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Role of Brassinosteroids in Berry Quality: A Case of Three Table Grape Cultivars

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Abstract. **The use of environmentally friendly methods to improve fruit quality and enhance their positive effects on human health has become one of the most important goals of modern fruit production systems. Brassinosteroids (BRs) belong to the sixth group of plant hormones and are used as plant growth regulators in many plant species and cultivars in plant production. This study aimed to determine the effect of applications of BRs on the physicochemical properties of three table grape cultivars (Italia, Michele Palieri, and Royal). The BRs were applied to the grape cultivars in three doses [0, 0.4, and 0.8 mg·L^{-1} 24-epibrassinolide (24-eBL)] during the veraison period and 1 week after the veraison period. The period between treatments and harvest was 45 days for all cultivars. Harvested grapes were analyzed for various parameters, including cluster weight, cluster width, cluster length, 100 berry weight, berry width, berry length, firmness, total soluble solids content (TSS), total acidity, total phenolics, total antioxidant capacity, tartaric acid, citric acid, and malic acid contents. The grape cultivars displayed varying responses to 24-eBL applications. The 0.4 mg·L^{-1} 24-eBL treatment increased the total phenolic content of 'Italia' and 'Michele Palieri' and tartaric acid and malic acid contents in 'Italia'. The 0.8 mg·L^{-1} 24-eBL application positively affected berry firmness of 'Italia'; cluster weight, berry length, tartaric acid, and malic acid of 'Royal'; and total phenolic content, total antioxidant capacity, tartaric acid, and malic acid of 'Michele Palieri'. The results of the study showed that BRs applications have the potential to improve the quality of table grapes, but the appropriate dose and phenological period of the cultivars are important factors that ensure its effectiveness.**

Grapevine, a fruit crop of economic importance and health benefits, is widely cultivated worldwide. Rich in phenolic compounds, grapes are consumed fresh as raisins, wine, vinegar, molasses, and juice. They also have applications in food additives, the pharmaceutical industry, and natural cosmetics. More than 36% are enjoyed as table fruit (Bourgaud et al. 2001; Medouni-Adrar et al. 2015). Grape cultivation, or viticulture, thrives in diverse geographical regions globally. Because it generates jobs and supports small farms, its economic and social impacts are significant (Mello 2012). Global grape production in 2024 was reportedly 72 million tons grown on 6.5 million ha of land (Food and Agriculture Organization 2025). Turkiye, which is located in the most suitable region for grape growing, is the gene center of grape vines and has a very old and deep-rooted vineyard culture (Koçtürk and Engindeniz 2009). Furthermore, Turkiye is the seventh largest country in the world and produces 3.8 million tons of grapes on 3.4 million acres of land (Food and Agriculture Organization 2025).

Quality reigns supreme as a determinant of commercial importance in the world of fruits. Fruit quality is a crucial parameter that reflects the growth and development of the fruit itself. Furthermore, it can be mainly categorized as external quality and internal quality. External quality assessment relies on readily observable characteristics such as the longitudinal and transverse diameters and firmness and weight of individual berries. Internal quality, however, is determined by analyzing the biochemical properties (Ali 2017). Beyond these fundamental categories, sensory properties also play a significant role in defining fruit quality. These encompass aspects such as fruit size, firmness, color, taste, texture, and aroma (Anjali et al. 2024). Additionally, nutritional value and resistance to mechanical damage are important considerations. Consumers primarily prioritize fruit appearance and taste, thus making these factors key determinants of market preference (Ruiz and Egea 2008). Among the flavor metabolites mentioned, sugar and organic acid compositions have the strongest link to the taste of fruit. These compositions are measured through total soluble solids (TSS) and titratable acidity (TA), which are commonly associated with the taste of various fruits, including table grapes (Ferguson and Boyd 2002; Muñoz-Robredo et al. 2011; Shiraishi et al. 2010).

Grape growers use a diverse range of treatments to increase yield, quality, nutritional value, and antioxidant content. Among these methods, the use of plant growth regulators (PGRs) has particular significance. These PGRs, especially plant hormones, play a crucial role in regulating fruit development by influencing processes like fruit set, cluster weight, berry size, fruit maturation, and coloring (Lurie 2024; Zhou et al. 2024). Additionally, PGRs can improve the flavor profile of fruits (Kumar et al. 2014). In the pursuit of environmentally friendly practices, recent research has highlighted the benefits of brassinosteroid (BRs) for plant growth (Ali 2017; Clouse and Sasse 1998). Despite their limited abundance within plants, BRs, which comprise the sixth group of plant hormones, are, surprisingly, as powerful in influencing growth and development as the other five groups of phytohormones (auxin, abscisic acid, cytokinin, gibberellin, and salicylic acid) (Li et al. 2022). Additionally, BRs exert their influence on various physiological processes like seed germination, plant development, flowering, root formations, and even rooting after planting (Clouse and Sasse 1998; Nemhauser and Chory 2004). Studies of viticulture have shown that BR applications during veraison, which is a crucial phenological stage in grape development, positively affect morphometric and quality parameters (Biesaga-Koscielniak et al. 2014; Farooq et al. 2009, 2010; Ghorbani et al. 2017; Raghu and Rao 2016; Vergara et al. 2018), increase sugar accumulation and total anthocyanin content in 'Cabernet Sauvignon' (Luan et al. 2013; Symons et al. 2006; Xi et al. 2013), and increase cluster and berry weights and the total sugar content in 'Horoz Karasi' (Babalık et al. 2023).

