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Impact of training systems and rootstocks on yield and quality of white Brazilian hybrid grapes

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Abstract: Conservation agricultural practices play a crucial role in improving crop yield and quality. In viticulture, particular attention has been given to the interaction between scion cultivars, rootstocks, and training systems. This study aimed to evaluate the effects of rootstocks and training systems on the yield and quality of the Brazilian hybrid white grapes 'BRS Lorena', 'IAC 116-31 Rainha', and 'IAC 21-14 Madalena'. For each cultivar, a randomized block design was adopted using a 2 × 2 factorial scheme, comprising two rootstocks ('IAC 766 Campinas' and 106-8 'Mgt') and two training systems (low and high espalier). Physicochemical characteristics of clusters, berries, and seeds, as well as the biochemical composition of the grape skins and pulp, were assessed over two production cycles. The results demonstrated that the appropriate combination of rootstock and training system can significantly influence grape yield and quality. 'BRS Lorena' performed best when grafted onto 106-8 'Mgt' under the high espalier system. 'IAC 21-14 Madalena' showed stable performance with 106-8 'Mgt', regardless of the training system. For 'IAC 116-31 Rainha', the most favorable combination was 'IAC 766 Campinas' rootstock with high espalier. These findings provide valuable insights for Brazilian viticulture, supporting the adoption of cultivation practices that enhance both productivity and grape quality.

Keywords: hybrid grapes; *Vitis* spp.; high and low espalier; phenolic compounds; antioxidant activity; 'BRS Lorena'; 'IAC 116-31 Rainha'; 'IAC 21-14 Madalena'.

Introduction

Viticulture is a significant pillar of global fruit production, with grapes being the fifth most cultivated fruit crop worldwide. In 2022, vine cultivation occupied 7.3 million hectares, resulting in a total production of 79.4 million tons. Of this amount, 48.8% was used for winemaking, 43.3% for fresh consumption, and 7.9% for raisin production (OIV, 2023). The leading wine grape-producing countries include China, Italy, France, Spain, and the United States, while major table grape producers are China, India, Turkey, Egypt, and Iran. Within this global context, Brazil ranks as the 14th largest producer of grapes for processing and 8th for table grapes (OIV, 2023). In 2022, Brazilian grape production was estimated at 1.45 million tons, with 48% allocated to processing and 52% to fresh consumption. The states of Rio Grande do Sul, Pernambuco, and São Paulo dominated national production, accounting for 85.3% of the total output (IBGE, 2023). Grapes significantly contribute to the total value of Brazilian fruit production, representing approximately 7.5% regardless of their intended use (Agrianual, 2023). It is worth noting that production variability among states is influenced by factors such as the cultivars grown, predominant soil types, edaphoclimatic conditions, and management practices employed.

To diversify wine products and expand options available to growers, the Agronomic Institute of Campinas (IAC) and the Brazilian Agricultural Research Corporation (Embrapa, 2028) have developed hybrid cultivars for wine and juice production through their breeding programs. The cultivars 'IAC 116-31 Rainha' (Seibel 7053 × Burgunder Kastenholtz), 'IAC 21-14 Madalena' (Seibel 11342 × Moscatel de Canelli), and 'BRS Lorena' (Malvasia bianca × Seibel 7053) have shown outstanding performance in terms of productivity and resistance to fungal diseases. However, there remains a lack of information on the phenolic composition and antioxidant activity of these white grapes, particularly under different rootstock and training system combinations—factors that can significantly influence these phenotypic characteristics (Koundouras et al., 2009; Barcia et al., 2014; Domingues et al., 2023).

In studies evaluating the influence of rootstocks, the use of well-defined scion cultivars is essential, as the effects of rootstocks are only expressed through their interaction with the scion. The scion determines the aboveground phenological and productive responses, while the rootstock influences the uptake and transport of water, nutrients, and signaling molecules. Therefore, selecting appropriate scions is a key step in rootstock trials and enables the identification of specific combinations that enhance grapevine performance and fruit quality under given environmental conditions.

Excellence in grape production is closely related to multiple factors, including the interaction between the scion cultivar and the rootstock. Rootstocks can influence several agronomic and physiological parameters of the scion, such as vigor, yield, cluster and berry size, distribution of photoassimilates, sugar concentration, fruit acidity, and other quality attributes relevant to juice and wine production (Tecchio et al., 2019; Leal et al., 2020; Heller-Fuenzalida et al., 2020; Nardello et al., 2023). Compatibility between scions and rootstocks in grapes destined for processing—especially in white cultivars such as 'IAC 116-31 Rainha', 'IAC 21-14 Madalena', and 'BRS Lorena'—remains largely unexplored under subtropical conditions.

Regarding the interaction between scion cultivars and training systems, the traditional low espalier system is predominantly used in Brazilian wine regions, with wires positioned at heights of 1.0, 1.3, and 1.6 meters above ground level (Simonetti et al., 2021; Domingues et al., 2023b). However, the adoption of a high espalier system, which includes an additional wire at 2.0 meters, has led to improvements in both grape yield and quality. These improvements are attributed to the increased exposed leaf area (Simonetti et al., 2021; Domingues et al., 2023b). Canopy architecture directly affects the microclimate surrounding the grapevine, modulating interactions with solar radiation, light interception, carbon assimilation, and photosynthesis—key processes involved in the biosynthesis and accumulation of phenolic compounds.

Phenolic compounds are fundamental to the quality and organoleptic properties of grapes and wines. In white grapes, these compounds are mainly concentrated in the skins and seeds, contributing significantly to color, flavor, and antioxidant capacity (Tian, 2020; Navarro et al., 2021). Flavonols, phenolic acids, and stilbenes are among the principal phenolic classes present in white grapes. Flavonols protect against oxidative stress and are associated with health benefits due to their anti-inflammatory and anti-carcinogenic properties. Phenolic acids contribute to the aromatic profile and stability of white wines, while stilbenes are known for their cardiovascular and antimicrobial effects (Leão et al., 2020). The concentration and profile of phenolic compounds are influenced by several factors, including cultivar, environmental conditions, ripeness, rootstocks, and training systems, making them a key element in the management of high-quality white grape and wine production.

