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Vine density influence on Chardonnay grape quality

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Abstract
This study investigates the influence of vine density on the quality of Chardonnay grapes, focusing on sugar content, and titratable acidity, and pH - key indicators of grape and wine quality. Conducted over two growing seasons (2022 and 2023) in a commercial vineyard in Buzias-Silagiu, four vine density treatments (1,500, 3,000, 4,500, and 6,000 vines/ha) were analyzed. Data on sugar content, acidity, and pH were collected at full grape maturity, with weather conditions carefully monitored. Results indicate that higher vine densities lead to lower acidity, with a significant negative correlation (r = -0.739), while vine density has weak correlations with sugar content and pH. Sugar content shows a positive correlation with pH (r = 0.529) and a negative correlation with acidity (r = -0.541). Warmer weather in 2023 contributed to higher sugar content (22.52 °Brix) and lower acidity (6.35 g/L) compared to 2022, which saw lower sugar (21.15 °Brix) and higher acidity (6.75 g/L). PH levels also increased from 3.20 in 2022 to 3.25 in 2023, aligning with the decrease in acidity. These findings highlight the critical role of vine density in modulating grape composition, especially in balancing sugar accumulation and acidity. Optimizing vine density based on climatic conditions is essential for producing high-quality Chardonnay grapes that meet the demands of winemaking.

Key words: grapevine, pH, sugar, titratable acidity

Introduction

In viticulture, vine density is a key factor that significantly impacts grape quality, affecting aspects such as fruit composition, yield, and overall vineyard performance [23]. The spacing between vines in a vineyard influences how individual plants compete for vital resources like sunlight, water, and soil nutrients, all of which are essential for vine growth and fruit development [21]. The concept of terroir—encompassing climate, soil, and topography—also interacts with vine density, further shaping grape characteristics. In cooler climates or regions with less fertile soils, lower vine densities can enhance resource availability per vine, improving berry quality [9]. On the other hand, in regions with more favorable growing conditions, higher vine densities promote competition, often resulting in smaller berries with more concentrated flavors, which are desirable for winemaking [14]. The influence of vine density also varies by grape variety, as different cultivars respond uniquely to spacing and competition [6]. For instance, Chardonnay, known for its sensitivity to environmental conditions, shows notable changes in berry composition depending on vine spacing and resource access [7]. Thus, optimizing vine density in relation to terroir and grape variety is crucial for producing high-quality wines that reflect the vineyard's unique characteristics [15].

Vine density also significantly affects berry sugar content, a critical measure of grape ripeness and wine quality. The number of vines per hectare determines the level of competition for sunlight, water, and nutrients, which are essential for photosynthesis and sugar accumulation in berries [8]. In higher-density vineyards, increased competition may reduce access to these resources, potentially limiting photosynthetic activity and sugar development [22]. Conversely, lower vine densities often improve resource availability, enhancing leaf area efficiency and promoting greater sugar accumulation [10]. Vine density also affects the microclimate within the canopy; dense canopies can reduce light penetration and increase humidity, both of which hinder sugar development [25]. Grape variety further modulates this interaction, as different cultivars respond differently to changes in vine density. For example, Chardonnay grapes often show higher sugar content at lower vine densities due to reduced competition and improved sunlight exposure [2]. Understanding the relationship between vine density and sugar accumulation is vital for managing vineyards to achieve optimal sugar levels for high-quality wine production [12].

Increased vine density typically heightens competition, leading to reduced vegetative growth and smaller, more concentrated berries [18]. This may lower titratable acidity, as reduced canopy size allows more sun exposure and warmer temperatures in the fruit zone, accelerating organic acid degradation, especially malic acid, during ripening [12]. Conversely, lower vine densities, with less competition, tend to support more vigorous canopies that provide shade and create cooler microclimates, preserving acidity levels in the berries [26]. Different grape varieties also react uniquely to changes in vine density, with some showing significant alterations in acidity due to their sensitivity to microclimatic factors like shading and light exposure [17]. Optimizing vine density is therefore essential for balancing sugar accumulation and acidity retention in berries, both of which are crucial to the wine's quality and style [16].

Another critical factor in wine quality is pH, affecting stability, microbial activity, and taste [24]. In high-density plantings, reduced canopy size can increase sun exposure and temperature around grape clusters, accelerating acid degradation and raising juice pH [13]. On the other hand, lower vine densities usually result in more vigorous canopies, which provide shade and maintain cooler microclimates, helping to preserve lower pH levels in the berries [4]. Grape variety also plays a role in this relationship, as some cultivars are particularly sensitive to canopy microclimate changes. Chardonnay, for instance, is known for its responsiveness to light and temperature variations, with vine spacing and canopy structure significantly affecting its juice pH [1].

