

Brassinosteroids: an alternative to vine cultivation to enhance drought tolerance, in semiarid land at Chihuahua, Mexico

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Abstract

Chihuahua is an internationally recognized state for its quality in the production of vines (*Vitis vinifera*), and wines. However, it is exposed to drought events and has presented economic and social problems due to the low availability of fresh water. The aquifers destined for intensive agriculture, such as Cuauhtémoc present the most pronounced deficit and they have been operating with deficits of $-197 \text{ mm}^3 \text{ year}^{-1}$. Chihuahua typically receives an average annual rainfall of 224.5 mm. These semiarid ecosystems, with water scarcity, are not suitable for viticulture unless supplementary irrigation is available. One alternative option is to apply brassinosteroids to enhance the response of antioxidant systems under drought stress. Although growers in Chihuahua use auxins, cytokinins, and gibberellins as enhancers in the vine crop, the application of brassinosteroids (BRs) is not yet used, because there is poorly knowledge about their role and its activity involved in the yield and quality components of the vines and their antioxidant capacity. The brassinosteroids are successfully used to increase production, the size and weight of bunches and berries, to improve the color of grapes, to extend their postharvest life, and to increase the tolerance of plants to abiotic stress, specifically drought. Therefore, this review collects, analyses, and summarizes recently published information and highlights the importance of the properties of brassinosteroids as an antioxidant response in metabolism, fruit production, and quality, their postharvest action in vine cultivation, and recommends their safety use for grape-growing areas in Chihuahua, Mexico, and regions in the world that suffer from drought.

Keywords: abiotic stress; antioxidant response; brassinosteroids; plant metabolism; *Vitis vinifera*

Introduction

The grapevine (*Vitis vinifera*) has been recognized as one of the most important fruit crops cultivated throughout the world; however, most of the world's emerging grape-growing areas have arid or semi-arid

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climates and suffer from soil water shortages at some stages during the growing cycle, causing damage to the grape industry (Min *et al.*, 2018). The Mexican wine industry, due to its quality, represents an economic growing activity in which the state of Chihuahua is the fifth largest wine producer nationwide, concentrated in the municipalities of Chihuahua, Ciudad Delicias, Casas Grandes, and Ciudad Juárez (Campos *et al.*, 2022). Chihuahua state is exposed to events of severe drought and has presented economic and social problems due to the scarce availability of water, the overexploitation, and a growing demand for water resources in the entity (Méndoza, 2022). Under drought stress in vines, there is a loss of hydraulic functionality induced by the formation of embolisms (Anderegg *et al.*, 2016). The formation and removal of emboli affect the hydraulics and transpiration of the vines (Lovisolo *et al.*, 2010). Also, the vine leaves wither, their margins turn yellow, shoot and leaf development are largely suppressed, and grape quality and productivity are greatly affected (Fanizza and Ricciardi, 2015). Therefore, it is necessary to find approaches to address this problem, and research has progressed remarkably in this field during the last decades (Min *et al.*, 2018). Plant hormones such as BRs have been applied to plants (Wang *et al.*, 2014), for example, on grape leaves or berries to protect them against damage caused by drought stress, demonstrating effectiveness in relieving stress by regulating physiological processes and gene expression, providing a solid foundation for its use in practical production (Min *et al.*, 2018). Under this kind of stress, a decrease in oxidative damage has been demonstrated in vines pretreated with BRs due to the overexpression of antioxidants and improved metabolic conditions. For example, it has been reported that treatment with 24-epibrassinolide improved ammonium assimilation, photosynthetic capacity, sucrose activity, enzymes such as phosphate synthase and nitrate reductase, and glutamine synthetase and decreased sucrose synthase, acid invertase, neutral invertase, thus allowing an increase in sucrose and starch; plants pretreated with 24-epibrassinolide increased the amount of proline, improving osmotic adjustment, drought tolerance in vines and regulating carbon and nitrogen metabolism (Zeng *et al.*, 2024). BRs are involved with the metabolism of the vine, the quality of the bunches, and the color of the berries (Luan *et al.*, 2013; Champa *et al.*, 2015; Babalik *et al.*, 2020). However, in Chihuahua state, the application of BRs and their benefits in their antioxidant and productive capacity is still unknown and has not reached practice. For which it is important to know their action on the yield and quality of the grapes (Ghorbani *et al.*, 2017). Therefore, the objective of this paper is to collect, summarize, synthesize, and analyze current information about the importance of the properties of BRs as an antioxidant response in metabolism, fruit quality, and production, and their postharvest action in vine cultivation, and to recommend its safety use in Chihuahua, Mexico. The information is contemplated to benefit vine producers in the drought regions to achieve better quality production and offer a useful tool to mitigate drought stress conditions.

Vine cultivation in Chihuahua, a state with water poverty conditions

The state of Chihuahua is located in the semi-arid northern region of Mexico (Figure 1).

