

Gibberellin and potassium sorbate synergy for parthenocarpy and sugar enhancement in Bali grapes, Indonesia

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Abstract. *Kamuhi RH, Dwiyani R, Darmawati IAP. 2025. Gibberellin and potassium sorbate synergy for parthenocarpy and sugar enhancement in Bali grapes, Indonesia. Asian J Agric 9: 568-581.* Bali grape (*Vitis vinifera* L. var. Alphonso Lavallee) is a high-value horticultural commodity; however, its fruit quality, particularly sweetness and seed content, often falls short of consumer expectations. This study aimed to evaluate the effects of gibberellin (GA3) and potassium sorbate applications on parthenocarpy induction and sugar content enhancement. The experiment employed a factorial randomized complete block design with two factors: GA3 concentrations (0, 50, 100, and 150 ppm) and potassium sorbate concentrations (0 and 0.3%), each with five replications, resulting in 40 experimental units. Results showed that both GA3 and potassium sorbate significantly affected cluster and fruit characteristics, including cluster length, pedicel length, fruit number and weight, as well as seed number and weight. The interaction between the two treatments had a significant effect on berry diameter, number of millerandage (undeveloped) berries, and sugar content. The combined application of 150 ppm GA3 and 0.3% potassium sorbate increased berry diameter to approximately 19 mm and sugar content by about 38% to 19°Brix, while reducing the number of millerandage berries to 1.60 per cluster. GA3 at 150 ppm effectively reduced seed number and seed weight, while increasing fruit number, fruit weight, cluster weight, and cluster size. Potassium sorbate also contributed to improving the physical quality of the fruit. These findings indicate a synergistic effect between GA3 and potassium sorbate. The combined application, which is both practical and cost-effective, offers a promising agronomic strategy to improve the fruit quality of Bali grape, thereby enhancing its competitiveness in both domestic and international.

Keywords: Fruit quality improvement, gibberellin, parthenocarpy, potassium sorbate, sugar content, tropical viticulture

INTRODUCTION

Bali grape (*Vitis vinifera* L. var. Alphonso Lavallee), locally known as *ribier*, is a high-value horticultural commodity predominantly cultivated in Buleleng District, Bali Province. This black grape variety is distinguished by fruit color ranging from deep purple to black (Yuwono 2015; Sucu and Altıncı 2024) and has shown good adaptability to tropical climates, enabling cultivation in various regions of Indonesia. Despite this adaptability, fruit quality remains below premium market standards, primarily due to small berry size, low sweetness, and high seed content (Isnaini et al. 2018).

A major drawback of the Alphonso Lavallee cultivar is its high seed content, which decreases consumer preference in both fresh and processed markets (Yamada and Sato 2016). Fruit quality is determined by complex genetic and environmental interactions, alongside agronomic practices such as the use of plant growth regulators (Sheng et al. 2022). These interactions differ significantly between temperate and tropical grapes, necessitating adjustments in cultivation techniques (Cai et al. 2024).

One promising approach to improving fruit quality and reducing seed content is the induction of parthenocarpy, or fruit development without fertilization. Although rare naturally, parthenocarpy can be induced through the application of plant hormones such as gibberellic acid GA3 (Liu et al. 2023). GA3 promotes seedless fruit development

by activating hormonal signaling pathways that trigger DELLA protein degradation and stimulate genes such as *Expansin* and *XET*, which are involved in cell expansion (Ishikawa et al. 2023; Shani et al. 2024). In tropical grape cultivars, GA3 application has been reported to reduce seed number, enhance sweetness, and improve certain quality attributes (Astawa et al. 2015; Sari et al. 2023). However, its effectiveness varies greatly depending on the cultivar specificity, environmental conditions, and timing of application, and most research has focused on GA3 as a single treatment without evaluating synergistic effects with other compounds.

Potassium sorbate, a potassium salt of sorbic acid widely recognized as a safe antimicrobial agent in horticulture, has potential as a complementary treatment. Beyond its role in suppressing post-harvest pathogens such as *Botrytis cinerea*, potassium sorbate can influence grape metabolism by activating enzymes related to sugar synthesis and accumulation (Zhang et al. 2023; Al-Saif et al. 2024). In grape production, potassium sorbate contributes to maintaining fruit quality attributes such as soluble solids content SSC, firmness, and skin color (Feliziani et al. 2014), while potassium ions support osmotic regulation and enhance carbohydrate metabolism (Hasanuzzaman et al. 2018; Wang et al. 2024). Foliar application of potassium salts, including potassium sorbate, has been shown to increase SSC and accelerate ripening in grape cultivars such as Sweet Scarlet and Scarlet Royal

(Obenland et al. 2015). Recent studies emphasize that potassium fertilization enhances the expression of sugar metabolism genes and accelerates sugar accumulation in grape berries (Wang et al. 2024).

Despite the potential benefits, studies investigating the combined application of GA3 and potassium sorbate in tropical grapes are limited. While studies on temperate grape varieties indicate that such combinations can yield greater improvements in fruit quality compared to single treatments (Correa et al. 2015; Estaji et al. 2022), their effectiveness in tropical environments where grape physiology, climate adaptation, and stress responses differ has not been fully confirmed (Cai et al. 2024). This gap is critical given the growing demand for seedless grapes in Asian markets, where consumer preference strongly favors ease of consumption, sweetness, and visual appeal (Sari et al. 2023; IndexBox 2025). Seedless grapes can command 20 to 30% higher prices than seeded varieties, providing strong economic incentives for farmers to adopt parthenocarpy-inducing technologies (Bai et al. 2022).

Addressing this knowledge gap is essential for developing cultivation strategies that are both economically viable and environmentally adaptive in tropical viticulture. The innovative approach of synergistically applying GA3 and potassium sorbate could potentially enhance fruit quality more efficiently than individual treatments, not only aligning with sustainable production goals but also positioning the study at the forefront of competitive market strategies in tropical viticulture.

Therefore, this study aims to (i) determine the optimal concentration of GA3 for inducing parthenocarpy in Bali grapes (*Vitis vinifera* L. var. Alphonso Lavallee); (ii) evaluate the effect of 0.3% potassium sorbate application on fruit sweetness; and (iii) assess the synergistic interaction between GA3 and potassium sorbate in promoting seedlessness and enhancing sugar content. Identifying the most effective treatment combination is expected to increase the market value of Bali grapes in both domestic and export markets, while also supporting the development of sustainable tropical grape cultivation.

MATERIALS AND METHODS

Study site and duration

The study was conducted from January to April 2025 at two locations: (i) a vineyard in Kalianget Village, Seririt Sub-district, Buleleng District, Bali, for in situ treatment and observation of Bali grape (*Vitis vinifera* L. var. Alphonso Lavallee); and (ii) the Plant Tissue Culture Laboratory, Faculty of Agriculture, Udayana University, Denpasar, for post-harvest fruit quality analysis. The vineyard site was chosen for its uniform agroclimatic conditions suitable for grape cultivation.

The vineyard in Kalianget Village is situated in a mid-altitude area with gentle to moderate slopes. The soil texture is sandy loam with moderate permeability and sufficient water-holding capacity to maintain root moisture without causing waterlogging. The soil pH ranges from

neutral (6.8-7.2). Throughout the study, we maintained the soil's health by applying 25 kg of manure per plant, ensuring the availability of nutrients and the organic matter content.

