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Research Article

Optimizing harvest timing: Impacts on physical characteristics and quality parameters of grapes

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Abstract

Harvest timing is a critical factor in viticulture, as it directly influences grape composition and, consequently, wine quality. This study evaluated the effects of harvest timing on the physical and chemical traits of two widely cultivated grape varieties from the Trebinje vineyard area, Bosnia and Herzegovina. Basic chemical parameters (total soluble solids, pH, titratable acidity) were measured alongside cluster and berry traits, including length, width, and weight of clusters; the number and weight of berries; the skin and flesh weight of 100 berries; and the number and weigh of seeds. Early-harvested grapes showed greater cluster weight but lower total soluble solids, higher titratable acidity, and lower pH compared to later harvests in both cultivars. Changes in cluster and berry traits were more pronounced in 'Vranac', where berry weight, skin and flesh mass increased significantly at later harvests, however, in 'Žilavka' only the seed weight was notably affected. Across all harvests period, 'Žilavka' consistently exhibited higher total soluble solids and lower pH values than 'Vranac', indicating a strong varietal effect on grape quality. These findings highlight that delaying harvest within the recommended window can enhance grape composition, while varietal differences determine the extent of morphological and chemical changes during ripening.

Keywords: berry traits; chemical parameters; cluster structure; grape quality

Introduction

Harvest time affects directly the quantity and quality of grape produced: therefore, the factors influencing grape ripening are the main topic of numerous studies that analyse this issue (Banjanin *et al.*, 2018; Gao *et al.*, 2019; Rouxinol *et al.*, 2023; Škrab *et al.*, 2024). Viticulturists and winemakers identify several types

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of ripeness, including technological ripeness, phenolic ripeness and aromatic ripeness. Technological ripeness refers to the stage when grapes achieve an optimal balance between sugars and acids, which is crucial for producing a specific or desired type of wine. Phenolic ripeness involves the formation of tannins and anthocyanins within grape skin and seeds, which are vital for producing red wines with deep colour and well-integrated tannins, whereas aromatic ripeness focuses on the synthesis of aroma compounds that are essential for the wine's distinctive character (van Leeuwen *et al*., 2023). Generally, a grape that is not fully ripe tends to be overly acidic and has a low sugar content, whereas a grape that is overripe may forfeit its optimal sensory qualities (Lu *et al*., 2024). Therefore, understanding the importance of harvest time is key for winemakers to make informed decisions regarding the selection of harvest dates, thereby enhancing their profitability.

The timing of grape harvest also has a considerable impact on the physical traits of the grape clusters and berries as well as the balance between total soluble solids, total acidity and total phenolic contents in grapes, which determines the wine's flavour, alcohol level, and aging potential. The soluble solids content, along with total phenolic content in grape generally decreases with berry size, while the relative seed mass and pH are positively correlated with berry weight. The composition of wine also changes based on berry size; wines produced from smaller berries tend to have higher alcohol and residual sugar content (Chen *et al*., 2018).

Although the reasons for variations in the size and composition of grape berries in vineyards are not yet fully understood, it is known that these characteristics are influenced by grape variety, environmental factors, and viticultural practices, including the timing of harvest (Wang *et al*., 2025). Viewed in this light, it is evident that the final berry size and composition represent the integrated impact of diverse biotic and abiotic factors (Melo *et al*., 2015).

Based on our knowledge, the relationship between harvest time and changes in berry size and chemical composition of grape varieties from the Trebinje winegrowing area (Herzegovina's vineyards) has not been extensively studied. Therefore, this study aims to evaluate the impact of harvest time on the morphological and physical traits and quality of the 'Žilavka' and 'Vranac' varieties, both of which are predominantly cultivated in this area. A 10-day interval was set between the selected harvest dates, and the optimal harvest date for each grape variety was ascertained through visual inspections, and the quantification of total soluble solids and titratable acidity in the grapes.