The winemaking industry was introduced by the Spanish during the conquest of the states of Baja California Norte and Sonora (Fuentes-Verduzco *et al.*, 2022). Although Sonora is the main producer of grapes for fresh consumption and Baja California Norte has stood out as the main wine region in Mexico (Acosta *et al.*, 2013), in Chihuahua, there are some vineyards in some municipalities among them Chihuahua, Delicias, Hidalgo del Parral, Casas Grandes, and Urique. Chihuahua state has won several awards due to its quality in winemaking such as the golden medal to Casa Porras in Mexico, Old Aqueduct Vineyard, Santa Clara Wines, and Don Tomas Mills in the Mexico International Wine Competition 2023 (Autonomous University of Chihuahua, 2023). However, the drought conditions in the state are a determinant factor for viticulture.

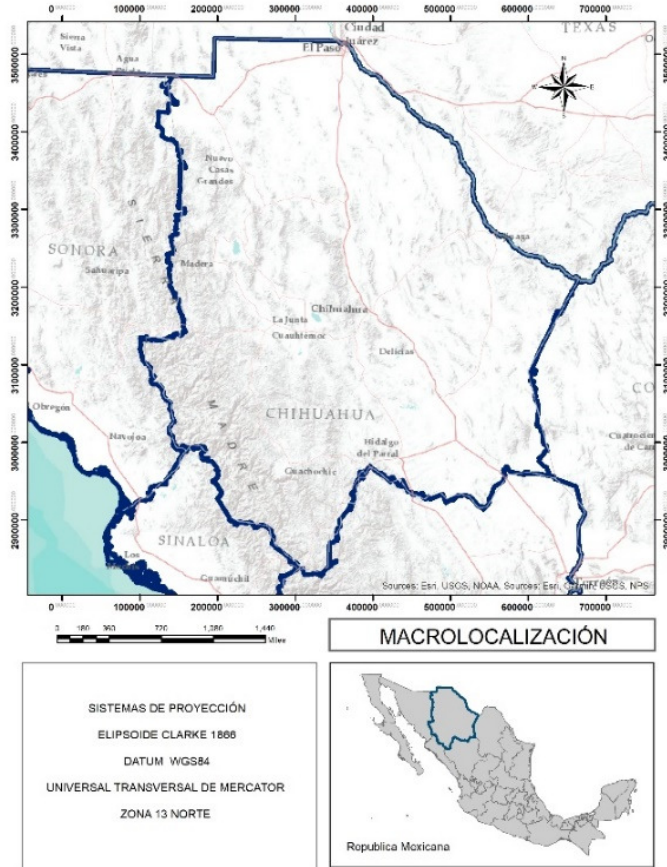


Figure 1. Geographical location of Chihuahua, Mexico

The serious problem of water scarcity has been aggravated by population growth, and the overexploitation of freshwater resources has occurred in various regions of North America (Asif *et al.*, 2023). Mexico, for its part, is the main importer in Latin America of virtual water in agricultural trade. Its water dependence from abroad is 42.5%, while the world average is 21.7% (Vázquez and Buenfil, 2020). During 2020 and 2021, Mexico suffered drought conditions in 88% of its territory, and it has become the second most severe drought event of the twenty-first century (Hernández and Jerez, 2023).

The state of Chihuahua is characterized by a high-water poverty index (Wurtz *et al.*, 2019) due to frequent droughts (Martínez-Sifuentes *et al.*, 2022). There are medium and high-water shortages with strong highlighted scarcities in the desert throughout the state of Chihuahua, and water poverty appears in the most productive territories (Wurtz *et al.*, 2019). It is exposed to events of climate change. It has presented economic and social problems for the scarce availability of water due to the overexploitation, and a growing demand for water resources in the entity (Méndoza, 2022). The aquifers in the areas where intensive agriculture is carried out, such as Cuauhtémoc and Meoqui-Delicias, present the most pronounced deficit, notably more than the aquifers that supply the city of Chihuahua, despite being the aquifers with the greatest storage capacity and even the extractions tend to increase over time from 2007 to 2014 (Gutiérrez *et al.*, 2016).

In addition, its aquifers have degraded in quantity and quality in recent years, operating with deficits of $-197 \text{ mm}^3 \text{ year}^{-1}$, as in the case of the Cuauhtémoc aquifer (CONAGUA, 2015). Table 1 presents relevant information regarding the negative availability of various aquifers in Chihuahua state due to overexploitation.

Ascensión, Cuauhtémoc, Jiménez, and Villa Ahumada no longer reach the quality or quantity of water for the population and agricultural irrigation as will be explained later, and could become ghost towns.