Numerous studies have explored the potential of BRs in viticulture by examining their effects on plant development, fruit quality, and phytochemical properties (Babalık et al. 2018; Işci and Gökbayrak 2015; Symons et al. 2006). However, a gap exists in research regarding the influence of BRs on organic acids, which play a vital role in shaping taste, flavor, and color of grapes. Additionally, previous studies have often focused on single grape cultivars. To address these issues, this study investigated the effect of BRs on three

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table one white (Italia) and two colored (Michele Palieri and Royal) grape cultivars. When selecting the cultivars, attention was focused on ensuring that they had similar maturity periods. All three cultivars have similar phenological periods, and the maturing of the clusters occurs at the end of August and the beginning of September. These cultivars were treated with doses of 0.4 and 0.8 mg·L^{-1} 24-epibrassinolide (24-eBL) because the most effective results were obtained with these doses in previous studies (Babalık et al. 2023; Ghorbani et al. 2017; Luan et al. 2013; Vergara et al. 2018; Xi et al. 2013). This research examined cluster and berry characteristics as well as various quality factors.

Materials and Methods

Experimental design and treatments. The study was conducted at a vineyard located within the Middle Black Sea Transitional Zone Agricultural Research Institute (lat. 40°32′17.20″N, long. 36°45′09.53″E) in Tokat Province in 2021. According to the Tokat classification, the climate is of the semi-humid/arid type. Figure 1 provides data regarding climate factors, namely, the monthly average temperature and total precipitation amount. These data were obtained from the Turkish State Meteorological Service of Tokat (Fig. 1). The characteristics of the vineyard soils are as follows: sand ratio, 54.02%; clay ratio, 31.58%; silt ratio, 14.39%; salt content, 0.02%; organic matter content, 1.18%; degree of saturation, 56%; soil texture, CL; electrical conductivity (EC), 0.57; pH, 7.78; phosphorus (P) ratio, 5.72; and potassium (K) ratio, 102.4. The following three table grape cultivars (*Vitis vinifera*) were investigated: Italia (white), Michele Palieri (colored), and Royal (colored). All cultivars matured at the same time. These vines were 11 years old at the time of the study, and they were grafted onto 1103 P rootstock. These vines were on a trellis system with a bilateral cordon and double T support with spacing of 3 × 1.75 m. They were spur-pruned to maintain approximately 20 ± 2 nodes per vine. For the experimental year, the vineyard received only nitrogen fertilizer, and weed control was managed mechanically. Additionally, disease control and pest control were performed according to the standard spraying program.

Treatments comprising BRs were applied two times at veraison (2 Aug) and again 1 week later (9 Aug) as spray to the whole vine. Treatment doses were 0 (control), 0.4 mg·L^{-1}, and 0.8 mg·L^{-1} 24-eBL (Babalık et al. 2023; Xi et al. 2013). Hormone treatments including the control were applied freshly prepared solutions that contained 0.1% Tween 80 (Merck, Darmstadt, Germany) as the surfactant. Control vines were sprayed with distilled water. No other manipulations of the grape clusters were performed. Figure 2 illustrates the treatment schedule and harvest times of the different grape cultivars.

Harvest and analyses.

The period between treatments and harvest was 45 d for all cultivars. Grapes were harvested upon reaching commercial maturity, as indicated by a total soluble solids (TSS; °Brix) content of 13% to 17%. Following the harvest, 10 clusters were randomly selected from each treatment group.

Cluster and berry growth parameters. From each cluster, 100 berries were randomly chosen from the upper, middle, and lower sections. Cluster length (cm; OIV 202) and width (cm; OIV 203) were measured using a ruler. The length and width (OIV 220 and OIV 221) of berries were measured (in mm) using an electronic vernier caliper. The weight of each cluster and combined weight of 100 berries were determined using an electronic balance. Additionally, berry firmness of each berry was assessed with a Durofel digital firmness meter (Agrosta Instruments, Agrotechnologie, Serqueux, France). The firmness values in the measuring range of the device varied between 0 and 100.

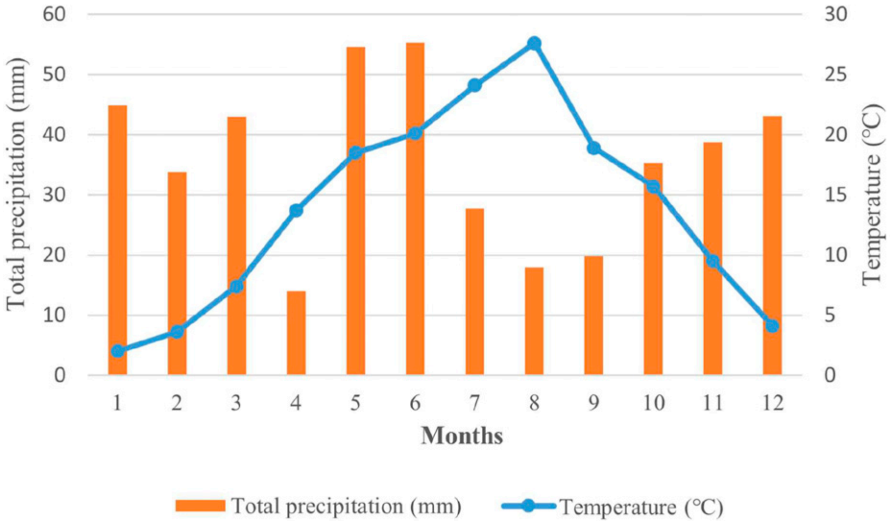

Fig. 1. Monthly temperatures and total precipitation values of the trial vineyard in 2021.

Chemical analysis and phytochemicals analysis. A digital refractometer (HI96801) was used to measure the TSS content of the grape juice. The pH of grape juice was measured using a pH meter (St 3100F; Ohaus, Parsippany, NJ, USA). The titratable acidity (%) of grape juice was determined using the 0.1 N sodium hydroxide titration method. The analysis was performed in triplicate for each treatment. From each replicate, 30 berries were wrapped in cheesecloth (two from the shoulder, two from the middle, and one from the bottom) and squeezed with a hand press. The resulting must was used for soluble solids, pH addition, and total acidity.