Materials and Methods

Plant material

Two grape varieties ('Žilavka' and 'Vranac') of *Vitis vinifera* L. were selected for this study to evaluate the changes in grape mechanical properties and quality based on harvest timing. 'Žilavka' is an autochthonous white wine grape variety planted primarily in the southern area of Bosnia and Herzegovina. This variety, together with its associated white varieties 'Bena' and 'Krkošija', occupies a dominant place in the assortment of Herzegovina's vineyards (40-50%). 'Žilavka' is characterized by great vigour and vertical growth. The shape of their clusters is conical, medium to medium-large in size, with round, medium-sized berries that are golden yellow or greenish-yellow in colour. 'Žilavka' is classified as a late grape variety, indicating that its grapes ripen in third epoch (Rotim and Crnjac, 2023).

'Vranac' is an autochthonous red variety of Montenegro, which is also widely spread in Herzegovina and Macedonia. Its clusters are cylindrical-conical in shape and medium-large in size, with round or slightly oval berries that are dark blue in colour. 'Vranac' is also is classified as a late grape variety (Maraš *et al*., 2015).

The typical shape of the 'Žilavka' and 'Vranac' grape cluster is shown in Figure 1.

(A) (B)

Figure 1. The shape of the 'Žilavka' (A) and 'Vranac' (B) grape cluster

Experimental site

'Žilavka' and 'Vranac' were planted in the commercial vineyard, situated at an altitude of 250 m in the Popovo polje near Trebinje town in Herzegovina region (42.96° N, 17.79° E). This area has a transitional climate that combines Mediterranean and continental (sub-Mediterranean) characteristics, with cool, rainy winters and hot summers (Banjanin *et al*., 2024). In 2024, the mean annual temperature for the Popovo polje is recorded at 16.3 °C, with an average precipitation of 1438.2 mm (Table 1). Popovo polje predominantly receives its rainfall in the winter season, experiencing limited rain during the summer (RHMS, 2024).

Table 1. Meteorological monthly data of the study area

Year	Average air temperature (°C)												Annual
	I	II	III	IV	V	VI	VII	VII	IX	X	XI	XII	average
2024	7.6	10.5	11.4	15.0	17.9	24.0	27.0	27.2	19.6	16.9	10.4	7.8	16.3
2023	7.5	6.7	10.0	11.4	17.7	21.9	26.2	24.4	22.0	18.0	11.0	8.8	15.5
2022	7.0	6.8	11	13.4	17.7	22.6	25.8	26.3	21.5	17.1	10.8	8.1	15.6
2021	5.4	6.6	9.0	12.4	16.8	20.4	23.3	23.3	19.5	15.1	10.4	6.8	14.1
1961-2024	5.6	6.6	9.3	12.9	17.4	21.6	24.3	24.2	19.7	15.3	11.0	7.1	14.6
Year	Total rainwater (mm)												Annual
	I	II	III	IV	V	VI	VII	VII	IX	X	XI	XII	rainfall
2024	101.5	164.3	156.8	55.6	91.7	100.0	68.2	44.8	306.9	79.3	115.3	153.8	1438.2
2023	293.4	103.4	121.3	174.5	181.9	49.4	72.4	205.0	99.1	53.3	399.2	68.2	1820.7
2022	155.2	144.3	130.6	111.6	93.4	65.3	65.1	67.4	234.1	155.7	231.5	210.4	1664.6
2021	179.1	163.5	154.2	152.8	86.2	84.3	52.2	87.8	125.1	191	232.8	220.9	1730.0
1961-2024	186.5	163.7	149.6	132.6	92.1	77.3	49.7	77.5	136.4	175.2	234.7	225.5	1700.8
Year	Relative humidity (%)												Annual
	I	II	III	IV	V	VI	VII	VII	IX	X	XI	XII	average
2024	67	69	71	72	70	62	53	50	68	74	66	72	66
2023	75	66	68	67	69	67	55	62	61	71	79	75	68
2022	68	66	66	65	67	67	53	51	66	68	72	73	65
2021	69	67	69	68	65	65	51	56	61	72	73	71	65
1961-2024	70	67	68	67	67	63	53	55	63	70	72	72	66

Source: RHMS (2024) - Republic Hydrometeorological Service of Republic of Srpska (Bosnia and Herzegovina)

The year 2024, during which the research was conducted, demonstrated changes in temperature and precipitation compared with the sixty-three-year average (1961-2024). In 2024, the Trebinje region recorded

an increase in the average annual air temperature of 1.7 °C, while the average annual precipitation decreased by 262.6 mm compared to the sixty-three-year average, indicating that the year of trial was generally warmer and less rainy than the previous multi-year period.