The aim of this study was, therefore, to evaluate the influence of rootstocks and training systems on the production, physicochemical properties, and biochemical quality of Brazilian hybrid white grapes.

Results

Yield, physicochemical, and biochemical parameters of 'BRS Lorena' grapes

A significant interaction was observed between rootstocks and training systems for grapevine production, yield, number and fresh mass of clusters, and seed fresh mass in 'BRS Lorena'. The highest values for production, productivity, and both number and fresh mass of clusters were obtained using the rootstock '106-8 Mgt', regardless of the training system (Suppl Table 1).

Although '106-8 Mgt' is moderately vigorous, it exhibits excellent rooting capacity and adaptability to various soil types, which may have contributed to the balance in vegetative vigor and enhanced efficiency in water and nutrient uptake. As a result, 'BRS Lorena' grapevines produced clusters with greater fresh mass. This rootstock may improve the translocation of photoassimilates to the fruits, increasing berry fresh mass in this hybrid.

The highest seed fresh mass was observed in vines grafted onto the 'IAC 766 Campinas' rootstock and trained using the high espalier system (Suppl Table 1).

These characteristics, along with the interaction with '106-8 Mgt', led to higher production and productivity of the vines, independent of the training system used (Suppl Table 1). The moderate vigor of 'BRS Lorena' contributes to an optimal balance between vegetative and reproductive growth, enabling efficient allocation of photoassimilates for high-quality fruit production. The high fertility of this cultivar ensures a greater fruit set per plant, thereby increasing overall productivity. This synergistic interaction between 'BRS Lorena' and '106-8 Mgt' maximizes photosynthetic efficiency and photoassimilate transport, resulting in increased yield and improved fruit mass and quality.

A significant interaction was also found between rootstocks and training systems in the physicochemical composition of 'BRS Lorena' grape must, except for pH (Suppl Table 2). The combination of the 'IAC 766 Campinas' rootstock with high espalier led to an increase in soluble solids (SS) and reducing sugar content in the must. The high espalier system increases leaf area exposed to sunlight, enhancing the photosynthetic rate. The 'IAC 766 Campinas' rootstock likely improves the transport efficiency of water and nutrients from soil to the scion, optimizing vine development.

This synergistic rootstock-training system combination is particularly advantageous for grapes such as 'BRS Lorena' destined for processing, as it reduces the need for chaptalization—a winemaking practice that involves sugar addition to must to raise alcohol levels. The naturally high sugar content ensures more efficient fermentation and improved wine quality. Therefore, the interaction between the 'IAC 766 Campinas' rootstock and high espalier maximizes photosynthetic efficiency and nutrient distribution, resulting in berries with enhanced chemical composition.

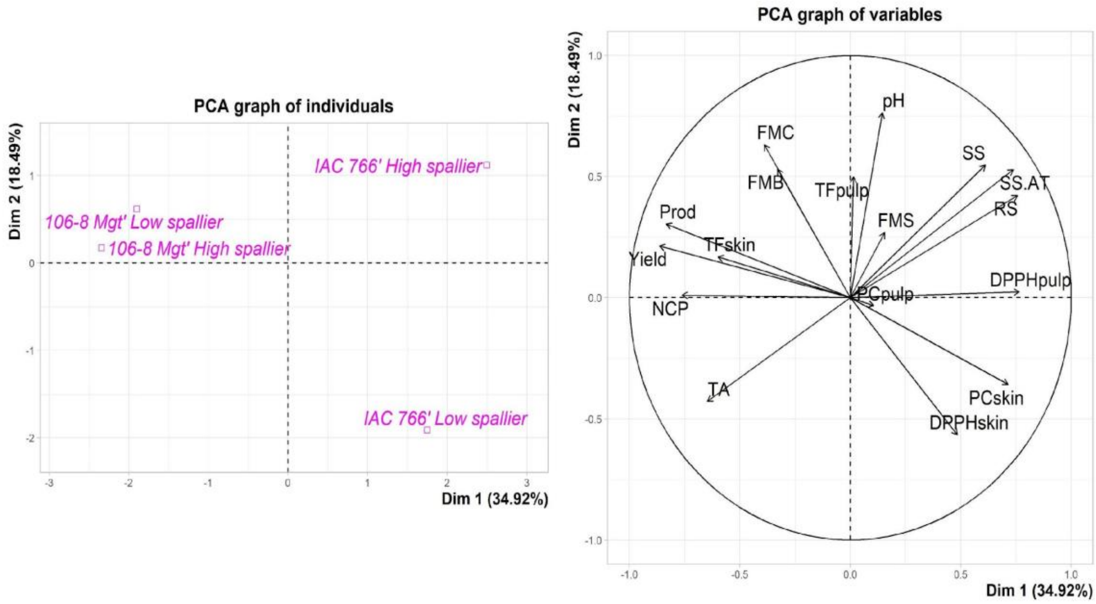

Figure 1. Principal component analysis (PCA) of 'BRS Lorena' vine grafted on 'IAC 766 Campinas' and 106-8 'Mgt' rootstocks and on low and high trellis systems. Note: number of cluster (NCP), fresh mass of clusters, berry and seeds (FMC, FMB and FMS), productivity (Prod), yield (yield), soluble solids (SS), titratable acidity (TA), reducing sugars (RS), phenolic compounds (PC), total flavonoid (TF) and antioxidant activity (DPPH and FRAP).