Table 1. Overexploited aquifers in the state of Chihuahua

Clue	Aquifer	Deficit (-)	R	DNCOM
0801	Ascensión	107	132	0
0803	Baja Babícora	3.4	90.6	0
0804	Buenaventura	65.1	66.5	0
0805	Cuauhtémoc	197.0	115.2	0
0806	Casas Grandes	20.4	180	0
0807	El Sauz-Encinillas	27.9	62.4	0
0808	Janos	44.4	141.9	15.7
0810	Samalayuca	6.1	16	0
0812	Palomas-GuadalupeVictoria	2.8	15.6	2.3
0821	Flores Magón- Villa Ahumada	110.4	137.5	0
0822	Santa Clara	12.4	59.4	35.8
0828	Los Moscos	0.8	37.7	0
0830	Chihuahua-Sacramento	45.5	56.6	0
0831	Meoqui- Delicias	172.2	211.2	0
0832	Jiménez-Camargo	142.1	173.3	5.5
0833	Valle de Juárez	86.5	125.9	0
0845	Felipe de Jesús	0.045	69.9	69.9
0847	Los Juncos	103.6	133.6	0.1
0848	Laguna de Palomas	-40	23.3	0

Source: Herrera *et al.* (2016). II National Congress of Irrigation and Drainage COMEII (2016).

Terms according to NOM-011-CONAGUA-2015. Units in mm³ year⁻¹ R: average annual recharge, DNCOM: natural discharge compromised.

Drought can produce anatomical and physiological changes in vines

Agricultural droughts are affected by hydrological droughts (Le *et al.*, 2016) and relate characteristics of meteorological droughts with agricultural impacts, focusing on the scarcity of soil moisture and the reduction of the groundwater level (Liu *et al.*, 2020). Agricultural droughts are described by defining water and soil moisture (Hao *et al.*, 2018). End-of-century projections indicate that drought risk in regions currently characterized by dryness is likely to increase due to projected reductions in soil moisture on a regional to global scale (Intergovernmental Panel on Climate Change, 2013). The problems produced by droughts are not only reflected in production, productivity, and economic returns, but in parallel, problems are generated in natural resources such as soil degradation and, therefore, the loss of biodiversity, effects known jointly as desertification. (Matailo-Ramirez *et al.*, 2019).

Despite the vines being grown in dry environments (Savoi *et al.*, 2017), the decrease in water supply significantly reduces the growth of shoots and the diameter of berries, which translates into a diminished yield; on the other hand, the water deficit produces a decrease in the reserve carbohydrates of the root system (Ferreira *et al.*, 2003). There is also a loss of hydraulic functionality induced by the formation of embolisms (Anderegg *et al.*, 2016). The formation and removal of emboli affect the hydraulics and transpiration of the vines (Lovisolo *et al.*, 2010).

Definition of brassinosteroids

BRs are hormones that regulate plant growth and its physiological, metabolic, and cellular processes (Tang *et al.*, 2016; Praveena *et al.*, 2020). BRs, defined as the sixth plant hormone group after the main plant hormones auxin, gibberellins, cytokinin, abscisic acid, and ethylene, are analogous to animal steroid hormones in structure (Taiz and Zeiger, 2010), and are polyhydroxysteroids of plant origin (Nolan *et al.*, 2020), and can confer drought stress tolerance (Yuan *et al.*, 2010; Fàbregas *et al.*, 2018; Cui *et al.*, 2023). Regarding this structure, BRs are steroids with 27, 28, or 29 carbon atoms; their molecules are composed of four rings (A, B, C, and D) and a side chain (Garrido-Auñón *et al.*, 2024) with different functional groups on A and B rings and the side chain (Bhatla and Lal, 2023). There are more than 70 BRs from plant sources; the one that has shown the most biological activity is Brassinolide, which is synthesized directly from campesterol (Garrido-Auñón *et al.*, 2024).

Discovery of brassinosteroids and their concentration in plants

BRs were discovered in *Pisum sativum* L. seedlings, where it was observed that the exogenous application of corn pollen caused the elongation of the treated internodes (Mitchell and Whitehead, 1941). BRs, like gibberellins and auxins, are widely distributed in the plant kingdom, in angiosperms as well as in gymnosperms (Hernández and García, 2016).

BRs have been found mainly in pollen, leaves, buds, flowers, and seeds in different proportions and shapes (Bajguz and Piotrowska-Niczyporuk, 2014). The concentration of BRs in plants is very low, generating technical difficulties for its isolation (Bajguz and Tretyn, 2003).

Regarding *Vitis* Cui *et al.* (2023) reported that the VvDET2 transcription was detected in grapevine organs such as roots, leaves, stems, tendrils, and berries, as well as the presence of endogenous BRs. It has been determined that water stress regulates VvDET2 expression by decreasing it and the content of total BRs in the leaves of grapevines, which verifies in Cabernet Sauvignon that the regulation of grape berry ripening and its response to water stress is related to VvDET2 transcription levels and total BR content.

Physiological functions of brassinosteroids

The recent discoveries of the physiological properties of BRs allow us to consider them as highly promising and appropriate natural substances for their use in plant protection and increase in agricultural production (Hernández and García, 2016).