Fifty randomly selected berries were homogenized with a blender, and pulp was prepared to be used in the phytochemical analysis. The Folin-Ciocalteu reagent method (Singleton and Rossi 1965) was used to determine the total phenolic content of the fruit. A fruit extract was mixed with Folin-Ciocalteu reagent and distilled water in a 1:1:20 ratio. After adding 7% sodium carbonate, the solution was incubated for 2 h, allowing it to develop a bluish color. Then, the absorbance of the solution was measured using a spectrophotometer at a wavelength of 750 nm. Results were expressed as micrograms (μg) of gallic acid equivalents per gram of fresh weight of fruit.

The Trolox equivalent antioxidant capacity method, as described by Ozgen et al. (2006), was used to determine the total antioxidant capacity (TAC) of the fruit. This method involves three steps. In the ABTS radical preparation, a solution of 7 mM ABTS (2,2′-Azino-bis 3-ethylbenzothiazoline-6-sulfonic acid) is mixed with 2.45 mM potassium bisulfate and incubated in the dark for 12 to 16 h. In the calibration with sodium acetate buffer, the absorbance of prepared radical solution is measured at 734 nm using a spectrophotometer after adjusting the solution with sodium acetate buffer (pH 4.5) to achieve a target absorbance of 0.700 ± 0.01 mL. During sample analysis and quantification, 20 μL of the fruit extract is mixed with 2.98 mL of the prepared buffer solution. The absorbance of this mixture is then measured at 734 nm using a spectrophotometer after a 10-min incubation period. The obtained absorbance values are compared with a standard curve generated using Trolox solutions at concentrations ranging from 10 to 100 μmol·L^{-1}. This allows for the calculation of the TAC and its expression as micromoles (μmol) of Trolox equivalent antioxidant capacity per gram of fresh weight of fruit.

Organic acid analysis. A high-performance liquid chromatography system was used for the analysis of organic acid using an isocratic method (Pretel et al. 2006). Fifty randomly selected grapes were homogenized with a blender, and pulp was prepared to be used in organic acid analysis. In this study, the identification of organic acids of the treatments was conducted by comparing their retention times with known organic acid standards. Specifically, tartaric acid, malic acid, and citric acid were quantified using their respective standards. Calibration curves were constructed for

Fig. 2. The 24-epibrassinolide (24-eBL) treatment schedule.

each organic acid by injecting solutions of known concentrations into the high-performance liquid chromatography system. These curves were then used to determine the organic acid content in the samples, which were expressed as $mg \cdot kg^{-1}$ of fresh weight.

Statistical analysis. The experiment was conducted in randomized blocks with a split-plot experimental design comprising three replications and three grapevines in each replicate. A total of 81 grapevines (three cultivars × three doses × three replicates × three grapevines in each replicate) were used in the experiment. All data were analyzed by performing an analysis of variance using the statistical program at SAS (version 9.1; SAS Inc., Cary, NC, USA). Duncan's multiple range test was used to identify significant differences between treatment means, with significance set a $\alpha = 0.05$.

Results and Discussion

Growth parameters of cluster and berries. Table 1 presents the results for cluster and berry morphometric parameters measured at harvest across the different treatment groups. Significant differences were observed in berry quality among the treatments. The application of 24-eBL during veraison significantly affected cluster and berry characteristics at harvest; however, the observed effects depended on the grape cultivar studied. There was a significant difference in the cluster weight, cluster width and length parameters, cultivar, and cultivar × treatment interaction; however, there were no statistically significant differences in the treatment means. When the cultivar means were examined in these three parameters,

Table 1. Effects of 24-epibrassinolide (24-eBL) treatments on cluster and berry properties of grapevine cultivars.

	Cultivar	Control	$0.4\ mg \cdot L^{-1}$ 24-eBL	$0.8\ mg \cdot L^{-1}$ 24-eBL	Mean
Cluster weight (g)	Italia	589.00 A-a	451.80 A-a	632.12 A-a	557.64 A
	Michele Palieri	387.85 A-a	373.51 A-a	272.24 A-b	344.53 B
	Royal	400.98 AB-a	355.62 B-a	439.93 A-ab	398.84 B
Mean		459.29 a	393.64 a	448.10 a	
Cluster width (cm)	Italia	15.807 A-a	15.417 A-a	14.000 A-a	15.074 A
	Michele Palieri	12.346 A-a	12.030 A-b	12.140 A-a	12.172 B
	Royal	13.390 A-a	11.166 B-b	12.156 AB-a	12.237 B
Mean		13.847 a	12.871 a	12.765 a	
Cluster length (cm)	Italia	23.470 A-a	23.333 A-a	23.637 A-a	23.480 A
	Michele Palieri	17.623 A-b	19.443 A-b	19.280 A-b	18.782 B
	Royal	17.110 A-b	17.417 A-c	18.890 A-b	17.805 B
Mean		19.401 a	20.064 a	20.602 a	
100 Berry weight (g)	Italia	517.27 A-a	445.33 B-b	502.73 AB-b	488.44 B
	Michele Palieri	522.87 A-a	540.60 A-a	552.27 A-b	571.91 A
	Royal	603.20 A-a	542.80 A-a	662.93 A-a	602.98 A
Mean		581.11 a	509.58 b	572.64 a	
Berry width (mm)	Italia	19.213 A-a	18.250 AB-a	17.470 B-b	18.311 B
	Michele Palieri	16.566 B-b	18.300 AB-a	20.000 A-a	18.288 B
	Royal	20.340 A-a	19.476 A-a	20.653 A-a	20.156 A
Mean		18.706 a	18.675 a	19.374 a	
Berry length (mm)	Italia	21.733 A-a	20.850 AB-a	19.226 B-c	20.603 B
	Michele Palieri	22.000 B-a	21.566 B-a	23.800 A-a	22.455 A
	Royal	20.793 AB-a	20.083 B-a	21.526 A-b	20.801 B
Mean		21.508 a	20.833 a	21.517 a	
Berry firmness	Italia	41.663 B-c	53.123 A-b	51.290 A-b	48.692 C
	Michele Palieri	74.663 A-a	73.623 A-a	69.623 A-a	72.637 A
	Royal	57.583 A-b	55.203 A-b	55.747 A-b	56.178 B
Mean		57.970 b	60.650 a	58.887 ab	

