



Synchronizing commercial maturity and enhancing organoleptic quality in table grape through hormonal and metabolic mediation induced by foliar sorbitol-calcium

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ABSTRACT

The table grape industry faces significant challenges regarding the organoleptic quality of early-season white seedless varieties, which often exhibit neutral aromatic profiles. This study evaluated the impact of foliar applications of 2.5% sorbitol, 0.7% calcium nitrate, and their combined complex (Sor-Ca) in 'Ivory™' grapes. We aimed to determine how these treatments modulate the hormonal balance, specifically absciscic acid (ABA) homeostasis, to address these physiological gaps. Results showed that Sor-Ca treatment altered harvest distribution by accelerating the ripening process, leading to a nearly two-fold increase in the proportion of fruit harvested during the initial harvest pass compared to the control, without affecting total cumulative yield. At commercial maturity, treated berries reached significantly higher sugar and phenolic levels. This metabolic shift was accompanied by an increase in total terpene concentration, primarily driven by gains in β -pinene, β -myrcene, and *D*-limonene. Hormonal profiling confirmed that these changes were linked to significantly higher active ABA levels and a 71% reduction in the inactive storage form, ABA-GE. These findings indicate that the Sor-Ca complex acts as a metabolic elicitor in 'Ivory™' table grapes, triggering the mobilization of hormonal reserves to synchronize sugar accumulation with aromatic maturation.

1. Introduction

Grapes (*Vitis vinifera* L.) represent one of the most economically significant horticultural crops globally, with Spain maintaining a dominant position in the international market (Alston & Sambucci, 2019; de Castro & Torres-Albero, 2018), is the second producer of table grapes in Europe with 364,000 ton (15,250 ha) (17.4% of the EU). Production is concentrated in the Southeast (Murcia, Alicante and Almería) and focuses on seedless varieties (Eurostat, 2024).

Within the Spanish context, the Southeastern region, particularly the Region of Murcia, has emerged as a paradigmatic enclave for intensive table grape production. This area accounts for a portion of the regional Gross Domestic Product and agricultural workforce, driven by a socio-technical transition from traditional seeded varieties to high-quality seedless (apyrene) cultivars (de Castro & Torres-Albero, 2018). The

success of this industry is largely attributed to continuous biotechnological innovation and the implementation of rigorous quality control systems, such as those governed by the protected designation of origin (PDO) "The Bagged Grape of the Vinalopó" (Guirao et al., 2024).

Despite these productive advancements, the table grape industry faces a critical challenge: the lack of organoleptic quality in early-season white seedless varieties (Akram et al., 2024; Wang et al., 2025). While consumers prioritize complex flavours and aromas, many commercial cultivars are characterized by a "neutral" aromatic profile, dominated by C6 compounds such as hexanal and (E)-2-hexenal, which impart green and herbaceous notes rather than the desirable floral or citrus descriptors associated with Muscat-type grapes (Maoz et al., 2020). This sensory deficiency is often exacerbated by agronomic practices that prioritize berry size and yield over organoleptic quality. Such high-yield strategies frequently lead to a reduction in the concentration of essential

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volatile components, compromising the overall aromatic intensity of the fruit (Maoz et al., 2020; Wang et al., 2017).

To mitigate these issues, various preharvest viticultural strategies have been explored to enhance the aromatic and nutritional profile of grapes (Alem et al., 2019; Cataldo et al., 2021). These include precision canopy management, regulated deficit irrigation, and the application of exogenous elicitors such as jasmonates and biostimulants (Cataldo et al., 2021) or as abscisic acid (ABA) treatment (Wang et al., 2022). Among these, calcium (Ca)-based treatments applied as foliar sprays have emerged as an additional viticultural strategy, capable of modulating secondary metabolism and volatile compound profiles in grape berries (Garde-Cerdán et al., 2023). However, the efficacy of these treatments is often limited by physiological barriers, particularly the restricted mobility of essential nutrients like calcium (Ca) during the post-veraison stage (Guirao et al., 2025). Ca is a vital macronutrient for maintaining cell wall integrity and fruit firmness, yet its translocation via the xylem declines sharply as the berry matures, often resulting in localized deficiencies that manifest as premature softening or cracking, which can occur either on the vine or during subsequent postharvest storage (Guirao et al., 2025; Yu et al., 2020).

Recent research has identified the use of polyols, specifically sorbitol, as a sustainable and innovative “vectoring” technology to overcome these limitations (Guirao et al., 2025). Sorbitol, a naturally occurring sugar-alcohol, possesses multiple hydroxyl groups that allow it to form stable, soluble complexes with Ca (Guirao et al., 2025). This complexation facilitates the translocation of Ca through the phloem, a route typically unavailable to the cation, thereby ensuring its delivery to the berries during critical ripening stages. Beyond its role as a carrier, sorbitol acts as a metabolic biostimulant, capable of triggering secondary metabolic pathways and enhancing the fruit antioxidant capacity and sugar accumulation (Conde et al., 2024; Guirao et al., 2024). In current research, foliar applications of sorbitol at concentrations between 1.0% and 2.5% are commonly employed to enhance the mobility of cations like calcium and zinc, providing a balance between effective nutrient delivery and the avoidance of leaf osmotic stress (Conde et al., 2024; Guirao et al., 2024).

The biosynthesis of grape aromas is a complex process regulated by an interplay of plant hormones (Fortes et al., 2015; Li, Yan, et al., 2024). ABA serves as a master regulator of ripening, coordinating the accumulation of sugars and the induction of the methylerythritol phosphate (MEP) pathway, which is responsible for the synthesis of monoterpenes (He et al., 2021; Li, Yan, et al., 2024). Recent findings suggest that foliar applications of polyols can stimulate ABA biosynthesis by several-fold, potentially acting as a catalyst for aromatic changes (Conde et al., 2024). While previous studies have utilized sorbitol-calcium (Sor-Ca) complexes primarily to control physiological disorders like berry drop or to improve firmness (Guirao et al., 2024), their potential to reconfigure the aromatic identity of a neutral cultivar remains largely unexplored.

This work represents an advancement over the existing literature as, for the first time, the Sor-Ca complex is evaluated not merely as a structural stabilizer, but as a metabolic elicitor capable of modulating the aromatic and hormonal profile of a neutral table grape cultivar. While traditional treatments have focused on structural traits, this study investigates the synergy between sorbitol and calcium in driving the “mobilization hypothesis”, where inactive hormone storage forms are converted into active signals to synchronize ripening and aromatic enhancement (Leng et al., 2013; Owen et al., 2009).

Thus, the main aim of this study is to evaluate the impact of pre-harvest foliar applications of a sorbitol-calcium complex on the ‘Ivory™’ table grape, a neutral-profile cultivar. Specifically, it seeks to determine how this treatment reconfigures the volatile organic compound (VOC) profile and modulates the endogenous hormonal balance, particularly ABA homeostasis, to promote an accelerated and higher-quality ripening program.

2. Material and methods

2.1. Plant material, experimental design, and foliar treatments

Table grapes of the ‘Ivory™’ variety (*Vitis vinifera* L. cv. Sheegene 21) were utilized for this study. The experiment was conducted during the 2024 growing season in a 4-year-old commercial vineyard (1103 Paulsen rootstock) located in Campotejar Alta (Murcia, Spain; 38°07'26.7"N 1°13'14.1"W). Vines were planted with a 3 × 3.5 m spacing and trained to a Spanish overhead trellis system protected with polyethylene (PE) mesh and low-density PE film during June and July. Water management consisted of a localized irrigation system with three emitters per vine (4 L h⁻¹ each), reaching a total volume of 3575 m³ ha⁻¹ at harvest.

The experiment followed a randomized complete block design with three rows. Each treatment was assigned to three field replicates, with each replicate consisting of a plot of three vines. To prevent cross-contamination and ensure the integrity of the results, untreated buffer vines were used to separate each block. Treatments were administered via foliar applications using a 15 L hand-pump atomizer (Sifran, S.L., Spain), approximately 1500 mL per vine (equivalent to 1400 L ha⁻¹). The four experimental treatments were: (a) 2.5% sorbitol (Barcelonesa de Drogas and Productos Químicos SAU, Spain); (b) 0.7% Ca(NO₃)₂ (Soluteck, Fertiberia S.A., Spain); (c) a combined calcium-sorbitol complex containing 2.5% sorbitol and 0.7% Ca(NO₃)₂ (Sor-Ca), and (d) water as a control. The 2.5% sorbitol concentration was selected to provide an effective metabolic signal to trigger the mobilization of hormone reserves while remaining within the physiological range that avoids leaf osmotic stress (Conde et al., 2024; Guirao et al., 2024; Solana-Guilabert et al., 2026). To enhance absorption and coverage, all solutions, including the control, were supplemented with a non-ionic surfactant (20% w/v polyglycol alkyl; Elogium, Sipcam Iberia SL, Spain). Foliar applications commenced on May 3, 2024, immediately following fruit set, and were repeated every 14 days for a total of five applications. The final treatment was applied on June 28, and no further applications were made after the harvests began. The fruit was harvested in three successive passes on July 10, 15, and 24, based on the optimum ripening stage determined by the producers.