The objective of this study is to investigate the influence of vine density on the quality of Chardonnay grapes, focusing on key parameters such as berry sugar content, titratable acidity, and juice pH. By examining how different vine densities affect resource competition, microclimatic conditions, and grape composition, the study aims to determine optimal vine spacing that enhances berry quality for high-quality wine production.

Material and Method

The study was conducted at Buzias-Silagiu, over two growing seasons, in a commercial Chardonnay vineyard. The vineyard was established on well-drained soils, typical of the region, characterized by loamy and sandy soils, which offer good drainage. This mixture of soil types is beneficial for vineyards, as it allows for better water retention and air circulation around the vine roots, encouraging balanced growth. Chardonnay vines (*Vitis vinifera L.)* were used for this study. Vines were planted in four density treatments: 1,500, 3,000, 4,500, and 6,000 vines per hectare.

The experiment followed a randomized complete block design with four replicates per treatment. Each plot measured 15 square meters, containing ten vines. Vines were planted in 2016 and have been cultivated under standard viticultural practices, including uniform irrigation, fertilization, and pest management protocols. Vines were spaced accordingly, with row spacing ranging from 1.4 to 2.5 meters and intra-row spacing from 1.0 to 1.4 meters, depending on the treatment group. Each treatment was replicated across three plots.
Weather conditions, including temperature, precipitation, and relative humidity, were recorded throughout the growing season using an on-site weather station. The average growing degree days (GDD) for the study period was approximately 11.85ºC in 2022 and 12.48ºC, providing an indication of the climate conditions during the grape development phases. Grape samples were taken at full maturity, determined by visual inspection and a standard sugar content threshold of 220°Brix. A representative sample of 50 grape clusters per plot was randomly harvested.

The sampling was done in the early morning to avoid the influence of temperature fluctuations on grape composition. The total acidity (TA) of grape juice was measured using titration with 0.1 N NaOH to a pH endpoint of 8.2, expressed as grams of tartaric acid per liter.
Sugar levels were determined using a handheld refractometer, calibrated to measure soluble solids in °Brix. Both measurements were performed in triplicate to ensure accuracy. The results for each plot were averaged, and the standard deviations were calculated. All laboratory equipment was calibrated prior to each use to ensure the accuracy and precision of the measurements.

Statistical Analysis

Data were analyzed using ANOVA to determine the significance of vine density on total acidity and sugar content. Post-hoc tests (Tukey's HSD) were applied to identify significant differences between treatment

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means at a significance level of $p < 0.05$. All statistical analyses were performed using XLSTAT (Addinsoft's XLSTAT software, version 2016.7.5).

Results and Discussion

Sugar content (ºBrix), titratable acidity (in g/L) and pH level for the Chardonnay variety during 2022 and 2023, taking into account different vine density treatments (1,500, 3,000, 4,500, and 6,000 vines per hectare) is illustrated in the Table 1.

Table 1. Sugar content (ºBrix), titratable acidity (in g/L) and pH level for the Chardonnay variety during 2022 and 2023

Growing season	Density (vines/ha)	Sugar Content (ºBrix)	Titratable Acidity (g/L)	pH
2022	1,500	19.9	7.5	3.2
	3,000	20.6	7.2	3.18
	4,500	21.3	6.8	3.19
	6,000	22.8	6.5	3.21
2023	1,500	24.0	6.8	3.25
	3,000	22.1	6.5	3.24
	4,500	23.4	6.2	3.23
	6,000	21.5	5.9	3.27

To perform a statistical analysis for the given data on sugar content, titratable acidity, and pH values of Chardonnay grapes across different vine densities in the years 2022 and 2023, were calculate the standard deviation, coefficient of variation, and assess the significance of the difference between means for each variable (Table 2).

Table 2. Summary of statistical analysis

Parameter	Year	Mean	SD	CV (%)	t-value	Significance
Sugar Content (°Brix)	2022	21.15	0.649	3.07	4.54	*
	2023	22.52	0.815	3.62		-
Titratable Acidity (g/L)	2022	6.75	0.272	4.06	-2.94	*
	2023	6.35	0.391	6.11		-
pH	2022	3.20	0.013	0.41	8.33	*
	2023	3.25	0.015	0.46		-

The statistical analysis of the parameters measured in Chardonnay grapes across the growing seasons of 2022 and 2023 reveals significant differences in sugar content, titratable acidity, and pH values.