Cultivars with the same uppercase letters in the same figure are not significantly different (Duncan, $\alpha = 0.05$). The 24-eBL treatments with the same lowercase letters in the same column are not significantly different (Duncan, $\alpha = 0.05$).

'Italia' had the highest value. When examined in terms of cultivar × treatment interaction, the effect of treatment on cluster weight was statistically significant for 'Royal'. For 'Royal', cluster weight displayed a dose-dependent response to 24-eBL. The lower concentration (0.4 mg·L^{-1}) slightly decreased cluster weight (355.62 g), while the higher concentration (0.8 mg·L^{-1}) significantly increased the cluster weight (439.93 g). The highest cluster weight (632.12 g) was recorded for 'Italia' treated with 0.8 mg·L^{-1} 24-eBL, while the lowest cluster weight (272.24 g) was observed with 'Michele Palieri', which was also treated with 0.8 mg·L^{-1} 24-eBL.

Cluster width values of 'Royal' were significantly different when the cultivar × treatment interaction was examined. The 0.4 mg·L^{-1} 24-eBL treatment for 'Royal' yielded the lowest value (11.166 cm), which was significantly lower than that yielded by both the control and the 0.8 mg·L^{-1} 24-eBL treatments. Cluster length values revealed no statistically significant differences among the cultivar × treatment interaction. The 0.8 mg·L^{-1} 24-eBL treatment resulted in the highest cluster length value of 23.637 cm for 'Italia', while the control group of 'Royal' exhibited the lowest value of 17.110 cm (Table 1). These findings suggest that the 24-eBL application may have a treatment-specific effect on cluster length. 'Italia' exhibited the highest effect.

Regarding the 100 berry weight (Table 1), statistical differences were significant, and the highest values were exhibited by Michele Palieri and Royal cultivars. Regarding the treatment averages, the 0.4 mg·L^{-1} 24-eBL treatment had a decreasing effect on the 100 berry weight compared with the control and 0.8 mg·L^{-1} 24-eBL treatments. The 100 berry weight and cultivar × treatment interaction across the grape cultivars showed significant differences only in 'Italia', whereas the differences in 'Michele Palieri' and 'Royal' were not statistically significant.

Cultivar means of berry width were statistically significant, and the highest value was exhibited by 'Royal'. Regarding the cultivar × treatment interaction, the berry widths of 'Italia' and 'Michele Palieri' were significantly different; however, the values of 'Royal' were not significantly different (Table 1). The 0.8 mg·L^{-1} 24-eBL treatment had contrasting effects on berry width depending on the cultivar. For 'Italia', it caused a decrease to 17.470 mm; however, for 'Michele Palieri', it increased the width to 20.000 mm.

Cultivar and cultivar × treatment interactions were associated with statistically significant differences in berry length, but not in the treatment means (Table 1). The 24-eBL treatments had cultivar-specific effects on berry length. For 'Italia', both the 0.4 mg·L^{-1} (20.850 mm) and 0.8 mg·L^{-1} (19.226 mm) 24-eBL treatments caused a reduction in berry length compared with that of the control. Conversely, for 'Michele Palieri', only the 0.8 mg·L^{-1} 24-eBL treatment significantly increased berry length (23.800 mm) compared with that of the control. 'Royal' also displayed a dose-dependent response, with the 0.4 mg·L^{-1} 24-eBL treatment decreasing the berry length (20.083 mm) and the 0.8 mg·L^{-1} 24-eBL treatment increasing it (21.526 mm) compared with that of the control. Statistical differences in berry firmness associated with cultivar, treatment, and cultivar × treatment interactions were significant for 'Italia' (Table 1). All 24-eBL treatments for 'Italia' significantly increased berry firmness compared with that of the control.

Chemical and phytochemicals analysis. Statistically significant differences in average pH values were associated with cultivar and treatment. Statistically significant differences in pH values associated with the cultivar × treatment interaction were observed only in 'Michele Palieri', while 'Italia' and 'Royal' exhibited no significant changes (Table 2). The 0.8 mg·L^{-1} 24-eBL treatment for 'Michele Palieri' caused a decrease in pH, suggesting a potential influence on grape acidity. The differences in pH among the treatments were statistically significant. The 0.8 mg·L^{-1} 24-eBL treatment led to an increase in pH. 'Michele Palieri' displayed the lowest and highest pH values under the 0.8 mg·L^{-1} 24-eBL treatment and the control treatment, respectively. The TSS content was significantly difference in cultivars. However, the cultivar × treatment interaction was statistically insignificant for 'Italia' but significantly different for 'Michele Palieri' and 'Royal' (Table 2). For 'Michele Palieri', the 0.8 mg·L^{-1} 24-eBL treatment increased the TSS content, but the opposite effect for 'Royal' was observed; for 'Royal', the same treatment decreased TSS. In addition, the differences in TSS values among the treatments were statistically insignificant. An analysis of berry acidity revealed statistically significant averages associated with treatment and cultivar. Regarding the cultivar × treatment interaction, statistically significant differences were only found for 'Italia' (Table 2). The 0.8 mg·L^{-1} 24-eBL treatment led to an increase in acidity. While 'Italia' displayed the highest acidity under the 0.8 mg·L^{-1} 24-eBL treatment, the lowest acidity was observed in 'Michele Palieri' under the control treatment.