Samples for biochemical, aromatic, and hormonal analyses were collected exclusively from the first harvest pass (July 10). For each treatment, three biological replicates (*n* = 3) were established. Each replicate consisted of a pool of nine clusters, with three clusters selected from each of the three field replicates. For subsequent biochemical analysis, berry samples were snap-frozen in liquid nitrogen and stored at −25 °C. For phytohormone determination, samples frozen in liquid nitrogen were completely freeze-dried immediately thereafter for 48 h at −80 °C. All berries used to determine respiration rate, colour, firmness, TSS, TA, total phenolic content, VOCs, and phytohormones were collected during the first harvest pass (H1), when the fruit reached commercial maturity.

2.2. Physicochemical parameters and physiological characterization

2.2.1. Crop yield and berry diameter

Each harvest day, the entire production of the selected rows was weighed using field scales, determining the kg obtained per treatment. The results are expressed as the cumulative percentage throughout the harvest and as total kg production. The equatorial diameter of a 45 grape selection per batch, within random places along the cluster, was measured with a digital calliper (± 0.01 mm). The results are expressed in mm.

2.2.2. Respiration rate, colour and firmness

The fruit was allowed to temper at room temperature (20 °C) for 2 h. Respiration rate was recorded according to Lorente-Mento et al. (2023). Briefly, table grape clusters were sealed in 3.7 L hermetic containers equipped with rubber septum for 1 h. Air samples of 1 mL were

recovered from the headspace of the containers and run into a gas chromatograph (Shimadzu CG-14B, Kyoto, Japan), together with a thermal conductivity detector and a 2 m, 1/8-in., CHROMOSORB 102 80/100 column. Results are expressed in $\text{mg CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$.

A TX-X2Ti texture analyser (Stable Micro Systems, Godalming, UK) with a flat probe was used to determine fruit firmness. A compression force was applied until reaching a 5% displacement in the equatorial diameter of 35 berries per treatment. Results were expressed in N mm^{-1} .

Colour of the berries was determined by calculating the hue angle (1) with the CIELAB colour space parameters a^* and b^* . Determinations were made with a model CR200 colorimeter (Konika Minolta, Kyoto, Japan) at harvest date.

$$h^\circ = \arctan \left(\frac{b^*}{a^*} \right) \quad (1)$$

2.2.3. Total soluble solids (TSS) and titratable acidity (TA)

TSS and TA were determined in the fresh grape juice. For extraction, manual squeezing with a cloth tissue was conducted. For broader representativity, 6 grapes of each cluster were selected from all areas of the cluster: 2 from the top, 2 from the middle and 2 from the bottom. TSS ($\text{g } 100 \text{ mL}^{-1}$) was determined with a refractometer Atago PR-101 (Atago Co. Ltd., Tokyo, Japan), whereas for TA ($\text{g eq. tartaric acid } 100 \text{ mL}^{-1}$), 1 mL of juice sample was diluted in 25 mL distilled water and titrated with an automatic titrator (785 DMP Titrino Metrohm, Herisau, Switzerland) with a solution of 0.1 N NaOH until reaching a pH 8.1 at 20 °C. The maturity index (MI) was calculated as the ratio between TSS and TA.

2.3. Determination of total phenolic content

Five mL of grape juice was mixed with 10 mL of methanol:water (80:20, v/v) with 2 mM sodium fluoride in a homogenizer T18 digital Ultraturrax (IKA Works Spain S.L., Barcelona, Spain) for 30 s. The solution was centrifuged at 10,000 rpm for 10 min at 4 °C. The supernatant was recovered and used for the reaction with the Folin-Ciocalteu reagent as previously described by Lorente-Mento et al. (2024). Total phenolic content was quantified by measuring the absorbance of the reaction at 760 nm, in duplicate, using a UV-1900 spectrophotometer.

2.4. Analysis of volatile organic compounds (VOCs)

For each treatment, 8 g of fresh berry tissue along with 1 g NaCl (12.5% w/w) were homogenized in ice with a T18 digital Ultraturrax (IKA Works Spain S.L., Barcelona, Spain) for 45 s. The ground berries were mixed with 40 μL of a 2-methyl-3-heptanone solution (10 mg L^{-1}) as an internal standard (IS) and were transferred to a hermetic crystal vial with a polypropylene cap. Headspace solid-phase microextraction (HS-SPME) was conducted. To collect the volatiles of the samples, a 50/30 mm DVB/CAR/PDMS (divinylbenzene/carboxen/polydimethylsiloxane) fiber (Supelco, Bellefonte, PA, USA) was inserted 1 cm in length into the vials. Samples were incubated at 40 °C for 40 min in constant agitation (250 rpm) using a Shimadzu AOC-6000 Plus autosampler. To isolate, identify and quantify the volatile compounds, a Shimadzu GC2030 chromatograph (Shimadzu Scientific Instruments, Inc., Columbia, MD, USA), coupled with a Shimadzu TQ8040 NX mass spectrometer detector was used. The gas chromatograph was equipped with an SLB-5 MS column of 30 m length $\times$ 0.25 mm diameter $\times$ 0.25 μm film thickness (Teknokroma, Barcelona, Spain) with helium as a carrier gas at a flow rate of 1 mL min^{-1} . The injector was at 230 °C, the ion source was at 230 °C, and the interface was at 280 °C. The sample acquisition in the injection port was programmed for 1 min. Oven temperature program started at 50 °C, then a $2^\circ \text{C min}^{-1}$ ramp until 100 °C, $3^\circ \text{C min}^{-1}$ until 180 °C, $20^\circ \text{C min}^{-1}$ until 230 °C, and held for 5 min. The mass spectrometer parameters were set at a mass range of 35–400, scan range of 1250 amu s^{-1} , an event time of 0.3 s and 70 eV electronic impact. Three methods were used for identification: (1)

retention time (RT) comparisons with commercial alkaline standard C8-C20 mixture solution (Sigma-Aldrich, Darmstadt, Germany) expressed in Kovats Index (KI), (2) similarity with the pure compounds analysed by GC-MS, and (3) similarity of the mass/charge ratio (m/z) to the reference database of the National Institute of Standards and Technology (NIST). Peaks meeting the criteria of 1: ≤ 10 Kovats index units difference between literature and experimentally obtained; 2: $\geq 90\%$ similarity with the pure compound, and 3: a m/z ratio matching the specific compound in the NIST database, were individually inspected and validated as a compound in the sample. The analyses were conducted in triplicate, and the results were expressed as $\mu\text{g g}^{-1}$ in fresh weight (F.W.) basis, percentage of the volatile by the sum of all compounds detected, odor activity value (OAV) (2) and relative aromatic impact (RAI) (3).

$$\text{OAV} = \frac{[\text{volatile}]}{\text{Detection threshold}} \quad (2)$$

$$\text{RAI } n (\%) = \frac{\text{OAV } n}{\sum \text{OAV}} \times 100 \quad (3)$$

2.5. Phytohormone extraction and quantification

Freeze-dried and ground table grape berry ($30.0 \pm 0.1 \text{ mg}$) tissue was used for the extraction and quantification of plant growth regulators, as described by García-Pastor et al. (2021), with some modifications. Under cold and dark conditions, freeze-dried samples were extracted using amber Eppendorf tubes and 1 mL of precooled (-20°C) extraction solvent solution of methanol:water:formic acid (80:15:5, v/v/v) with 250 mg L^{-1} 2,6-Di-tert-butyl-4-methylphenol (BHT), along with 50 μL at 100 ng mL^{-1} of IS mix. The IS mix contained deuterated forms of ABA (Sigma-Aldrich, Darmstadt, Germany), ABA-catabolites (National Research Council of Canada, Plant Biotechnology Institute, Saskatoon, SK, Canada), IAA and IAAsp (OChemIm, Olomouc, Czech Republic), and cytokinins (OChemIm, Olomouc, Czech Republic): d4-ABA (d4-abscisic acid), d5-ABA-GE (d5-abscisic acid glucose ester), d4-7'-OH-ABA (d4-7'-OH-hydroxy-abscisic acid), d3-DPA (d3-dihydrophaseic acid), d5-IAA (d5-indole-3-acetic acid), d5-IAA-Asp (d5-indole-3-acetic acid-aspartate), d6-IP (d6- N^6 -(Δ^2 -isopentenyl) adenine), d6-IPR (d6- N^6 -(Δ^2 -isopentenyl) adenine riboside), d6-IPRP (d6- N^6 -(Δ^2 -isopentenyl) adenine riboside-1-phosphate), d5-tZR (d5-trans-zeatin riboside) and d5-cZR (d5-cis-zeatin riboside). Samples were vortexed for 10 s to ensure proper mixing, and further incubated on ice for 20 min. Following incubation, samples were vortexed again and centrifuged at 15,000 rpm for 10 min at 4 °C. The supernatant was recovered and evaporated in a vacuum at -52°C according to the Fernández-Cancelo et al. (2025). Samples were then reconstituted with 500 μL of precooled methanol:water (50:50, v/v) containing 1 mM ammonium formate. Afterwards, the mixture was vortexed for 10 s and sonicated in a cold bath for 10 min, this process was repeated twice consecutively. The extracts were filtered through 0.2 μm nylon filters into silanized amber vials prior to LC/MS-MS analysis. Aliquots of 10 μL were injected on an HPLC system (Agilent 1200 series, Berkshire, United Kingdom) coupled with a Q-Trap 6500 mass spectrometer (AB Sciex, Framingham, MA, USA) with a $50 \times 2.1 \text{ mm}$, 1.9 μm particle size Hypersild Gold column (ThermoFisher, UK) with a flow rate of 0.4 mL min^{-1} at a constant temperature of 30 °C. mobile phases consisted of (A) water with 0.1% formic acid and 1 mM ammonium formate and (B) methanol with 0.1% formic acid and 1 mM ammonium formate in a variable gradient: increasing B at 5% for 1 min, 40% for 5 min, 95% for 1 min, and then decreasing B to 5% at 8.5 min. Quantification was conducted with a twelve-point calibration curve for each metabolite, ranging from 0.01 to 250 ng mL^{-1} . Results were manually inspected, ensuring chromatograph peak assignments. Phytohormone concentrations are expressed in $\text{ng } 100 \text{ mg}^{-1}$ in dry weight (D.W.).