An experimental vineyard with 'Žilavka' and 'Vranac' vines was established in 2010, and both cultivars were grafted onto the rootstock 'Kober 5BB' (*Vitis berlandieri* ×*Vitis riparia*). The row and vine spacing was 2 × 0.8 m and the vines were trained using Single Guyot pruning with 10 buds per vine (8 buds were left on the canes and 2 buds on the spurs). The experimental vineyard was equipped with a drip irrigation system.

At the end of February, the vines were manually pruned to encourage vine regeneration and to balance their vegetative growth. During the growing season, all unproductive shoots were eliminated, facilitating better illumination and easier disease management. All other vineyard management practices, including weed control, pest management, disease control, irrigation, and fertilization, were carried out in a consistent manner.

Experimental design

Throughout this study, a trial site comprising three rows was chosen for each variety. Each row was divided into three blocks, with one block containing 10 vines (Figure 2). At the time of harvest, one block per row was harvested for both varieties. During the ripening process, grape samples were collected at three chosen harvest time points, comprising 10 clusters from 5 randomly selected vines of the 'Žilavka' and 'Vranac' varieties (two representative clusters per vine).

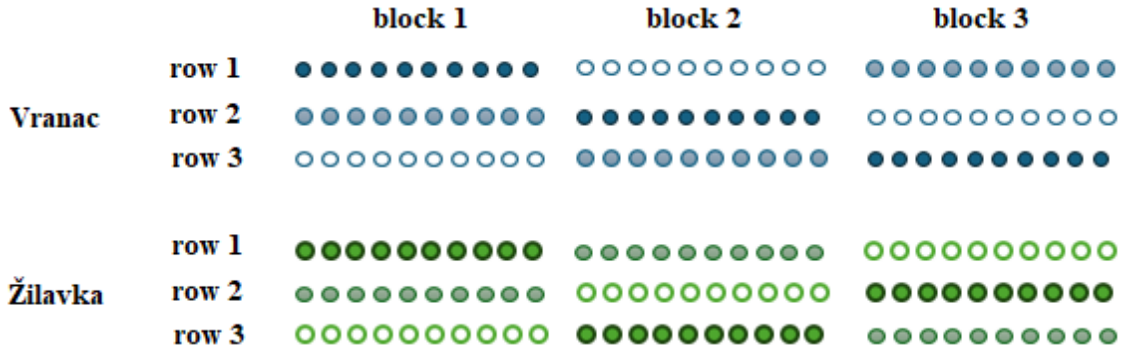

Figure 2. Diagram of the experimental design

The harvest of 'Vranac' and 'Žilavka' grapes in the Herzegovina region occurs when the total soluble solids content (TSS) in the grape juice is between 22 and 23 °Brix, with titratable acidity (TA) ranging from 5 to 6 g L^{-1} tartaric acid. Therefore, in order to select the appropriate grape harvest dates, several measurements of TSS and TA were carried out, starting from the moment the berries changed colour, i.e., the onset of ripening (beginning of August).

Determination of the physical traits of the grape clusters and berries

To determine the physical traits of the grapes, ten representative clusters were gathered from each variety at three selected harvest times. Physical traits of grape clusters and berries were determined according to the CODE system issued by the International Organization of Vine and Wine (OIV, 2009). The length (cm), width (cm), and weight of the cluster (g), as well as the number of berries in the cluster, were measured. Weight of the rachis (g) was determined after manual removal of berries. The mechanical traits of the grape clusters were analyzed for each cluster, and the outcomes are reported as an average for 10 clusters. The physical traits of the grape berries were also assessed, including the single berry weight (g), weight of the skin of 100 berries (g), weight of the flesh of 100 berries (g), number of seeds in 100 berries, and weight of the seeds in 100 berries.

Determination of the basic chemical properties of grape

The total soluble solids (TSS), titratable acidity (TA) and pH value were determined for each grape sample and variety. Total soluble solids (°Brix) of the grapes were measured using a digital refractometer Atago PAL-3; accuracy: ± 0.1% Brix (Tokyo, Japan) and expressed as °Brix (ISO, 2003). Titratable acidity (g L^{-1} tartaric acid) was determined by titration with 0.1 mol L^{-1} NaOH (AOAC, 2000), while pH was measured in an AG 8603 digital potentiometer; pH accuracy ± 0.01 pH (Mettler Toledo, Schwerzenbach, Switzerland).