Statistically significant differences in total phenolic contents were associated with cultivar, treatment, and cultivar × treatment interactions. The highest mean values were exhibited by 'Royal' under the 0.4 mg·L^{-1} 24-eBL treatment. The 24-eBL application had a cultivar-dependent effect on phenolic content. For 'Italia', the 0.4 mg·L^{-1} 24-eBL treatment significantly increased the total phenolic content compared with that of control. Conversely, both 24-eBL concentrations (0.4 mg·L^{-1} and 0.8 mg·L^{-1}) led to significant increases in 'Michele Palieri'. However, the 'Royal' displayed the opposite trend, with only the higher concentration (0.8 mg·L^{-1}) causing a decrease in total phenolics. The highest total phenolic content was observed in 'Michele Palieri' treated with 0.8 mg·L^{-1} 24-eBL, thus highlighting the potential for enhancing phenolics in this cultivar with this specific treatment. Conversely, under the control treatment, 'Italia' exhibited the lowest total phenolic content (Table 3).

Statistically significant differences in mean values were associated with cultivar and treatment. 'Michele Palieri' and 'Royal' had the highest cultivar values, while the control and 0.8 mg·L^{-1} 24-eBL had the highest treatment values. The antioxidant values associated with the cultivar × treatment interaction were significantly different for 'Italia' and 'Michele Palieri', but not for 'Royal' (Table 3). The 24-eBL application exhibited cultivar-specific effects on antioxidant activity. For 'Italia', both the 0.4 mg·L^{-1} and 0.8 mg·L^{-1} 24-eBL

Table 2. Effects of 24-epibrassinolide (24-eBL) treatments on pH, total soluble solids content, and total acidity of Italia, Michele Palieri, and Royal table grape cultivars.

	Cultivar	Control	0.4 mg·L^{-1} 24-eBL	0.8 mg·L^{-1} 24-eBL	Mean
pH	Italia	3.620 A-c	3.706 A-b	3.556 A-c	C 3.627
	Michele Palieri	4.050 A-a	4.020 A-b	3.926 B-a	A 3.998
	Royal	3.790 A-b	3.790 A-a	3.810 A-b	B 3.627
Mean		3.820 a	3.838 a	3.764 b	
TSS (°Brix, %)	Italia	16.667 A-a	17.833 A-a	16.600 A-a	A 17.033
	Michele Palieri	13.700 B-b	13.466 B-b	14.400 A-b	C 13.855
	Royal	16.733 A-a	16.233 A-b	14.433 B-a	B 15.800
Mean		15.700 a	15.244 a	15.744 a	
TA (g/L)	Italia	0.540 AB-a	0.438 B-a	0.599 A-a	A 0.526
	Michele Palieri	0.299 A-c	0.310 A-b	0.333 A-c	C 0.314
	Royal	0.393 A-b	0.381 A-ab	0.415 A-b	B 0.396
Mean		0.410 b	0.376 b	0.449 a	

Cultivars with the same uppercase letters in the same figure are not significantly different (Duncan, α = 0.05). The 24-eBL treatments with the same lowercase letters in the same column are not significantly different (Duncan, α = 0.05). TSS = total soluble solids; TA = total acidity.

Table 3. Effects of 24-epibrassinolide (24-eBL) treatments on total phenols (mg gallic acid equivalent/g fresh weight) and total antioxidant capacity (TAC; µMol Trolox equivalent/g fresh weight) of Italia, Michele Palieri, and Royal table grape cultivars.

	Cultivar	Control	0.4 mg·L^{-1} 24-eBL	0.8 mg·L^{-1} 24-eBL	Mean
Total phenols (mg gallic acid equivalent/g fresh weight)	Italia	1792.20 B-c	2468.89 A-b	1910.60 B-c	C 2057.23
	Michele Palieri	2582.23 B-b	3930.56 A-a	4072.23 A-a	B 3528.34
	Royal	4032.20 A-a	4015.56 A-a	3272.20 B-b	A 3773.34
Mean		2802.23 c	3471.67 a	3085.00 b	
TAC (µmol Trolox equivalent/g fresh weight)	Italia	2.106 C-b	2.600 B-c	3.476 A-c	B 2.727
	Michele Palieri	5.830 A-a	4.440 B-b	6.060 A- a	A 5.443
	Royal	5.940 A-a	5.406 A-a	5.100 A-b	A 5.482
Mean		4.625 a	4.148 b	4.878 a	

Cultivars with the same uppercase letters in the same figure are not significantly different (Duncan, $\alpha = 0.05$). The 24-eBL treatments with the same lowercase letters in the same column are not significantly different (Duncan, $\alpha = 0.05$).

treatments significantly increased antioxidant values compared with those of the control. Conversely, 'Michele Palieri' displayed the opposite response, and the 0.4 mg·L^{-1} 24-eBL treatment resulted in a decrease in antioxidant activity. The differences in antioxidant values among the treatments were statistically significant across all cultivars.