2.6. Statistical analysis

For production yield and harvest distribution, data were subjected to a two-way analysis of variance (ANOVA) to evaluate the effects of foliar treatments, harvest passes, and their interaction. Physicochemical, aromatic, and hormonal parameters were analysed using samples collected exclusively from the first harvest pass (July 10). A one-way ANOVA was performed to identify significant differences between the four foliar treatments. When significant effects were identified ($p < 0.05$), means were separated using the Duncan's multiple range test.

To further evaluate the combined physiological and metabolic responses of the 'Ivory™' table grapes, a multivariate statistical analysis was performed on the full dataset of 47 variables, comprising physicochemical, hormonal, and aromatic profiles. A principal component analysis (PCA) was conducted based on the correlation matrix to reduce the dimensionality of the data while preserving the maximum variance. To enhance the interpretability of the results, a Varimax rotation with Kaiser normalization was applied to the extracted factors. Retained components were selected according to the Kaiser criterion (eigenvalues >1), with the first two components. This multivariate framework allowed for the identification of specific metabolic shifts and synergies induced by the calcium-sorbitol complex relative to the control and individual treatments. Statistical analyses were carried out with the IBM SPSS Statistic software for Windows, version 31.0.

3. Results

3.1. Harvest distribution and production yield

The foliar application of the calcium-sorbitol complex significantly altered the harvest distribution of 'Ivory™' table grapes by significantly accelerating the commercial ripening window. During the initial harvest pass (H1), the Sor-Ca treatment achieved a yield of 13.84 ± 1.42 kg vine⁻¹, representing a significant increase over the 6.83 ± 1.71 kg vine⁻¹ produced by the control group ($p < 0.05$) (Fig. 1A). This accelerated ripening is also reflected in the cumulative harvest percentages; the Sor-Ca and Ca treatments reached 22.39% and 21.12% of their total production in the first pass, respectively, nearly doubling the 12.27% recorded for the untreated vines (Fig. 1B). By the second pass (H2), the calcium-containing treatments had reached cumulative harvest rates of approximately 69%, while the control and sorbitol-only vines significantly lagged at roughly 56% ($p < 0.05$). Consequently, the production recorded during the final harvest pass (H3) was significantly lower in the Ca and Sor-Ca treatments compared to the control. This reduction does

not indicate a loss in total productivity, but rather reflects the advancement of the harvest window, as the majority of the yield in these groups had already reached commercial maturity and been harvested during the H1 and H2 passes.

3.2. Physicochemical quality and functional profile at commercial maturity

This shift in harvest timing was underpinned by a marked improvement in physicochemical quality parameters at the point of commercial maturity (Table 1). TSS reached their peak in the Sor-Ca group at 18.50 ± 0.14 g 100 mL⁻¹, in addition, the other foliar treatments, including sorbitol and calcium individually, successfully outperformed the control with 16.97 ± 0.24 g 100 mL⁻¹ ($p < 0.05$). Simultaneously, TA exhibited highly specific responses to each treatment, the Sor-Ca complex induced the lowest acidity (0.50 ± 0.01 g tartaric acid 100 mL⁻¹), whereas the application of sorbitol alone resulted in a significant increase to 0.60 ± 0.00 g 100 mL⁻¹ compared to the control with 0.56 ± 0.00 g tartaric acid 100 mL⁻¹ ($p < 0.05$). Reflecting the balance between sugars and acids, the TSS/TA ratio was significantly higher in the Sor-Ca treatment (37.00 ± 0.79) compared to all other groups.

Table 1

Berry diameter, firmness, hue angle, respiration rate, total soluble solids (TSS), titratable acidity (TA), and total phenols for each treatment in 'Ivory™' table grapes at harvest. Different lowercase letters indicate statistically significant differences ($p < 0.05$) between treatments.

	Control	Sor	Ca	Sor-Ca
Berry diameter (mm)	21.31 ± 0.18b	22.28 ± 0.22a	21.35 ± 0.27b	21.99 ± 0.20a
Firmness (N mm ⁻¹)	3.14 ± 0.10a	2.99 ± 0.12a	3.05 ± 0.12a	3.18 ± 0.14a
Colour (h°)	114.15 ± 0.25a	113.30 ± 0.29b	113.35 ± 0.31b	114.39 ± 0.23a
Respiration rate (mg CO ₂ kg ⁻¹ h ⁻¹)	20.98 ± 0.98a	20.52 ± 0.31ab	19.80 ± 0.29ab	18.21 ± 1.32b
TSS (g 100 mL ⁻¹)	16.97 ± 0.24b	17.83 ± 0.21a	18.26 ± 0.25a	18.50 ± 0.14a
TA (g tartaric acid 100 mL ⁻¹)	0.56 ± 0.00b	0.60 ± 0.00a	0.53 ± 0.01c	0.50 ± 0.01d
Maturity Index (MI) TSS/TA	30.30 ± 0.43c	29.72 ± 0.35c	34.45 ± 0.80b	37.00 ± 0.79a
Total phenols (mg eq. gallic acid 100 mL ⁻¹)	16.72 ± 0.06b	16.66 ± 0.05b	17.41 ± 0.16a	17.58 ± 0.11a

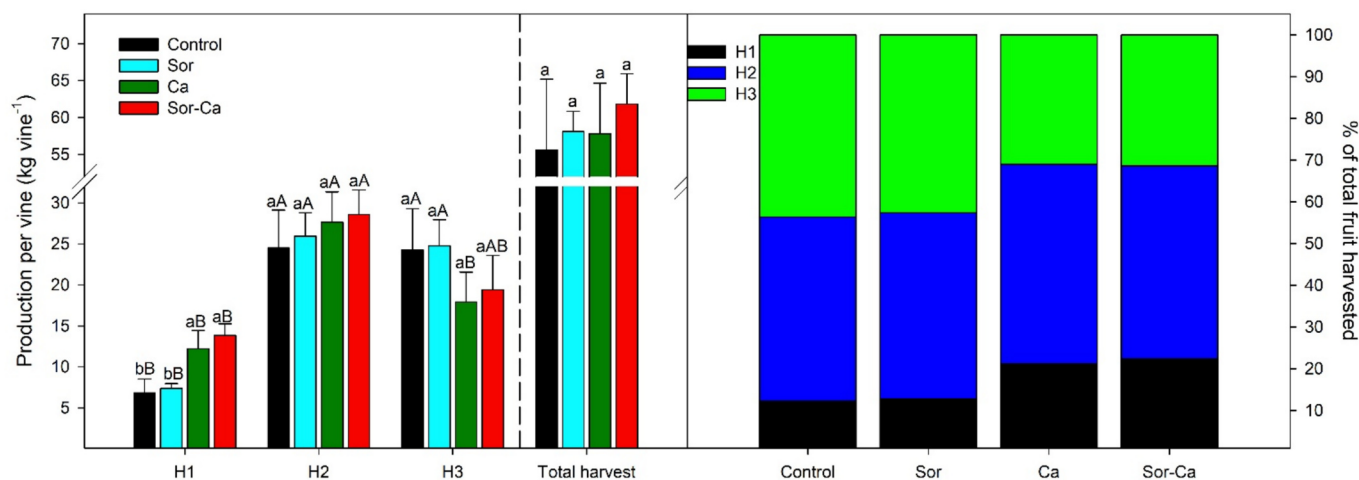


Fig. 1. Yield (kg harvested per vine) for each treatment across three harvest passes (H1, H2, and H3) and the cumulative total yield (A), and the proportion of fruit harvested (%) in each pass for every treatment (B). Data are expressed as mean $\pm$ standard error. Different lowercase letters indicate statistically significant differences ($p < 0.05$) between treatments, while different uppercase letters indicate differences ($p < 0.05$) between harvest passes.