Statistical analysis

Mechanical traits were averaged across 10 clusters per harvest. All chemical measurements were performed in triplicate, and the results are presented as the mean ± standard deviation. Experimental data were subjected to one-way analysis of variance (ANOVA) using SPSS software (v.7.5, SPSS Inc., Chicago, IL, USA). Fisher's least significant difference (LSD) was computed at a 5% significance level for mean comparisons.

Results

The initial harvest date in this experiment was set when the TSS in the grape juice was just below 22 °Brix, while the second and third harvests were spaced about 10 days apart. The second harvest date for both varieties is considered optimal, as the TSS in the grape juice were within the recommended ranges at that time. Table 2 outlines the harvest dates for each variety throughout the ripening process, while the variations of the key chemical harvest maturity indices (TSS and TA) during ripening are detailed in Table 3.

Table 2. Harvest dates during the ripening process

Harvest time	'Vranac' variety	'Žilavka' variety
1st harvest	August 25 2024	August 28 2024
2nd harvest	September 3 2024	September 5 2024
3td harvest	September 12 2024	September 15 2024

Table 3. Harvest maturity indices for 'Vranac' and 'Žilavka' grapes during ripening

'Vranac'	**Parameters**	**5-days intervals following the onset of ripening (August 3 2024)**							
	Total soluble solids (°Brix)	16.79	17.11	18.12	19.03	20.75	22.33	22.47	23.11	23.25
	Titratable acidity (g L^{-1})	9.9	9.1	8.3	7.7	7.4	5.6	5.5	5.1	4.9
'Žilavka'	**Parameters**	**5-days intervals following the onset of ripening (August 5 2024)**							
	Total soluble solids (°Brix)	16.23	16.64	17.41	18.39	20.33	22.14	22.29	22.73	23.26
	Titratable acidity (g L^{-1})	10.1	9.9	8.6	8.3	7.9	5.9	5.9	5.5	5.3

The 'Žilavka' grape harvest started on August 28, 2024, which is recognized as the early or first harvest. A subsequent harvest took place on September 5, 2024, identified as the optimal harvest (second harvest), and the third harvest was on September 15, 2024, referred to as the late harvest. Harvesting of the 'Vranac' grape initiated earlier, starting on August 25, with additional harvests on September 3 and September 12, 2024.

Harvest date had a significant impact on most physical traits of the 'Vranac' and 'Žilavka' grape varieties. In this study, early-harvest grapes (the first harvest) demonstrated a significantly greater cluster weight and a notably higher number of berries per cluster than those harvested later in both grape varieties. The differences

in cluster length depending on the harvest time were not statistically justified for either of the two varieties studied (Tables 4 and 5).

Table 4. Physical traits of the grape clusters for the 'Vranac' variety at different timings of harvest

Harvest time ('Vranac')	Cluster length (cm)	Cluster width (cm)	Cluster weight (g)	Rachis weight (g)	Number of berries per cluster
I (August 25)	16.9 ± 1.8	10.0 ± 2.8	312.9 ± 96.4[a]	10.1 ± 3.9[a]	116.7 ± 12.3[a]
II (September 3)	15.5 ± 3.8	11.2 ± 2.5	217.6 ± 71.8[b]	7.4 ± 1.6[b]	92.7 ± 8.9[b]
III (September 12)	17.3 ± 3.1	8.6 ± 1.6	221.5 ± 65.8[b]	6.8 ± 3.0[b]	82.5 ± 10.1[b]
F test	NS	NS	**	**	**
$LSD_{0.05}$			72.6	2.7	11.9

NS (not significant) indicates that there is no difference between the treatments. Different letters in each column represent significant difference among treatments. Asterisks indicate significance levels: ** $p < 0.05$

Table 5. Physical traits of the grape clusters for the 'Žilavka' variety at different timings of harvest