This combination also led to lower titratable acidity and a higher soluble solids/titratable acidity (SS/TA) ratio (Suppl Table 2), key characteristics for processing grapes. This ratio reflects the balance between sweetness and acidity, which directly affects flavor. Acidity plays a crucial role in both the microbiological stability and sensory freshness of wine. The observed low acidity and high SS/TA ratio achieved with this combination provide improved sensory attributes, yielding a sweeter and more palatable fruit suitable for premium wine production.

Higher total flavonoid concentrations and antioxidant activity were observed in the skins and pulps of grapes trained under the high espalier system, regardless of rootstock (Suppl Table 3). This further confirms the efficiency of this system in grape cultivation. Antioxidant activity was higher in the peel than in the pulp, likely due to its direct exposure to UV radiation, which enhances the synthesis of flavonoids and phenolic compounds.

Regarding the bioactive composition of 'BRS Lorena' grape skins, total phenolic content and antioxidant activity measured via DPPH assay showed no significant differences across rootstocks or training systems. However, the combination of 'IAC 766 Campinas' and high espalier increased antioxidant activity in the pulp, as measured by the FRAP method. As with DPPH, FRAP values were higher in the peel than in the pulp, attributable to the peel's greater exposure to sunlight and its protective function.

In this study, flavonoids were the main contributors to antioxidant activity in both the skins and pulps of the grapes.

Yield, physicochemical, and biochemical parameters of 'IAC 21-14 Madalena' grapes

A significant interaction was observed between rootstocks and training systems for the number of clusters per plant, fresh mass of clusters, production, and yield of 'IAC 21-14 Madalena' vines (Suppl Table 4). Regardless of the rootstock used, the highest values for these variables were obtained under the high espalier training system.

Thus, due to its ability to optimize light interception, the high espalier system promoted greater cluster number and fresh mass, leading to higher production and productivity. This effect is particularly beneficial for the 'IAC 21-14 Madalena' cultivar, indicating that an appropriate training system can compensate for rootstock variation, ensuring consistent and high-quality yields.

Regarding the physicochemical characteristics of 'IAC 21-14 Madalena' grapes, no significant interaction was found between rootstocks and training systems for pH, titratable acidity (TA), soluble solids (SS), SS/TA ratio, or reducing sugar content in the must (Suppl Table 5).

However, a significant interaction was observed for secondary metabolites in the skins and pulps of 'IAC 21-14 Madalena' grapes (Suppl Table 6). Total flavonoid concentration in the pulp was higher in vines trained under the high espalier system and grafted onto the '106-8 Mgt' rootstock, reaching 0.39 mg 100 g^{-1}. These results suggest that the high espalier system creates an environment favorable to flavonoid production, likely due to improved sunlight exposure, which is a key factor for the synthesis of these compounds. In contrast, the low espalier system led to lower flavonoid concentrations, indicating that reduced light exposure may limit flavonoid biosynthesis.

Pulp antioxidant activity also varied significantly between treatments. The combination of high espalier and the 'IAC 766 Campinas' rootstock resulted in the highest antioxidant activity, as measured by DPPH (988.21 μM g^{-1}) and FRAP (9.98 mmol Fe kg^{-1}) assays. These findings indicate that the interaction between rootstocks and training systems can influence the antioxidant potential of white grapes. The high espalier system likely provides more favorable conditions for

maintaining antioxidant activity, possibly due to enhanced photosynthetic efficiency and greater production of photoassimilates.
These results suggest that the high espalier system supports increased flavonoid synthesis and antioxidant maintenance in grapes due to better sunlight exposure and enhanced photosynthetic activity. However, the effects of rootstock and training system interactions vary and can significantly influence antioxidant responses. These findings underscore the importance of considering both factors—rootstock and training system—in strategies aimed at improving the nutritional and functional quality of grapes.
The interaction between high espalier and the 'IAC 766 Campinas' rootstock was also effective in increasing phenolic compound and total flavonoid concentrations in the skins of 'IAC 21-14 Madalena' grapes (Suppl Table 6). These results indicate that this combination provides favorable conditions for the synthesis of phenolic compounds and flavonoids in grape skins, likely due to greater light exposure and improved canopy photosynthetic performance.
In white grapes, the accumulation of secondary metabolites and antioxidant activity not only enhances product quality but also increases market value and the functional benefits associated with grape and grape-derived product consumption.