Physiologically, the treatments influenced the fruit metabolic intensity, with the Sor-Ca application significantly lowering the respiration rate to $18.21 \pm 1.32 \text{ mg CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$ relative to the control with $20.98 \pm 0.98 \text{ mg CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$ ($p < 0.05$) (Table 1). The functional profile of the berries was also strengthened in the calcium-containing groups, as both the Ca and Sor-Ca treatments resulted in significantly higher total phenolic content (17.41 ± 0.16 and $17.58 \pm 0.11 \text{ mg gallic acid equivalents } 100 \text{ g}^{-1}$, respectively) than the control fruit ($16.72 \pm 0.06 \text{ mg gallic acid equivalents } 100 \text{ g}^{-1}$) ($p < 0.05$). While physical attributes like berry firmness remained statistically consistent across all experimental groups ($p > 0.05$), the Sor and Ca treatments showed a significant reduction in the hue angle ($p < 0.05$), indicating a shift toward a more advanced colour profile at harvest.

3.3. Characterization of volatile organic compounds (VOCs) and aromatic impact

The volatile profile of 'IvoryTM' table grapes at harvest was primarily defined by two dominant chemical groups: terpenes and aldehydes (Table 2). Foliar application of the Sor-Ca complex induced a significant increase in the total terpene concentration, which climbed to $36.81 \pm 3.57 \mu\text{g g}^{-1}$ from the $26.45 \pm 2.23 \mu\text{g g}^{-1}$ observed in the control group ($p < 0.05$). This aromatic enhancement was attributed to higher concentrations of key compounds, specifically β -pinene, β -myrcene, α -

limonene, γ -terpinene, and terpinolene ($p < 0.05$).

Interestingly, the application of sorbitol on its own also triggered specific modifications in the fruit's secondary metabolism. The Sor treatment significantly boosted geraniol concentrations to $0.95 \pm 0.08 \mu\text{g g}^{-1}$ compared to just $0.40 \pm 0.18 \mu\text{g g}^{-1}$ in the control berries ($p < 0.05$) (Table 2). This treatment also appeared to specifically favor the accumulation of neral and geranial, compounds that were either negligible or significantly lower in all other experimental groups ($p < 0.05$).

While the total sum of aldehydes remained statistically stable across treatments, the Sor-Ca group exhibited a significant reduction in (E)-2-nonenal ($p < 0.05$) (Table 2). Regarding other chemical groups, the concentration of furans and pyrones, specifically pyranone, was significantly lower in both the Sor and Ca individual treatments compared to the control ($p < 0.05$). In the alcohols and esters category, while total concentrations did not differ significantly, the ester methyl laureate was significantly more abundant in the Sor treatment than in the Sor-Ca complex ($p < 0.05$).

These quantitative variations directly dictated the sensory potential of the fruit, as reflected by the odor activity values (OAV) and the relative aromatic influence (RAI) (Table 3). The total terpene OAV reached its peak in the Sor-Ca treatment (2856.45 ± 234.2), representing a significant increase over the control (2165.71 ± 238.32), while the total aldehyde OAV concurrently decreased ($p < 0.05$). Consequently, the RAI of terpenes rose significantly to $67.12 \pm 3.56\%$ in

Table 2

Concentration ($\mu\text{g g}^{-1}$) and proportions (%) of volatile compounds (sorted by volatile groups) from treated table grapes at harvest. Results are expressed as the mean $\pm$ standard error. Different letters mean statistically significant differences ($p < 0.05$) between treatments for each compound.

Compound	Control		Sor		Ca		Sor-Ca	
	$\mu\text{g g}^{-1}$	%	$\mu\text{g g}^{-1}$	%	$\mu\text{g g}^{-1}$	%	$\mu\text{g g}^{-1}$	%
Aldehydes								
Hexanal	$2.47 \pm 0.45\text{a}$	6.84	$1.93 \pm 0.06\text{a}$	6.18	$1.96 \pm 0.11\text{a}$	5.17	$2.18 \pm 0.18\text{a}$	4.71
(E)-2-Hexenal	$5.84 \pm 0.37\text{a}$	16.17	$4.82 \pm 0.25\text{a}$	15.40	$5.46 \pm 0.32\text{a}$	14.4	$6.04 \pm 0.64\text{a}$	13.02
Nonanal	$0.18 \pm 0.02\text{a}$	0.49	$0.17 \pm 0.01\text{a}$	0.55	$0.16 \pm 0.01\text{a}$	0.43	$0.16 \pm 0.01\text{a}$	0.34
(E)-2-Nonenal	$0.10 \pm 0.01\text{a}$	0.29	$0.11 \pm 0.01\text{a}$	0.35	$0.09 \pm 0.01\text{a}$	0.25	$0.06 \pm 0.01\text{b}$	0.14
Decanal	$0.08 \pm 0.01\text{a}$	0.23	$0.08 \pm 0.00\text{a}$	0.26	$0.08 \pm 0.00\text{a}$	0.21	$0.09 \pm 0.00\text{a}$	0.20
(E)-2-Decenal	$0.02 \pm 0.01\text{a}$	0.06	$0.01 \pm 0.00\text{a}$	0.03	$0.01 \pm 0.00\text{a}$	0.02	$0.01 \pm 0.00\text{a}$	0.02
Neral	$0.00 \pm 0.00\text{b}$	0.00	$0.06 \pm 0.01\text{a}$	0.2	$0.00 \pm 0.00\text{b}$	0.00	$0.00 \pm 0.00\text{b}$	0.00
Geranial	$0.04 \pm 0.02\text{b}$	0.11	$0.07 \pm 0.01\text{a}$	0.22	$0.03 \pm 0.01\text{b}$	0.09	$0.03 \pm 0.00\text{b}$	0.06
Undecanal	$0.05 \pm 0.04\text{a}$	0.14	$0.01 \pm 0.00\text{a}$	0.04	$0.01 \pm 0.00\text{a}$	0.04	$0.01 \pm 0.00\text{a}$	0.02
(E,E)-2,4-Decadienal	$0.01 \pm 0.00\text{a}$	0.02	$0.01 \pm 0.00\text{a}$	0.03	$0.01 \pm 0.00\text{a}$	0.02	$0.01 \pm 0.00\text{a}$	0.02
Σ	$8.80 \pm 0.79\text{a}$	24.34	$7.27 \pm 0.30\text{a}$	23.26	$7.83 \pm 0.38\text{a}$	20.63	$8.60 \pm 0.79\text{a}$	18.53
Terpenes and terpenoids								
α -Thujene	$0.10 \pm 0.04\text{a}$	0.29	$0.04 \pm 0.01\text{a}$	0.12	$0.07 \pm 0.02\text{a}$	0.18	$0.12 \pm 0.03\text{a}$	0.25
β -Pinene	$1.94 \pm 0.83\text{b}$	5.38	$1.80 \pm 0.59\text{b}$	5.75	$3.02 \pm 0.70\text{ab}$	7.96	$4.61 \pm 0.84\text{a}$	9.94
β -Myrcene	$0.88 \pm 0.26\text{b}$	2.44	$0.66 \pm 0.15\text{b}$	2.10	$1.09 \pm 0.18\text{ab}$	2.87	$1.78 \pm 0.32\text{a}$	3.84
<i>o</i> -Cymene	$0.06 \pm 0.01\text{a}$	0.16	$0.05 \pm 0.01\text{a}$	0.17	$0.06 \pm 0.00\text{a}$	0.17	$0.07 \pm 0.00\text{a}$	0.16
<i>D</i> -Limonene	$19.97 \pm 2.27\text{b}$	55.26	$17.40 \pm 0.39\text{b}$	55.64	$21.93 \pm 0.43\text{ab}$	57.83	$26.02 \pm 2.08\text{a}$	56.11
γ -Terpinene	$2.00 \pm 0.28\text{b}$	5.52	$1.41 \pm 0.20\text{b}$	4.50	$2.17 \pm 0.17\text{ab}$	5.71	$3.10 \pm 0.47\text{a}$	6.68
Terpinolene	$0.09 \pm 0.00\text{ab}$	0.24	$0.06 \pm 0.01\text{b}$	0.19	$0.09 \pm 0.00\text{ab}$	0.24	$0.13 \pm 0.03\text{a}$	0.29
Linalool	$0.07 \pm 0.01\text{ab}$	0.21	$0.12 \pm 0.03\text{a}$	0.40	$0.06 \pm 0.02\text{ab}$	0.15	$0.05 \pm 0.01\text{b}$	0.1
Terpinen-4-ol	$0.55 \pm 0.08\text{ab}$	1.54	$0.70 \pm 0.06\text{a}$	2.24	$0.51 \pm 0.20\text{ab}$	1.35	$0.17 \pm 0.11\text{b}$	0.38
α -Terpineol	$0.06 \pm 0.00\text{a}$	0.16	$0.06 \pm 0.00\text{a}$	0.19	$0.05 \pm 0.02\text{ab}$	0.13	$0.02 \pm 0.05\text{b}$	0.05
Nerol	$0.05 \pm 0.02\text{a}$	0.14	$0.05 \pm 0.02\text{a}$	0.13	$0.01 \pm 0.01\text{a}$	0.17	$0.02 \pm 0.02\text{a}$	0.05
Citronellol	$0.14 \pm 0.11\text{a}$	0.40	$0.05 \pm 0.01\text{a}$	0.16	$0.03 \pm 0.01\text{a}$	0.07	$0.01 \pm 0.00\text{a}$	0.02
(-)-Carvone	$0.01 \pm 0.00\text{a}$	0.02	$0.01 \pm 0.00\text{a}$	0.02	$0.00 \pm 0.00\text{a}$	0.01	$0.00 \pm 0.00\text{a}$	0
Geraniol	$0.40 \pm 0.18\text{b}$	1.10	$0.95 \pm 0.08\text{a}$	3.05	$0.45 \pm 0.07\text{b}$	1.19	$0.56 \pm 0.07\text{b}$	1.22
Geranic acid	$0.12 \pm 0.05\text{a}$	0.35	$0.21 \pm 0.01\text{a}$	0.67	$0.12 \pm 0.01\text{a}$	0.31	$0.14 \pm 0.01\text{a}$	0.29
Σ	$26.45 \pm 2.24\text{b}$	73.21	$23.57 \pm 0.84\text{b}$	75.37	$29.66 \pm 0.33\text{ab}$	78.21	$36.81 \pm 3.58\text{a}$	79.38
Furans and pyrones								
(4H)-Pyranone	$0.28 \pm 0.08\text{a}$	0.78	$0.02 \pm 0.01\text{b}$	0.07	$0.04 \pm 0.00\text{b}$	0.10	$0.23 \pm 0.11\text{ab}$	0.51
5-HMF	$0.42 \pm 0.24\text{a}$	1.17	$0.03 \pm 0.02\text{a}$	0.11	$0.03 \pm 0.01\text{a}$	0.09	$0.47 \pm 0.36\text{a}$	1.02
Σ	$0.71 \pm 0.312\text{a}$	1.95	$0.06 \pm 0.02\text{a}$	0.18	$0.07 \pm 0.01\text{a}$	0.19	$0.71 \pm 0.48\text{a}$	1.53
Alcohols and esters								
1-Dodecanol	$0.15 \pm 0.10\text{a}$	0.42	$0.33 \pm 0.06\text{a}$	1.06	$0.33 \pm 0.01\text{a}$	0.87	$0.24 \pm 0.07\text{a}$	0.53
Methyl laureate	$0.03 \pm 0.00\text{ab}$	0.08	$0.04 \pm 0.00\text{a}$	0.14	$0.04 \pm 0.01\text{ab}$	0.10	$0.02 \pm 0.01\text{b}$	0.04
Σ	$0.18 \pm 0.10\text{a}$	0.49	$0.38 \pm 0.07\text{a}$	1.2	$0.37 \pm 0.00\text{a}$	0.97	$0.26 \pm 0.08\text{a}$	0.57

