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Posted Date: 24 September 2025

doi: 10.20944/preprints202509.1911.v1

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Review

Enhancing Calcium Transport with Polyols in Table Grapes: A Sustainable Tool for Agriculture

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Abstract

Table grapes suffer significant losses from issues such as fungal infections, cracking, and berry shattering, which affect them both in the vineyard during ripening and throughout postharvest storage. Current control methods, such as sulfur dioxide (SO_2) treatments, are increasingly constrained by potential fruit damage and regulatory limitations, prompting a search for sustainable alternatives. This review proposes sorbitol as an innovative preharvest solution to enhance table grape quality through improved calcium (Ca^{2+}) transport. Ca is a vital macronutrient for cell wall integrity and fruit resistance; however its inherent low mobility in the phloem restricts its effective delivery to developing fruits, particularly after veraison. Sorbitol, a naturally occurring sugar-alcohol, acts as a "vector" by forming stable, soluble complexes with Ca, thereby facilitating its crucial translocation to fruit tissues. Preharvest foliar applications of these calcium-sorbitol complexes have demonstrated numerous benefits-, improving fruit firmness, reducing the incidence of cracking and shattering, mitigating fungal decay, and boosting antioxidant activity. These effects collectively enhance overall fruit quality and extend storability. Future investigations will aim to further clarify the molecular mechanisms involved and explore sorbitol's potential to complex with other poorly mobile nutrients and plant elicitors, opening new avenues for sustainable crop management.

Keywords: preharvest treatment; fruit ripening; nutritional quality; polyols; postharvest

1. Introduction

Grapes are the fruit of the *Vitis* genus which grows in clusters of berries. Table grapes are highly valued in the agri-food sector and appreciated by consumers for their complex flavour as well as its nutritional value given by many compounds such as sugars, organic acids, fibre, minerals, vitamins, flavones, flavanones, volatile compounds, pigments and, and anthocyanins in the case of red table grapes [1]. As a non-climacteric fruit, grapes are required to be harvested at an adequate maturity point. Otherwise, the accumulation of sugars, organic acids and pigments may not reach minimum requirements for commercialization, as well as the functional compounds related to human health such as polyphenols [2]. The synthesis of stilbenes, flavonoids, and phenolic acids proceeds through the phenylpropanoid pathway. Key branch-point enzymes involved in this pathway include phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), stilbene synthase (STS), anthocyanidin reductase (ANR), leucoanthocyanidin reductase (LAR), and UDP-glucose: flavonoid 3-O-glucosyltransferase (UFGT) [3]. These enzymes participate in the biosynthesis of phenolic compounds, including anthocyanins, which are directly associated with red pigmentation. However, table grapes face several challenges during ripening process and storage period that can result in significant economic losses and food waste. Given the growing demand for sustainable alternatives to current solutions such as hormone treatments (abscisic acid, gibberellins) or other chemicals like sulfur dioxide (SO_2), which pose environmental limitations and concerns, this review proposes and explores the potential of polyols, particularly sorbitol, as an innovative agricultural tool to enhance

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Ca transport in table grapes. It details how the complexation of Ca, an essential macronutrient with low mobility in the phloem and vital for cellular integrity and fruit resilience, with sorbitol can overcome this transport limitation, boosting its beneficial effects on fruit quality, shelf-life, and resistance to biotic and abiotic stresses, in alignment with sustainability goals.

2. Main Challenges in Table Grape Production and Postharvest

Major table grape issues include fungal infections, cracking, pedicel abscission, dehydration of berries and rachis, softening or colour loss [4]. These physiological disorders can disrupt plant cell homeostasis leading to an increase in enzymatic activity and the formation of reactive oxygen species (ROS), which affect the cell integrity and ultimately leading to a shortened shelf-life period for the grapes [5]. The current strategies used for controlling table grapes issues and ensuring fruit quality may be limited in the context of a global market that prioritizes food waste reduction and developing more sustainable strategies and practices for food production. The purpose of this review is to delve into the potential of sorbitol, Ca, and calcium-sorbitol complexes as sustainable solutions for enhancing the quality and shelf-life of table grapes.