Organic acid analysis. Statistically significant differences in the parameters of tartaric acid, malic acid, and citric acid were associated with cultivar, treatment, and the cultivar × treatment interactions (Table 4). The highest tartaric acid and malic acid values were observed in 'Italia'. The 24-eBL application had a dose-dependent effect on tartaric acid in some, but not all, cultivars. A biphasic response was observed in 'Italia'. The 0.4 mg·L^{-1} 24-eBL treatment increased the tartaric acid content, while the higher concentration (0.8 mg·L^{-1} 24-eBL) decreased the tartaric acid content compared with that under the control treatment. Conversely, 'Michele Palieri' displayed a clear dose-dependent increase in tartaric acid with both 24-eBL concentrations. 'Royal' also exhibited a dose response, but in the opposite direction, with the 0.4 mg·L^{-1} 24-eBL treatment leading to decreased tartaric acid content and the 0.8 mg·L^{-1} 24-eBL treatment leading to increased tartaric acid content.

'Italia' exhibited a biphasic response; the 0.4 mg·L^{-1} 24-eBL treatment increased he malic acid content and the higher concentration (0.8 mg·L^{-1} 24-eBL) decreased the malic acid content compared with that of the control. Conversely, both 24-eBL concentrations for 'Michele Palieri' led to decreased malic acid content. However, 'Royal' exhibited the opposite trend, with increases in malic acid observed with both 0.4 mg·L^{-1} and 0.8 mg·L^{-1} 24-eBL treatments compared with that of the control (Table 4).

Similar to other organic acids, the citric acid content exhibited statistically significant differences across the grape cultivars (Table 4). In 'Italia' and 'Michele Palieri', citric acid values decreased as the dose of 24-eBL increased, whereas in 'Royal', citric acid values increased with higher doses of 24-eBL. The differences in the citric acid contents among treatments were statistically significant across grape cultivars. The highest citric acid content was found in 'Royal' treated with the highest concentration (0.8 mg·L^{-1}) of 24-eBL, while the lowest value was found in 'Michele Palieri' treated with the same concentration.

In this study, we performed an analysis of variance to elucidate the effects of cultivar, treatment, and the cultivar × treatment interaction on the quality of table grapes (Table 5). The results showed that cultivar has a major influence on cluster and berry growth and chemical, phytochemical, and organic acid parameters. In addition, total phenols, total antioxidant capacity, tartaric acid, malic acid, and citric acid, which play an important role in determining quality factors such as taste and aroma of grapes, were significantly associated with cultivars, treatments, and cultivar × treatment interactions.

Discussion

This study investigated the effects of 24-eBL, a type of BR, on the morphometric quality of 'Italia', 'Michele Palieri', and 'Royal' grapes by evaluating factors such as cluster weight, berry weight, size, firmness, and color, which are crucial to consumer appeal and the market value. Numerous studies have shown the potential of exogenous phytohormone applications, particularly BRs, to improve the external characteristics of grapes (Li et al. 2022; Sharma 2021). In 'Flame Seedless' and 'Thompson Seedless', BR applications increased berry length, weight, and width (Champa et al. 2015; Ghorbani et al. 2017; Li et al. 2022). A study that examined the effects of different concentrations of BR on postharvest 'Rish Baba' grapes reported that the 1.5 mg·kg^{-1} 24-eBL treatment was effective and reduced fruit weight (Pakkish et al. 2019). However, the effectiveness of BR appears to be cultivar-dependent. For instance, Vergara et al. (2020) found no significant changes in quality (total acidity, berry size) or yield (berry and cluster weights) parameters of 'Red Globe' treated with 0, 0.4, and 0.8 mg·L^{-1} 24-eBL doses. These studies indicated that the effects of BR applications on cluster and berry parameters vary by grape cultivar. This study revealed cultivar-specific responses of cluster and berry parameters to 24-eBL applications. While the exact mechanism by which BRs control grape berry growth remains unclear (Vergara et al. 2020), potential explanations for the observed yield and yield component changes can be explored. Furthermore, BRs are known to play a vital role in various plant growth and development processes, including cell expansion, division, pollen

Table 4. Effects of 24-epibrassinolide (24-eBL) treatments on tartaric acid, malic acid, and citric acid of Italia, Michele Palieri, and Royal table grape cultivars.

	Cultivar	Control	0.4 mg·L^{-1} 24-eBL	0.8 mg·L^{-1} 24-eBL	Mean
Tartaric acid (mg·kg^{-1})	Italia	6038.48 B-a	6404.33A- a	5996.66 C-b	A 6146.49
	Michele Palieri	3571.33 C-b	5398.62 B-b	6606.59 A-a	B 5192.18
	Royal	3464.94 B-c	3364.27 C-c	3709.55 A-c	C 3512.92
Mean		4358.25 c	5055.74 b	5437.60 a	
Malic acid (mg·kg^{-1})	Italia	2167.45 B-a	2501.08 A-a	1818.68 C-a	A 2162.40
	Michele Palieri	663.83 A-c	398.34 B-c	359.70 C-c	C 473.96
	Royal	1563.00 C-b	1602.98 B-b	1658.88 A-b	B 1608.28
Mean		1464.76 b	1500.81 a	1279.09 c	
Citric acid (mg·kg^{-1})	Italia	197.29 A-b	169.81 B-b	146.74 C-b	B 171.28
	Michele Palieri	161.09 A-c	118.15 B-c	97.44 C-c	C 125.56
	Royal	396.34 C-a	418.39 B-a	482.04 A-a	A 432.26
Mean		251.57 a	235.45 c	242.07 b	

Cultivars with the same uppercase letters in the same figure are not significantly different (Duncan, $\alpha = 0.05$). The 24-eBL treatments with the same lowercase letters in the same column are not significantly different (Duncan, $\alpha = 0.05$).

Table 5. Summary statistics of the correlation of grape quality characteristics with cultivars and 24-epibrassinolide (24-eBL) treatments.