Table 3

Odor detection threshold, Odor Activity Value (OAV) and Relative Aromatic Influence (RAI) of each volatile compound sorted by chemical class from treated table grapes at harvest. OAV is the ratio between the compound concentration divided to its odor detection threshold. RAI is defined as the OAV of the compound divided by the sum of all OAVs in the sample. Results are expressed as the mean $\pm$ standard error. Different letters mean statistically significant differences ($p < 0.05$) between treatments for each compound.

Compound	Ref.	Odor detection threshold (µg g ⁻¹)	Control		Sor		Ca		Sor-Ca	
			OAV	RAI (%)	OAV	RAI (%)	OAV	RAI (%)	OAV	RAI (%)
Aldehydes										
Hexanal	1	0.00450	549.04 ± 99.44a	13.04 ± 1.17a	429.41 ± 14.11a	11.08 ± 0.67a	436.12 ± 24.74a	10.66 ± 0.63a	485.61 ± 39.12a	11.43 ± 0.77a
(E)-2-Hexenal	2	0.79000	7.39 ± 0.47a	0.18 ± 0.01a	6.10 ± 0.32a	0.16 ± 0.01a	6.91 ± 0.40a	0.17 ± 0.01a	7.64 ± 0.81a	0.18 ± 0.01a
Nonanal	2	0.00310	56.94 ± 6.39a	1.39 ± 0.16a	55.88 ± 2.42a	1.44 ± 0.09a	52.53 ± 3.81a	1.29 ± 0.11a	50.56 ± 2.32a	1.20 ± 0.08a
(E)-2-Nonenal	1	0.00008	1305.17 ± 98.16a	31.83 ± 2.63a	1362.67 ± 94.64a	34.95 ± 1.53a	1164.3 ± 73.97a	28.39 ± 1.38a	790.61 ± 113.90b	18.83 ± 3.28b
Decanal	2	0.00260	31.95 ± 2.73a	0.79 ± 0.12a	31.34 ± 0.72a	0.81 ± 0.04a	30.96 ± 0.61a	0.76 ± 0.03a	35.36 ± 1.55a	0.84 ± 0.06a
(E)-2-Decenal	2	0.00490	4.61 ± 2.65a	0.11 ± 0.07a	1.86 ± 0.03a	0.05 ± 0.00a	1.67 ± 0.21a	0.04 ± 0.01a	2.23 ± 0.65a	0.05 ± 0.01a
Neral	2	0.00880	0.00 ± 0.00b	0.00 ± 0.00b	7.06 ± 0.75a	0.18 ± 0.02a	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b
Geranial	1	0.03200	1.19 ± 0.5b	0.03 ± 0.01b	2.11 ± 0.20a	0.05 ± 0.01a	1.07 ± 0.22b	0.03 ± 0.01b	0.86 ± 0.13b	0.02 ± 0.00b
Undecanal	2	0.14000	0.37 ± 0.30a	0.01 ± 0.01a	0.10 ± 0.01a	0.00 ± 0.00a	0.11 ± 0.02a	0.00 ± 0.00a	0.08 ± 0.01a	0.00 ± 0.00a
(E,E)-2,4-Decadienal	1	0.18000	0.05 ± 0.01a	0.00 ± 0.00a	0.05 ± 0.00a	0.00 ± 0.00a	0.05 ± 0.00a	0.00 ± 0.00a	0.04 ± 0.00a	0.00 ± 0.00a
Σ			1956.69 ± 172.15a	47.63 ± 1.70ab	1896.57 ± 78.38a	48.73 ± 0.76a	1693.72 ± 62.24ab	41.33 ± 0.82b	1373.01 ± 110.28b	32.55 ± 3.44c
Terpenes and terpenoids										
α-Thujene	n/a									
β-Pinene	2	0.18000	10.80 ± 4.60b	0.28 ± 0.12b	10.00 ± 3.27b	0.26 ± 0.08b	16.77 ± 3.87ab	0.41 ± 0.10ab	25.61 ± 4.66a	0.60 ± 0.09a
β-myrcene	1	0.01400	62.99 ± 10.82b	1.53 ± 0.25b	46.93 ± 10.73b	1.21 ± 0.27b	77.87 ± 12.55b	1.91 ± 0.32ab	127.09 ± 22.72a	2.97 ± 0.45a
o-Cymene	2	0.00500	11.67 ± 0.91ab	0.28 ± 0.03a	10.52 ± 1.57b	0.27 ± 0.04a	12.76 ± 0.98ab	0.31 ± 0.03a	14.43 ± 0.73a	0.34 ± 0.01a
α-Limonene	1	0.01000	1996.82 ± 226.86b	48.06 ± 1.81bc	1739.80 ± 22.32b	44.77 ± 0.67c	2193.59 ± 24.71ab	54.20 ± 0.13b	2602.51 ± 208.38a	61.16 ± 3.12a
γ-Terpinene	2	2.50000	0.80 ± 0.11b	0.02 ± 0.00ab	0.56 ± 0.08b	0.01 ± 0.00b	0.87 ± 0.07ab	0.02 ± 0.00ab	1.24 ± 0.19a	0.03 ± 0.00a
Terpinolene	2	0.20000	0.43 ± 0.00ab	0.01 ± 0.00a	0.30 ± 0.04b	0.01 ± 0.00a	0.45 ± 0.02ab	0.01 ± 0.00a	0.66 ± 0.13a	0.02 ± 0.00a
Linalool	1	0.00600	12.48 ± 1.54ab	0.31 ± 0.05ab	20.62 ± 5.55a	0.54 ± 0.16a	9.75 ± 3.84ab	0.24 ± 0.09ab	7.79 ± 2.00b	0.18 ± 0.04b
Terpinen-4-ol	2	0.34000	1.63 ± 0.24ab	0.04 ± 0.00ab	2.06 ± 0.17a	0.05 ± 0.00a	1.51 ± 0.58ab	0.04 ± 0.01ab	0.51 ± 0.32b	0.01 ± 0.01b
α-Terpieol	1	0.33000	0.17 ± 0.00a	0.00 ± 0.00a	0.18 ± 0.01a	0.00 ± 0.00a	0.15 ± 0.05ab	0.00 ± 0.00a	0.07 ± 0.01b	0.00 ± 0.00a
Nerol	1	0.30000	0.17 ± 0.06a	0.00 ± 0.00a	0.18 ± 0.08a	0.00 ± 0.00a	0.05 ± 0.05a	0.00 ± 0.00a	0.07 ± 0.07a	0.00 ± 0.00a
Citronellol	1	0.01000	14.38 ± 11.38a	0.36 ± 0.28a	4.87 ± 1.22a	0.12 ± 0.03a	2.78 ± 0.87a	0.07 ± 0.02a	1.11 ± 0.29a	0.03 ± 0.01a
(-)-Carvone	1	0.05000	0.16 ± 0.08a	0.00 ± 0.00a	0.14 ± 0.03a	0.00 ± 0.00a	0.07 ± 0.04a	0.00 ± 0.00a	0.04 ± 0.03a	0.00 ± 0.00a
Geraniol	1	0.00750	53.14 ± 24.73b	1.27 ± 0.56b	127.14 ± 10.78a	3.26 ± 0.21a	60.12 ± 9.97b	1.46 ± 0.22b	75.25 ± 9.53b	1.78 ± 0.26b
Geranic acid	3	2.20000	0.06 ± 0.02a	0.00 ± 0.00a	0.09 ± 0.00a	0.00 ± 0.00a	0.05 ± 0.01a	0.00 ± 0.00a	0.06 ± 0.01a	0.00 ± 0.00a
Σ			2165.71 ± 238.32b	52.16 ± 1.79c	1963.39 ± 32.4b	50.52 ± 0.80c	2376.78 ± 23.47ab	58.68 ± 0.29b	2856.45 ± 234.2a	67.12 ± 3.56a
Furans and pyrones										
(4H)-Pyranone	2	35	0.01 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.01 ± 0.00a	0.00 ± 0.00a
5-HMF	2	1000	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a
Σ			0.01 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.00 ± 0.00a	0.01 ± 0.00a	0.00 ± 0.00a
Alcohols and esters										
1-Dodecanol	2	1.2000	0.12 ± 0.08a	0.00 ± 0.00a	0.28 ± 0.05a	0.01 ± 0.00a	0.27 ± 0.01a	0.01 ± 0.00a	0.20 ± 0.06a	0.00 ± 0.00a