2.1. Fungal Incidence and Decay

Postharvest decay of table grapes represents one of the primary causes of fruit loss reaching up to 40 % of world production [6]. The high moisture content of table grapes makes the fruit particularly susceptible to fungal infections, with grey rot caused by Botrytis cinerea being especially prevalent. Botrytis cinerea can proliferate under typical table grape storage conditions (0 °C to 4 °C) [7], as well as other fungal pathogens, including Alternaria alternata, Rhizopus oryzae, Colletotrichum acutatum, and Penicillium expansum [8–11]. Optimal temperature maintenance is mandatory to ensure quality of table grapes during transport, storage and commercialization, highlighting the need for fungi control in order to minimize fruit loss. As Ca is a key component in cell wall structure and a signalling agent, fruits with a Ca^{2+} deficiency are prone to fungal infestation [12]. Fungal infection control is commonly addressed with SO_2 treatments [13] due to its antifungal properties. However, excessive SO_2 exposure may cause fruit damage such as bleaching, discolouration, pitting and cracking [14].

2.2. Cracking

Fruit cracking devalues both commercial value and visual appeal of the grapes [15,16], while making the fruit vulnerable to biotic infections [17–19]. This disorder is defined as the 'breacking, cracking, or splitting of the berry skin' [20]. Cracking occurs during the third phase of grape development, when grapes begin to soften, sugars accumulate, and the rapid expansion of pulp cells exceeds the mechanical properties of the cuticle, leading to the cuticle's incapability to sustain its integrity [20,21]. Several factors can lead fruit cracking: 1- Environmental factors such as rain and high humidity during developmental stages, especially during blossom or harvest are "serious limitations in profitable grape production", high humidity and increasing temperature accelerate fruit cracking, with a linear increase in cracking as the temperature rises from 10 to 40 °C [20]; 2- The structure and composition of the cell wall from the pericarp directly influence mechanical properties and cracking vulnerability [15,22,23]; 3- Vegetal hormones, such as abscisic acid (ABA), auxin, giberellins (GA), ethylene and jasmonic acid are involved in fruit cracking [15,24]; 4- Nutrient deficiency , especially of Ca and Boron (B), can increase fruit cracking incidence as Ca is related to cell wall integrity [25], and its deficiency is tightly related to many disorders, and B has a role in cell wall development, cell division and sugar transport [20].

2.3. Berry Shattering

Berry drop (shattering) is a phenomenon where the berry detaches from the pedicel due to the degradation of pectins and celluloses along with the increased hydrolytic enzymes in the abscission

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zone [26]. Various factors can be attributed to shattering such as environmental conditions [25], genetic predisposition [27] or the use of growth regulators like ethephon and ABA [28,29]. Berry abscission happens in a specific location called the abscission zone (AZ) which is located between the pedicel and the berry. Cells from AZ differ physiologically from other cells and after specific signalling, generally enabled by plant hormones, hydrolytic enzymes are synthetized, degrading the cell wall and therefore causing abscission [30,31]. Shattering usually occurs during handling in harvest, transport, and storage. However, in extreme cases such as high temperatures (≥ 40 °C) during the fruit set, this phenomenon can occur during on-tree ripening, as was observed [32]. Berry shattering is a common issue during storage, transport, and commercialization of table grapes, causing important economic losses [31].

2.4. Colour Loss and Browning

Colour is highly determinant in consumer acceptance [33]. Browning during postharvest storage is a common issue in table grapes which that can be caused by enzymatic and non-enzymatic reactions [34]. Irregularities and lack of colour have been observed to be related with low expression of ripening-related genes involved in ABA biosynthesis [28,35] under high temperatures [36] and a lack of sunlight exposure [37] during ripening season.

2.5. Dehydration and Rachis Browning

Rachis development of colour is also indicative for table grapes storage suitability, as irregularities in size and browning of this part could indicate dehydration and a predisposition to advanced senescence [33]. For the consumer, a green rachis is a sign of freshness while a brown one indicates senescence or degradation. This perception is an "important cause of rejection on the consumer's side and fruit loss" [38,39]. The rachis is the principal structure from which berries hang, representing approximately 4 % of the total mass of the grape cluster, but its respiration rate is 11 to 28 times higher than the berries [39,40]. Its high metabolic rate makes it particularly susceptible to dehydration and enzymatic browning during postharvest. Rachis browning is influenced by many factors that encompasses environment factors, grape physiology and agronomic handling, such as: 1- Water loss is "considered the main factor in rachis browning" [39,41]. Table grapes are highly sensitive to dehydration, especially the rachis, due to the absence of the epidermal layer and waxy cuticle present in berries [41]; 2- Low temperatures and high relative humidity are the most suitable conditions in order to reduce rachis browning and water loss [40,41]; 3- Packaging technologies such as sealed packages with low density polyethylene (LDPE) or microperforated film, are effective in reducing water loss and delaying browning [41]; 4- Biochemical and physiological processes, such as enzymatic browning, are associated to polyphenol oxidase (PPO) activity, which oxides phenolic compounds (the substrate) into quinones, causing the brown colour [40–42].

