Scientific Papers. Series B, Horticulture. Vol. LXIX, No. 2, 2025
Print ISSN 2285-5653, CD-ROM ISSN 2285-5661, Online ISSN 2286-1580, ISSN-L 2285-5653

POTASSIUM INFLUENCE ON ‘VICTORIA’ AND ‘PERLA DE CSABA’ TABLE GRAPES QUALITY

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Abstract

The study was conducted between 2021 and 2023 and evaluated the influence of potassium on the quality of ‘Victoria’ and ‘Perla de Csaba’ table grapes. The samples were collected from a private vineyard in Masca, Arad County. Three doses of potassium (120, 130, and 140 kg/ha) were applied at three critical phenological stages (before flowering, pre-veraison, and post-harvest). The results indicated that the different potassium (K) doses significantly ($p \leq 0.05$) influenced the grapes' quality. Notably, the dose of 130 kg (K) had a major impact on varieties, influencing sugar content, aromas, and berry size uniformity. The 140 kg/ha potassium dose increased the average bunch weight and significantly ($p \leq 0.05$) decreased berry acidity, particularly in the ‘Perla de Csaba’ variety. The study highlights the importance of balanced potassium fertilisation to improve key grape quality parameters, such as sugar content and bunch weight. The results suggest that adjusting potassium doses according to grape variety may optimise grape quality outcomes.

Key words: *blooming, harvest, potassium, table grape, veraison,*

INTRODUCTION

A vital component of many physiological and biochemical functions, potassium (K) is necessary for the vigorous growth and development of grapevine (Marcuzzo et al., 2021). Along with nitrogen and phosphorus, potassium is one of the three main macronutrients. It has a direct impact on the quantity and quality of grapes produced as well as the plantation's ability to manage biotic and abiotic challenges (Ciotta et al., 2021).

Balanced fertilisation, according to the specific requirements of the soil and climatic conditions, can considerably increase grape yield and quality while ensuring the crop's long-term viability (Villette et al., 2020). This mobile nutrient helps regulate osmotic pressure in plant cells, promoting water uptake and maintaining turgor pressure. It also regulates stomatal opening, which is essential for transpiration and indirectly influences photosynthesis, affecting vegetative growth and carbohydrate accumulation (Hu et al., 2023).

Applying potassium before bud break promotes root and bud development, preparing the vineyard for rapid growth, flowering, and high-quality grape yields (Schreiner & Osborne, 2020). Table grape varieties have slightly different nutritional requirements compared to wine grape varieties. Potassium plays an essential role in meeting these needs by enhancing the physical characteristics and flavour of the berries (Pushpavathi et al., 2021). This nutrient also aids in the accumulation of energy stores in plants, which is necessary for an appropriate beginning of the growing season (Monteiro et al., 2021).

Potassium promotes bud development and differentiation, contributing to consistent and prolific flowering. This process supports the formation of compact and well-formed clusters, although other factors also play a role (El-Boray et al., 2019).

Potassium regulates ion transport and osmotic balance, indirectly enhancing water and nutrient uptake. This supports efficient and healthy vine growth following budbreak (Eshghi et al., 2011). Potassium facilitates proper water and nutrient absorption, preparing the vines for efficient and healthy growth following budbreak, while also promoting

carbohydrate buildup, which is necessary for grape development (Eshghi et al., 2011).
Applying potassium before budbreak also helps to produce grapes with an appropriate balance of acidity and sugars, which is vital for table grape flavour quality (Rogiers et al., 2017).
Prior to veraison, grapevine potassium requirements increase significantly to support sugar accumulation and final berry development. Adequate potassium application at this stage is critical for optimal nutrition, water consumption efficiency, resistance to abiotic stressors (drought, salinity), and grape quality (Wang et al., 2023). Unlike wine grapes, where potassium primarily influences fermentation and pH balance, proper potassium intake influences major table grape qualities such as skin firmness, colour, and flavour, all of which are important for the clusters commercial appreciation (Zhang et al., 2016). Research on potassium deficiency during the ripening stage indicates that it can reduce grape yield and quality while increasing susceptibility to pathogens and environmental stressors (Sánchez-Mora et al., 2017). Therefore, adequate soil fertility management and timely potassium application are essential for increasing table grape crop efficiency. Applying potassium to table grape varieties after harvest is necessary for preserving vine health and guaranteeing high-quality yields in the next growing seasons (Youssef & Roberto, 2014). Following harvest, the vine continues to build up the nutritional reserves required for future growth. By restocking these reserves, potassium application during this period improves the plant's ability to withstand abiotic stressors and pathogenic infections in the following growing season (Rogiers et al., 2017).
Furthermore, potassium enhances post-harvest durability by supporting cell wall integrity and reducing water loss, which contributes to increased resistance to storage-related decay. Particularly in vulnerable varieties like 'Italia' and 'Afuz Ali', an additional potassium supply might boost tolerance to certain biotic stressors, including fungal pathogens, particularly in vulnerable varieties like 'Italia' and 'Afuz Ali' (Mehmood et al., 2021).
While previous studies have examined the general role of potassium in grapevine development, there is limited research on the optimal potassium doses applied at specific phenological stages for table grape varieties, particularly for 'Perla de Csaba' and 'Victoria'. The purpose of the study was to evaluate the effects of three potassium fertilisation doses (120, 130, and 140 kg/ha) applied at three critical stages of the vegetative cycle: before budbreak (spring), prior veraison (early grape ripening), and after harvest (autumn) on the growth, yield, and quality parameters (such as sugar accumulation, acidity balance, skin firmness, and cluster compactness) of the 'Perla de Csaba' and 'Victoria' table grape varieties. These varieties were selected due to their economic significance and their sensitivity to potassium-driven changes in fruit quality and yield. Also, the study aims to provide information regarding sustainable fertilisation strategies that maximise table grape output and market value by examining potassium's role in critical metabolic and developmental processes.