BRs act in various processes, for example, rhizogenesis (Hernández and García, 2016), root growth, plant development (Wei and Li, 2016), cell elongation and proliferation; they are regulators in the biosynthesis of gibberellins (Unterholzner *et al.*, 2015). They are involved in cell senescence, xylem differentiation, reproduction phases, photomorphogenesis, seed germination (Sasse, 2003), root initiation, flowering time (Divi and Krishna, 2009), abscission (Hernández and García, 2016), fruit ripening processes, and the tolerance response to various biotic and abiotic stresses (Kaur *et al.*, 2015).

Other works have demonstrated that BRs modulate nitrogen physiological response promote nitrogen uptake (Xing *et al.*, 2022), and modulate abscisic acid-induced stomatal closure (Ha *et al.*, 2016). They also regulate gene expressions in the root, shoots, and leaves (Trevisan *et al.*, 2020).

Biosynthesis of Brassinosteroids

BRs have been isolated from various species of Bryophytes, Pterophytes, Gymnosperms, and Angiosperms, including mono and dicotyledonous plants; sixty-two BRs components and fifteen biosynthetic precursors have been detected in different plants (Zullo and Bajguz, 2019). BR biosynthetic gene expression is under organ-specific and developmental regulation (Shimada, 2003). The BRs biosynthetic pathway and the genes involved in BRs biosynthesis have been identified mainly in *Arabidopsis*.

Brassinolide (BL), the most active BR, is synthesized from campesterol through various pathways. Experiments have revealed the presence of two parallel pathways from campestanol to castasterone called the C-6 early and late oxidation pathways shown in Figure 2.

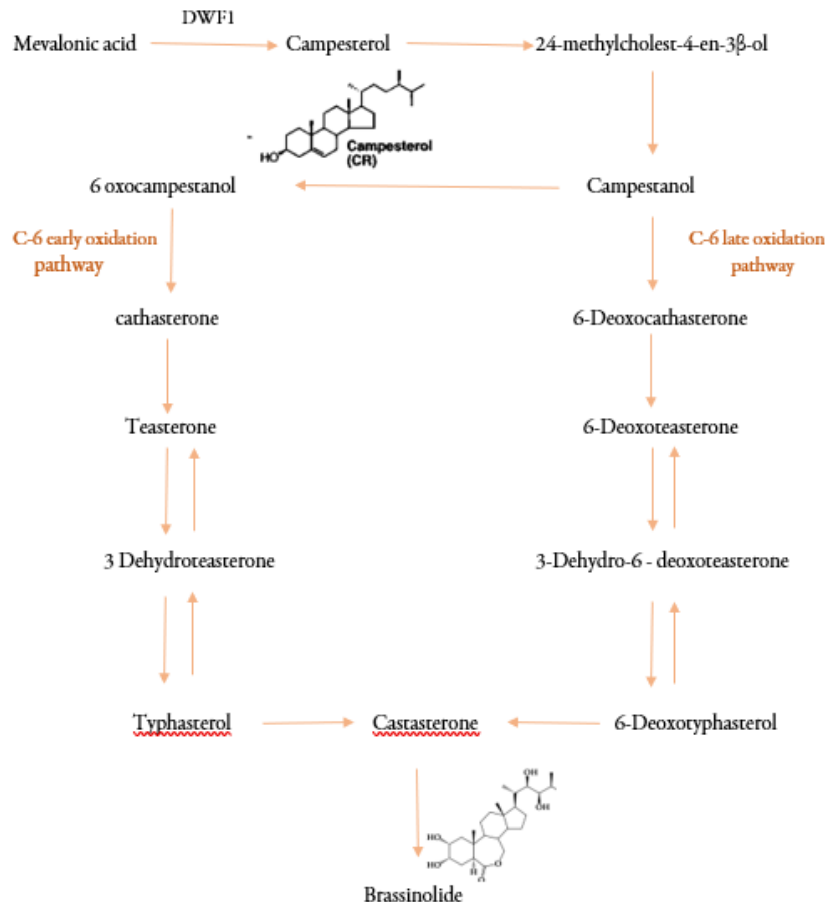


Figure 2. Proposed biosynthetic pathways for BL in *Arabidopsis* (modified from: (Noguchi *et al.*, 2000))

Unlike animals, plant steroids are recognized through receptors located on the cell membrane to initiate the signalling cascade to regulate different physiological processes that occur during their growth and development (Coll, 2006).

There is a surface receptor kinase complex responsible for perceiving BRs that are formed by BRASSINOSTEROID INSENSITIVE 1 (BRI1) and BRI1 ASSOCIATED PROTEIN 105 KINASE 1 (BAK1) (Tang *et al.*, 2010). BRI1, which is located in the plasmatic membrane and is rich in Leucine repeats (He *et al.*, 2005) starts up a signal transduction cascade that regulates transcription (Clouse, 2011). Once BR is bound, it allows the activation of BR1 Kinase activity (She *et al.*, 2011). BR then initiates cellular cascades

and binds steroids in the extracellular domain of BRI1 causing phosphorylation and activation of BRI1-CD, and transduction of the signal through an intracellular kinase to the nucleus, modifying gene expression, and resulting in cell division (He *et al.*, 2005).