Periodic measurements recorded an average air temperature of 26.06°C (range: 25.79-26.57°C) and an average relative humidity of 48.7% (range: 37.14-60.00%). These conditions are characteristic of the tropical monsoon climate and are relevant to the phenology of fruit development (anthesis → veraison). Detailed information on soil and microclimatic characteristics is essential for interpreting the results and for replicating the study in other sites with similar conditions.

Plant material, experimental design, and layout

Twelve productive and uniform grapevines were selected from a single vineyard block. The experiment employed a factorial randomized complete block design (RCBD) with two treatment factors:

Factor A: Gibberellin (GA3) concentration at four levels, G0 = 0 ppm (control), G1 = 50 ppm, G2 = 100 ppm, and G3 = 150 ppm.

Factor B: Potassium Sorbate concentration at two levels, P0 = 0% (control) and P1 = 0.3%.

The combination of the two factors produced eight treatment combinations, each replicated five times, resulting in a total of 40 experimental units (Table 1). Each experimental unit consisted of a single fruit cluster, thereby minimizing intra-plant variation and allowing more precise treatment application to the target organ.

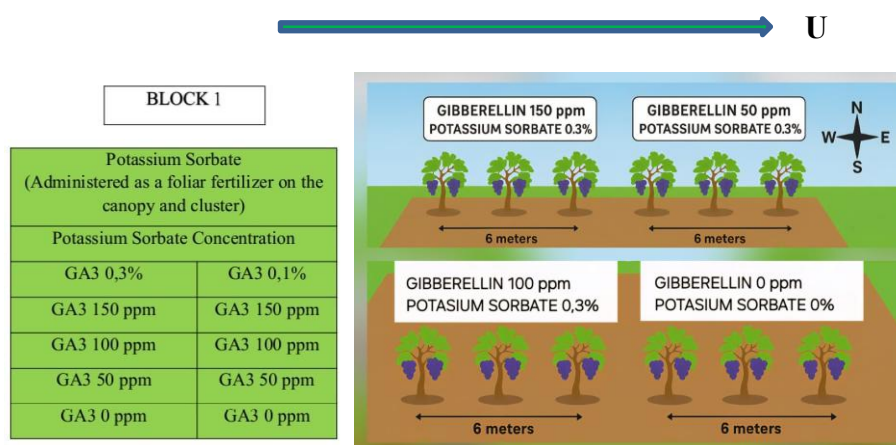
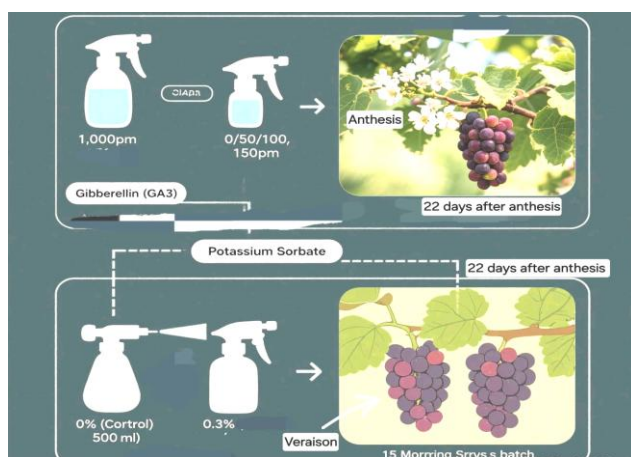
The experiment was arranged in randomized complete blocks, where each block contained all treatment combinations randomly assigned. Blocking was implemented by grouping experimental units based on plant orientation (north-south versus east-west) and row position (higher versus lower elevation) to minimize variation in light exposure and soil drainage across plots. This approach ensured that differences in microenvironmental factors such as sunlight intensity and water runoff were accounted for within blocks. The field layout featured uniform spacing between experimental units to facilitate consistent treatment application and accurate observation (Figure 1).

Justification for treatment concentration selection

The selected GA3 concentrations (0, 50, 100, and 150 ppm) reflect commonly used agronomic doses that are effective for inducing parthenocarpy in grapes without causing tissue damage, allowing assessment of dose-response effects on fruit morphology and quality. The potassium sorbate concentration of 0.3% represents a safe and widely used foliar treatment known to improve fruit quality without phytotoxicity, while the 0% control enables evaluation of its specific effects. These concentrations balance biological efficacy and safety, facilitating investigation of potential synergistic interactions between GA3 and potassium sorbate.

Table 1. Combination of treatments and field application of GA3 and potassium sorbates

Treatment code	Gibberellin (GA3) concentration	Potassium sorbate concentration	Replicate 1	Replicate 2	Replicate 3	Replicate 4	Replicate 5
G0P0	0 ppm	0%	G0P0	G3P0	G2P1	G0P0	G1P1
G0P1	0 ppm	0.30%	G2P1	G0P1	G3P1	G1P0	G3P0
G1P0	50 ppm	0%	G1P0	G2P0	G1P1	G3P1	G0P1
G1P1	50 ppm	0.30%	G3P1	G1P1	G0P0	G2P1	G2P0
G2P0	100 ppm	0%	G2P0	G0P0	G3P0	G1P1	G3P1
G2P1	100 ppm	0.30%	G3P0	G3P1	G0P1	G2P0	G0P0
G3P0	150 ppm	0%	G0P1	G1P0	G2P0	G3P0	G1P0
G3P1	150 ppm	0.30%	G1P1	G2P1	G1P0	G0P1	G2P1

**Figure 1.** Experimental layout**Figure 2.** Flowchart of treatment timing (anthesis/veraison)

Treatment preparation and application

Gibberellin (GA3) application

GA3 solutions were prepared from a 1,000 ppm stock solution diluted with distilled water to concentrations of 0, 50, 100, and 150 ppm. A sticking agent (Queen) was added to improve adherence to the plant surface. Each fruit cluster received approximately 15 mL of GA3 solution per application. Treatments were applied twice per cluster: once at anthesis and again 22 days after anthesis (DAA). Each application involved spraying the inflorescences 15

times in the morning to minimize evaporation and enhance absorption.

Potassium sorbate application

A 0.3% stock solution of potassium sorbate was prepared by dissolving 1.5 g in 500 mL of distilled water. From this stock, two working concentrations were made: 0% (control) and 0.3% (treatment). Each plant received two foliar sprays of potassium sorbate, with approximately 15 mL applied per cluster. The first spray was given at 22 DAA on the canopy leaves, and the second at veraison on the fruit clusters. Each application consisted of 15 sprays performed in the morning to optimize absorption.

The detailed stages of preparation and treatment application are presented in Figure 2, which includes a flowchart of the treatment schedule during the anthesis and veraison phases.

Plant maintenance

Plants were managed using standard viticultural practices, including manual weeding, organic fertilization (25 kg cow manure per plant), regulated irrigation, and eco-friendly pest management throughout the study period.

Harvesting and post-harvest handling

Harvest was conducted manually based on fruit maturity indicators: skin color change (green to reddish-purple), softening flesh, and reduced acidity. Post-harvest handling involved: (i) Manual sorting based on size, color,

and physical defects; (ii) Water flotation to distinguish full from empty berries; (iii) Selected fruits were analyzed for sugar content and other quality parameters in the laboratory.