3. Current Strategies for Quality Control of Table Grapes

Contemporary strategies for maintaining table grape quality are multifaceted, encompassing both pre- and postharvest interventions. Preharvest protocols, such as girdling, a practice of removing a ring of bark from the trunk or canes to enhance berry size and hasten maturity, are widely employed. Furthermore, the preharvest application of plant growth regulators or elicitors can influence fruit development, colour, and resistance to disease. Postharvest, maintaining fruit integrity is crucial. Modified atmosphere packaging (MAP) is a primary technology used to slow respiration and senescence by altering the gas composition surrounding the fruit. The application of sulfur dioxide (SO_2) remains a standard fungicidal treatment to control Botrytis cinerea (gray mold), though concerns over residue and potential bleaching have spurred research into alternatives. Promising new approaches include the application of natural compounds like essential oils, which exhibit antimicrobial properties. These can be used alone or in conjunction with other technologies, such as the application of 1-methylcyclopropene (1-MCP), a compound that inhibits ethylene action, or

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chitosan nanoemulsions, which form a protective, semi-permeable coating on the fruit surface. These combined strategies aim to extend shelf-life and preserve the sensory and nutritional qualities of table grapes.

3.1. Preharvest Strategies

3.1.1. Girdling

Girdling is an ancient and widely adopted horticultural practice in viticulture, particularly for table grapes, involving the precise removal of a narrow ring of bark, typically 3 to 6 mm in width, from the trunk or canes of the vine [43–46].This technique fundamentally alters the plant's physiological transport mechanisms by interrupting the phloem's downward flow of photosynthates, essential mineral nutrients, and plant hormones from canopy to the roots [45–47]. Consequently, these vital resources are redirected and accumulate in the plant parts situated above the girdle, significantly benefiting the developing fruit clusters and berries [45–49]. This localized accumulation leads to elevated concentrations of sugars, auxins (IAA), and abscisic acid (ABA) within the berries, which are crucial for fruit development and ripening [46]. As a preharvest strategy, girdling is primarily applied to achieve several commercial objectives, including promoting substantial increases in berry size and overall bunch weight, and accelerating the fruit's maturation process [21,44,47,48,50,51]. However, the effectiveness and outcomes of girdling are highly cultivar-dependent, sensitive to the precise timing of application, and influenced by environmental conditions, sometimes requiring considerable labour or posing potential physiological stress to the vine [44,49,51].

The impact of girdling on table grape quality extends across a diverse range of parameters, albeit with notable variability based on cultivar and application context. While girdling is often effective in deepening skin colour, especially in red varieties like 'Hanxiangmi' and 'Crimson Seedless', and can advance maturation [49,52–54], its influence on sugar content and acidity can be inconsistent. Some studies reported increased total soluble solids, while others observe a decrease in sugar content or an elevation in titratable acidity, for example in 'Italia' grapes [44,49,53,55,56]. Importantly, research indicates that girdling typically leads to a reduction in berry cuticle thickness, which may heighten the fruit's susceptibility to cracking, although certain Ca treatments appear to mitigate this adverse effect [21,57]. Furthermore, girdling can significantly modify fruit texture. Varieties such as 'Áron' and 'Melinda' have shown increased berry hardness and skin thickness postgirdling, presenting a pattern that deviates from the natural softening trend observed during normal ripening despite higher sugar levels [45]. In terms of aromatic profiles, girdling alone might reduce the overall concentration of volatile compounds, but when synergistically combined with other interventions like foliar potassium fertilization, it can markedly enhance the accumulation of key aromatic compounds, particularly terpenes, contributing to a more complex and desirable flavor in cultivars like 'Hanxiangmi' [49,56]. These complex and often cultivar-specific responses underscore the need for tailored application strategies to optimize table grape quality.