Yield, physicochemical, and biochemical parameters of 'IAC 116-31 Rainha'grapes
A significant interaction was observed between rootstocks and training systems for the number of clusters per plant, production, and productivity of the 'IAC 116-31 Rainha' grapevine. It was noted that increases in production and yield were directly related to the number of clusters per plant (Suppl Table 7), since cluster and berry fresh mass were not influenced by the treatments.
High espalier, in combination with the 'IAC 766 Campinas' rootstock, resulted in higher production and productivity in 'IAC 116-31 Rainha' vines, likely due to improved vegetative development and more favorable leaf distribution. Furthermore, the interaction between rootstock and training system can influence the plant's resistance to biotic and abiotic stressors. Vigorous rootstocks such as 'IAC 766 Campinas' confer greater resilience to the vine, helping to mitigate the negative effects of pests, diseases, and adverse climatic conditions.
A significant interaction was also observed for variables affecting the physicochemical quality of 'IAC 116-31 Rainha' grapes (Suppl Table 8). The combination of high espalier and the 'IAC 766 Campinas' rootstock increased soluble solids and reducing sugars while decreasing titratable acidity. This led to a higher SS/TA ratio, a key indicator of the balance between sweetness and acidity. This balance is ideal for the 'IAC 116-31 Rainha' cultivar, improving the sensory profile of the grapes and enhancing the quality of the juices and wines derived from them.
The 'IAC 766 Campinas' rootstock combined with high espalier proved to be the most effective combination for improving the physicochemical characteristics of 'IAC 116-31 Rainha' grapes. The SS/TA ratio ranged from 24.29 to 29.26, which is considered adequate for processing grapes according to Brazilian standards, which recommend a range between 15 and 45 (Brasil, 2005). Flavor perception is influenced by compounds that stimulate the taste buds, including soluble solids and volatile substances accumulated during fruit development. Soluble solids content is a decisive factor in winemaking, as it influences the need for chaptalization to reach the desired alcohol content.
Grape pH values ranged from 3.60 to 3.79, which is within the recommended range for grapes intended for processing (Brasil, 2005).
This rootstock-training system combination not only improves fruit quality but also contributes to consistent and stable yields across seasons, showing good adaptability to the edaphoclimatic conditions of the study area.
Total flavonoid concentrations in the pulp were higher when using the 'IAC 766 Campinas' rootstock, regardless of the training system (Suppl Table 9). These results suggest that this rootstock may enhance flavonoid synthesis in the pulp of 'IAC 116-31 Rainha' grapes, possibly due to improved compatibility with the scion.
DPPH values were also higher in the pulp when the 'IAC 766 Campinas' rootstock was combined with the high espalier system. These results indicate that this combination significantly improves antioxidant activity in the pulp of 'IAC 116-31 Rainha' grapes.
Once again, the 'IAC 766 Campinas' rootstock in combination with the high espalier system had a positive influence on total phenolic compounds, total flavonoids, and antioxidant activity (DPPH and FRAP) in the grape skins (Suppl Table 9). This suggests that this combination favors both the synthesis and accumulation of these secondary metabolites, which are important for protecting cells against oxidative damage, as previously discussed.
The effectiveness of the high espalier system can be attributed to its increased capacity for light interception, enhancing the efficiency of sunlight capture, which is crucial for photosynthesis and the biosynthesis of bioactive compounds. The results obtained reinforce the importance of selecting appropriate combinations of rootstocks and training systems to optimize the quality of white grapes, thereby promoting both health-related and commercial benefits.
Differences in antioxidant compound values were observed depending on the assay method, with DPPH values being higher than FRAP. This variation may be intrinsically related to the different mechanisms of action involved in each assay.

Principal Component Analysis (PCA)

Yield and quality of 'BRS Lorena' grapes
The principal component analysis (PCA) revealed important relationships among the evaluated variables. Component 1, which explains 34.92% of the total variation, was strongly associated with variables such as yield, soluble solids, fresh berry mass, total phenolic compounds, and antioxidant capacity (FRAP) in both skin and pulp (Figure 1). This suggests that these characteristics are highly correlated, and an increase in one may be associated with an increase in the others. Component

2, which explains 18.49% of the variation, was associated with variables such as fresh seed mass and titratable acidity, indicating that these parameters are independent of those represented by Component 1.
Production showed a positive correlation with fresh berry mass and soluble solids, indicating that higher yields may be associated with fruits of greater mass and higher soluble solids content—desirable attributes for 'BRS Lorena' grapes intended for processing. Antioxidant capacity (FRAP), in both peel and pulp, was located near the center of the biplot, suggesting a moderate correlation with most variables, except for titratable acidity.
PCA also revealed that the combination of the 'IAC 766 Campinas' rootstock with high espalier was associated with a favorable set of traits promoting both high yield and fruit quality, as indicated by the proximity of variables such as productivity, soluble solids, and antioxidant activity (Figure 4).
In conclusion, PCA indicates that the combination of 'IAC 766 Campinas' rootstock with high espalier promotes greater yield and quality in 'BRS Lorena' grapes, as evidenced by the positive associations with variables such as production, fresh cluster mass, and soluble solids. Additionally, antioxidant activity was improved, although negatively correlated with titratable acidity, which must be balanced to optimize wine quality.

Yield and quality of 'IAC 21-14 Madalena' grapes
Principal component analysis (PCA) illustrated the distribution of productive, physicochemical, and bioactive variables in 'IAC 21-14 Madalena' grapes across principal components 1 and 2, which together explained 42.07% of the total variation (Figure 2). This analysis was essential to understand how different grape traits correlate and contribute to overall variability.
PC1, accounting for 23.23% of the total variation, was strongly associated with variables such as yield, soluble solids, number of clusters per plant, fresh seed mass, total phenolic compounds in pulp, and antioxidant activity in both peel and pulp (DPPH). This correlation indicates that increases in one of these variables are likely to be accompanied by increases in the others. In contrast, PC2, which explained 18.84% of the variation, was associated with titratable acidity, and both total phenolic compounds and antioxidant activity (FRAP) in the peel, suggesting these traits are not influenced by the dominant variables in PC1.
PCA also showed that the combination of the 'IAC 766 Campinas' rootstock with high espalier offered significant benefits in terms of grape production and quality. This combination promoted high yields, greater soluble solids, and higher antioxidant activity—important attributes for grapes destined for processing, such as 'IAC 21-14 Madalena' (Figure 4).
Thus, PCA suggests that this combination enhances both grape yield and quality, supported by its positive association with variables such as productivity, cluster number per plant, soluble solids, and antioxidant capacity.

Yield and quality of 'IAC 116-31 Rainha' grapes
Principal component analysis (PCA) was applied to all variables assessed in the 'IAC 116-31 Rainha' cultivar grafted onto the 'IAC 766 Campinas' and '106-8 Mgt' rootstocks, and trained using high and low espalier systems. The variability in the dataset was explained by two main components: PC1 and PC2, which together accounted for 60.98% of the total variation (Figure 3).
When grafted onto the 'IAC 766 Campinas' rootstock and trained on a high espalier system, the 'IAC 116-31 Rainha' hybrid showed increased titratable acidity, fresh cluster mass, antioxidant activity (DPPH and FRAP), and fresh seed mass (Figure 4).
The variables evaluated included fresh mass of clusters (FMC), fresh mass of berries (FMB), fresh mass of seeds (FMS), productivity (Prod), yield (Yield), soluble solids (SS), titratable acidity (TA), reducing sugars (RS), phenolic compounds (PC), total flavonoids (TF), and antioxidant activity (DPPH and FRAP).
Productivity was strongly influenced by the number of clusters per plant. PCA also indicated that the combination of the 'IAC 766 Campinas' rootstock and high espalier system offered considerable advantages in terms of both yield and quality (Figure 4), suggesting that this may be the most suitable strategy to maximize both parameters for 'IAC 116-31 Rainha' grapes.
Thus, PCA suggests that this combination enhances grape production and quality, as demonstrated by its positive association with variables such as yield, number of clusters per plant, soluble solids, bioactive compounds, and antioxidant activity (Figure 4).