Observed variables

The observed variables in this study were grouped into two main categories: physical parameters and quality parameters, as presented in Tables 2 and 3, respectively. Table 2 outlines the physical parameters assessed, including measurements related to cluster and berry morphology, along with the instruments or methods used for data collection. Meanwhile, Table 3 presents the quality parameters, focusing on factors that influence fruit development and sweetness, such as the presence of millerandage and sugar content.

Instrumentation

All measurements followed precision protocols. The tools included: digital balance (± 0.01 g), refractometer, digital caliper (± 0.01 mm), measuring tape, and camera for documentation. A handsprayer was used for uniform application of treatments.

Data collection and sources

Primary data: Collected via direct field observation and lab measurements.

Secondary data: Sourced from scientific journals and agricultural references to support interpretation and discussion.

Data analysis

Observational data were analyzed using analysis of variance (ANOVA) based on a factorial randomized complete block design (RCBD) at a significance level of $p < 0.05$, employing the latest version of SPSS software to

ensure accuracy. Prior to analysis, assumptions of normality and homogeneity of variances were evaluated using the Shapiro-Wilk test and Levene test, respectively. The results of these tests were explicitly reported to confirm that the data met the necessary assumptions for ANOVA.

A two-way factorial ANOVA was conducted to examine the main effects of gibberellin (GA3) and potassium sorbate, as well as their interaction effects, on the physical and quality parameters of the fruit. The analysis of interaction effects considered the assumptions of normality of residuals, homogeneity of variances across treatment combinations, and independence of observations. Testing for interaction allowed assessment of whether the effect of one factor depends on the level of the other factor.

ANOVA results were presented comprehensively, including F-values, degrees of freedom (df), p-values, and effect sizes when relevant. Upon detecting significant differences, post hoc analysis was performed using the Honestly Significant Difference (HSD) test at the 5% significance level to identify specific differences between treatments. Details of the post hoc test settings, such as the control of Type I error and significance thresholds, were described to ensure reproducibility.

Final results were tabulated with mean values, standard deviations, statistical test outcomes, and significance grouping letters to facilitate interpretation and comparison among treatment groups.

Ethical compliance

This study was conducted in accordance with applicable national guidelines and regulations for agricultural research. Given that the research involved field trials on plants without the involvement of human or animal subjects, formal ethical approval was not required.

Table 2. Observed physical parameters and measurement methods

Variable	Description	Instrument/Method
Cluster length (cm)	Measured from base to tip	Measuring tape
Pedicle length (cm)	Length of fruit stalk	Ruler
Number of berries per cluster	Manual count at harvest	Hand counting
Berry diameter (mm)	Widest point of the fruit	Digital caliper
Single berry weight (g)	Mean of multiple samples	Digital balance
Cluster weight (g)	Whole cluster weight	Digital balance
Number of seeds per berry	Manual count post-dissection	Manual
Seed weight (g)	Total/mean seed weight	Analytical balance

Table 3. Observed quality parameters and measurement methods

Variable	Description	Instrument/Method
Hen and chicken (millerandage) count	Small/undeveloped berries per cluster	Visual/manual count
Sugar content ($^{\circ}$ Brix)	Juice sugar level	Refractometer

Note: Parthenocarpy was defined as fruit set without seed formation, confirmed by seed count at harvest. Fruit sweetness was quantified using $^{\circ}$ Brix measurements from juice samples

RESULTS AND DISCUSSION

This study aimed to determine the effects of gibberellin hormone (GA3), both individually and in combination, on various growth and yield parameters of grapevines.

Effect of GA3 and potassium sorbate on growth parameters and grape yield

The results of this study (Table 4) indicate that the application of gibberellin (GA3) and potassium sorbate individually exerted highly significant effects on various aspects of grape cluster growth and quality. However, analysis of variance revealed that the interaction between the two treatments was observed only for the variables of berry diameter, the occurrence of hen and chicken (millerandage), and sugar content (°Brix). In contrast, for other variables such as cluster length, pedicel length, cluster weight, and berry weight, no significant interaction was detected. These findings suggest that most of the plant responses to GA3 and potassium sorbate treatments occurred independently, except in certain fruit quality characteristics.

Effect of GA3 and potassium sorbate on growth, yield, and fruit quality of Bali grapevines based on 5% honest significant difference (HSD) test

The analysis of variance results (Table 5) indicate that the treatments of gibberellin (GA3) concentration and potassium sorbate have highly significant effects on various growth, yield, and quality parameters of Bali grapes. The gibberellin treatment significantly affected bunch length, pedicel length, number of fruits per bunch, fruit weight per fruit, fruit weight per bunch, number of seeds per fruit, and seed weight per fruit. Similarly, potassium sorbate treatment also showed significant effects on these parameters. Furthermore, a significant interaction

between gibberellin and potassium sorbate treatments was observed for fruit diameter, the number of hen and chicken fruits (millerandage), and sugar content (°Brix). The mean values for each treatment based on the 5% Honestly Significant Difference (HSD) test are presented in Table 5. These findings have practical implications for grape cultivation and plant treatments, inspiring further research and innovation in this field

Table 4. Significance of the effects of gibberellin and potassium sorbate on various observational variables of Bali grape, Alphonso Lavallee variety

Observation variable	Analysis of variance results
Bunch length (cm)	Highly significant effect of GA3 and potassium sorbate (**)
Pedicel length (cm)	Highly significant effect of GA3 and potassium sorbate (**)
Number of fruits per bunch	Highly significant effect of GA3 and potassium sorbate (**)
Fruit weight per bunch (g)	Highly significant effect of GA3 and potassium sorbate (**)
Weight per fruit (g)	Highly significant effect of GA3 and potassium sorbate (**)
Number of seeds per fruit	Highly significant effect of GA3 and potassium sorbate (**)
Seed weight per fruit (g)	Highly significant effect of GA3 and potassium sorbate (**)
Fruit diameter (mm)	Significant interaction between GA3 × potassium sorbate (Interaction) **
Hen and chicken Fruit	Significant interaction between GA3 × potassium sorbate (Interaction) *
Sugar content (°Brix)	Significant interaction between GA3 × potassium sorbate (Interaction) *

Note: * Significant effect at the 5% level of significance (P<0.05), ** Highly significant effect at the 1% level of significance (P<0.01)

Table 5. Effects of GA3 and potassium sorbate treatments on growth, yield, and fruit quality parameters of Bali grapevines

Observed variables	Gibberellin treatment				HSD 5%	Potassium sorbate treatment		HSD 5%	SE mean	SE diff
	0 ppm	50 ppm	100 ppm	150 ppm		0%	3%			
Bunch Length (cm)	14.4 a	18.3 b	19.3 bc	20.1 c	1.48	17.6 a	18.45 b	0.78	0.42	0.59
Pedicel (cm)	0.52 a	0.9 b	1.0 b	1.27 c	0.22	0.82 a	1.03 b	0.12	0.06	0.09
Number of Fruits Per Bunch (fruit)	26.3 a	35.6 ab	46.8 bc	53.8 c	14.83	35.65 a	45.6 b	7.86	4.2	5.94
Weight Per Fruit (g)	3.19 a	3.38 ab	3.87 b	4.76 c	0.55	3.65 a	3.96 b	0.29	0.16	0.22
Fruit Weight Per Bunch (g)	74.1 a	109.5 a	128.8 ab	189.6 b	80.06	102.8 a	148.2 b	42.42	10.13	14.33
Number of Seeds (seeds)	3.80 c	2.80 bc	2.20 ab	0.70 a	1.52	2.90 b	1.85 a	0.80	0.43	0.61
Seed Weight (g)	1.73 c	1.26 b	0.75 a	0.43 a	0.04	1.15 b	0.93 a	0.02	0.11	0.15