Sugar Content (°Brix)

The average sugar content in 2022 was 21.15 °Brix with a standard deviation of 0.649 and a coefficient of variation (CV) of 3.07%, indicating relatively low variability among the samples. In contrast, the 2023 season saw an increase in average sugar content to 22.52 °Brix, with a higher standard deviation of 0.815 and a CV of 3.62%. The t-value of 4.54 suggests a statistically significant difference between the two years ($p < 0.05$). This increase in sugar content in 2023 can likely be attributed to warmer growing conditions, which may have enhanced photosynthesis and sugar accumulation in the grapes. Karibasappa and Adsule (2008) [11] reported average sugar content of 18.00 °Brix for Chardonnay grapes in central-west climate of India. The study noted that temperatures during the ripening period contributed to lower sugar levels. Dimovska et al. (2010) [5] found an increase from 19.7 °Brix to 23.2 °Brix over ten years, attributing the increase to favourable weather conditions. This result closely aligns with the findings of present research of 21.15 °Brix in 2022 and 22.52 °Brix in 2023.

Titratable Acidity (g/L): For titratable acidity, the mean value for 2022 was 6.75 g/L with a standard deviation of 0.272 and a CV of 4.06%, indicating moderate variability. In 2023, the average titratable acidity decreased to 6.35 g/L, with a standard deviation of 0.391 and a CV of 6.11%, indicating increased variability in the samples. The t-value of -2.94 indicates a significant reduction in acidity from 2022 to 2023 ($p < 0.05$). This decline in titratable acidity aligns with the observed increase in sugar content, reflecting a common trend in grape ripening where warmer temperatures often lead to lower acidity levels in the fruit. Titratable acidity levels in Chardonnay grapes were 4.9 g/L in 2010, rising to 5.3 g/L in 2011, which aligns with the observation by Sadras et al. (2013) [19] that warmer growing conditions generally result in lower acidity levels, as observed

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in Australia's Barossa Valley. Lower titratable acidity (5.8 g/L) in Chardonnay grape juice from La Mancha, Spain, was found by Chacón-Vozmediano et al. (2021) [3].

pH. The average pH value in 2022 was 3.20 with a very low standard deviation of 0.013 and a CV of 0.41%, reflecting a tight clustering of data points. In 2023, the mean pH increased to 3.25, with a slightly higher standard deviation of 0.015 and a CV of 0.46%. The t-value of 8.33 indicates a highly significant difference ($p < 0.05$) between the years. The increase in pH correlates with the observed decrease in titratable acidity, confirming that the warmer conditions in 2023 contributed to a shift in the acidity profile of the grapes. An average of 3.52 pH in 2010 and 3.57 pH in 2011 was found by Sadras et al. (2013) [19], noting a decrease in acidity in years with higher temperatures. Chacón-Vozmediano [3] also reported a higher pH average value of 3.4 in Chardonnay variety, from 2000 to 2019. The pH values from the current research fall within the limits (3.15 – 3.54) obtained by Simpson and Miller (1984) [20] more than 50 years ago for the Chardonnay variety in the Hunter valley from New South Wales, which indicates that the variability climate did not significantly influence this parameter.

The Principal Component Analysis (PCA) biplot shows F1 (explaining 73.45% of the variation) and F2 (explaining 17.50% of the variation) which indicates that the PCA model effectively summarizes the relationships between variables and treatments.