Harvest time ('Žilavka')	Cluster length (cm)	Cluster width (cm)	Cluster weight (g)	Rachis weight (g)	Number of berries per cluster
I (August 28)	15.2 ± 4.1	10.8 ± 3.1	274.2 ± 56.2[a]	11.1 ± 3.5	126.7 ± 6.1[a]
II (September 5)	14.8 ± 3.7	9.6 ± 4.4	235.9 ± 51.9[b]	7.9 ± 2.3	120.5 ± 4.6[b]
III (September 15)	15.5 ± 5.3	9.5 ± 4.2	226.7 ± 52.9[b]	9.2 ± 3.1	114.6 ± 4.3[c]
F test	NS	NS	**	NS	**
$LSD_{0.05}$			29.3		5.1

NS (not significant) indicates that there is no difference between the treatments. Different letters in each column represent significant difference among treatments Asterisks indicate significance levels: ** $p < 0.05$

The findings of the study also showed that the 'Vranac' berries from the third harvest (late harvest) had a significantly greater weight of skin and flesh per 100 berries compared to those from earlier harvests. The differences in the other examined physical traits of the 'Vranac' berries were not statistically justified (Table 6).

Table 6. Physical traits of the grape berries for the 'Vranac' variety at different timings of harvest

Harvest time ('Vranac')	Berry weight (g)	Skin weight of 100 berries (g)	Flesh weight of 100 berries (g)	Number of seeds in 100 berries	Weight of seeds in 100 berries (g)
I (August 25)	2.3 ± 0.2	18.1 ± 0.6[b]	181.1 ± 11.5[b]	186.7 ± 18.1	8.8 ± 0.3
II (September 3)	2.2 ± 0.2	16.9 ± 2.4[b]	199.4 ± 25.2[b]	176.7 ± 17.5	8.3 ± 0.9
III (September 12)	2.5 ± 0.2	26.7 ± 2.6[a]	224.7 ± 10.0[a]	190.1 ± 27.1	9.9 ± 0.2
F test	NS	**	**	NS	NS
$LSD_{0.05}$		4.2	20.3		

NS (not significant) indicates that there is no difference between the treatments. Different letters in each column represent significant difference among treatments. Asterisks indicate significance levels: ** $p < 0.05$

The changes in the physical traits of the 'Žilavka' berries due to the harvest timing were less pronounced compared to the 'Vranac'. Moreover, the only parameter within the physical traits of 'Žilavka' berries that was influenced by the harvest time was the weight of seeds in 100 berries. In this study, the weight of seeds in 100 berries was significantly higher in early harvested 'Žilavka' grapes compared to later ones (Table 7).

Table 7. Physical traits of the grape berries for the 'Žilavka' variety at different timings of harvest

Harvest time ('Žilavka')	Berry weight (g)	Skin weight of 100 berries (g)	Flesh weight of 100 berries (g)	Number of seeds in 100 berries	Weight of seeds in 100 berries (g)
I (August 28)	2.1 ± 0.11	7.3 ± 0.5	194.3 ± 10.1	123.3 ± 22.6	5.0 ± 0.4[a]
II (September 5)	1.9 ± 0.13	7.4 ± 1.7	176.2 ± 11.9	115.0 ± 15.2	2.5 ± 0.9[b]
III (September 15)	1.9 ± 0.13	6.6 ± 1.2	180.2 ± 11.4	106.7 ± 20.8	3.3 ± 0.9[b]
F test	NS	NS	NS	NS	**
$LSD_{0.05}$					1.5

NS (not significant) indicates that there is no difference between the treatments. Different letters in each column represent significant difference among treatments. Asterisks indicate significance levels: ** $p < 0.05$

Table 8 illustrates the changes in total soluble solids content (TSS), titratable acidity (TA), and pH of 'Vranac' grapes based on the timing of their harvest. The study results indicated that early-harvested 'Vranac' grapes (first harvest) had a significantly lower TSS, increased TA, and a lower pH value compared to 'Vranac' grapes collected in the second and third harvests. Additionally, the study results indicated that there was a significant difference in the basic chemical properties of the 'Vranac' grape variety between the second and third harvests. The 'Vranac' grape collected during the second harvest had a considerably lower TSS, TA, and a reduced pH value when compared to grapes harvested in the third harvest.