Observed variables	The interaction effect between GA3 and potassium sorbate									
	GA3 0 ppm		GA3 50 ppm		GA3 100 ppm		GA3 150 ppm		HSD 5%	SE mean
	0%	3%	0%	3%	0%	3%	0%	3%		
Fruit Diameter (mm)	13.72 a	16.82 b	17.04 bc	17.04 bc	17.98 bc	18.18 bc	18.16 bc	18.94 c	1.96	0.42
Number of "Hen and Chicken" Fruits	8.2 b	3.8 a	3.2 a	3.4 a	2.8 a	2.2 a	1.8 a	1.6 a	3.99	0.86
Sugar Content (°Brix)	14.0 a	15.4 a	14.6 a	18 ab	16.0 bc	19.0 c	18.2 c	19.4 c	2.0	0.43

Note: Numbers followed by the same letter within the same row indicate that there is no significant difference according to the 5% Honestly Significant Difference (HSD) test

Discussion

The effect of GA3 and potassium sorbate on bunch and pedicel length

Based on Table 5, the application of gibberellic acid (GA3) had a significant effect on both bunch length and pedicel length. At a concentration of 0 ppm, the average bunch length was 14.40 cm, increasing to 20.10 cm at 150 ppm. A similar trend was observed for pedicel length, which increased from 0.52 cm at 0 ppm to 1.27 cm at 150 ppm. These findings indicate that increasing GA3 concentrations consistently promotes the elongation of reproductive organs, suggesting its role in stimulating cell division and elongation through hormonal pathways (Hadden and Sponzel 2015). The mode of action begins with GA3 binding to the gibberellin receptor (GID1) within the cell, forming a complex that inactivates growth-repressing DELLA proteins (Shani et al. 2024). This interaction activates the expression of genes involved in the synthesis of growth-related proteins, such as expansin enzymes, which loosen the cell wall to allow expansion (Camut et al. 2021). GA3 also enhances α -amylase activity, hydrolyzing starch into simple sugars to provide an energy source for cell division and enlargement (Ricardo et al. 2022) is particularly impressive. Furthermore, GA3 regulates genes associated with microtubule formation, thereby extending the fruit growth phase and optimizing assimilate transport to the bunch through increased phloem activity (Cai et al. 2024), as illustrated in Figure 2, which shows a progressive increase in bunch length with higher GA3 doses.

Meanwhile, the application of potassium sorbate also had a significant effect on the same variables. At a concentration of 0.3%, the bunch length reached 18.45 cm, longer than the untreated control at 17.60 cm. Similarly, pedicel length increased to 1.03 cm compared to 0.82 cm in the control. These results suggest that potassium sorbate contributes to improving nutrient uptake efficiency and overall plant metabolic activity. Its mechanism of action involves K^+ ions functioning as osmotic regulators, maintaining cell turgor pressure to support cell expansion. Potassium's role in regulating stomatal opening and closure, a key process in plant physiology, is also significant. By controlling the osmotic pressure of guard cells, potassium optimized CO_2 uptake for photosynthesis while minimizing water loss (Al-Saif et al. 2024). More than 60 metabolic enzymes are activated by K^+ , including those involved in sucrose and starch synthesis (Zörb et al. 2014). Additionally, potassium facilitates the loading of sucrose into the phloem and its translocation to the fruit as the primary sink organ (Alebidi et al. 2023). It strengthens the cell wall by enhancing lignin and pectin deposition (Villette et al. 2020). Nevertheless, as potassium sorbate is a salt of sorbic acid, excessive concentrations may lead to ionic imbalances that impair plant physiology. The interaction between GA3 and potassium sorbate did not result in a synergistic effect because they act through distinct physiological pathways (Shehzad et al. 2020). Overall, GA3 at a concentration of 150 ppm was the most effective treatment for increasing both bunch and pedicel length in grapevines. Although the effect of potassium

sorbate was relatively smaller, this compound still holds agronomic relevance in supporting precision-based cultivation systems (Huang et al. 2023; Puri et al. 2023).

The effect of GA3 and potassium sorbate on generative yield components of grapevines

The study focuses on the role of GA3 and potassium sorbate in enhancing fruit production. The application of GA3 significantly increased the number of fruits per bunch, from 26.30 fruits in the control to 53.80 fruits at a dose of 150 ppm. GA3 activates hormonal pathways that modulate the expression of genes related to cell division and elongation in the ovary and inhibits growth-repressing genes such as DELLA, thereby stimulating the formation of parthenocarpic fruits without fertilization (Bai et al. 2022). The inhibition of DELLA genes accelerates the proliferation and elongation of ovary cells, enabling fruit development without embryos. Additionally, GA3 increases levels of supporting hormones such as auxin (IAA), which stimulates growth and differentiation of ovary tissues, thereby significantly enhancing flower-to-fruit conversion (Camut et al. 2021). Meanwhile, potassium sorbate at a concentration of 0.3% increased the number of fruits per bunch from 35.65 to 45.60, primarily due to its potassium ion (K^+) content that acts as an osmotic regulator, maintains cell turgor pressure, and activates metabolic enzymes supporting cell division and differentiation in young ovary tissues (Yahmed and Mimoun 2019). Potassium sorbate also contributes to increased fruit number through regulation of stomatal opening to enhance photosynthetic efficiency and facilitate the transport of photosynthates to reproductive tissues (Azab et al. 2022), optimal turgor pressure and enzyme activation support efficient and optimal ovary development and fruit formation.

Unlike single applications, the combination of GA3 at 150 ppm and potassium sorbate at 0.3% produced the largest fruit diameter of 18.94 mm, demonstrating a significant synergistic effect. In this combination, GA3 activates hormonal pathways that modulate gene expression, regulating cell wall loosening and cell expansion, including the activation of expansin enzymes that loosen cell walls, and extend the fruit filling phase by increasing the transport of assimilates and essential metabolites to the fruit (Correa et al. 2015). Potassium sorbate enhances the physiological efficiency of the plant by supplying potassium ions that serve as cofactors for photosynthesis and carbohydrate metabolism enzymes, maintain cell turgor, and strengthen enzymatic activities that optimize protein synthesis and carbohydrate accumulation to support cell expansion (Alebidi et al. 2023). Potassium ions also facilitate the distribution of photosynthates through the phloem to the fruit as the primary storage organ, reinforce plasma membrane integrity, and increase resistance to oxidative stress (Villette et al. 2020). The synergy between GA3 hormonal regulation and potassium nutrition accelerates cell expansion and improves overall metabolic efficiency, resulting in a more optimal physiological response of the plant for fruit enlargement (Pahi et al. 2020).