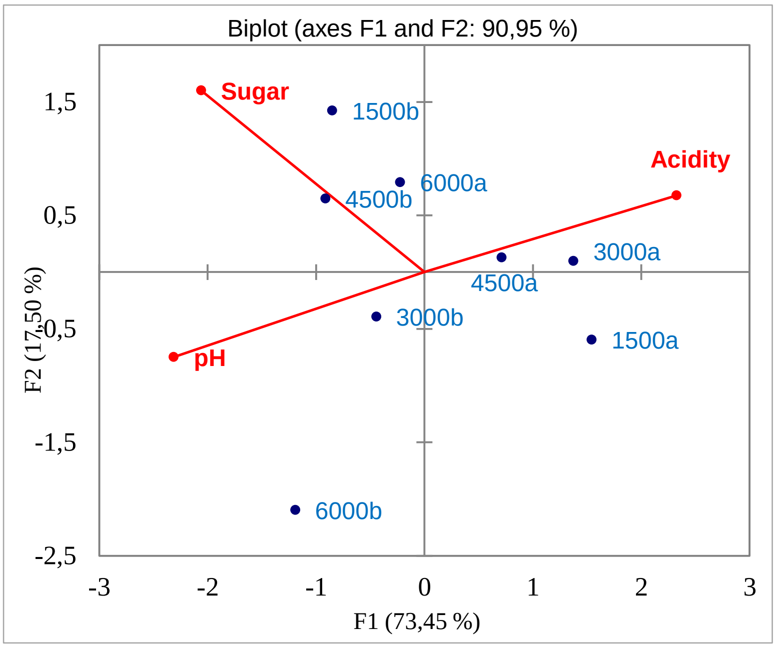

Figure 2. Principal Component Analysis (PCA) diagram for Chardonnay variety from Buziaș-Silagiu vineyards, during 2022-2023 growing seasons. (The blue dots represent the vine density treatments in the two years (a = 2022, b = 2023). The labels indicate the different treatments for 1,500 vines/ha, 3,000 vines/ha, 4500/vines/ha and 6000 vines/ha))

Vines density in 2023 which experienced higher temperatures, likely leading to higher sugar accumulation. The positive correlation between sugar and the 2023 season treatments is consistent with the interpretation that warmer weather can increase photosynthesis and sugar concentration in grapes. Climate conditions in 2022 maintained higher acidity in the grapes compared to the warmer conditions of 2023. The acidity is not directly related to either sugar or pH, but still plays a distinct role in differentiating the treatments. Treatments like 1500 and 6000 vine density in (2023 are near the pH vector, suggesting these conditions resulted in higher pH values**.**

The correlation matrix (Table 3) presents Pearson correlation coefficients between vine density, sugar content, titratable acidity, and pH, with significant correlations ($\alpha = 0.05$).

Table 3. Correlation matrix (Pearson (n))

Variables	Density	Sugar	Acidity	pH
Density	**1**	0.137	**-0.739**	0.171
Sugar	0.137	**1**	-0.541	0.529
Acidity	**-0.739**	-0.541	**1**	**-0.728**
pH	0.171	0.529	**-0.728**	**1**

Values in bold are different from 0 with a significance level alpha=0.05

Vine density shows a strong, significant negative correlation with acidity (r = -0.739), indicating that higher vine densities are associated with lower acidity levels. The correlations between density and both sugar (r = 0.137) and pH (r = 0.171) are weak and not significant. Sugar content has a significant negative correlation with acidity (r = -0.541), meaning that as sugar levels increase, acidity tends to decrease. There is also a significant positive correlation between sugar and pH (r = 0.529), suggesting that higher sugar levels are associated with higher pH values. The correlation between sugar and vine density (r = 0.137) is weak and not significant. Acidity is significantly negatively correlated with pH (r = -0.728), indicating that lower acidity is associated with higher pH values. This correlation is both strong and significant.

These results highlight the strong inverse relationship between vine density and acidity, as well as between acidity and both sugar content and pH, reflecting important physiological interactions in the grapevine.

Conclusions

The findings of this study highlight significant differences in sugar content, titratable acidity, and pH in Chardonnay grapes across two growing seasons (2022 and 2023) under varying vine densities. The warmer 2023 season led to higher sugar levels (22.52 °Brix) compared to 2022 (21.15 °Brix), with a statistically significant increase, likely due to enhanced photosynthesis. The PCA biplot demonstrates that the 2023 growing season**,** with its higher temperatures, was associated with higher sugar content and pH, and lower acidity. Conversely, titratable acidity decreased from 6.75 g/L in 2022 to 6.35 g/L in 2023, reflecting the typical inverse relationship between sugar accumulation and acidity in warmer conditions.

The pH values also rose significantly, from 3.20 in 2022 to 3.25 in 2023, consistent with the decrease in acidity. A strong negative correlation between vine density and acidity (r = -0.739) was observed, indicating that higher vine densities result in lower acidity levels. However, vine density had weak correlations with both sugar content (r = 0.137) and pH (r = 0.171), suggesting these parameters are less affected by density alone. Additionally, a significant positive correlation between sugar content and pH (r = 0.529) was found, along with a strong negative correlation between acidity and pH (r = -0.728). The vine density treatments appear to influence grape composition, but the growing season (i.e., climate) seems to have a stronger impact on sugar content, acidity, and pH.

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