MATERIALS AND METHODS

Study Area and Soil Characteristics

The Miniș-Masca region of Western Romania is renowned for its vineyards. The climate and soil properties significantly influence grape production quality. The region has a continental climate with notable seasonal fluctuations. Summers are generally warm, while winters can be cold and frosty. Precipitation is moderately distributed throughout the year, with drier summers, creating ideal conditions for viticulture and promoting high-quality grape production.

Soil characteristics

The area is characterized by cambisols with good fertility, suitable for viticulture when properly managed. The topsoil (0-30 cm) consists of loamy sand and sandy loam textures (Table 1), providing efficient drainage and aeration beneficial for vine root systems. Deeper layers (30-60 cm) transition to sandy loam or silt-clay loam, improve moisture retention and support deeper root growth.
The soil pH ranges from 6.0 to 7.0 (slightly acidic to neutral), while calcium, magnesium, and iron concentrations are moderate to high, influencing soil fertility.

Table 1. Characteristics of different soil types in the Masca area

Soil Type	Organic Matter (%)	Total N (%)	Available P (mg/kg)	Available K (mg/kg)	pH	Micronutrients
Cambisols	2.5-4.0	0.2-0.3	10-20	150-200	6.0-7.0	Generally adequate (moderate Fe, Zn, Cu, Mn)
Loamy Sand	1.0-2.0	0.1-0.2	5-10	100-150	6.0-7.0	Typically lower; may require supplementation
Sandy Loam	1.5-3.0	0.15-0.25	10-15	150-200	6.0-7.0	Moderately available; better than loamy sand

The diverse soils from Masca, contributes to the area's aptitude for viticulture. The soils are predominantly well-drained, which is important for grapevine health since it prevents waterlogging and promotes deep root growth. Furthermore, the mineral composition of the soils, influence the flavour profiles of the wines.

Masca area climate (2021-2023)

The distribution of precipitation during the growing seasons (2021, 2022, and 2023) is unbalanced (Figure 1), with certain months receiving more rainfall, raising the risk of fungal diseases, and less moisture, increasing water stress. Precipitation amounts vary substantially over time, with 2021 having both the highest (278.9 mm in January) and lowest (5.5 mm in March) levels. Rainfall changes had an effect on grapevine water supplies.

Each of the three seasons has unique precipitation values or deficits in key months for grapevine development. The wetter April of 2023 promotes fast early growth, whereas the dryer August of 2022 accelerates ripening.