Table 8. Basic chemical properties of 'Vranac' grapes at different timings of harvest

Harvest time ('Vranac')	Total soluble solids (Brix)	Titratable acidity ($g\ L^{-1}$)	pH value
I (August 25)	21.77 ± 0.12[c*]	4.7 ± 0.6[a]	3.45 ± 0.10[c]
II (September 3)	22.80 ± 0.31[b]	4.3 ± 0.7[b]	3.70 ± 0.25[b]
III (September 12)	23.43 ± 0.36[a]	3.8 ± 0.6[c]	3.83 ± 0.23[a]
F test	**	**	**
$LSD_{0.05}$	0.56	0.31	0.11

Different letters in each column represent significant difference among treatments. Asterisks indicate significance levels: ** $p < 0.05$

Table 9 illustrates the changes in TSS, TA and pH of 'Žilavka' grapes based on the timing of their harvest. The study's findings indicated that 'Žilavka' grapes harvested early exhibited a notably lower TSS, higher TA, and a reduced pH value in comparison to those harvested later. Upon analysing the two harvest times (second harvest versus third harvest) for the 'Žilavka' grapes, the results indicated that there were no significant variations in TSS, TA, and pH.

Table 9. Basic chemical properties of 'Žilavka' grapes at different timings of harvest

Harvest time ('Žilavka')	Total soluble solids (Brix)	Titratable acidity ($g\ L^{-1}$)	pH value
I (August 28)	21.83 ± 0.23[b*]	4.9 ± 0.2[a]	3.29 ± 0.03[b]
II (September 5)	23.67 ± 0.51[a]	4.2 ± 0.3[b]	3.44 ± 0.04[a]
III (September 15)	23.50 ± 0.90[a]	4.2 ± 0.3[b]	3.51 ± 0.03[a]
F test	**	**	**
$LSD_{0.05}$	1.22	0.51	0.09

Different letters in each column represent significant difference among treatments. Asterisks indicate significance levels: ** $p < 0.05$

Discussions

The physical traits of the grape clusters and berries is largely determined by the genetic potential of the variety, but they are also greatly affected by environmental conditions and vineyard management techniques, including harvest timing (Doumouya *et al*., 2014). In this study, the harvest time significantly influenced the key physical traits of grapes and berries in both analysed varieties. A range of studies has illustrated that the timing of harvest greatly influences the physical traits of both grape clusters and berries (Rolle *et al*., 2011; Nedomová *et al*., 2016; Nistor *et al*., 2024).

In general, early-harvest grapes (the first harvest) demonstrated a larger cluster weight than those harvested later in both grape varieties. This finding can be explained by the fact that the number of berries per cluster in both varieties was significantly higher in early harvested grapes compared to later ones. The data presented also indicates that the decline in the number of berries per cluster from the initial to the last harvest was more pronounced in 'Vranac' than in 'Žilavka'.

The dropping of berries from the cluster is a concerning phenomenon influenced by external environmental factors and the internal physiology of the grapevine (Guirao *et al*., 2024). A number of scientists agree that the key factors leading to berry drop in the later ripening stages of grapes are the sensitive structure of the stem's tissue, the formation of an abscission zone in the berry, uneven ripening, endogenous auxin deficiency at a particular stage of berry development, and damage caused by birds or insect attacks (Clarke and Rogiers, 2019; Crisosto *et al*., 2020; Li *et al*., 2020; Zhu *et al*., 2022).

This study also found that in the 'Vranac' variety, all physical traits related to berries, apart from the grape weight and the number and weight of seeds in 100 berries, showed considerable variation based on the timing of the harvest. The 'Vranac' berries obtained during the third harvest (late harvest) revealed an increase in berry weight and had a significantly larger weight of skin and flesh per 100 berries compared to earlier harvests. These findings indicate that the berries continued to grow from the first to the third harvest, even though all three selected harvest times fell within the acceptable period for picking 'Vranac' grapes in the Herzegovina region. This pattern of behaviour is not typical for grapes, as the berries do not significantly increase in size when ripe, but rather undergo changes in their chemical composition (Pop *et al*., 2025).

The changes in the physical traits of the 'Žilavka' berries due to the harvest timing were less pronounced compared to the 'Vranac'. Moreover, the only parameter within the mechanical properties of 'Žilavka' berries that was influenced by the harvest time was the weight of seeds in 100 berries. In this study, the weight of seeds in 100 berries was significantly higher in early harvested 'Žilavka' grapes compared to later ones.