(continued on next page)

Table 3 (continued)

Compound	Ref.	Odor detection threshold (µg g ⁻¹)	Control		Sor		Ca		Sor-Ca	
			OAV	RAI (%)	OAV	RAI (%)	OAV	RAI (%)	OAV	RAI (%)
Methyl laureate	2	0.0015	18.44 ± 3.25ab	0.46 ± 0.10ab	29.2 ± 3.19a	0.75 ± 0.08a	24.45 ± 4.70ab	0.60 ± 0.12ab	13.10 ± 5.38b	0.32 ± 0.14b
Σ			18.57 ± 3.29ab	0.46 ± 0.10ab	29.48 ± 3.24a	0.76 ± 0.08a	24.72 ± 4.70ab	0.61 ± 0.12ab	13.30 ± 5.40b	0.32 ± 0.14b

1: Belitz et al. (2009); 2: Van Gemert (2011); 3: Wu et al. (2025).

the Sor-Ca group, up from 52.16 ± 1.79% in the control, while the relative impact of aldehydes fell from 47.63 ± 1.70% to 32.55 ± 3.44% (*p* < 0.05). Additionally, the Sor treatment showed a significantly higher RAI for alcohols and esters (0.76%) compared to the Sor-Ca group (0.32%), primarily due to the increased OAV of methyl laureate (*p* < 0.05). Overall, these results demonstrate that the Sor-Ca complex induces a targeted shift in the ‘Ivory™’ grape aroma, shifting the balance away from green-fatty aldehyde notes toward more desirable floral and citrus-like terpene descriptors.

3.4. Endogenous phytohormone profiling

The analysis of plant growth regulators (PGRs) in ‘Ivory™’ table grapes at harvest revealed a significant change of the hormonal profile, particularly within the ABA metabolic pathway (Fig. 2A). The application of the Sor-Ca complex acted as a catalyst for ABA accumulation, driving active ABA levels to 12.55 ± 0.79 ng 100 mg⁻¹ D.W., a significant increase over the 8.91 ± 0.43 ng 100 mg⁻¹ D.W. recorded in the control group (*p* < 0.05). This rise in the active hormone was accompanied by a depletion of its storage form, ABA-GE, which fell from 9.93 ± 2.52 ng 100 mg⁻¹ d.w. in the control to just 2.85 ± 0.21 ng 100 mg⁻¹ D.W. in the Sor-Ca treated fruit (*p* < 0.05). Mirroring this trend, all foliar treatments, especially the Sor-Ca complex, induced a significant accumulation of the catabolite 7'-OH ABA (reaching 4.97 ± 0.68 ng 100 mg⁻¹ D.W.) while simultaneously reducing (DPA) levels (*p* < 0.05).

Auxin profile also showed distinctive modifications, with a clear differentiation between treatments (Fig. 2B). The Sor treatment was remarkably effective in promoting the free IAA, reaching a value of 0.16 ± 0.004 ng 100 mg⁻¹ D.W., whereas the rest of the treatments behaved similarly to control (*p* < 0.05). Nevertheless, a physiological response was revealed in the increase of the conjugate form, indole-3-acetic acid aspartate (IAA-Asp) in all treated berries. This response was more prominent in the Ca treatment fruit, where IAA-Asp levels reached 2.57 ± 0.47 ng 100 mg⁻¹, compared to the content measured in control fruit (1.36 ± 0.11 ng 100 mg⁻¹ D.W.), suggesting a homeostatic adjustment to maintain auxin balance (*p* < 0.05).

Regarding cytokinins, the data showed a general downward trend in the most active forms, though the Sor-Ca complex provided a notable exception (Fig. 2C). Concentrations of N⁶-(Δ²-isopentenyl) adenine (IP) significantly decreased in both the Sor (1.88 ± 0.10 ng 100 mg⁻¹ D.W.) and Sor-Ca (1.63 ± 0.24 ng 100 mg⁻¹ D.W.) groups relative to the 3.02 ± 0.15 ng 100 mg⁻¹ d.w. found in control grapes (*p* < 0.05). Similarly, N⁶-(Δ²-isopentenyl)adenine riboside (IPR) was significantly reduced by the sorbitol treatment (*p* < 0.05). Despite this general decline, the Sor-Ca complex specifically promoted a significant increase in *trans*-zeatin riboside (tZR), which rose to 0.07 ± 0.01 ng 100 mg⁻¹ D.W., effectively doubling the concentration observed in the control (*p* < 0.05). In contrast, *cis*-zeatin riboside (cZR) remained stable across all experimental conditions. Taken together, these results demonstrate that the Sor-Ca complex rebalances the berry hormonal status at harvest, favouring ABA-driven ripening processes while modulating the interplay between auxins and cytokinins.

3.5. Multivariate integration of metabolic and physiological modifications

A principal component analysis (PCA) was performed to integrate

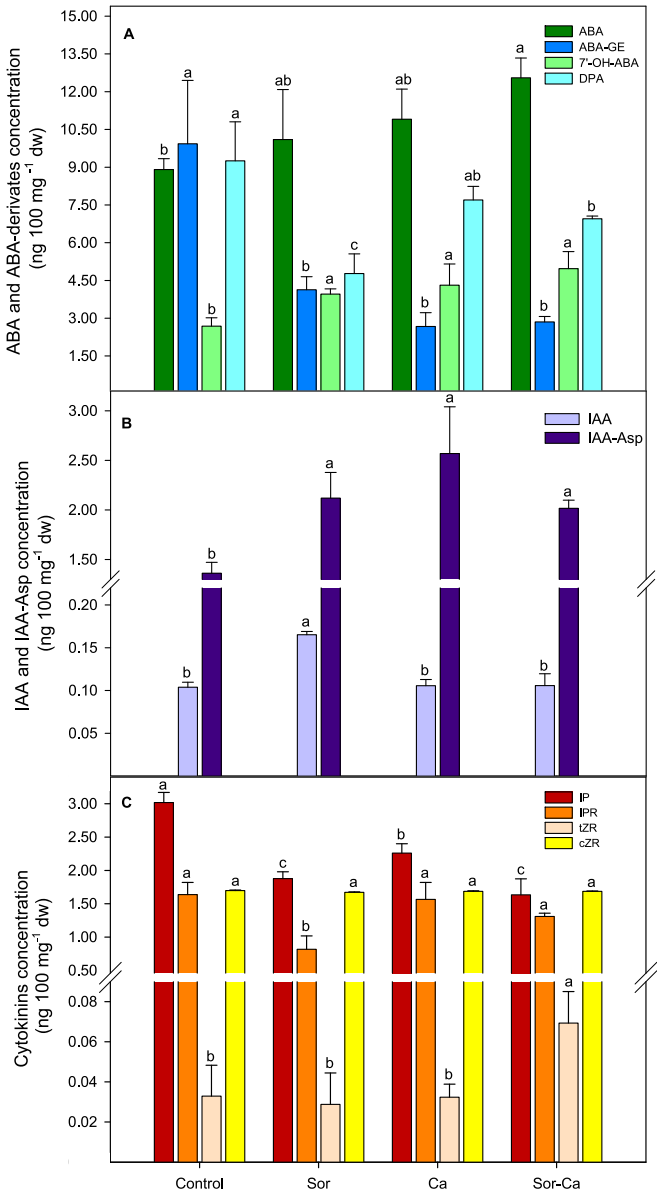


Fig. 2. Contents of abscisic acid (ABA) derivatives (A): ABA glucosyl ester (ABA-GE), 7'-hydroxy-ABA (7'-OH ABA), and dihydrophaseic acid (DPA); contents of indole acetic acid (IAA) and indole acetic acid aspartate (IAA-Asp) (B); and contents of cytokinins (C): N⁶-(Δ²-isopentenyl)adenine (IP), N⁶-(Δ²-isopentenyl)adenine riboside (IPR), *trans*-zeatin riboside (tZR), and *cis*-zeatin riboside (cZR) in ‘Ivory™’ table grapes at harvest. Results are expressed as the mean ± standard error. Different letters indicate statistically significant differences (*p* < 0.05) between treatments for each hormone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the physicochemical, hormonal, and volatile datasets, explaining

56.65% of the total variance. The first component (PC1) accounted for 34.17%, while the second component (PC2) contributed 22.47%.

