenological stages, stimulates flavonoid biosynthesis. Consistent with these findings, Gambacorta et al. (2022) reported that early leaf removal increased flavonoid and anthocyanin concentrations, total polyphenol content, antioxidant capacity, and color intensity. Similarly, Alatzas et al. (2023), reported that leaf removal significantly increased anthocyanin concentration and total phenolic content under water deficit conditions, and also enhanced total soluble solids. These findings support the view that improvements in light microclimate and source–sink balance induced by leaf removal promote phenolic accumulation and berry ripening.

The Year Main Effect was statistically significant for several parameters. The 2023 growing season resulted in higher total phenolic (510.37 mg L^{-1}) and flavonoid (108.45 mg g^{-1}) contents compared with 2022, emphasizing the strong influence of environmental factors such as temperature, light intensity, and water availability on phenolic metabolism (Poni et al. 2006; Tardáguila et al. 2008).

In summary, basal leaf removal functions as an effective cultural practice in viticulture by influencing sugar–acid balance and phenolic metabolism, thereby playing a decisive role in determining grape quality.

4. Conclusions

This study comprehensively evaluated the effects of basal leaf removal applied at different phenological stages on yield, cluster architecture, berry morphology, and chemical and phenolic composition of the 'Karaerik' grape cultivar under the ecological conditions of Erzincan. The results clearly demonstrated that the response of vines to leaf removal was strongly dependent on the timing of application.

Leaf removal caused an overall reduction in yield per vine, with the most pronounced decreases observed when treatments were applied during the flowering stage. This yield reduction was mainly associated with decreased fruit set and a lower number of berries per cluster. However, despite the negative impact on yield, leaf removal promoted improvements in several key quality-related parameters, particularly berry size and weight, indicating a redistribution of assimilates toward fewer but larger berries.

In terms of cluster structure, basal leaf removal significantly reduced cluster compactness by decreasing berry number, thereby promoting the formation of looser and better-aerated clusters. Such structural modifications are agronomically desirable, as they improve cluster microclimate, enhance light penetration and air circulation, and may indirectly reduce the risk of cluster-related disorders. Flowering-stage applications were particularly effective in reducing cluster compactness, although this benefit was accompanied by greater yield losses.

Leaf removal also exerted a marked influence on grape chemical and phenolic composition. Increases in total soluble solids, maturity index, total phenolic content, and total flavonoid content, together with decreases in titratable acidity, indicate that leaf removal accelerated ripening and enhanced biochemical quality. Early and mid-phenological applications, especially at pre-flowering, full flowering, and fruit set stages, were most effective in stimulating phenolic and flavonoid accumulation, highlighting the importance of early canopy manipulation in quality-oriented viticulture.

Overall, basal leaf removal can be considered an effective cultural practice for improving grape quality; however, its successful implementation depends critically on phenological timing. While applications during flowering resulted in excessive yield reductions, treatments conducted at fruit set and pea-size berry stages provided a more favorable balance between yield preservation and quality enhancement. Therefore, leaf removal strategies for 'Karaerik' grapes should be carefully optimized by considering cultivar-specific responses, production goals, and regional climatic conditions, particularly in table grape systems where both yield and quality are of primary importance.

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