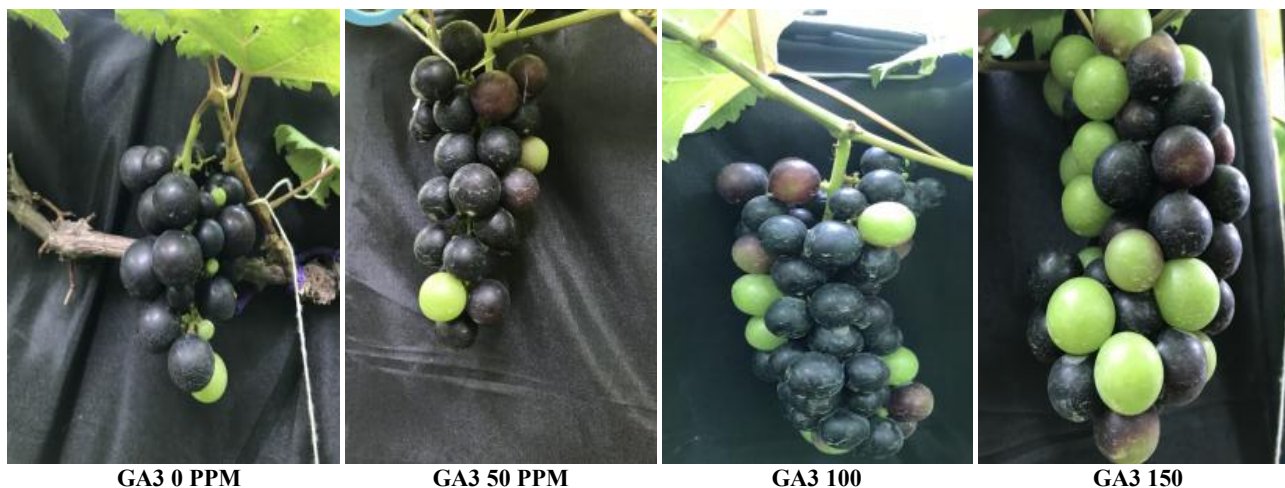


Figure 2. Increase in grape cluster length under GA3 treatment

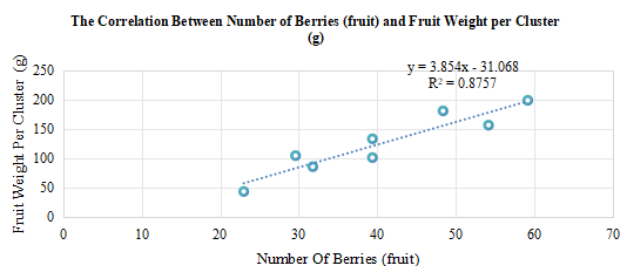


Figure 3. Correlation between the number of berries and fruit weight per cluster

Individual fruit weight increased from 3.19 to 4.76 g with GA3 application, which stimulates cell division and elongation and enhances the accumulation of photosynthates in the fruit through improved metabolic efficiency and assimilate transport to fruit tissues, thus providing energy and essential precursors for growth and fruit filling (Estaji et al. 2022). GA3 mechanism also involves inhibition of DELLA genes, accelerating cell proliferation and elongation (Camut et al. 2021). Potassium sorbate increased fruit weight from 3.65 to 3.96 g by maintaining plasma membrane integrity, strengthening cell walls, and activating enzymes that optimize carbohydrate metabolism, protein synthesis, and nucleic acid production, supporting cell division and development during fruit growth (Villette et al. 2020; Azab et al. 2022). Potassium ions function as osmotic regulators that maintain cell turgor, facilitate cell expansion and division, and enhance photosynthetic efficiency through stomatal regulation and improved transport of photosynthates to fruit tissues (Yahmed and Mimoun 2019; Al-Saif et al. 2024). Thus, GA3 and potassium sorbate synergistically increase individual fruit weight through complementary hormonal, genetic, physiological, and metabolic mechanisms.

Bunch weight also increased significantly, from 74.10 to 189.60 g with GA3 application, which regulates the expression of genes involved in cell division and

elongation, thereby expanding the size and number of fruits per bunch and supporting fruit filling by increasing the transport of assimilates and essential metabolites to fruit tissues (Kaplan et al. 2017; Estaji et al. 2022). GA3 inhibits DELLA genes, which accelerates cell proliferation and prolongs the fruit filling phase, resulting in heavier and higher-quality bunches (Camut et al. 2021). Potassium sorbate increased bunch weight from 102.80 to 148.20 g by enhancing photosynthetic efficiency through stomatal regulation and optimizing CO₂ uptake, as well as facilitating sucrose transport via the phloem to the fruit as the main storage organ (Alebidi et al. 2023; Al-Saif et al. 2024). Potassium ions in potassium sorbate also activate metabolic enzymes that support carbohydrate synthesis and energy metabolism, improving fruit filling and overall bunch yield (Zörb et al. 2014; Azab et al. 2022). Thus, the combined hormonal mechanism of GA3 and the physiological effect of potassium sorbate synergistically enhance bunch weight and overall grapevine productivity.

When compared to the varietal standard for grapes, which typically produce around 34 berries per bunch with a bunch weight of approximately 142.60 g, the results of this study show a clear improvement beyond the baseline. The 50 ppm GA3 treatment produced 35.60 berries per bunch, while the 100 and 150 ppm treatments yielded 46.80 and 53.80 berries, respectively. The 0.3% potassium sorbate treatment also resulted in 45.60 berries per bunch, all exceeding the varietal standard. These findings demonstrate that the application of GA3 and potassium sorbate, whether applied individually or in combination, is effective in optimizing the genetic yield potential of grapevines. The correlation between berry number and bunch weight is presented in Figure 3, with an R² value of 0.8757, indicating a strong relationship between yield component enhancement and overall bunch productivity.

The effect of GA3 and potassium sorbate on parthenocarpy

The application of gibberellin (GA3) significantly reduced the number of seeds per fruit, indicating the stimulation of parthenocarpic fruit development, which is

fruit formation without fertilization. At a dose of 150 ppm GA3, the seed count drastically decreased from 3.80 to only 0.70 seeds per fruit (Table 5; Figure 4). This demonstrates that GA3 promotes fruit development through cell division and elongation in the ovary without embryogenesis, supported by the suppression of regulatory genes such as Leafy Cotyledon and Baby Boom (Cheng et al. 2015; Bai et al. 2022).

The mechanism by which GA3 induces parthenocarpy involves activating hormonal pathways that regulate gene expression for cell proliferation and elongation in the ovary, while repressing growth-inhibiting DELLA genes (Camut et al. 2021). Additionally, GA3 elevates levels of auxin (IAA), which further supports parthenocarpic fruit growth (Li et al. 2024). This genetic regulation results in seedless fruits with fully developed pericarp tissue despite the absence of embryo formation (Parada et al. 2017) (Figure 5).

Increased metabolic enzyme activity and cell wall loosening triggered by GA3 further facilitate fruit tissue development independently of seed formation (Parada et al. 2017; Li et al. 2024). Therefore, GA3 application not only consistently reduces seed formation but also tends to

improve the agronomic quality of the fruit (Melo et al. 2024).