As illustrated in the PCA biplot (Fig. 3), PC1 represents the primary axis for aromatic and maturity differentiation. High positive loadings on PC1 were recorded for β -myrcene (0.939), geraniol (0.56), and total phenols (0.697). Conversely, this axis showed strong negative loadings for titratable acidity (-0.885) and green-note volatiles such as (E)-2-nonenal (-0.873). This component effectively separates berries with a high terpene profile and advanced maturity from those defined by herbaceous descriptors and higher acidity.

PC2 primarily reflects the fruit hormonal homeostasis and storage status (Fig. 3). Strong positive loadings were observed for the inactive hormone storage form ABA-GE (0.923) and citronellol (0.851). In contrast, total soluble solids (-0.806), the active hormone catabolite 7'-OH-ABA (-0.677), and the auxin conjugate IAA-Asp (-0.684) loaded negatively. Furthermore, the segregation of the Sor treatment is defined by its association with free IAA and geraniol, while the Sor-Ca complex is characterized by its proximity to active ABA, *t*ZR, and high TSS, reflecting a synchronized ripening program.

The PCA biplot (Fig. 3) reveals a clear spatial segregation between the experimental groups. The Sor-Ca treatment is uniquely positioned in the quadrant associated with high monoterpene concentrations, increased phenolic content, and advanced sugar levels. In contrast, the control group is in the diametrically opposite sector, characterized by

higher acidity, markers of hormone storage (ABA-GE), and an aromatic profile dominated by green-fatty aldehydes. The Sor treatment is in the quadrant with negative PC1 and PC2 values, showing a spatial proximity to IAA content and specific alcohols, esters and terpene compounds such as methyl laurate, 1-dodecanol, geraniol and geranic acid. On the other hand, Ca treatment remains generally neutral between treatments. These multivariate distributions confirm that the Sor-Ca complex reconfigures berry metabolism by synchronizing sugar accumulation with a transition from a neutral to a terpene aromatic identity.

4. Discussion

4.1. Nutrient mobility and phloem transport mechanisms

Effectively delivering calcium (Ca) to table grape after veraison remains a fundamental challenge in viticulture. As a phloem-immobile nutrient, Ca typically enters the berry via the xylem, driven by transpiration (Guirao et al., 2025). However, after veraison, xylem functionality in the berry declines and transpiration rates drop significantly, often leading to localized Ca deficiencies that manifest as cracking or softening (Guirao et al., 2025; Yu et al., 2020).

The combined Sor-Ca treatment doubled the early yield in the first harvest pass (H1) and significantly enhanced fruit quality. This success is attributed to the vectoring properties of sorbitol. As a sugar-alcohol

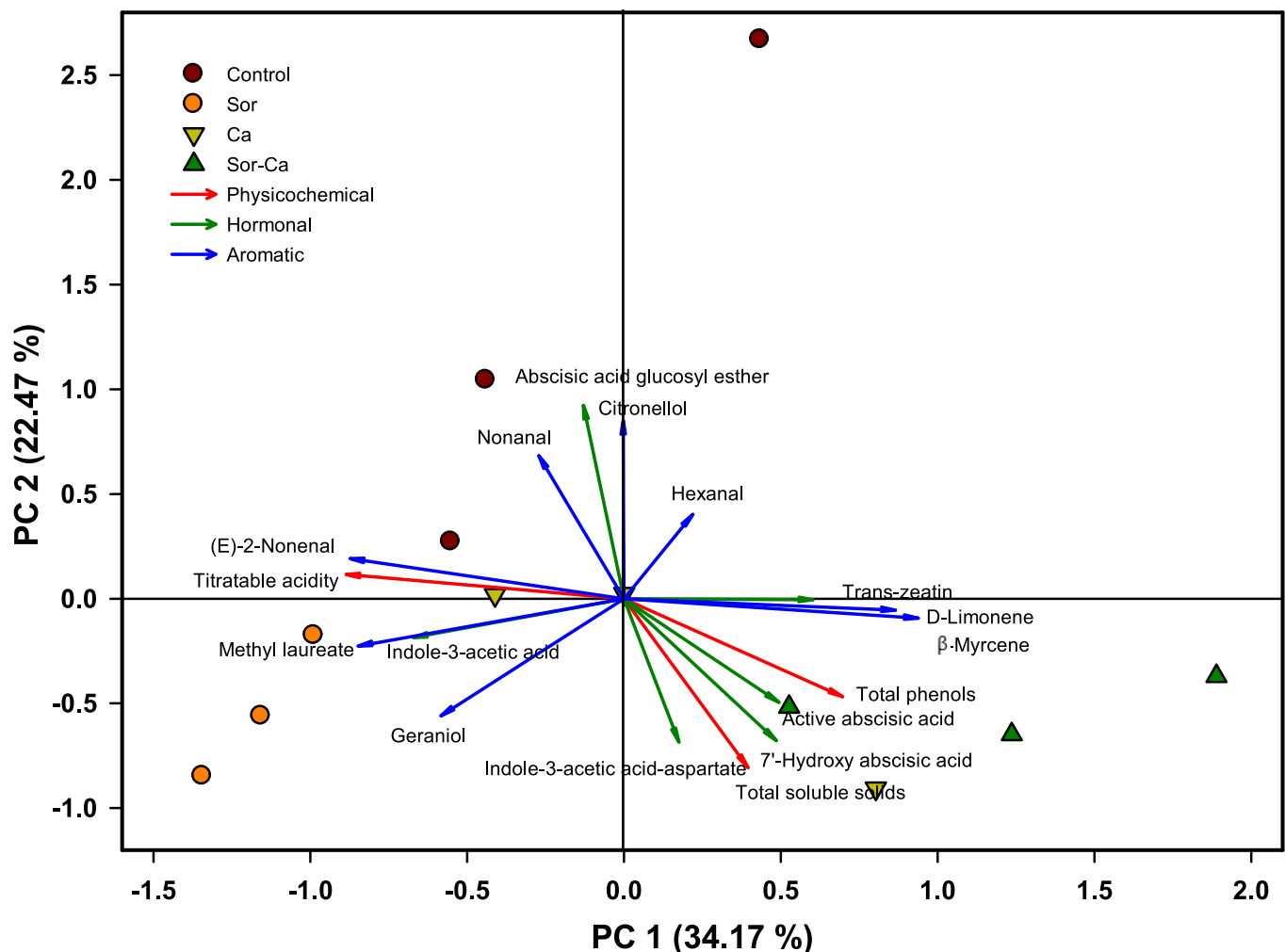


Fig. 3. Principal component analysis (PCA) biplot of selected physicochemical traits, volatile compounds, and hormones at harvest. Total soluble solids; Titratable acidity; Total phenolic content; Active abscisic acid; ABA glucosyl ester; 7'-hydroxy-ABA; Indole-3-acetic acid; indole-3-acetic acid-aspartate; *Trans*-zeatin riboside; β -Myrcene; *D*-Limonene; (E)-2-nonenal; Hexanal; Nonanal; Citronellol; Methyl laurate; Geraniol. The biplot shows the most representative vectors for treatment segregation.

with multiple hydroxyl groups, sorbitol forms stable, soluble complexes with Ca, facilitating its translocation through the phloem, a route normally restricted to this cation (Guirao et al., 2025). This “carrier-mediated” transport allows Ca to reach sink organs (the berries) during the stages of development when they are most susceptible to physiological disorders (Guirao et al., 2025, 2024).

4.2. Aromatic profile transitions and secondary metabolism

Table grape aromas are generally classified into four categories: Muscat (high monoterpenes), Strawberry/Fox (high esters like methyl anthranilate), Aromatic (moderate terpenes), and Neutral (low volatiles, mostly C6 aldehydes and alcohols) (Li et al., 2023; Maoz et al., 2020; Moriyama et al., 2024).