3.1.2. Hormone Applications

Preharvest application of elicitors represents a robust and eco-friendly strategy for enhancing the quality and yield of table grapes, addressing challenges such as fungal decay and suboptimal colouration [58–61]. Key elicitors include salicylic acid (SA) and its derivatives acetylsalicylic acid (ASA) and methyl salicylate (MeSA), as well as methyl jasmonate (MeJA) and oxalic acid (OA), all of which are naturally occurring plant compounds [62–70]. These compounds act as plant hormones, orchestrating various physiological processes, including defense responses and ripening [62,64,68,71,72]. Treatments with SA, ASA, and MeSA, particularly MeSA at 0.1 mM, have demonstrated significant efficacy in alleviating disease caused by Botrytis cinerea in cultivars like 'Crimson' and 'Magenta' [60]. This disease control is primarily mediated through the stimulation of the plant's antioxidant system, increasing the activity of enzymes such as ascorbate peroxidase (APX),

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catalase (CAT), and peroxidase (POD) [60,73]. Furthermore, these salicylate applications lead to higher total acidity, increased content of bioactive compounds (e.g., total phenolics and anthocyanins), and enhanced antioxidant activity in treated berries compared to controls [59,60]. Similarly, MeJA treatments, depending on concentration, can significantly impact grape ripening, with lower doses (e.g., 0.1 and 1 mM) accelerating maturation and increasing vine yield, while higher concentrations (e.g., 5 and 10 mM) may delay ripening and reduce yield [58,59]. This dual effect of MeJA underscores the importance of optimal concentration for desired agronomic and commercial outcomes, including improved berry size, firmness, and total soluble solids content [58].

The beneficial effects of elicitors extend beyond disease resistance, profoundly influencing various quality attributes of table grapes. Salicylates enhance the concentration of total phenolics and anthocyanins, which are crucial for pigmentation and possess significant antioxidant activity, contributing to the fruit's health benefits [49,59,60,65–67,69,70,74–76]. For example, preharvest salicylate treatments led to significantly higher concentrations of five identified anthocyanins (delphinidin-3-glucoside, cyanidin-3-glucoside, petunidin-3-glucoside, peonidin-3-glucoside, and malvidin-3-glucoside) in both 'Crimson' and 'Magenta' cultivars [59,60]. These treatments also boost the levels of important organic acids, such as ascorbic, succinic, and fumaric acids [67,77], with MeSA at 0.1 mM proving most effective in this regard [60]. The increased activity of antioxidant enzymes (APX, CAT, POD) induced by salicylates helps to scavenge reactive oxygen species (ROS), which accumulate under pathological and senescence conditions, thereby delaying ripening and senescence processes and maintaining berry quality, firmness, and colour during cold storage [59,60,73,77]. MeJA treatments at appropriate concentrations (e.g., 0.1 mM) not only accelerate berry ripening and improve crop yield but also increase total phenolics and individual anthocyanin concentrations, leading to enhanced homogeneous pigmentation and higher firmness and total soluble solids at harvest [58,78–83]. These effects translate into improved market value due to earlier harvests and fruit with superior organoleptic and nutritional properties [58].

Oxalic acid (OA), another natural compound, offers a distinct mechanism for enhancing table grape quality, particularly colour in poorly pigmented cultivars like 'Magenta' [61]. Preharvest OA treatment (e.g., 5 mM) significantly increases endogenous abscisic acid (ABA) content and ABA glucose ester (ABA-GE) in berries, a critical hormone that regulates ripening [61]. This elevation in ABA is mediated by the upregulation of the VvNCED1 gene, which plays a key role in ABA biosynthesis and subsequent anthocyanin accumulation [61,84–86]. The accumulation of ABA directly contributes to improved colour and higher individual and total anthocyanin content at harvest[59,61,78,87–92]. OA treatments also lead to significantly lower glucose and fructose content but higher tartaric, ascorbic, and succinic acids at harvest, indicating a modulated ripening profile [61]. Moreover, OA boosts the activity of antioxidant enzymes (APX, CAT, POD) during berry development and maintains their activity during postharvest storage, thereby delaying the loss of firmness and colour and reducing susceptibility to postharvest decay caused by Botrytis cinerea [61,62,64,91,93]. Compared to other elicitors, OA at 5 mM has shown particularly strong effects, for instance example, a 2.4-fold increase in skin total anthocyanins compared to a 1.5-fold increase with MeSA, making it a highly effective tool for improving colour and overall quality in low-pigmented table grapes [61].