Discussion

The interaction between rootstocks and grapevines has been well documented, demonstrating that this relationship significantly influences grapevine growth, development, and fruit quality. Specifically, the interaction between rootstocks and training systems affects phenological stages, directly impacting grape production and quality (Hernandes et al., 2010; Domingues et al., 2023).
'BRS Lorena' is a grape cultivar commonly used for processing and is known for its seeds, which are rich in tannins that contribute astringency to wines and juices (Rizzon et al., 2002). Moreover, the seeds are rich in flavonoids, phenolic compounds, and antioxidants, which are beneficial for plant defense and fruit quality. These compounds neutralize free radicals that could otherwise damage fruit cells, and their importance extends to the cosmetics industry, human health, and oncology (Aires et al., 2024).
As a hybrid cultivar with moderate vigor, high fertility, and broad climatic adaptability across Brazilian regions (Camargo et al., 2008), 'BRS Lorena' pairs well with rootstocks such as '106-8 Mgt'. This rootstock, although less vigorous, is efficient

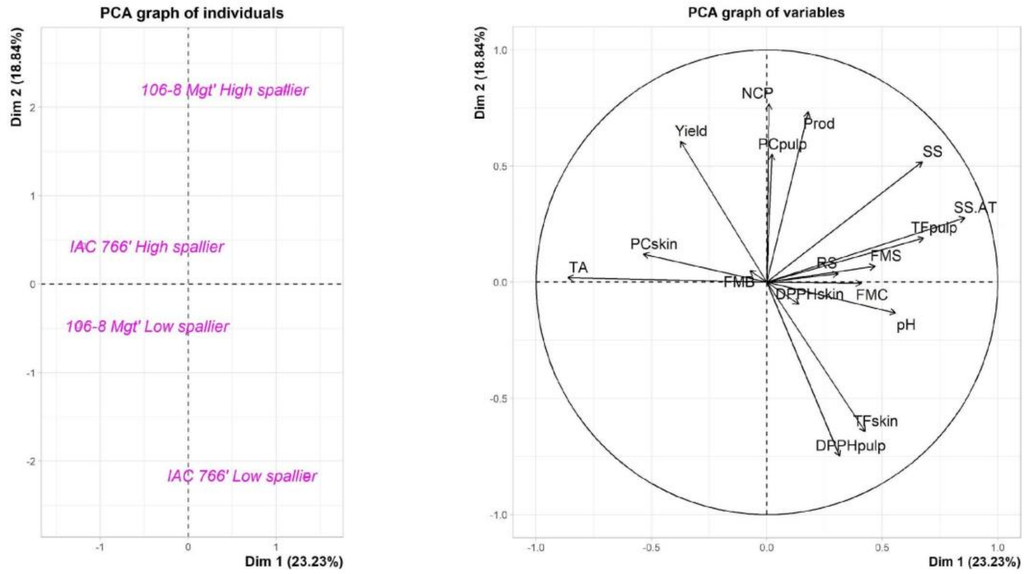

Figure 2. Principal component analysis (PCA) of 'IAC 21-14 Madalena' vine grafted on 'IAC 766 Campinas' and 106-8 'Mgt' rootstocks and on low and high trellis systems. Note: number of clusters (NCP), fresh mass of clusters, berry and seeds (FMC, FMB and FMS), productivity (Prod), yield (yield), soluble solids (SS), titratable acidity (TA), reducing sugars (RS), phenolic compounds (PC), total flavonoid (TF) and antioxidant activity (DPPH and FRAP).

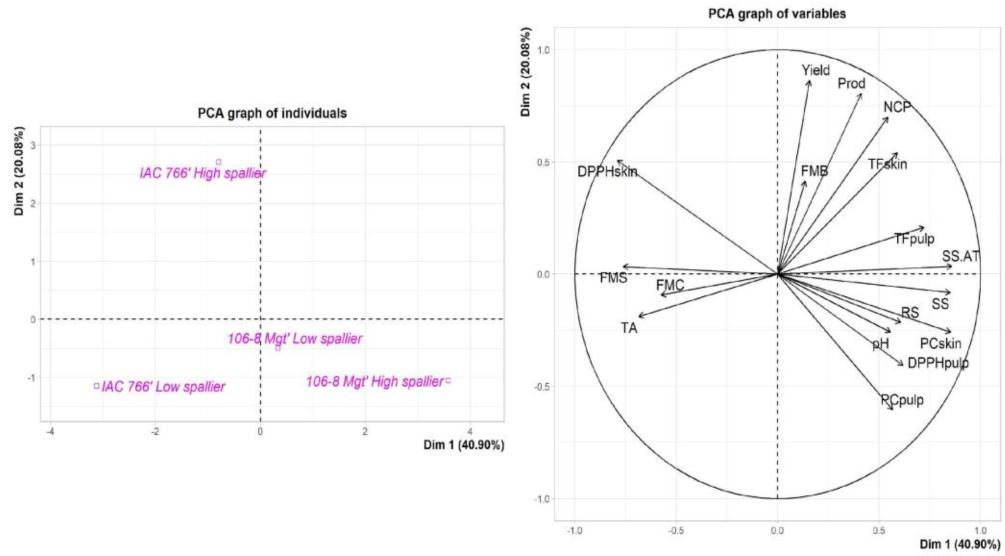

Figure 3. Principal component analysis (PCA) of 'IAC 116-31 Rainha' vine grafted on 'IAC 766 Campinas' and 106-8 'Mgt' rootstocks and on low and high trellis systems. Note: number of cluster (NCP), fresh mass of clusters, berry and seeds (FMC, FMB and FMS), productivity (Prod), yield (yield), soluble solids (SS), titratable acidity (TA), reducing sugars (RS), phenolic compounds (PC), total flavonoid (TF) and antioxidant activity (DPPH and FRAP).