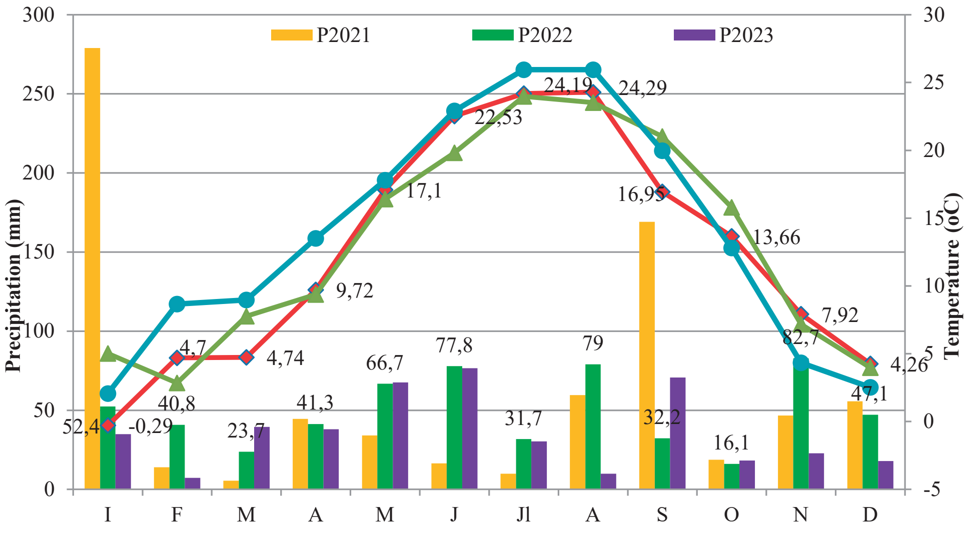

Figure 1. Temperature and precipitation in Masca area during 2021-2023 time

Warmer temperatures accelerated the harvest season (particularly in 2022), necessitating close monitoring to achieve optimal grape ripeness. Lower precipitation in 2023 resulted in smaller berries with more concentrated flavours, which improved wine quality but lowered overall yield. A phenomenon reported during the 2023 grape harvest was a decrease in the number of seeds in the berries, or sometimes their absence, as a result of high temperatures associated with low levels of precipitation.

Experimental Design

A randomized complete block design (RCBD) was implemented to control field variability. The experiment was organised in a factorial design, with two factors: Factor A (potassium dose): 120, 130, and 140 kg/ha; Factor B (application timing): T1 (before flowering - bud break stage, when average daily temperatures exceeded 10°C), T2 (pre-veraison - 2-3 weeks before the onset of veraison), and T3 (after harvest - immediately after harvest to support reserve building). Each treatment combination was repeated three times. The plot size for each replication was (0.10 ha) to guarantee adequate representation of the vine population. While the main focus was on three potassium (K) doses, an untreated control (without K application) was added to evaluate the relative response. The fertiliser was calibrated to supply 120, 130, and 140 kg K_2O per hectare. Application time for these doses was: before flowering (T1): application was scheduled when the vines reached the bud break stage, typically when average daily temperatures exceeded 10°C and just prior to full bloom; pre-veraison (T2): application was made during the berry development phase, approximately 2–3 weeks before the onset of veraison; post-harvest (T3): application was made immediately after harvest, during the period when vines were building reserves for the following season. Potassium was applied as a granular fertiliser, evenly distributed throughout the allocated plots. In T1 and T2, the fertiliser was gently incorporated into the soil with a shallow cultivator to ensure excellent contact with the root zone. The fertiliser for T3 was spread on the surface since little soil disturbance was desired throughout the post-harvest period. Vines were constantly monitored to determine the timing of phenological stages (bud break, flowering, veraison, and harvest). This ensured that K applications corresponded closely to the specified phenological cycles. All personnel involved in fertilizer application and data collection adhered to standard safety protocols, including the use of personal protective equipment (PPE).

Data collection

Soil samples were taken from the 0-30 cm layer before the study began and after each treatment phase in order to monitor changes in accessible potassium and overall soil fertility.

Plant growth parameters (vine shoot length, leaf area index (LAI), and canopy density were measured on a regular basis); yield components [the number of clusters per vine, cluster weight, and overall grape yield (kg/ha) were recorded at harvest]; and fruit quality (sugar content, acidity, pH, and phenolic content) were analysed on representative samples from each plot. Data were collected at critical growth stages: post-application for T1 and T2 treatments (flowering and veraison), and at harvest (T3) for evaluating final yield and quality.

Plant growth parameters

Vine shoot length was measured manually using a tape measure from the shoot base to the tip of a representative sample of shoots per vine. The leaf area index (LAI) was determined using a ceptometer (LP-80 AccuPAR Ceptometer - Decagon Devices, Inc.) to record photosynthetically active radiation above and below the canopy, and the device's software used the light extinction coefficient to compute the LAI.

Canopy density was measured visually using a standardised canopy rating scale and then analysed using image analysis tools to determine the percentage of ground cover by foliage. When these standardised approaches were used regularly across the vineyard, provide trustworthy data on shoot length, LAI, and canopy density.

During the harvest, a representative sample of vines from each plot was selected to count the number of clusters per vine. Several clusters were randomly selected from both varieties and weighed on a calibrated scale to determine the average cluster weight. Finally, each plot was harvested, and the overall yield was measured and converted to kg/ha according to the plot area. Table grape samples were harvested from representative vines, crushed and pressed to produce juice.

The sugar content was measured with a refractometer (°Brix - C-Tech SAL0025), and the titratable acidity was evaluated by titrating the juice with a standard sodium hydroxide solution and reported as a percentage of tartaric acid. The pH was determined using a calibrated pH meter. The total phenolic content was determined using a spectrophotometric test (Spectrophotometer 6 nm, model V721), with results displayed in gallic acid equivalents.