In addition, BRI1-EMS SUPPRESSOR 1 (BES1) binds to the CANNTG promoter element (E-box) motif in the SAURAC1 promoter to activate gene expression, too; indeed, BES1 has been shown to interact with MYC-like (BIM), leading to increased binding of BES1 to the SAUR-AC1 promoter (Yin *et al.*, 2005). Similarly, MYB30 and BES1 bind to a conserved MYB-binding site and E-box sequences, respectively, in the promoters of BR- and AtMYB30-regulated genes, thus promoting the expression of a subset of BR target genes (Divi and Krishna, 2009). So, various physiological and biochemical responses are induced in plants, and a variety of genes have even been described that respond to the stressors at the transcription level (Sirhindi, 2013).

For example, the BR6ox and DWF4 genes are most expressed in apical shoots, followed by silique expression (Shimada, 2003). These results indicate that BRs are more actively synthesized in young and developing organs and are consistent with the notion that BRs function as growth-promoting hormones in plants (Divi and Krishna, 2009).

Effects of brassinosteroids on plant metabolism and abiotic stress

Plants respond and adapt to various environmental stressors to survive even under harsh conditions. Phytohormones are capable of regulating a variety of processes in plants and work as chemical messengers to communicate cellular activities in higher plants (Vob, 2014). Plant responses to different types of stress are associated with the generation of reactive oxygen species, suggesting that BRs may function as a common signal in plant stress response signaling pathways (Bajguz and Piotrowska-Niczyporuk, 2014) mainly by modulating the main components of the antioxidant defense system (Kaur *et al.*, 2015; Vardhini and Anjum, 2015) against various types of abiotic stress: high temperature (Janeczko *et al.*, 2011), light (Kurepin *et al.*, 2012), cold (Wang *et al.*, 2014), drought (Mahesh *et al.*, 2013), soil salinity (Abbas *et al.*, 2013; Kaur *et al.*, 2015), floods (Liang *et al.*, 2009), metals and metalloids (Bajguz, 2010; Cannata *et al.*, 2015) and organic contaminants (Ahammed *et al.*, 2013).

Besides, some works reported an increase in catalasterone (CS) levels under drought stress in pea plants (Jäger *et al.*, 2008), and barley (Gruszka *et al.*, 2016). Meanwhile, Oliver *et al.* (2011) worked with grass *Sporobolus stapfianus* exposed to drought and reported a yielded high-quality protein kinase-based signaling cascades and BR involvement in the regulation of the cellular protection response. There are reports of an increase in the expression of BR-biosynthesis genes under drought conditions in *Phormium tenax*, a garden plant (Bai *et al.*, 2017), in *Setaria italica* (Tang *et al.*, 2017), and barley (Janiak *et al.*, 2018).

On the other hand, it has been shown in several works that the use of foliar hormones is a useful tool under drought-stress conditions. Between them: foliar BR analog DI-31 sprays in Lulo plants to face situations of water stress conditions caused by low water availability in the soil (Catañeda-Murillo *et al.*, 2022), and with the same product, Pérez-Borroto *et al.*, (2022) increased soybean drought resilience. For his part, Ahmad *et al.* (2022) applied exogenously supplied BR to genotypes of *Brassica rapa* to alleviate drought stress through osmolyte concentration, levels of antioxidant enzymes, and photosynthetic system. The results of the application of BRs from research carried out on various crops under drought stress conditions are presented in Table 2.

Table 2. Results of the application of BRs from research carried out on various crops under drought stress conditions