Meanwhile, potassium sorbate also had a significant effect on seed number. Treatment with 0.3% potassium sorbate resulted in an average of 1.85 seeds per fruit, which was lower than the control without application, at 2.90 seeds per fruit. Although not classified as a plant growth regulator, potassium sorbate is suspected to enhance the parthenocarpic response by increasing hormonal stability and physiological efficiency. In contrast to GA3, which functions through hormonal pathways, potassium sorbate influences seed formation via non-hormonal physiological mechanisms involving ionic balance, osmotic pressure, and cellular metabolism. Potassium ions (K^+), the primary component of potassium sorbate, play a vital role in enzyme activation, maintenance of turgor pressure, and improvement of photosynthate transport efficiency to reproductive tissues (Zörb et al. 2014; Hasanuzzaman et al. 2018). These physiological effects influence the sink strength in young fruit tissues, which directly affects assimilate allocation and seed development (Rogiers et al. 2017).

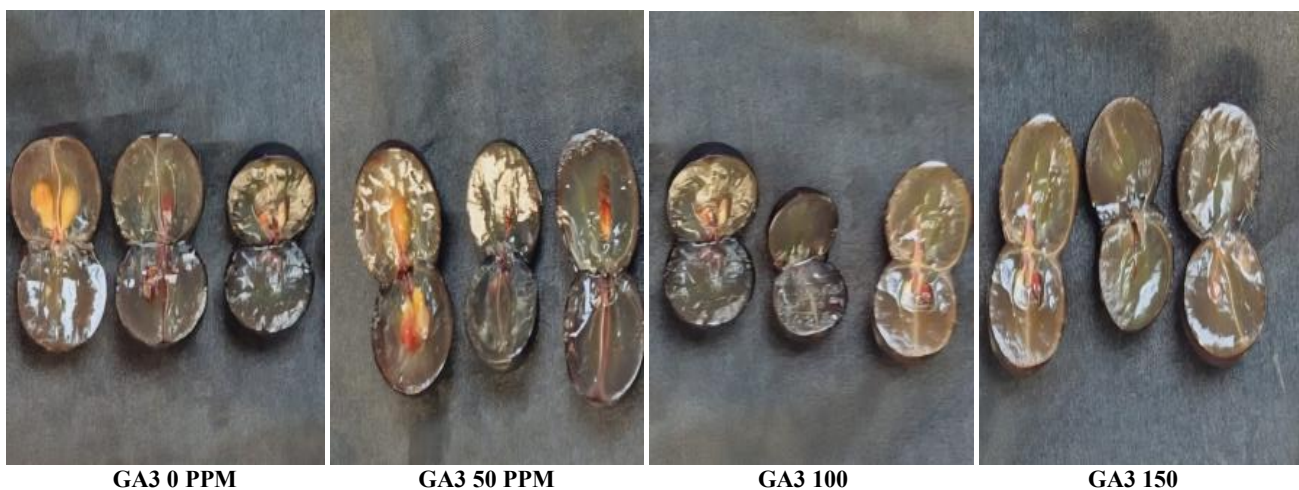


Figure 4. Number of grape seeds under GA3 treatment

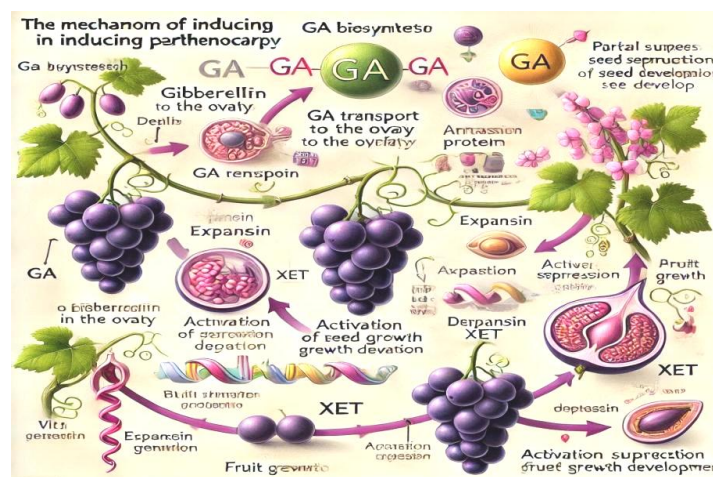


Figure 5. Proposed mechanism of gibberellin (GA3) action in the induction of parthenocarpy in fruit development

The reduction in seed number may also result from local disturbances in the fertilization process, such as decreased pollen viability or inhibited pollen tube growth due to potassium ion accumulation (Karimi et al. 2021). Barreto et al. (2022) also demonstrated that high potassium concentrations can inhibit fertilization, thereby reducing seed formation. Therefore, although potassium sorbate does not directly induce parthenocarpy like GA3, its application can still be used to regulate seed number, especially in grape cultivars intended for fresh consumption.

In line with seed number, seed weight per fruit also decreased due to the application of gibberellin and potassium sorbate. Based on Table 5, the highest seed weight was recorded under the 0 ppm GA3 treatment at 1.73 g, which significantly decreased to 0.43 g at 150 ppm. This reduction supports the tendency for parthenocarpic fruit formation, as a reduction in seed weight accompanied the decrease in seed number. Data from Figure 5 further confirm this result, showing that 150 ppm GA3 reduced seed weight from 1.73 g to only 0.43 g.

In addition, 0.3% potassium sorbate also reduced seed weight to 0.93 g compared to the control at 1.15 g. This decrease further supports the role of potassium sorbate in inhibiting seed formation and development, possibly through its influence on hormone synthesis and metabolism related to seedless fruit formation. The relationship between seed number and seed weight is clarified by a correlation analysis yielding an R^2 value of 0.8745 (Figure 6), indicating a very strong linear relationship. A decrease proportionally followed each decrease in seed number in seed weight. Agronomically, this finding is important, as a reduction in seed number and weight increases the flesh-to-seed ratio, which directly improves consumption quality and market value. The decline in seed weight also indicates reduced embryogenesis and endosperm formation, further supporting the development of parthenocarpic fruits through both physiological and hormonal mechanisms.

Gibberellic acid (GA3) induced parthenocarpy has been shown to significantly improve both the quality and quantity of grapes, particularly in cultivars intended for the table grape market. In the Red Globe cultivar, the application of GA3 at concentrations of 40 to 70 mg/L during the early stages of fruit development markedly increased cell size, fruit diameter, and fruit volume, while also modulating hormonal balance by elevating auxin (IAA) and zeatin levels and reducing abscisic acid (ABA) content (Li et al. 2024). The application of GA3 prior to the anthesis stage in Cabernet Franc and

Cabernet Sauvignon cultivars have also been reported to extend rachis length and reduce cluster density without affecting seed number, resulting in looser and more visually appealing bunches (Gao et al. 2020). These results align with the findings of Kaptan et al. (2017), who observed that GA3 application in the Kyoho variety increased the percentage of seedless fruit from 3.3 to 98.6% and in Red Globe from 3.0 to 85.2%, primarily through inhibition of pollen tube growth and fertilization. Furthermore, GA3 promotes pericarp cell elongation,

contributing to berry enlargement, cluster loosening, and accelerated fruit ripening, as reported by Baneh et al. (2017).