	Cultivar		Treatment		Cultivar × treatment	
	F value	*P*	*F* value	*P*	*F* value	*P*
Cluster weight (g)	9.79	0.0013	0.98	0.3927	1.45	0.2575
Cluster width (cm)	11.63	0.0006	1.51	0.2480	0.78	0.5538
Cluster length (cm)	22.38	<0.0001	0.88	0.4318	0.35	0.8425
100 Berry weight	10.31	0.0010	4.49	0.0262	1.20	0.3441
Berry width (mm)	12.14	0.0005	1.65	0.2203	6.36	0.0023
Berry length (mm)	12.08	0.0005	1.80	0.1939	5.99	0.0030
Berry firmness	220.50	<0.0001	2.73	0.0924	10.03	0.0002
pH	104.73	<0.0001	4.54	0.0253	2.75	0.0601
TSS (Brix,%)	28.92	<0.0001	0.86	0.4387	3.66	0.0237
Total acidity (g/L)	74.98	<0.0001	8.68	0.0023	3.57	0.0259
Total phenols (mg gallic acid equivalent/g fresh weight)	454.18	<0.0001	59.54	<0.0001	57.69	<0.0001
Total antioxidant capacity (μmol Trolox equivalent/g fresh weight)	122.59	<0.0001	6.75	0.0065	8.34	0.0005
Tartaric acid (mg·kg^{-1})	1.56	<0.0001	2.73	<0.0001	2.24	<0.0001
Malic acid (mg·kg^{-1})	2.26	<0.0001	4.33	<0.0001	5.29	<0.0001
Citric acid (mg·kg^{-1})	2.77	<0.0001	6.65	<0.0001	5.86	<0.0001

tube formation, and tissue differentiation (Bishop and Koncz 2002; Clouse 2002; Sasse 2003). However, their effectiveness in these processes can be significantly influenced by several factors. The dose, timing, and cultivar differences are critical factors that determine the outcome of BR treatments (Müssig 2005). In some instances, BRs may lead to only modest growth increases or inhibit growth entirely. For example, higher BR concentrations can inhibit cell elongation, particularly primary root elongation, and lateral root formation (Sasse and Sasse 1994). These observations highlight the importance of considering these factors when studying the effects of BRs on plant growth. In the context of this research, the cultivar-specific responses observed in grape berry parameters following 24-eBL treatments underscore the need to further investigate the interplay between BR treatment doses and grape cultivars.

Studies have explored the link between BR treatments and sugar accumulation in grapes. Symons et al. (2006) reported an association between increased endogenous BR levels and elevated transcript levels of VvDWF1 and VvBRI1 genes in 'Cabernet Sauvignon' grapes during the 8- to 10-week period after flowering. This coincided with increased grape yield and quality, suggesting a potential role of BRs in regulating sugar accumulation. The expression of genes involved in BR synthesis overlapped with the fruit ripening process, highlighting potential hormonal coordination during berry development. While Symons et al. (2006) focused on BR signaling genes, Xu et al. (2015) investigated VvHT1, VvHT2, and VvHT3 genes encoding hexose transporters in 'Cabernet Sauvignon' grape. These transporters are crucial for facilitating sugar uptake into grape berries. However, they observed distinct expression patterns for these HT genes during the veraison stage, which is a critical period for sugar accumulation. These findings suggest that BRs might influence sugar accumulation in grapes through their interaction with genes like VvDWF1 and VvBRI1, potentially regulatinghexose transporter expression (VvHT1, VvHT2, VvHT3) during berry development.

Building upon the link between BRs and sugar accumulation in grapes, other studies (Hayes et al. 2007; Symons et al. 2006; Xu et al. 2015) explored the role of hexose transporters (VvHTs) and revealed that VvHT3 transcript levels mirrored the sugar accumulation pattern in grapes, suggesting its potential role in this process. The findings of those studies support our observations. In our study, 'Michele Palieri' treated with 24-eBL displayed increased TSS levels compared with those of the control, which suggested a potential maturation-dependent induction of sugar-related genes by BRs. However, cultivar differences appear to play a crucial role in BR responses. In 'Cabernet Sauvignon' treated with different 24-eBL (Hayes et al. (2007), only the 0.4 mg·L^{-1} treatment increased TSS compared with that of the control. Similarly, Babalık et al. (2020) reported that the effectiveness of 24-eBL treatments on yield and quality of 'Alphonse Lavalle' was highly dependent on dose and timing. In 'Carmenere', a consistent decrease in VvHT3 expression from veraison to harvest was noted and could be attributed to cultivar differences or cultivation conditions (Pastenes et al. 2014). These findings highlight the importance of cultivar specificity when considering BR application strategies. The decrease in TSS observed in 'Royal' in our study may be attributed to similar factors. Cultivar differences could explain the contrasting response of 'Royal' and 'Michele Palieri'. Alternatively, cultivation conditions or the application period and dose used may not have been optimal for promoting sugar accumulation in 'Royal'.

Previous research suggested that BRs, particularly the exogenous application of 24-eBL (a BR analog), can enhance fruit ripening and the accumulation of phenolic compounds (Luan et al. 2013; Xi et al. 2013). Studies have shown that 24-eBL application increased total phenolics and antioxidant contents in various grape cultivars, including Thompson Seedless (Asghari and Rezaei-Rad 2018; Ghorbani et al. 2017), Yan73, and Cabernet Sauvignon (Xu et al. 2014). Babalık et al. (2020) studied 'Alphonse' and concluded that the 0.4 mg·L^{-1} 24-eBL application during the veraison period increased the total phenolic substance amount by 28% in the first year compared with that observed with other 24-eBL concentrations. In line with these findings, we observed an increased total phenolic content and total antioxidant capacity in 'Italia' and 'Michele Palieri' following 24-eBL treatments. However, the response of 'Royal' appeared different. The 0.8 mg·L^{-1} 24-eBL treatments for 'Royal' resulted in decreased total phenolic content and did not statistically significantly affect the total antioxidant capacity. Similar to many other parameters investigated, the phenolic content results highlight the importance of cultivar-specific response to 24-eBL treatments. Increased yield and quality after BR treatments for different horticultural plants and the effects of BRs are closely related to environmental conditions, BR concentrations, and the phenological period of the plant (Divi and Krishna 2009; Vardhini and Anjum 2015). Understanding the underlying mechanisms by which 24-eBL influences phenolic metabolism in different grape cultivars is crucial to optimizing BR application strategies to enhance grape quality.