Authors	Crop	Treatment	Dose	Results
Raza <i>et al.</i> (2023)	<i>Triticum aestivum</i> , Wheat	nano-biochar and BRs	Nano-biochar (0.75% w/w) was incorporated in the soil at the time of sowing and BRs (120 mg L ⁻¹) foliar spray	They divulged an increase in vegetative growth, grain weight, and yield, improvement of leaf area index, relative water contents, chlorophyll contents, stomatal conductance, and increase of N, P, and K contents in grains,
Barros <i>et al.</i> (2021)	<i>Eucalyptus urophylla</i> Eucalyptus	24-epibrassinolide	100 nM Plants sprayed	The authors concluded an increase in the antioxidant enzyme activities, chloroplastic pigments, PSII efficiency, electron flux, and net photosynthetic rate.
Phan <i>et al.</i> (2024)	<i>Glycine max</i> , Soybean	BRs	0.2 ppm Leaf sprayed	The work describes the highest total number of firm pods, the highest number of firm seeds, and the highest yield.
Naveen <i>et al.</i> (2021)	<i>Brassica juncea</i> , Indian mustard, RH 725	brassinolide	20 mg/L Foliar sprayed at 50% flowering.	In this study, the hydrogen peroxide, malondialdehyde, and electrolyte leakage decreased RH 725 at 50% flowering. That allows for improving the antioxidant system and photosynthetic efficiency.
Jangid, and Dwivedi (2017)	<i>Lycopersicon esculentum</i> tomato	24-epibrassinolide	1, 3 μ M and Nitric oxid 50, or 100 μ M both in single and combined foliar application	This work revealed the improvement of drought tolerance by increasing SOD activity, fruit yield, and other physiological processes.
Pérez-Borroto <i>et al.</i> (2022)	<i>Glycine max</i> , Soybean	DI-31 BR functional analogue	The stock solution of DI-31 (22.3 mM) was prepared in 50% (v/v) Ethanol in foliar plication	These results reported the prevention of reductions in canopy development, an increase in plant performance and antioxidant response, and a promotion of nitrogen homeostasis.
Pérez-Borroto <i>et al.</i> (2021)	<i>Arabidopsis thaliana</i> wild-type plants	24-Epibrassinolide and DI-31	Stock solutions of DI-31 (22.3 mM) and 24-Epibrassinolide (4.1 mM) in ethanol 50%, the DI-31 was added when the MS medium had cooled to below 40 °C.	This research compares 24-Epibrassinolide and DI-31 and both increased drought-response. The DI-31 action as a growth enhancer was more successful than 24-Epibrassinolide, and repressed stress-responsive genes regulated by the AREB/ABF transcriptional factors.
Wang <i>et al.</i> (2019)	<i>Vitis vinifera</i> Cabernet Sauvignon grape seedlings	0.10 μ M 24-Epibrassinolide	The plants were grown in Hoagland's nutrient solution containing 24-Epibrassinolide dissolved with 1 mL, 98% ethanol	24-Epibrassinolide alleviated the leaf morphology, decreased the H ₂ O ₂ content and O ₂ production rate, and enhanced the contents of antioxidants and the activities of antioxidases involved in the ascorbate-glutathione cycle.

Gillani <i>et al.</i> (2022)	<i>Zea mays</i> Maize	Brassinosteroids	100 mg L ⁻¹	BRs improved the growth of maize genotypes such as root growth, shoot growth, enhanced chlorophyll contents, and activated stress-responsive genes.
Song <i>et al.</i> (2015)	<i>Leymus chinensis</i> Chinese ryegrass	Brassinosteroids	0.1 mg/L	The authors communicate an enhancement in plant height, leaf area, dry weight, water content, root activity, proline, soluble protein, soluble sugar, photosynthetic pigment, accumulation of dry matter, superoxide dismutase, catalase, peroxidase, ascorbate peroxidase, and glutathione reductase activity.

In semi-arid regions, the most serious problem for plants is drought stress. Various studies have focused on *Vitis* in this type of stress, highlighting the use of BRs as a viable alternative: regarding the vine seedlings, under drought conditions, the use of 24-epibrassinolide protected the photosynthetic pigment content and photosystem II efficiency and reduced oxidative damage by increasing the antioxidant system; it also improved the superoxide dismutase, catalase, peroxidase, and ascorbate peroxidase activities and contributed to the accumulation of ascorbic acid, glutathione, abscisic acid, jasmonic acid, auxin, and gibberellic acid. This synthetic analogue of BRs pre-treatment also promoted autophagy activity, stimulating the degradation of damaged chloroplasts (Zeng *et al.*, 2022).

On the other hand, anthocyanin can be produced by plants in response to biotic or abiotic stress (Ahmad *et al.*, 2022); they are key regulators of drought stress tolerance (Cirillo *et al.*, 2021). In the ripening of grape berries, exogenous 24-epibrassinolide treatment allowed an increase in the expression of several structural and regulatory genes involved in anthocyanin biosynthesis, such as the transcription factors VvMYBA1 and VvMYBA2, chalcone synthase (VvCHS), flavonoid-3'-hydroxylase (VvF3' H), dihydroflavonol-4-reductase (VvDFR), and leucoanthocyanidin-dioxygenase (Gl-D-D-DIOxygenase): 3-O-glucosyltransferase (VvUGT) (Luan *et al.*, 2013). Another work expressed that 24-epibrassinolide increases the level of expression of genes also involved in anthocyanin metabolism: VvCHI1, VvCHS2, VvCHS3, VvLDOX under light conditions in Cabernet Sauvignon (Zhou *et al.*, 2018). The EBR treatment applied by Xu *et al.* (2015) resulted in increases in mRNA levels of genes encoding metabolic sucrose invertase (VvcwINV), monosaccharide (VvHT3, 4, 5 and 6) and disaccharide transporters (VvSUC12 and 27) in Cabernet Sauvignon.