Although potassium sorbate is not a plant growth regulator, it has been shown to play an important role in enhancing the post-harvest resilience of grapes. Feliziani et al. (2014) reported that preharvest application of potassium sorbate to the Thompson Seedless cultivar significantly reduced the incidence of *Botrytis cinerea* (gray mold) during cold storage, while simultaneously increasing endochitinase enzyme activity and resveratrol content in the fruit skin, without affecting physical quality parameters such as berry size and total soluble solids. In addition, the potassium content in potassium sorbate can act as a cofactor for various enzymes involved in photosynthesis and carbohydrate metabolism, such as Rubisco, ATPase, and enzymes regulating sugar synthesis and transport (Azab et al. 2022). This improvement in photosynthetic efficiency and assimilate distribution supports the role of GA3 in inducing parthenocarpy by providing sufficient energy and metabolic precursors for the development of seedless fruits (Tian et al. 2023). Therefore, integrating GA3 application for parthenocarpy induction with potassium sorbate treatment for post-harvest protection represents a comprehensive cultivation strategy to produce high-quality seedless grapes with thick flesh, extended shelf life, and higher economic value.

The role of GA3 and potassium sorbate in modulating fruit formation and sugar quality

The phenomenon of hen and chicken, characterized by the presence of normal-sized (hen) and undersized or undeveloped (chicken) berries within the same grape cluster, is a critical indicator in evaluating bunch quality. According to Table 5, the highest number of hen and chicken berries was found in the 0 ppm GA3 treatment without potassium sorbate, reaching 8.20 berries per bunch. This number differed significantly from other treatments and indicates a high level of millerandage. In contrast, the combination of 150 ppm GA3 and 0.3% potassium sorbate resulted in the lowest number of hen and chicken berries, at only 1.60 per bunch. This sharp reduction indicates the increased effectiveness of combining hormonal treatment with supportive compounds in producing more uniform and well-developed fruit.

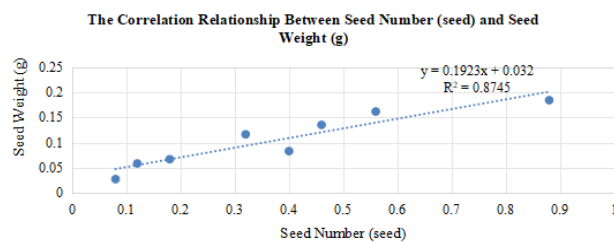


Figure 6. Correlation between the number of seeds (seed) and seed weight (g)

The reduction in hen and chicken berries reflects the success of parthenocarpic induction and physiological improvement in pollination and fruit development processes. In general, millerandage occurs due to disruptions during flowering or fertilization, nutritional deficiencies, or hormonal imbalances (Alrashdi et al. 2017). In this study, GA3 application significantly suppressed abnormal fruit development. When combined with potassium sorbate, the results were more optimal, reducing the number of hen and chicken berries from 8.20 to only 1.60 per bunch.

This synergistic effect arises from the combined actions of GA3 and potassium sorbate. GA3 supports ovary development and reduces flower abortion (Bai et al. 2022), while repressing the expression of genes that induce embryo abortion, thereby producing more uniform fruits (Wang et al. 2020). Meanwhile, potassium sorbate enhances cell turgor pressure and optimizes photosynthate distribution through the role of potassium as its main component (Molaei et al. 2021; Mahmoud et al. 2022). Therefore, this treatment combination effectively reduces millerandage symptoms and improves the morphological quality of the fruit cluster.

In addition to improving fruit uniformity, GA3 and potassium sorbate treatments also positively influenced the chemical quality of the fruit, particularly sugar content. According to Table 4, the combination of 150 ppm GA3 and 0.3% potassium sorbate yielded the highest sugar content, reaching 19.40°Brix, significantly higher than the untreated control (14.00°Brix). This result demonstrates that the treatment not only enhances morphological parameters but also improves the nutritional quality of the fruit.

This increase in sugar content reflects the plant's physiological efficiency in accumulating carbohydrates during ripening. GA3 is known to enhance the fruit's capacity to absorb photosynthates (sink strength), while potassium sorbate supports fruit filling by increasing turgor pressure and metabolic enzyme activity (Li et al. 2024; Wang et al. 2024). Rani et al. (2018) also reported that potassium sorbate positively affects the increase in total sugars and total soluble solids (TSS) during ripening and storage, supporting these findings.

Interestingly, a strong negative correlation was observed between the number of hen and chicken berries and sugar content. Figure 7 shows that fewer abnormal fruits in a bunch correlate with higher sugar levels in the fruit. The linear regression equation between these two parameters is $y = -7.1379x + 19.502$ with a coefficient of determination of $R^2 = 0.825$. This antagonistic relationship suggests competition between non-productive tissues, such as seeds and small berries, and the main fruit tissue for photosynthate uptake. When these unproductive parts are reduced, energy and nutrient allocation can be focused on enlarging and ripening the main fruit, thereby significantly increasing sugar content (Obenland et al. 2015).

From a physiological perspective, potassium sorbate, as a source of potassium ions (K^+), plays an essential role in increasing the sugar content of grapes through its function as a cofactor for various enzymes involved in photosynthesis and carbohydrate metabolism, such as Rubisco, ATPase, and enzymes regulating sugar synthesis and transport (Azab et al. 2022). Adequate potassium availability can enhance leaf photosynthetic activity, improve energy use efficiency (Zörb et al. 2014), maintain optimal turgor pressure to support the active transport of sucrose through the phloem to the fruit as a sink organ (Xu et al. 2020), and protect tissues from oxidative stress that may disrupt ripening metabolism (Bernardo et al. 2018).

Studies on Flame Seedless grapes and apples have shown that potassium application from the veraison stage to ripening can increase total soluble solids (TSS), a key indicator of sugar content (Obenland et al. 2015; Rani et al. 2018). This effect is thought to occur through enhanced expression of genes responsible for sucrose and fructose synthesis, as well as increased activity of invertase and sucrose synthase (Alebidi et al. 2023). Therefore, the combined use of GA3 and potassium sorbate not only improves fruit size and uniformity but also optimizes sugar quality by enhancing physiological performance and modulating the plant metabolic pathways.

In addition to the macroscopic effects previously described, the increase in sugar content (°Brix) resulting from GA3 and potassium sorbate treatments can also be explained through complex physiological mechanisms and biochemical pathways. GA3, as a growth hormone, plays a role in regulating the expression of genes related to carbohydrate metabolism, including key enzymes such as invertase, sucrose synthase, and amylase. GA3 enhances the hydrolysis of starch into simple sugars, glucose and fructose, which then serve as energy sources and precursors for sucrose synthesis (Hadden and Sponcel 2015; Hadden 2020). Moreover, GA3 influences sugar transport regulation by activating sugar transporter proteins, SUTs or sucrose transporters, that facilitate the movement of sucrose from sources, leaves, to sinks, fruits (Shani et al. 2024).