3.2. Postharvest Strategies

3.2.1. Modified Atmosphere Packaging Technology

Several postharvest strategies addressing table grape issues have been considered. Among these, modified atmosphere packaging (MAP) is a convenient, minimally invasive method to maintain quality of grapes during storage [94–98]. In MAP technology, the package headspace is usually replaced with specific concentration of atmospheric gases such as O_2, CO_2, and N, as well as other compounds such as ozone (O_3), ethanol or nitric oxide (NO). Low concentrations of O_2 are used but not low enough to produce anoxia, and moderate concentration of CO_2, aiming to slow down berries

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decay, reducing the respiration rate and hindering the proliferation of microorganisms, especially moulds. CO_2 and O_3 prestorage treatment atmospheres are useful to control berry decay as well as to maintain quality traits of the fruit. Admane et al. (2018) [5] successfully maintained table grape quality with CO_2 and O_3 prestorage treatments following 45 days of storage at 0 °C with MAP (2 % CO_2 - 5 % CO_2). However, CO_2 treatment caused organoleptic quality loss and lower anthocyanin content whereas 20 μL L^{-1} O_3 treatment enhanced anthocyanin content as well as maintained good flavour and visual appeal [5]. Ethanol at 2.25 ppm was found to retain berry firmness during storage period. Nevertheless, increased cracking incidence, acetaldehyde and ethyl acetate accumulation, which may lead to unpleasant aromas and off-flavours [13] while NO at 300 μL L^{-1} has been showed induction of the expression of VvSOD, VvCAT, VvPOD2, and VvGR for 60 days at 0 °C, thereby activating antioxidant enzyme activity and alleviating oxidative damage caused by ROS [99].

3.2.2. Sulfure Dioxide Applications: Benefits and Limitations

SO_2 has been widely used since 1925, playing a major role in table grapes preservation strategies [5,100] . It is stated that, more than just a biocide, SO_2 has a metabolic effect, promoting the defense mechanism of the plant [101]. The observed mechanism of action suggest an elevated expression of genes related to the production of H_2O_2, thereby augmenting respiratory burst oxidase homolog and superoxide dismutase (SOD) enzymatic activity [102] as well as the upregulation of genes related to glutathione synthesis and cyclic pathways [101], while the genes associated with ethylene signalling and cell wall degradation were downregulated [103]. Additionally, other authors reported physiological effects such as higher firmness of vegetal tissue due to SO_2 and H_2O_2 mediating effects on cell wall pectin demethylation [104], a process associated with key enzymes such as pectin methyl esterase, polygalacturonase, pectate lyase and β-galactosidase [15]. Considering the broad and extensive use of SO_2 in maintaining postharvest quality of table grapes during cold storage, SO_2 packaging technologies such as perforated SO_2-generating plastic liners and SO_2-generating pads have been designed and evaluated to enable a controlled and sustained release of the gas throughout the storage period [105]. Although the use of SO_2 can be effective in controlling berry decay, there are major limitations related to this treatment. SO_2 injury can express as bleaching, discolouration and fruit pitting [14]. Also, European Regulation (EC) Nº 1333/2008 on food additives limits the usage of SO_2 sulphites in fresh table grapes to 10 mg kg^{-1}.

3.2.3. Alternative Solutions

Other treatments aimed at preserving grapes include active packaging with essential oils, such as tea tree oil [106], oregano essential oils [107], thymol, eugenol or carvacrol [108]. However, detrimental effects of effective doses of these essential oils make them perceptible at the time of consumption with persistent aromas from the essential oils and off-odors occasionally detected in the fruit. Thus, strategies using essential oils in addition to 1-MCP application [109] or chitosan nanoemulsion [110] are gaining popularity in order to reduce EO doses in postharvest treatments.

3.3. The Need for Sustainable and Innovative Solutions

As global retailers and large-scale production groups continue to expand, private and public regulations are expected to become more demanding in regulatory restrictions at both national and international levels, along with growing consumer concern [111]. This evolving regulatory and market environment highlights the need for alternative solutions that can maintain table grape quality and extend shelf-life without compromising sensory or physicochemical attributes, while also meeting environmental, economic, and social sustainability goals. In this context, preharvest treatments with polyols represent a promising approach to enhancing the quality, durability, and productivity of table grapes.

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4. The Crucial Role of Ca in Fruit Quality at Harvest and Postharvest

4.1. Ca as a Structural Component, Signaling Agent, and Its Mobility in the Plant

Ca is an essential macronutrient that plays a multifaceted role in plant physiology. It is an integral component the the cell wall, where it helps to stabilize pectin molecules as calcium-pectate, contributing to the cell rigidity and integrity. This structural role is fundamental for maintaining turgor pressure, which is essential for cell expansion and overall plant growth. Furthermore, Ca has a key role in cellular function and communication, as it is involved in the stabilization of membranes, regulating their permeability and fluidity [112]. Nevertheless, a defining characteristic of Ca is its low mobility through the phloem [113–115]. This results in limited translocation of Ca from mature leaves to developing tissues, such as young leaves, fruits, and sink organs, and the potential occurrence of physiological disorders, such as blossom end rot (BER).