On the other hand, an increase in trans-resveratrol, β -carotene, and ascorbic acid was found, supporting the role of BRs in producing pigments and antioxidant compounds in grapes (Babalik *et al.*, 2020). Practical applications can be suggested in concentrations of 0.6 and 0.8 mg L⁻¹ of 24-eBL applied at veraison to the vines for the accumulation of total phenols, β -carotene, ascorbic acid, and trans-resveratrol for the Alphonse Lavallée variety while the application consisting of 0.6 mg L⁻¹ of 24-eBL in spaced applications: 7 days after the setting of the berry, veraison and 30 days after veraison seems to be the best treatment for anthocyanin (Babalik *et al.*, 2020). Meanwhile, the exogenous application of epibrassinolide (EBR) increases the concentration of proanthocyanidin in the Berry skin (Xu *et al.*, 2015) and significantly increases the total phenolic content, total tannin content, and total anthocyanin content of Yan73, a new breed red grape, and Cabernet Sauvignon wines (Xu *et al.*, 2014).

Furthermore, a high endogenous concentration of catasterone and its direct precursor 6-deoxo catasterone have been quantified during the veraison and ripening stage, suggesting a role for ripening (Symons *et al.*, 2006). In this regard, one response of plants to drought stress is to control sugar metabolism (Li *et al.*, 2023). Recent studies carried out by Xu *et al.* (2015) have shown that BRs are involved in the accumulation of sugar during the ripening of Cabernet Sauvignon where an increase in soluble sugars in the berry was found and they proposed that BRs could regulate the release of sugar from the leaves to the berries in the vines.

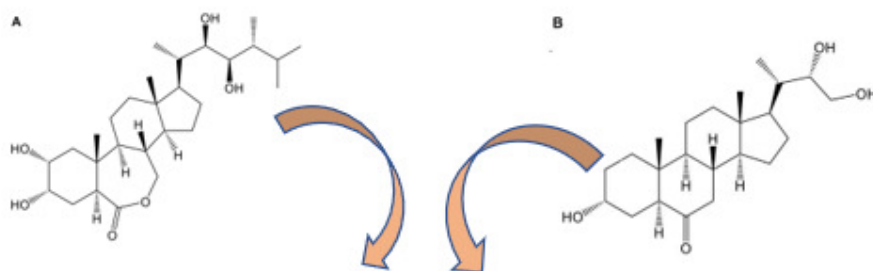
Other works have shown that exogenous applications of 24-epibrassinolide during veraison are effective in increasing sugar accumulations, reducing total acidity at harvest, and significantly increasing total anthocyanin content in Cabernet Sauvignon (Luan *et al.*, 2013; Xi *et al.*, 2013). On the other hand, it has been described that the treatment with 24 epibrasinolides in the berries promoted the enzymatic activity of the "early" acidic and "late" neutral invertases of the cell wall (Xu *et al.*, 2015).

Use of brassinosteroids to increase the size of the bunch and grapevine berries and the yield

Favorable results have been obtained using BRs hormones in grapevine cultivation, for example, Champa *et al.* (2015) demonstrated a significant increase in the weight and breadth of the bunch, as well as in the weight, length, and breadth of the grapevine using aqueous solutions of BRs with 0.5 and 1.0 mg L⁻¹. For its part, the concentration of 0.2 mg L⁻¹ of 24-epibrassinolide (24-eBL) applied to the vines on three occasions: 7 days after berry set, veraison, and 30 days after veraison provided the highest yield and significant weight gain of cluster and the weight, the length and the width of the berries notably higher (Babalik *et al.*, 2020). Regarding the firmness of the berries, the bunches sprayed with BR maintained greater firmness compared to the control. The groups treated with 0.1 and 0.5 mg L⁻¹ of BRs showed greater efficacy in maintaining the firmness of the berries, contrary to the highest doses of 1.0 mg L⁻¹ (Champa *et al.*, 2015). On the other hand, the 0.6 mg L⁻¹ treatments absorbed by the BRs spray leaf increased the yield in kilograms in the field (Ghorbani *et al.*, 2020). The positive effect of BR on these parameters is an advantage because the best price for table grapes is always obtained by bunches with large berries in national and export markets (Champa *et al.*, 2015).

Exogenous applications of brassinosteroids improve the color, soluble solid, anthocyanins, and antioxidant capacity of vine berries

The results of various studies show that exogenous applications of different analog BRs to Redglobe grape clusters: 24-epibrassinolide, Triol, and Lactone and the analog, B-2000^R, whose chemical structures are shown in Figure 3, have resulted in an increase of berry color, soluble solids content, and total anthocyanins, particularly the methylated and unmethylated di- and trihydroxylated derivatives, altering the distribution of anthocyanin groups. The increase in the color of the berries induced by the treatment with BR analogs could be due to its effect on the content of soluble solids, anthocyanin concentration, or the combination of these two effects in the berries (Vergara *et al.*, 2018). Other works have shown the same results with exogenous 24-epibrassinolide treatment increasing the total anthocyanin content in the skin of the berries (Luan *et al.*, 2013) and also improving the antioxidant capacity (Xi *et al.*, 2013).