in water and nutrient uptake, adapts well to diverse soil types, and provides a stable base for canopy development (Pommer et al., 2003; Camargo et al., 2008). Its capacity to support a high fruit load without compromising fruit quality demonstrates superior nutrient and water transport efficiency and resistance to biotic and abiotic stress (Khan et al., 2020).

From a metabolic standpoint, regardless of rootstock or training system, the soluble solids (SS) content in this study was above the minimum standard established by Brazilian legislation (14 °Brix) for grapes destined for processing (Brasil, 2000), and exceeded the 15.5 °Brix minimum required by U.S. regulations (Final, 2007). This is closely related to photosynthesis, the process by which plants convert light, water, and CO_2 into glucose and oxygen. Higher photosynthetic activity increases carbohydrate synthesis, which is subsequently stored in the fruit as soluble sugars (Domingues et al., 2023; Del Zozzo et al., 2024).

This energy efficiency is crucial for the biosynthesis of sugars and organic acids, both of which define must quality. Sugars are essential not only for sweetness and flavor, but also for alcoholic fermentation (Maicas, 2021).

In terms of training systems, the high espalier increases canopy exposure to sunlight, optimizing photosynthesis and promoting sugar accumulation (Domingues et al., 2023). In parallel, the 'IAC 766 Campinas' rootstock improves water and nutrient absorption, resulting in uniform fruit ripening, lower titratable acidity, and increased soluble solids (Calili et al., 2023).

During ripening, grape acidity decreases as berry expansion and respiration dilute organic acids. This process raises pH and lowers titratable acidity—critical factors for producing high-quality wines (Van Leeuwen et al., 2023). Organic acids such as malic and tartaric are consumed via cellular respiration during maturation, leading to lower acidity and increased pH in the must (Joshi et al., 2021). The 'IAC 766 Campinas' rootstock, in combination with high espalier, promotes a balanced sensory profile, enhancing sweetness and maintaining sufficient acidity for wine palatability (Hranilovic et al., 2021). Moreover, training systems that provide greater light exposure facilitate the synthesis and accumulation of anthocyanins and flavonols, which are strongly influenced by solar radiation (Martínez-Lüscher et al., 2019).

In viticulture, flavonoids are particularly valued for their health-promoting effects, including reduced risks of cardiovascular diseases, cancer, and neurodegenerative conditions (Aires et al., 2024). White grapes are especially rich in glycosylated quercetin, kaempferol, and dihydroflavonols (Masa et al., 2007), whose antioxidant actions in both plants and humans are well documented. These compounds neutralize oxidative stress by stabilizing free radicals. In grapes, they protect fruit integrity and contribute to sensory attributes such as flavor, bitterness, and astringency, with the seeds being a major reservoir for phenolics (Masa et al., 2007). Although white grapes contain fewer antioxidants than red grapes, they still offer significant amounts, with resveratrol being the predominant compound (Assumpção et al., 2019).

Among training systems, the high espalier adds approximately 40 cm of vertical height, increasing sunlight interception and improving photosynthetic efficiency (Domingues et al., 2023). This enhances carbohydrate production, supporting seed, cluster, and berry development. The larger canopy also improves ventilation and reduces humidity around the fruit, lowering disease incidence and promoting healthier growth (Ferrara et al., 2021).

The vertical leaf orientation in high espaliers optimizes exposure to solar radiation, increasing photoassimilate production, which is crucial for cluster development. Enhanced air circulation also helps reduce pathogen presence, resulting in clusters with greater mass and yield (Costella et al., 2024).

Phenolic compounds, particularly flavonoids, contribute significantly to sensory traits such as taste, bitterness, astringency, and pungency (Pereira et al., 2014). These properties are essential in winemaking. Flavonoid accumulation is influenced by multiple factors, including genotype, climate, vineyard practices, ripening stage, berry size, and extraction methods (Rienth et al., 2021; Yu et al., 2022).

The synergy between the 'IAC 766 Campinas' rootstock and high espalier can be attributed to optimized water and nutrient uptake by the rootstock and improved solar radiation interception by the training system, which enhances photosynthetic efficiency and secondary metabolite production (Domingues et al., 2023). Flavonoids and phenolic compounds in grape skins and pulps are key contributors to nutritional and sensory quality, offering color, aroma, and antioxidant activity (Murtha et al., 2021). These antioxidants play a protective role against oxidative stress and are linked to the prevention of chronic diseases such as cancer and cardiovascular disorders (Oluwole et al., 2022).

For 'IAC 116-31 Rainha', the combination of high espalier and the 'IAC 766 Campinas' rootstock provides a more favorable source–sink balance, enhancing photoassimilate availability for fruit development (Domingues et al., 2023; Souza et al., 2015). Vigorous rootstocks like 'IAC 766 Campinas' support increased growth due to their enhanced nutrient and water uptake capacity (Tecchio et al., 2022b). This rootstock is suitable for both Vitis vinifera and Vitis labrusca and has been associated with increased yield and long-term productivity (Souza et al., 2015; Butiuc-Keul et al., 2023).