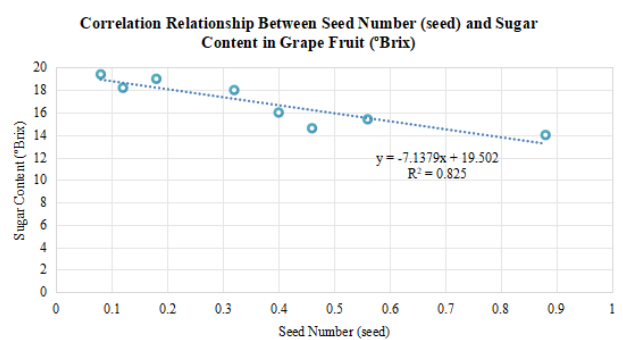


Figure 7. Correlation graph between seed number (seed) and sugar content (°Brix)

Meanwhile, potassium sorbate provides potassium ions, K^+ , which are essential cofactors for various enzymes involved in photosynthesis and carbohydrate metabolism, such as ribulose biphosphate carboxylase oxygenase, Rubisco, and ATPase. Adequate K^+ availability supports stomatal function in maintaining water and gas balance, thereby enhancing photosynthesis and the production of sugar precursors (Zörb et al. 2014; Azab et al. 2022). Potassium also helps maintain cell turgor pressure, ensuring efficient active transport of sucrose through the phloem (Xu et al. 2020).

From a hormonal perspective, GA3 interacts with other hormones such as auxin and cytokinin in regulating fruit development and sugar accumulation. GA3 can modulate auxin synthesis and distribution, which together regulate the expression of genes responsible for cell division and differentiation of the pericarp tissue, thereby increasing the sink strength of the fruit to absorb and store sugars (Galimba et al. 2019). The interaction between GA3 and stress hormones like abscisic acid (ABA) also influences fruit ripening, where GA3 tends to delay ripening. At the same time, ABA promotes it, so the balance between these hormones determines the duration of sugar accumulation (Hadden 2020).

Potassium sorbate, on the other hand, may help reduce oxidative stress by activating antioxidant pathways that maintain metabolite stability during ripening, including soluble sugars (Bernardo et al. 2018). Thus, the presence of K^+ helps sustain cellular homeostasis during the critical ripening phase.

Together, these mechanisms increased sugar synthesis driven by GA3, enhanced photosynthetic efficiency, and sucrose transport facilitated by K^+ and balanced hormonal regulation contribute to the significant increase in sugar content, °Brix, observed in grapes treated simultaneously with GA3 and potassium sorbate.

Future research directions: Integrating genomic, metabolomic, and multi-location studies

The results of this study demonstrate that applying gibberellic acid (GA3) and potassium sorbate individually had significant effects on morphological parameters and yield components of grapevines, including bunch length, pedicel length, bunch weight, fruit diameter, and fruit length. Increasing GA3 concentration from zero to one hundred fifty parts per million consistently promoted elongation of reproductive organs via binding to the GID1 receptor, inactivating DELLA repressor proteins, and activating growth-related genes such as expansin, which loosens cell walls to facilitate cell division and elongation (Hedden and Sponsel 2015; Camut et al. 2021; Shani et al. 2024). GA3 also enhances starch hydrolysis into simple sugars, regulates microtubule formation, extends the fruit enlargement phase, and increases assimilate transport to the bunch via the phloem (Ricardo et al. 2022; Cai et al. 2024). Potassium sorbate, through potassium ions, increased bunch length and pedicel length by regulating cellular osmotic pressure, maintaining turgor pressure, controlling stomatal aperture, and activating enzymes involved in photosynthesis and sucrose synthesis (Zörb et al. 2014; Al-

Saif et al. 2024). Additionally, potassium facilitates sucrose loading into the phloem and strengthens cell walls through lignin and pectin deposition (Villette et al. 2020; Alebidi et al. 2023). No significant synergistic effect was observed between GA3 and potassium sorbate, likely due to their operation via different physiological pathways (Shehzad et al. 2020).

The positive effects of GA3 were evident in increased bunch weight and fruit size. At the same time, potassium sorbate contributed to higher bunch weight by improving the plant's nutritional status and optimizing cell filling. Changes in fruit diameter and length highlight GA3 direct role in cell division and elongation of pericarp tissue through activation of expansin and xyloglucan endotransglycosylase enzymes (Camba et al. 2022; Han et al. 2025). Potassium sorbate influence on fruit size, though comparatively smaller, acts indirectly by enhancing physiological conditions.

Comparing these findings with studies in temperate viticulture, such as Correa et al. (2015), shows that grapevine responses to GA3 tend to be greater in temperate climates, likely due to cooler temperatures and longer photoperiods that extend generative growth phases. This contrast highlights the need for tropical-specific adaptations in hormone and nutrient management, given tropical climates fluctuating rainfall, high temperatures, and shorter photoperiods that can alter growth responses and metabolic processes.

Limitations of this study include data collected over a single growing season at one location, restricting generalizability. Moreover, while GA3 promoted growth and parthenocarp effectively, higher doses may carry risks of phytotoxicity, which was not extensively evaluated here. The need for future multi-season trials to investigate the potential negative effects of overdosing GA3 and to define safe and effective concentration ranges under tropical conditions is a clear call to action for further research.

Physiologically, GA3 induces parthenocarp by stimulating ovary development without fertilization, whereas potassium plays a key role in soluble sugar accumulation by enhancing sucrose translocation. It's important to understand that differences in fruit ripening duration between tropical and temperate grapes likely explain variation in sugar accumulation. This knowledge can help us better understand and predict the effects of climate on fruit ripening and sugar buildup.

Responses to GA3 and potassium sorbate may also vary due to environmental factors such as climate, soil type, and cultivation practices across locations. Temperature and humidity fluctuations in tropical regions affect hormone metabolism and nutrient uptake efficiency, potentially modifying treatment interactions (Cipcigan et al. 2022). Thus, broader multi-season and multi-location field trials are necessary to validate the consistency of effects across diverse agroclimatic zones.

Practically, understanding the physiological mechanisms of GA3 and potassium sorbate is vital for developing precision cultivation strategies tailored to tropical viticulture. Optimizing application timing such as GA3 at early anthesis and around twenty-two days after

anthesis, and potassium sorbate at twenty-two days after anthesis and veraison will maximize benefits while minimizing risks such as metabolic stress or ionic imbalances (Santos et al. 2020).

Future research integrating genomic and metabolomic analyses, a novel approach, can identify key genes and metabolic pathways responsive to these treatments, enabling the development of targeted, locally adapted application protocols (Modina et al. 2023). Multi-seasonal and multi-location studies combined with physiological and post-harvest quality assessments, including storage life and flavor stability, will provide comprehensive insights to optimize GA3 and potassium sorbate use. These efforts will support maximizing yield and fruit quality in tropical viticulture while maintaining sustainability and adaptability to climate and cultivar variability.

In conclusion, the combined application of 150 ppm gibberellin (GA3) at the anthesis stage and 0.3% potassium sorbate at veraison was the most effective treatment to enhance both yield and quality of Bali grapes. This treatment significantly triggered parthenocarpy, increased berry size and sugar content, reduced millerandage incidence, and decreased seed number per berry. It also improved fruit weight, cluster weight, and the lengths of clusters and pedicels. These results demonstrate a clear synergistic interaction between GA3 and potassium sorbate, suggesting that applying GA3 at early anthesis followed by potassium sorbate at veraison can be recommended as an optimized protocol for grape growers in Bali and comparable tropical regions to maximize production and fruit quality while considering cost and resource availability. To confirm these findings and ensure broader applicability, multi-location and multi-season trials are necessary across diverse agroclimatic zones and grape cultivars. Additionally, future research should focus on uncovering the molecular mechanisms behind the interaction of GA3 and potassium sorbate. Such studies will provide a stronger scientific basis for tailored recommendations to improve grape productivity and quality in tropical and subtropical viticulture systems.

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