The Brassinosteroids analogues favor the production of dihydroxylated anthocyanins, which are responsible for the red and pink colors of grape berries and increase the levels of soluble solids.

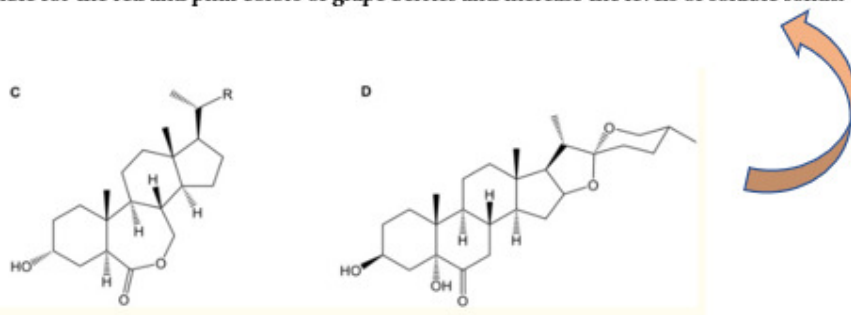


Figure 3. Chemical structure of the different BR analogs: 24-epibrasinolide (A), 3 α -22 (S), 23-trihydroxy-24-nor-5 α -cholan-6-one (B, Triol), 3 α -hydroxy-20-RB-homo-7-oxa-5 α -cholestan-6-one (C, lactone) and 3 β -5 α -25 (R)-dihydroxy-spirostan-6-one (D, commercial formulation, B-2000^R) (modified from: (Vergara *et al.*, 2018))

Effect of brassinosteroids on postharvest grape quality

In addition to improving the quality of bunches and berries and allowing better coloration of the grapes, the application of brassinosteroids in foliar sprays before harvest in the size of the berry of 4-5 mm in diameter, two weeks after fruit set and in the veraison proved to be effective in maintaining the physiological, biochemical and organoleptic qualities of Flame Seedless grapes under storage at low temperature 3-4 °C and 90-95% RH for up to 60 days in contrast to the control which was commercially acceptable only up to 45 days (Champa *et al.*, 2015). In addition, an increase in the soluble sugar content was found, verifying the role of BR in regulating different ripening parameters in grapes (Luan *et al.*, 2013). These authors observed the same effect on anthocyanin production. In addition, they found an increase in the soluble sugar content, verifying the role of BR in regulating different ripening parameters in grapes (Luan *et al.*, 2013).

Conclusions

In Chihuahua, Mexico grape production is a profitable crop for the wine industry and for fresh consumption. However, various social and economic problems have arisen in the state due to severe droughts that have caused a shortage of fresh water and overexploitation of aquifers which have been degraded in quality and quantity in recent years. Under drought stress, the quality and productivity of the grapes are gravely affected. The water deficit produces a decrease in the vigor of the plant, the growth of the shoots, the diameter

of the berries, and the carbohydrate reserve of the root system. The leaves become dehydrated, and there is also a loss of hydraulic functionality induced by the formation of embolisms and this affects the transpiration of the vines, which translates into a decrease in yield.

Besides, in Chihuahua, the use of hormones such as auxins, cytokinins, and gibberellins in the wine fields is common, but the application of BRs is starting and therefore remains unknown about their role in the yield and components of the vines and their antioxidant capacity. The BRs are phytohormones that regulate plant growth and defense and its physiological, metabolic, and cellular processes. BRs have been found in different organs, such as buds, flowers, pollen, leaves, and seeds. Although the concentration of BRs in plants is very low, the use of BRs is an important source because they improve drought stress tolerance. They function as a common signal in the signalling pathways of grapevine, in antioxidant defense, through osmolyte concentration, and photosynthetic system. Under drought stress in *Vitis*, they stimulate not only the antioxidant system and the photosynthetic capacity, but also the autophagic activity, and hormone concentrations. In addition, they represent an excellent option to improve the quality in colour, weight, length, and sugar concentration of the berries and the quality of the bunches; which achieves an increase in yield per hectare in the crop and allows to raise the price in the national or international market. BRs are also a good option to prolong the postharvest life of the grapes. This study strongly recommends its safe use in vine cultivation in Chihuahua, Mexico, and regions in the world that suffer from drought.

Authors' Contributions

Conceptualization: MEMP and TJRA; Funding acquisition: CONAHCYT; Investigation: MEMP and TJRA; Methodology: MEMP TJRA JLJC RAPQ and LRHO; Supervision: MEMP TJRA JLJC RAPQ and LRHO; Writing original draft: MEMP TJRA and JLJC; Writing review and editing: MEMP and TJRA; Project administration: TJRA; Formal analysis: JLJC; All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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