The controlled variables in this investigation, however, do not support any conclusions concerning the causality of berry growth during the period they are ready for harvest. In this light, further studies are needed to understand the changes in the physical traits during the ripening process. In that context, experiments conducted over several years are significantly more effective.

The ripeness of grapes significantly impacts their quality, making it essential to determine the optimal harvest time for achieving the desired grape quality (Garcia-Hernandez *et al*., 2025). The sugar content (total soluble solids) is a crucial parameter in winemaking. Based on the level of residual sugar, wines are classified as dry, semi-dry, and sweet. Dry wine contains the least residual sugar: less than 4 g L^{-1} for red wines and less than 2 g L^{-1} for white wines. The total acidity and pH are also important components in winemaking. A low level of acidity can result in a "flat" and dull flavour, while excessive acidity may lead to an overly sour and astringent taste. The pH levels can alter the colour of wine, especially in red wines. Overall, a pH exceeding 3.6 adversely impacts wine colour and quality.

In this study, the timing of the harvest significantly affected the total soluble solids (TSS), titratable acidity (TA) and pH of the grapes in both analysed varieties. The study's findings indicated that grapes harvested early exhibited lower TSS, higher TA, and a lower pH value when compared to grapes harvested later in both cultivars. These findings are in line with those of previous studies (Khalil *et al*., 2024; Moradi *et al*.,

2024). However, it should be emphasized that the TA values recorded for the grapes of both varieties were significantly low, which is not a positive indicator for wine production. This result is not unexpected, given that grapes cultivated in warmer locations such as the Trebinje area, tend to have lower TA compared to wine grapes grown in cooler areas or during cooler seasons (Yuyuen *et al*., 2015). This hypothesis is further supported by the fact that the average air temperature at the research site during the experimental year was significantly above the sixty-three-year average (Table 1), which may have additionally led to a decrease in grape acidity compared to the usual acidity values for 'Žilavka' and 'Vranac' varieties.

In the current study, the TSS and pH of 'Vranac' grapes at the third harvest (late harvest) were significantly higher than those of the first and second harvests, respectively, while TA followed a reverse trend, as expected. Compared to the first harvest (initial harvest), the second harvest (optimal harvest) greatly affected the increase in TSS and pH, while also leading to a marked reduction in the TA of the 'Vranac' grapes. Previous studies that analysed the variability of TSS, TA and pH in grapes based on harvest times reported similar trends to the current study (Zhao *et al*., 2019; Mucalo *et al*., 2024).

Considering the only two harvest times (second harvest versus third harvest) in the 'Žilavka' variety, the results did not reveal any significant differences for TSS, TA, and pH. These results, along with those related to the physical traits of the 'Žilavka' berries depending on the harvest timing, suggest that the metabolic activities in 'Žilavka' grapes are considerably less pronounced from the second to the third harvest compared to the 'Vranac'.

This study's results revealed that 'Žilavka' grapes have higher TSS and lower pH than 'Vranac' grapes during each harvest, suggesting that these quality characteristics, among other factors, depend on variety. Several studies have confirmed that grape variety has a significant impact on grape quality, including the quality attributes assessed in this study (Vool *et al*., 2015; Atak *et al*., 2025).

Conclusions

The timing of the harvest greatly influenced the physical traits of the grapes and berries in both grape varieties. The early-harvest grapes exhibited a greater cluster weight and had a higher number of berries per cluster than those harvested later in both grape varieties. The study results also showed that the changes in the physical traits of grape clusters and berries were more pronounced in 'Vranac' than in 'Žilavka'. Additionally, 'Žilavka' grapes had a higher total soluble solids content and lower pH values than 'Vranac' grapes during each harvest, indicating that these quality traits are influenced by the grape variety. The study's findings highlight that delaying harvest within the recommended window can enhance grape composition, while varietal differences determine the extent of morphological and chemical changes during ripening.

Authors' Contributions

Conceptualization: MD and SM; Data curation: MD and SM; Formal analysis: MSM, FT and AA; Funding acquisition: MD and SM; Investigation: FT, MSM and AA; Methodology: MB; Project administration: MB and FB; Resources: MD and SM; Software: MB; Supervision: SM and MB; Validation: MD and FB; Visualization: MSM and AA; Writing - original draft MD, SM, and MB; Writing - review and editing: MD, SM and MB.

All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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