Several studies have confirmed the benefits of 'IAC 766 Campinas' as a grapevine rootstock (Tecchio et al., 2019; Tecchio et al., 2022; Domingues et al., 2023; Sánchez et al., 2023). Nevertheless, productivity is also influenced by other factors such as edaphoclimatic conditions, carbohydrate accumulation, and endogenous hormone levels (Simonetti et al., 2021; Quamruzzaman et al., 2021; Nawaz et al., 2020). These factors contribute to increased photosynthetic efficiency, sugar accumulation, and phenolic compound synthesis. The increase in soluble solids and reducing sugars, along with the reduction in acidity, improves must quality and supports the production of high-quality wines and juices (Yang et al., 2020; Ofoedu et al., 2022).

From a sensory standpoint, sugar accumulation in berries toward the end of ripening is essential for the formation of phenolic compounds (Kuhn et al., 2013). Grapes primarily accumulate glucose and fructose, with fructose typically being predominant at harvest (Zhang et al., 2012). These sugars serve as precursors for aroma and flavor-related compounds (Kuhn et al., 2013). Tartaric and malic acids make up over 90% of organic acids in grapes and are critical for wine acidity (Chen et al., 2018; Silva et al., 2022). Grape pH should remain below 3.3 to ensure final wine quality (Rizzon et al., 2002). Proper rootstock selection—such as 'IAC 766 Campinas'—enhances vegetative vigor and sugar accumulation, while maintaining ideal acidity levels (Simonetti et al., 2021; Tecchio et al., 2022; Sánchez et al., 2023).

Rootstock choice can also influence phenolic compound content, as observed in 'IAC 116-31 Rainha'. Greater phenolic concentrations improve antioxidant capacity and cell protection (Dias et al., 2017; Nwachukwu et al., 2021). These compounds, being secondary metabolites, vary in structure and function, enabling the plant to respond to various environmental stressors and biological threats (Al-Khayri et al., 2023).

Additionally, high phenolic content in grape skins enhances sensory attributes, favoring juice and wine processing. However, white cultivars naturally contain lower levels of phenolics compared to red grapes (Mota et al., 2018). Nevertheless, phenolic content plays a decisive role in determining flavor, color, and aroma (Abe et al., 2007).

Elevated concentrations of secondary metabolites and antioxidant activity are highly desirable for their health benefits and for improving sensory quality and commercial value (Karageçili et al., 2023). Positive rootstock–scion interactions can optimize nutrient absorption and photoassimilate translocation, thereby enhancing both the nutritional and functional quality of grapes (Falchi et al., 2020; Alfaro et al., 2021; Kulmann et al., 2022). However, standardization in antioxidant research remains a challenge due to variations in assay methods (FRAP, DPPH, ABTS, ORAC) and in the grape tissues analyzed (skin, pulp, seed), making result comparisons complex (Lago-Vanzela et al., 2011; Gonzáles-Centeno et al., 2013).

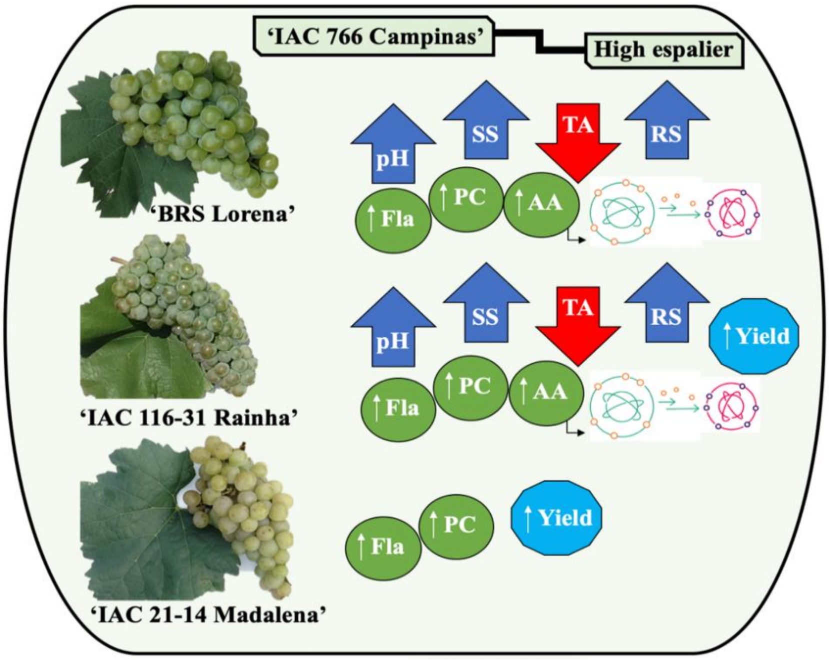

Figure 4. Graphical abstract of three Brazilian grapevine hybrids, 'BRS Lorena', 'IAC 116-31 Rainha' and 'IAC 21-14 Madalena' and their interaction with high espalier and 'IAC 766 Campinas' rootstock. Note: yield (yield), soluble solids (SS), titratable acidity (TA), reducing sugars (RS), phenolic compounds (PC), total flavonoid (Fla) and antioxidant activity (AA).

Materials and Methods

Experimental area location and growing conditions

The experiment was conducted during the 2017/2018 and 2019/2020 production cycles, with vines in their 7th and 8th year of production, at the Advanced Fruit Research and Development Center of the Agronomic Institute (IAC), part of the São Paulo Agency for Agribusiness Technology (APTA), located in Jundiaí, SP, Brazil (23º 06' S and 46º 55' W, at an altitude of 745 m). The annual average rainfall was 1,400 mm, with an average annual temperature of 19.5 ºC and relative humidity of 70.6%. According to the Köppen classification, the region has a Cfb climate, and the soil is classified as Dystrophic Red Cambisol (Embrapa, 2018).