Statistical Analysis

Statistical analyses were conducted using Excel 2019 (Microsoft Corporation. 2019. Microsoft Excel. Version 2019. Redmond, WA:

Microsoft) and XLSTAT (Addinsoft. 2019. XLSTAT Statistical and Data Analysis Solution. Version 2019. Paris: Addinsoft) to evaluate the effect of different K_2O doses on vine growth, yield, and fruit quality. A one-way and two-way Analysis of Variance (ANOVA) was performed to assess the impact of K_2O application rates on vine shoot length, cluster weight, grape yield, and sugar content, with statistical significance set at $p \leq 0.05$. Additionally, multiple regression analyses were used to determine the relationship between K_2O application and key yield components. Principal Component Analysis (PCA) was applied to identify the primary factors influencing grape yield and quality, summarizing the variance within the dataset and highlighting treatment responses across growing seasons.

RESULTS AND DISCUSSIONS

In this section, the results of the field study for 'Victoria' and 'Perla de Csaba' varieties, are presented over the 2021-2023 growing seasons. Based on Table 2 data, both varieties show an increasing trend in vine growth parameters over the three-year period.

For the 'Victoria' variety, vine shoot length increased from 2021 to 2023, while LAI and canopy density also improved. Similarly, the 'Perla de Csaba' variety exhibited growth with vine shoot length, LAI and canopy density.

Table 2. Growth parameters for 'Victoria' and 'Perla de Csaba' cultivars, for different K_2O doses and application timings, during 2021-2023 growing seasons

Variety	Year	K_2O dose (kg/ha)	Application timing	Vine shoot length (cm)	LAI (m^2/m^2)	Canopy density (%)
Victoria	2021	120	T1	60.1^{b}	3.58^{ab}	75.2^{a}
Victoria	2021	130	T2	61.5^{b}	3.43^{b}	70.5^{b}
Victoria	2021	140	T3	67.4^{a}	3.62^{a}	73.8^{ab}
Perla de Csaba	2021	120	T1	55.2^{c}	3.24^{c}	70.4^{b}
Perla de Csaba	2021	130	T2	57.0^{bc}	3.32^{bc}	69.5^{b}
Perla de Csaba	2021	140	T3	62.5^{a}	3.58^{ab}	72.6^{ab}
Victoria	2022	120	T1	64.0^{b}	3.18^{c}	76.8^{a}
Victoria	2022	130	T2	68.7^{a}	3.35^{b}	78.0^{a}
Victoria	2022	140	T3	66.5^{ab}	3.82^{a}	79.2^{a}
Perla de Csaba	2022	120	T1	58.0^{c}	3.50^{b}	73.5^{b}
Perla de Csaba	2022	130	T2	59.1^{bc}	3.28^{c}	74.8^{ab}
Perla de Csaba	2022	140	T3	61.5^{a}	3.61^{a}	72.3^{b}
Victoria	2023	120	T1	67.0^{b}	4.09^{a}	78.4^{a}
Victoria	2023	130	T2	69.8^{a}	3.90^{ab}	80.0^{a}
Victoria	2023	140	T3	65.4^{b}	4.20^{a}	80.9^{a}
Perla de Csaba	2023	120	T1	59.3^{c}	3.17^{c}	72.7^{b}
Perla de Csaba	2023	130	T2	62.7^{b}	3.35^{b}	73.4^{b}
Perla de Csaba	2023	140	T3	65.3^{a}	3.95^{a}	75.0^{ab}

*LAI - leaf area index; Different letters indicate significant differences at $p \leq 0.05$ within each column; "a" represents the highest statistically significant value; "b" and "c" indicate significantly lower values than "a"; the same letter (e.g., ab), are not significantly different from each other.

'Victoria' consistently exhibited longer vine shoot lengths compared to 'Perla de Csaba' across all years. In general, higher K_2O doses resulted in longer vine shoots, particularly in 2021 and 2022. In 2023, 'Victoria' had its longest shoot length at 130 kg/ha, while 'Perla de Csaba' followed the trend of increasing shoots length with higher K_2O. Statistical differences indicate significant variations, with 140 kg/ha (T3) often leading to significantly longer shoot length. 'Victoria' had higher LAI values compared to 'Perla de Csaba' in most cases, indicating a denser leaf canopy. The highest LAI values were typically observed under the highest K_2O dose, particularly in 2023. In some instances, 130 kg/ha resulted in lower LAI than 120 or 140 kg/ha. 'Victoria' had higher canopy density values compared to 'Perla de Csaba' in all years. The highest canopy density values were recorded in

'Victoria' at 140 kg/ha (T3) in 2023. For 'Perla de Csaba', canopy density was relatively stable across treatments but slightly increased with higher K_2O doses. Unlike vine shoot length and LAI, canopy density was less sensitive to K_2O application timing. These results align with previous research indicating that 'Victoria' berries are larger than those of other varieties, which may contribute to increased shoot vigour. The higher LAI and canopy density observed in 'Victoria' further suggest a more vigorous growth habit, potentially due to its genetic predisposition (Hill et al. 2006). Higher K_2O doses generally resulted in longer vine shoots and increased LAI; this effect can be attributed to potassium's role in promoting photosynthesis and protein synthesis, thereby enhancing vegetative growth (Neve, 2012). The relatively stable canopy density across different K_2O treatments, especially in 'Perla de Csaba', indicates that while potassium influences shoot length and leaf area, its effect on canopy density might be less pronounced (Mpelasoka et al., 2003). This could be due to canopy density being more influenced by factors such as pruning practices and overall vine architecture (Boonterm et al., 2013). The data suggest that K_2O application timing (T1, T2, T3) had a less significant impact on the measured growth parameters compared to the dosage. This finding implies that ensuring an adequate potassium supply is more critical than the specific timing of application (Avenant et al., 1997).