The control ‘Ivory™’ grapes exhibited a profile dominated by C6 aldehydes and alcohols, such as hexanal and (E)-2-hexenal, which are characteristic of neutral varieties like ‘Thompson Seedless’ or ‘Victoria’ (Li et al., 2023). These compounds provide the “green”, “grassy”, and “herbaceous” notes typical of under-ripe or neutral berries (Fei et al., 2026; Moriyama et al., 2024; Qian et al., 2017). However, the application of the Sor-Ca complex induced a shift toward an aromatic profile, significantly increasing the total terpene concentration to $36.81 \pm 3.57 \mu\text{g g}^{-1}$. This enhancement included gains in β -pinene, β -myrcene, and ν -limonene. In contrast, the application of sorbitol alone specifically boosted geraniol and induced the accumulation of neral and geranial, which were absent in the control.

These findings suggest that while ‘Ivory™’ is genetically positioned as a neutral or lightly aromatic cultivar, the foliar treatments acted as metabolic elicitors, pushing its aromatic identity toward the Muscat-type spectrum. The increase in the Relative Aromatic Influence (RAI) of terpenes to 67.12% in the Sor-Ca group demonstrates a transition from green-fatty notes to more maturity-related floral and citrus-like descriptors.

The observed changes in the volatile profile between the treated and untreated grapes could be rooted in the activation of specific biosynthetic pathways, primarily the methylerythritol phosphate (MEP) pathway for terpenes and the lipoxygenase (LOX) pathway for C6 volatiles (Lu et al., 2022; Qian et al., 2017; Salifu et al., 2022).

The Sor-Ca treatment significantly reduced the concentration of (E)-2-nonenal, a finding that supports the observed advanced maturation program. Since this compound is typically associated with green and fatty aromas, its decline suggests that the Sor-Ca complex influences alcohol dehydrogenase (ADH) and enal isomerase activities within the LOX pathway to favor aromatic quality (Kalua & Boss, 2009; Kuhn et al., 2013). This shift, coupled with the stability of total aldehydes across treatments, helps the fruit transition from neutral notes to a more mature profile.

The surge in monoterpenes in Sor-Ca treated grapes is primarily driven by the activation of the plastidial MEP pathway, which is established as the dominant route for these compounds in grapevine (Luan & Wüst, 2002; Salifu et al., 2022). The foliar treatment likely acted as a metabolic biostimulant, enhancing the flux of precursors through this pathway to coordinate the aromatic maturation of the berries (Guirao et al., 2025; Li, Yan, et al., 2024). This metabolic shift not only increased the terpene concentration but also effectively reduced aldehyde levels, providing a chemical explanation for the improved flavour profile observed in modern table grape breeding programs (Maoz et al., 2020).

4.3. Hormonal regulation of ‘Ivory™’ ripening

The hormonal profile of ‘Ivory™’ grapes at harvest underwent profound changes following the application of the Sor-Ca complex, primarily characterized by a strategic shift in abscisic acid (ABA) homeostasis. Our results revealed a significant increase in active ABA ($12.55 \pm 0.79 \text{ ng } 100 \text{ mg}^{-1} \text{ D.W.}$) alongside a depletion of its inactive

storage form, ABA-GE, which fell to $2.85 \pm 0.21 \text{ ng } 100 \text{ mg}^{-1} \text{ D.W.}$ Our results showed that both Ca and Sor-Ca treatments advanced the ripening window and increased active ABA levels. This indicates that, under these experimental conditions, calcium promotes ripening in ‘Ivory™’ grapes rather than delaying it, as reported in other cultivars (Martins et al., 2021). The 71% depletion of ABA-GE in the Sor-Ca group specifically points to the mobilization of hormonal reserves (Leng et al., 2013; Owen et al., 2009). This process potentially involves the activation of calcium-dependent -glucosidase to release free ABA, a mechanism proposed in similar ripening models (Fortes et al., 2015; Sun et al., 2010). Additionally, the rise in 7'-OH-ABA alongside lower DPA levels suggests a redirection of ABA catabolism toward the 7'-hydroxylation route in treated fruit, providing a clear enzymatic basis for the observed hormonal shift (Castellarin et al., 2016).

In non-climacteric fruits like the grape, ABA is recognized as the primary trigger for the onset of ripening (veraison), regulating sugar accumulation, berry softening, and pigment synthesis (Fortes et al., 2015; Kuhn et al., 2013; Wheeler et al., 2009). The sharp increase in active ABA observed in the Sor-Ca group explains the significant acceleration of the commercial ripening window and the doubling of yield in the first harvest pass (H1).

The auxin profile also demonstrated a clear homeostatic adjustment. While sorbitol alone boosted free IAA, the Sor-Ca and Ca-only treatments led to a significant accumulation of the conjugated form IAA-Asp. In grape berries, low levels of free IAA are required for ripening to proceed, as auxins typically function as ripening inhibitors that delay the accumulation of sugars and anthocyanins (Deluc et al., 2007; Kuhn et al., 2013; Wheeler et al., 2009). The sequestration of free IAA into IAA-Asp, mediated by the GH3 gene family, is a well-documented mechanism for removing active auxin from the system to enable the ABA-driven ripening program to dominate (Böttcher et al., 2013; Fortes et al., 2015; Kühn et al., 2016). This high conjugation rate in treated fruit confirms a more advanced physiological ripening state compared to the control.

The cytokinin dynamics provided further evidence of synchronized maturity. The Sor-Ca complex specifically induced a significant rise in *tZR*, effectively doubling the concentration compared to the control. Cytokinins are known to interact with ABA to promote sink strength and fruit expansion (Fortes et al., 2015; Li, Javed, et al., 2022; Li, Quan, et al., 2022). The spatial synergy between *tZR* and total yield shown in our PCA scores plot confirms that this hormone is a critical driver for the harvest homogeneity and productivity increases observed in the ‘Ivory™’ variety.

4.4. Multivariate integration of physiological and metabolic data

The multivariate analysis showed a close association in the PCA space between active ABA and total terpene concentration. This relationship indicates that the ABA-driven ripening program acts as a metabolic key regulator for the methylerythritol phosphate pathway, the primary route for monoterpene biosynthesis in grapes (MEP pathway) (Li, Yan, et al., 2024). Scientifically, ABA treatment upregulates key rate-limiting enzymes in this pathway, such as DXS and HDR, facilitating the transition from green-aldehyde descriptors to sophisticated floral and citrus notes (Li, Yan, et al., 2024). Notably, the PCA reveals that the biosynthetic pathways of terpenes and ripening-related hormones function as independent metabolic sinks (Hocking et al., 2016; Kuhn et al., 2013; Martins et al., 2018). This suggests that while they are regulated by synchronized hormonal triggers, the synthesis of aromatic compounds and the accumulation of primary metabolites (sugars) are distinct processes that the Sor-Ca treatment successfully harmonizes.

5. Conclusions

This study demonstrates for the first time that a foliar Sor-Ca

complex functions as a metabolic elicitor in neutral table grape cultivars, rather than acting merely as a structural stabilizer. The research validates the “mobilization hypothesis,” where the application of this complex triggers the conversion of inactive hormone storage forms into active signals to synchronize ripening and aromatic maturation (Leng et al., 2013; Owen et al., 2009). The key findings show that Sor-Ca treatment doubled the early yield by driving a 71% depletion of inactive ABA-GE reserves to significantly increase active ABA levels. Simultaneously, the treatment influenced auxin metabolism by promoting the conjugation of free IAA into IAA-Asp, effectively removing ripening inhibitors to facilitate the maturation program (Böttcher et al., 2013; Fortes et al., 2015).

The practical impact for the table grape industry is substantial, as these metabolic shifts allow neutral varieties to achieve a sophisticated aromatic profile characterized by floral and citrus-like terpenes. Beyond aroma and hormones, the Sor-Ca complex demonstrates the capacity to synchronize advanced maturity with physiological stability. While high sugar accumulation is often associated with high metabolic turnover, the treated grapes showed a significantly lower respiration rate, likely due to the calcium-mediated stabilization of cell (Guirao et al., 2025; Martins et al., 2018; Yu et al., 2020). This structural integrity allowed the ‘Ivory™’ berries to reach superior sugar levels (18.50 g 100 mL⁻¹ TSS) and an advanced maturity index without suffering from common disorders associated with rapid ripening, such as premature softening or loss of colour (Guirao et al., 2025; Zhu et al., 2024). Finally, the total cost for five applications is approximately €0.83 per vine, based on €2.5/kg for sorbitol and €1.5/kg for calcium nitrate. With an average production of 60 kg per vine, the cost is €0.007 per kilogram of grapes. This expense is offset by the increase in yield during the first harvest pass. This allows access to early markets with higher prices.

CRedit authorship contribution statement

Alberto Guirao: Writing – original draft, Software, Investigation, Formal analysis. **María del Carmen Alamar:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Conceptualization. **Ander Solana-Guilabert:** Methodology, Investigation, Formal analysis. **Daniel Valero:** Writing – review & editing. **Alejandra María Albert-Bermejo:** Formal analysis. **María Emma García-Pastor:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Juan Miguel Valverde:** Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Domingo Martínez-Romero:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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Synchronizing commercial maturity and enhancing organoleptic quality in table grape through hormonal and metabolic mediation induced by foliar sorbitolcalcium

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