The vineyard was spaced at 2.5 m between rows and 1.0 m between plants, totaling a planting density of 4,000 plants ha^{-1}. In accordance with local cultural practices, short pruning (one bud) was carried out in both production cycles, followed by the application of 5% hydrogen cyanamide. After sprouting, only one productive shoot per cane was maintained, and buds were removed and tied to the wires. Axillary shoots were removed, and defoliation was performed. Additional cultural practices included weeding, and applications of herbicides, fungicides, and insecticides. Fertilization was conducted using chemical fertilizers based on soil analysis, following the recommendations outlined in Technical Bulletin 100 of the Agronomic Institute (Tecchio et al., 2022).

Scion cultivars, experimental design and treatments

The scion cultivars evaluated in this study were the Brazilian hybrid white grapes 'IAC 116-31 Rainha' (Seibel 7053 × Burgunder Kastenholtz), 'IAC 21-14 Madalena' (Seibel 11342 × Moscatel de Canelli), and 'BRS Lorena' (Malvasia bianca × Seibel 7053). Each cultivar was evaluated independently using a randomized block design in a 2 × 2 factorial scheme, corresponding to two rootstocks — 'IAC 766 Campinas' [('106-8 Mgt' × Vitis caribaea)] and '106-8 Mgt' [Vitis riparia × (Vitis cordifolia × Vitis rupestris)] — and two training systems: low espalier (three wires at 1.0, 1.3, and 1.6 m above the ground) and high espalier (four wires at 1.0, 1.3, 1.6, and 2.0 m), as described by Domingues et al. (2023). The experiment consisted of five blocks, each containing three plants per plot.

Grafting was performed in 2010 using the full cleft grafting technique, following established guidelines for woody plant propagation (Pommer et al., 2003). At the time of grafting, rootstocks were approximately 12 months old and sourced from certified, uniform nursery stock. After grafting, plants were established in the field, and data collection began in the 7th and 8th years of production, corresponding to the 2017/2018 and 2019/2020 growing seasons. This timeline ensured full vine establishment and consistent productivity for the evaluation of agronomic and biochemical parameters under field conditions.

Evaluated variables

Production components and physical characteristics of clusters, berries, stems and seeds

After harvest, clusters from each plant were counted and weighed to calculate yield (kg $plant^{-1}$) and productivity (t ha^{-1}). Cluster fresh mass was assessed by sampling 10 clusters per experimental plot. Additionally, 100 berries per plot were used to determine berry fresh mass using a precision balance (0.0001 g).

Physico-chemical quality of the musts (unfermented juice of grapes) and bioactive compounds in the peel and pulp

The physicochemical quality of the must (unfermented grape juice) was assessed using 50 berries per experimental plot. Soluble solids (SS) were determined with a digital Atago® refractometer equipped with automatic temperature compensation and expressed in °Brix, following the methodology described by Brasil (2005). Titratable acidity (TA) was measured by potentiometric titration, also according to Brasil (2005), and expressed as a percentage of tartaric acid. The SS/TA ratio was then calculated. The pH was measured using a digital pH meter, following the same reference. Reducing sugar content was quantified using the Somogyi–Nelson colorimetric method, based on a glucose standard curve, with spectrophotometric readings performed at 510 nm, as described by Nelson (1944).

For the determination of bioactive compounds in the skins and pulp, berries were longitudinally halved, the seeds removed, and the skins and pulp were separated. The samples were immediately frozen in liquid nitrogen, manually macerated in a porcelain mortar using a pestle, and stored at −80 °C until biochemical analysis. Total phenolic compounds were determined using the Folin–Ciocalteu method (Singleton et al., 1965), with results expressed as milligrams of gallic acid equivalents (mg GAE) per 100 g of fresh mass. Total flavonoid content was assessed using a spectrophotometric method adapted from Blatt et al. (1998) and Awad et al. (2000), with results expressed as milligrams of quercetin equivalents per 100 g of fresh mass. Antioxidant activity was evaluated using two methods: DPPH and FRAP. The DPPH method, following Brand-Williams et al. (1995) and adapted by Rossetto et al. (2009), was based on the scavenging activity of the DPPH radical (2,2-diphenyl-1-picrylhydrazyl), with absorbance measured at 517 nm and results expressed as µg Trolox equivalents per gram of sample (TEAC). The FRAP assay, based on the reduction of Fe^{3+} to Fe^{2+} (Benzie and Strain, 1996), involved absorbance measurements at 594 nm, and results were expressed as µmol Fe^{2+} per 100 g of fresh mass.

Statistical analysis

Mean values from both production cycles for each cultivar were subjected to analysis of variance (ANOVA) to assess the effects of rootstocks, training systems, and their interaction. Means were compared using Tukey's test ($p \leq 0.05$), performed with Sisvar version 6.0 software (Ferreira, 2011). Additionally, to characterize the interaction between rootstocks and training systems and assess variable correlations, principal component analysis (PCA) was performed using Statistical Analysis Software version 4.0 (SAS).

Conclusions

The most recommended combination observed in this study was the use of the 'IAC 766 Campinas' rootstock together with the high espalier training system, which maximized production, productivity, and quality of the Brazilian hybrid white grapes 'IAC 21-14 Madalena' and 'IAC 116-31 Rainha'. For the 'BRS Lorena' cultivar, the high espalier system associated with the '106-8 Mgt' rootstock resulted in higher values for production parameters. However, considering that grape and must quality are essential for processing purposes, better grape quality was achieved in vines grafted onto the 'IAC 766 Campinas' rootstock. The combination of these cultivars grafted onto 'IAC 766 Campinas' and trained with the high espalier system led to improved nutritional and functional characteristics of the grape clusters and must. In addition, the observed increase in antioxidant capacity suggests potential health benefits for consumers, thereby enhancing the commercial value of the grapes. Therefore, this strategy should be considered by winegrowers seeking to increase both efficiency and quality in the production of grapes intended for processing.

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