Throughout the three growing seasons, the 'Victoria' variety consistently outperformed the 'Perla de Csaba' cultivar in every yield component (Table 3).

Table 3. Yield components for 'Victoria' and 'Perla de Csaba' cultivars, under different K_2O doses (120, 130, and 140 kg/ha) applied at different timings (T1, T2, and T3) during the 2021-2023 growing seasons

Variety	Year	K_2O dose (kg/ha)	Application timing	Clusters per vine	Cluster weight (g)	Grape yield (kg/ha)
Victoria	2021	120	T1	8.0[a]	150[a]	10,000[a]
Victoria	2021	130	T2	8.4[a]	155[a]	10,200[a]
Victoria	2021	140	T3	8.9[a]	160[a]	10,400[a]
Perla de Csaba	2021	120	T1	7.1[b]	140[b]	9,500[b]
Perla de Csaba	2021	130	T2	7.5[b]	145[b]	9,700[b]
Perla de Csaba	2021	140	T3	7.8[b]	150[b]	9,900[b]
Victoria	2022	120	T1	9.0[a]	165[a]	11,000[a]
Victoria	2022	130	T2	9.5[a]	170[a]	11,100[a]
Victoria	2022	140	T3	10.1[a]	175[a]	11,400[a]
Perla de Csaba	2022	120	T1	8.2[b]	155[b]	9,100[b]
Perla de Csaba	2022	130	T2	8.5[b]	160[b]	9,200[b]
Perla de Csaba	2022	140	T3	9.3[b]	165[b]	9,600[b]
Victoria	2023	120	T1	10.0[a]	160[a]	10,300[a]
Victoria	2023	130	T2	10.5[a]	165[a]	10,700[a]
Victoria	2023	140	T3	11.0[a]	170[a]	10,900[a]
Perla de Csaba	2023	120	T1	8.9[b]	150[b]	10,000[b]
Perla de Csaba	2023	130	T2	9.5[b]	155[b]	10,300[b]
Perla de Csaba	2023	140	T3	10.1[b]	160[b]	10,500[b]

Different letters indicate significant differences at $p \leq 0.05$ within each column; "a" represents the highest statistically significant value; "b" indicate significantly lower values than "a"; the same letter (e.g., ab), are not significantly different from each other.

In 2021, 'Victoria' had all significantly higher ($p \leq 0.05$) yield parameters than the respective values for 'Perla de Csaba'. This trend continued in 2022 and 2023, with 'Victoria' exhibiting a steady increase in clusters per vine, cluster weight and grape yield. In contrast, 'Perla de Csaba' maintained lower values. These statistically significant differences ($p \leq 0.05$) indicate that the 'Victoria' variety is more vigorous and productive under the given conditions, which suggests that genetic factors or better adaptation to the growing environment may be contributing to its superior performance.