The taste profile of grapes is a complex interplay between various biochemical components, including sugars, organic acids, and phenolic compounds. The biochemical composition of grapes varies primarily because of genotype, environmental factors, and agricultural practices (Muñoz-Robredo et al. 2011). The observed differences in responses could be attributed to the inherent characteristics of each grape cultivar. Preiner et al. (2013) reported variations in tartaric acid, malic acid, and citric acid contents across seven grape cultivars, thus supporting the concept of cultivar specificity in organic acid composition. Additionally, the timing of 24-eBL treatments may play a role in organic acid composition. Lv et al. (2022) reported that the 10 μM 24-eBL treatments for 'Shine Muscat' increased the amount of tartaric acid in grape berries. Zheng et al. (2020) observed a lower impact of BR treatments on organic acid contents in 'Kyoho' when applied at the beginning of berry softening. Our limited understanding of genes related to organic acid biosynthesis and regulation in grapes (Wang et al. 2022) hinders a complete explanation of how BRs influence organic acid contents across different cultivars. This concept is supported by Preiner et al. (2013), whose 3-year study of seven grape cultivars revealed variations in tartaric acid, malic acid, and citric acid content. Therefore, the different responses of cultivars to treatments can be explained by the specific characteristics of the cultivars and their different responses to the treatments.

In the study, BRs were applied during the veraison period, which is one of the most important growth periods of the bunches. While the treatments provided improvements in chemical, phytochemical, and organic acid properties of ‘Italia’ and ‘Michele Palieri’, this situation was limited to bunch weight and berry properties of ‘Royal’. This limitation was a result of sensitivity and reflects broader ecological and biological response mechanisms in which plants adjust their metabolic pathways to optimize nutrient uptake, stress resistance, and survival to changing environmental influences (Keller 2015). Similar to our study, Kaya et al. (2024) found variations in ‘Royal’ according to years and treatments. Such adaptive metabolic responses can significantly impact qualitative aspects of grape production and affect not only the organic acid profile but also other critical components that determine grape quality, such as sugar content, phenolics, and aromatic compounds. To explain the specific feature of this cultivar in detail, the physiological and genetic differences of the cultivar must also be investigated. However, this variability demonstrates the inherent genetic predisposition of plants to respond to nutrient availability and environmental stressors as well as highlights the complex dynamics governing plant physiology and nutrient metabolism (Verdenal et al. 2021).

Studies have consistently highlighted the cultivar-specific responses of grapes to BR treatments, with significant variability observed in physical, biochemical, and phytochemical parameters across different grape cultivars. This variability extends to dosage and timing, thus mirroring the challenges encountered with many plant growth regulators used in agriculture. While BRs have shown promise in enhancing yield, optimizing their application for commercial use requires overcoming these challenges. Additionally, while the treatment of exogenous BRs offers a promising avenue for studying plant metabolism, it is crucial to acknowledge the inherent limitations of this approach. The use of concentrations that often exceed physiological levels can lead to nonrepresentative responses and potentially mask the intricacies of endogenous hormonal regulation (Gomes 2011). Furthermore, the observed variability in responses across different grape cultivars underscores the importance of considering genotypic differences when interpreting the effects of BRs. In this study, the use of three different cultivars showed variations in the examined parameters. As Xu et al. (2015) pointed out, factors such as cultivation conditions and analytical methodologies can also influence the measured parameters, thereby complicating the direct attribution of observed changes solely to BR treatments. These considerations emphasize the need for a comprehensive approach that incorporates both exogenous and endogenous perspectives to fully understand the role of BRs in grapevine physiology.

Conclusion

The present study aimed to evaluate the impact of 24-eBL treatment during veraison on the quality attributes of three table grape cultivars (Italia, Michele Palieri, and Royal). The results indicated that 24-eBL treatments induced cultivar-specific responses in terms of cluster and berry characteristics and chemical, phytochemical, and organic acid compositions. The 0.4 $\text{mg}\cdot\text{L}^{-1}$ 24-eBL treatment provided a significant increase in cluster weight, berry length, berry firmness, and TSS amount in ‘Italia’ and a significant increase in the total phenolic content in ‘Italia’ and ‘Michele Palieri’. The 0.8 $\text{mg}\cdot\text{L}^{-1}$ 24-eBL treatment positively affected TSS, total phenolic content, total antioxidant capacity, and tartaric acid amount in ‘Michele Palieri’. The BR treatments resulted in limited or no significant improvements in ‘Royal’. These findings underscore the importance of cultivar specificity when considering BR treatments in grapevine cultivation. The observed differential responses suggested that an optimized 24-eBL dosage and timing are crucial to achieving desired outcomes of different grape cultivars.

Phenolic compounds and organic acids are important parameters that determine the quality of the fruit. Grapes with improved total phenolic content, total antioxidant capacity, and organic acids as a result of BRs may be preferred by consumers who want higher-quality products and are environmentally conscious. This study highlighted the potential of BRs to enhance the nutritional and sensory qualities of grapes. By positively influencing phenolic compound accumulation and antioxidant capacity, 24-eBL treatments offer opportunities to develop grape cultivars with improved health benefits.

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