Increasing K_2O doses led to a higher number of clusters per vine, with the highest values observed under 140 kg/ha (T3). The increase in cluster number was more noticeable in 2022 and 2023, suggesting a cumulative effect of K fertilization or favourable environmental conditions. ‘Perla de Csaba’ also followed a similar trend but with slightly lower cluster counts compared to ‘Victoria’, indicating a variety-dependent response to K application. Higher K_2O doses led to increased cluster weight in both varieties. The heaviest clusters were recorded at 140 kg/ha (T3), particularly in 2022. ‘Victoria’ had consistently heavier clusters compared to ‘Perla de Csaba’, likely due to its more vigorous growth and greater ability to partition assimilates. The increase in cluster weight from 120 kg/ha to 140 kg/ha was more pronounced in 2022 and 2023, indicating that adequate potassium supply enhances fruit development. Grape yield followed a similar pattern to cluster weight and number, with the highest yields recorded under 140 kg/ha (T3). ‘Victoria’ showed superior yields compared to ‘Perla de Csaba’, reaffirming its higher productivity potential. The largest yield increase due to K fertilization was observed in 2022, suggesting optimal environmental conditions or improved nutrient uptake. In 2023, yield slightly declined despite higher cluster numbers, possibly due to variations in environmental factors such as temperature, precipitation, or nutrient availability. T3 (after harvest) consistently resulted in the highest values for all yield components, suggesting that post-harvest K application supports better nutrient storage and subsequent growth. T2 (pre-veraison) showed moderate improvements, while T1 (before flowering) had the lowest values, possibly due to earlier nutrient uptake limitations. Keller (2015) highlighted that cultivar-specific traits greatly influence vine vigour and yield potential, while Reynolds (2022) noted that efficient resource utilization is a key determinant of higher cluster weight and overall yield. The superior performance of ‘Victoria’ underscores the importance of cultivar selection in viticultural practices and suggests that further research into the genetic and physiological bases of these differences could inform breeding programs aimed at enhancing yield performance (Ferrara et al., 2017). The positive correlation between elevated K_2O doses and the number of clusters per vine aligns with existing literature emphasizing potassium's role in reproductive development (Obenland et al., 2015). Potassium is integral to various physiological processes, including enzyme activation and assimilates translocation, which are crucial for fruit set and development (Orak, 2017). The more noticeable increase in cluster numbers during 2022 and 2023 may be attributed to the accumulation of K reserves in the vine's perennial structures, enhancing reproductive capacity over time (Mpelasoka et al., 2003). Additionally, environmental factors such as optimal rainfall and temperature during these seasons had synergistically amplified the effects of potassium fertilization (Kodur, 2011). The augmentation of cluster weight with higher K_2O applications is consistent with potassium's known influence on grape development (Mpelasoka et al., 2003). Potassium facilitates the translocation of sugars and other metabolites to developing fruits, thereby increasing their size and weight (Conde et al., 2007). The superior cluster weights observed in 'Victoria' compared to 'Perla de Csaba' suggest a varietal difference in the efficiency of K utilization, possibly due to inherent genetic factors influencing growth vigour and assimilate partitioning. The pronounced increase in cluster weight during 2022 and 2023 further indicates that sustained K fertilization, coupled with favourable environmental conditions, can significantly enhance berry development. The overall grape yield, reflecting both the number of clusters and their individual weights, exhibited a positive response to increased K_2O fertilization (Howell, 2001). The highest yields recorded at the 140 kg/ha application rate (T3) corroborates studies highlighting potassium's critical role in maximizing grapevine productivity. The slight decline in yield observed in 2023, despite higher cluster numbers, is attributed to environmental variables such as temperature fluctuations, precipitation patterns, or nutrient availability affecting berry size and quality. The superior performance of post-harvest K applications (T3) across all yield components suggests that this timing is optimal for replenishing the vine's nutrient reserves. Post-harvest is a critical period when vines actively restore carbohydrates and mineral nutrients in their perennial tissues, which are essential for supporting early shoot growth and fruit development in the subsequent season (Mpelasoka et al., 2003). Applying potassium during this period ensures its availability during key physiological stages, thereby enhancing overall vine health and productivity (Delgado et al., 2004). In contrast, earlier applications (T1 and T2) may not align as effectively with the vine's nutrient uptake patterns, potentially limiting their efficacy. The consistently higher yield components in 'Victoria' compared to 'Perla de Csaba' indicate a varietal-dependent response to K fertilization. This disparity may stem from genetic differences influencing growth habits, nutrient uptake efficiency, and assimilate allocation. 'Victoria' variety consistently exhibits superior fruit quality compared to 'Perla de Csaba' across all three growing seasons (Table 4).

For instance, in 2021, 'Victoria' grapes had a sugar content of 18.0°Brix versus 17.0°Brix for 'Perla de Csaba', higher acidity, a lower pH and a higher phenolic content. This trend continues in 2022 and 2023, with 'Victoria's sugar content increasing from 2022 to 2023, while 'Perla de Csaba' consistently remains about 1°Brix lower.

Table 4. Grape berry quality for 'Victoria' and 'Perla de Csaba' cultivars, during 2021-2023 growing seasons

Variety	Year	K_2O dose (kg/ha)	Application timing	Sugar content (°Brix)	Acidity (% TA)	pH	Phenolic content (mg GAE/L)
Victoria	2021	120	T1	18.0[b]	0.61[b]	3.35[b]	448[b]
Victoria	2021	130	T2	18.9[a]	0.65[b]	3.40[b]	453[b]
Victoria	2021	140	T3	18.4[b]	0.68[a]	3.42[b]	461[a]
Perla de Csaba	2021	120	T1	17.3[c]	0.59[c]	3.49[b]	430[b]
Perla de Csaba	2021	130	T2	17.9[b]	0.60[b]	3.51[b]	429[b]
Perla de Csaba	2021	140	T3	18.2[b]	0.67[a]	3.58[a]	436[a]
Victoria	2022	120	T1	18.1[b]	0.62[b]	3.40[b]	459[b]
Victoria	2022	130	T2	18.6[b]	0.66[b]	3.47[a]	463[b]
Victoria	2022	140	T3	18.9[a]	0.69[a]	3.45[b]	471[a]
Perla de Csaba	2022	120	T1	17.5[c]	0.60[c]	3.30[b]	432[b]
Perla de Csaba	2022	130	T2	17.2[c]	0.62[b]	3.52[a]	439[a]
Perla de Csaba	2022	140	T3	17.9[b]	0.68[a]	3.56[a]	440[a]
Victoria	2023	120	T1	18.4[b]	0.63[b]	3.44[b]	452[b]
Victoria	2023	130	T2	18.9[a]	0.68[a]	3.41[b]	465[b]
Victoria	2023	140	T3	19.1[a]	0.66[a]	3.48[a]	473[a]
Perla de Csaba	2023	120	T1	17.9[b]	0.61[b]	3.49[b]	441[b]
Perla de Csaba	2023	130	T2	18.2[b]	0.63[b]	3.54[a]	455[a]
Perla de Csaba	2023	140	T3	18.7[a]	0.67[a]	3.39[b]	449[a]

*Different letters indicate significant differences at $p \leq 0.05$ within each column; "a" represents the highest statistically significant value; "b" and "c" indicate significantly lower values than "a"; the same letter (e.g., ab), are not significantly different from each other.

Similar patterns were observed for acidity, pH, and phenolic content, with 'Victoria' always showing statistically significant ($p \leq 0.05$) higher values for acidity and phenolics, and lower pH values than 'Perla de Csaba'. These results suggest that the 'Victoria' variety produces grapes with a more favourable composition for winemaking and higher overall quality, likely due to better adaptation or inherent genetic advantages under the given environmental conditions.

The higher sugar content in 'Victoria' (Table 4) suggests greater efficiency in carbohydrate accumulation, a trait often linked to genetic factors governing photosynthetic capacity and assimilate partitioning (Keller, 2020). Previous studies have reported that varieties with superior sugar accumulation tend to exhibit higher sink strength, allowing better mobilization of carbohydrates to developing berries (Gutiérrez-Gamboa et al., 2021). This aligns with our findings, as 'Victoria' consistently outperformed 'Perla de Csaba' in °Brix levels, likely due to a more efficient source-sink relationship.

The observed differences in acidity and pH reinforce the role of potassium fertilization and varietal metabolism in regulating berry composition. Higher acidity and lower pH values in 'Victoria' indicate a greater retention of organic acids, which is desirable for maintaining freshness and microbial stability in table grapes and wines (Brunetto et al., 2019; de Orduña R., 2010).

Grapevines regulate pH through potassium accumulation, which influences the balance between malic and tartaric acids during ripening (Sweetman et al., 2009). The lower pH in 'Victoria' suggests that this variety might have a more efficient acid retention mechanism compared to 'Perla de Csaba', contributing to its superior quality.

Phenolic compounds, which impact colour, texture, and antioxidant properties, were significantly higher in 'Victoria' across all seasons. This aligns with recent findings that certain grape varieties possess an inherent advantage in phenolic biosynthesis, which can be further enhanced through optimal potassium nutrition (Hu et al., 2023; Sperling et al., 2024). The higher phenolic content in 'Victoria' suggests a stronger activation of the phenylpropanoid pathway, which is essential for flavonoid and tannin synthesis (Delgado et al., 2004).

Studies indicate that potassium plays a critical role in secondary metabolite accumulation, which enhances both nutritional value and sensory attributes (Hu et al., 2023). Furthermore, the year-to-year increase in sugar and phenolic content in 'Victoria', particularly in 2023, may be attributed to the cumulative effects of sustained potassium fertilization and favourable environmental conditions (van Leeuwen et al., 2019).

Previous research has shown that multi-season nutrient applications lead to improved carbohydrate and secondary metabolite accumulation, as perennial tissues store reserves that contribute to fruit development in subsequent seasons (Nistor et al., 2022). This effect was more pronounced in 'Victoria', further indicating its superior ability to utilize potassium for growth and quality enhancement.

The PCA biplot (Figure 2) provides valuable insights into the relationships between the 'Victoria' (V) and 'Perla de Csaba' (PC) table grape varieties, their responses to different potassium (K_2O) treatments (T1 - 120 kg/ha, T2 - 130 kg/ha, T3 - 140 kg/ha), and the key variables influencing their growth and fruit quality.

The first two principal components, F1 (66.38%) and F2 (11.34%), collectively explain 77.72% of the total variance, indicating that the PCA captures a substantial portion of the dataset's variability and provides a reliable representation of the relationships among the variables.

Relationships among variables

Grape yield (Gy), phenolic content (Ph), canopy structure (LAI, Cw, CD, Cv, VSL), and sugar (S) exhibit a positive correlation. This suggests that increased canopy density and larger leaf area contribute to higher grape yields, greater phenolic content, and enhanced sugar accumulation.

Conversely, pH and acidity (A) display distinct associations with the two grape varieties, reflecting their differential responses to potassium treatments.

'Victoria's response to K_2O treatments

'Victoria' (represented by V22T3, V23T2, and V23T3) shows a stronger positive response to increased K_2O application. Specifically, higher potassium levels (T2 and T3) are associated with increased yield, improved canopy vigour, and enhanced fruit quality (phenolic content and sugar).

The positive correlation between 'Victoria' and acidity (A) under higher potassium treatments suggests that this variety maintains a more balanced pH and acidity level, which is favourable for fruit quality. Among the potassium treatments, T3 (140 kg/ha) appears to have the most pronounced effect on improving yield and quality traits in 'Victoria'.

'Perla de Csaba's response to K_2O treatments

'Perla de Csaba' (represented by PC21T1, PC22T1, and PC23T2) exhibits a more scattered distribution in the PCA biplot and is positioned away from the high-yield variables. This indicates a weaker response to K_2O application regarding productivity. Interestingly, pH is more strongly associated with 'Perla de Csaba' (PC21T3, PC22T3), indicating that this variety tends to maintain a higher pH and lower acidity compared to 'Victoria'.

Despite increased potassium doses, 'Perla de Csaba' does not show a significant positive correlation with key productivity and quality

traits, suggesting that its response to fertilization is more limited.
These findings provide a clear understanding of how potassium application influences grape yield and quality, aiding in the optimization of fertilization strategies for different grape varieties.

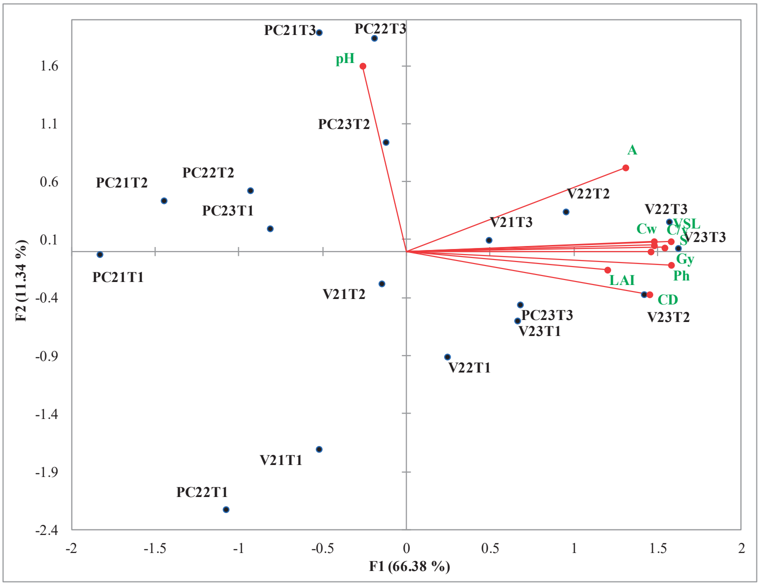

Figure 2. The PCA biplot represents the relationships between variables and treatments (2021-2023): V –'Victoria'; PC – 'Perla de Csaba'; T1 –treatment 120 kg K_2O; T2 – treatment 130 kg K_2O; T3 –treatment 140 kg K_2O; Clusters per vine (C/v), Grape yield (Gy), Vine shoot length (VSL), Cluster weight (Cw), LAI (Leaf area index), Canopy Density (CD), Sugar (S), Acidity (A), Phenolic content (Ph)

CONCLUSIONS

The study demonstrated that 'Victoria' consistently outperformed 'Perla de Csaba' in vine growth, yield, and fruit quality during the 2021–2023 growing seasons. Among the potassium fertilization treatments, the highest dose (140 kg/ha, T3) applied post-harvest resulted in the most significant improvements across all measured parameters, particularly in the 'Victoria' variety. 'Victoria' exhibited greater shoot length, leaf area index (LAI), and canopy density, which contributed to enhanced photosynthetic efficiency and increased yield components such as cluster weight, total grape yield, and the number of clusters per vine. While 'Perla de Csaba' also responded positively to potassium fertilization, its improvements were comparatively modest. Fruit quality parameters, including sugar content, acidity balance, phenolic concentration, and lower pH values, were more pronounced in 'Victoria,' indicating a stronger varietal response to increased potassium availability. Principal Component Analysis (PCA) revealed strong associations between potassium application, vine growth, and productivity, supporting the role of potassium fertilization in optimizing agronomic traits. The study suggests that post-harvest potassium application (T3) is the most effective strategy for enhancing vine growth, yield, and fruit composition during the observed period. However, further research is needed to evaluate the long-term effects of potassium fertilization on soil health, environmental sustainability, and economic viability. Future studies should explore how potassium interacts with other macronutrients, assess the cumulative impact on vine longevity, and investigate the cost-effectiveness of high-dose potassium applications across diverse climatic and soil conditions. These insights will contribute to developing more sustainable and precise potassium fertilization practices for table grape production.

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