Ca ions (Ca^{2+}) are integral to the signaling networks of eukaryotic cells, including plants. They act as secondary messengers that connect external stimuli to internal cellular responses. The concentration of cytosolic Ca is regulated by a complex system of Ca channels, pumps, and sensors, which maintain homeostasis and facilitate the generation of Ca signals in response stimulus, such as hormones, biotic and abiotic stresses, and developmental factors [116]. In response to external signals, an early event in the signaling process consists of a translocation of Ca^{2+} from extracellular space or from internal stores, where Ca^{2+} is concentrated, into the cytosol, raising the cytosolic free Ca^{2+}. The specific characteristics of the resulting Ca signal, such as its frequency, amplitude, and waveform are shaped by both the type and intensity of the stress faced [117].

Signaling is regulated by elemental components that control the magnitude and duration of cytosolic Ca fluctuations [117]. Ca^{2+}-permeable ion channels allow the influx of Ca^{2+} ions into the cytosol in response to drought stress. The opening of these channels is often triggered by various environmental factors, leading to an increase in intracellular Ca levels. Ca^{2+}/protons (H^+) antiporters help maintain Ca homeostasis by exchanging Ca^{2+} for H^+ across the plasma membrane. This exchange is vital for regulating cellular pH and Ca concentrations during drought stress. Ca^{2+}-ATPases actively pump Ca^{2+} out of the cytosol, helping to restore Ca homeostasis after a transient increase in Ca levels, which is essential for resetting the Ca signaling pathways and preparing the plant for subsequent stress events. The initial key elements of the Ca signaling are Ca^{2+} channels and Ca^{2+} sensor proteins. Most of these sensor proteins are characterized by the presence of EF-hands, a conserved helix-loop-helix structural domains that coordinate Ca^{2+} ions through an acidic loop region [118]. In plants, the main types of EF-hand containing Ca^{2+} binding proteins include calmodulins, calmodulin-like proteins, calcineurin B-like proteins, and calcium-dependent protein kinases (CDPKs) [119]. CDPKs play a significant role in regulating secondary metabolism through two main pathways. They phosphorylate enzymes directly involved in metabolic processes, such as PAL, and they modify transcription factors that control the expression of genes linked to secondary metabolite biosynthesis. PAL initiates the biosynthesis of phenylpropanoids by catalyzing the deamination of L-phenylalanine into trans-cinnamic acid and ammonia [120]. This enzyme is key to the formation of various polyphenolic compounds in plants, including flavonoids, lignins, and other phenylpropanoids, which contribute to structural integrity and stress responses. Under drought conditions ABA is synthesized, triggering a signaling chain in guard cells that lead to stomatal closure, thereby minimizing water loss. A critical step in this response is the elevation of cytosolic Ca^{2+} levels, facilitated by its flux through both plasma membrane and intracellular Ca^{2+} channels. This rise in Ca^{2+} is essential for stomatal closure, which is induced by ABA, and involves hyperpolarization-activated and voltage-dependent channels, some of which are modulated by ROS [117].

4.2. Physiological Disorders Associated with Ca Deficiency

Calcium deficiency disorders usually have multifactorial causes that lead to lower Ca^{2+} concentrations in a specific plant tissue, resulting in diseases triggered by the shortage of mineral.

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Among Ca^{2+} deficiency symptoms, bitter pit is commonly observed in apples [121,122] as dark circular lesions beneath the skin surface of the fruit. The affected spots are brown, dry, and porous texture, tending to appear as necrotic tissue, and are commonly located at the calyx area. In tomatoes and pepper, deficiency may lead to BER, showing a sunken dark area at the vegetables end [122,123]. In pineapples [124–126] and loquat [127,128], internal browning may appear with Ca deficiency, when fruit is stored at chilling injury-promoting temperatures. Mangoes tend to manifest spongy tissues when Ca nutrition is insufficient [129]. Nevertheless, preharvest exogenous foliar treatments with Ca solutions have proven to be an effective solution to alleviate these symptoms.

4.3. Effect of Ca Application on Fruit Quality

Foliar applications of Ca solutions are a common agricultural practice (Table 1). The application of sprayed Ca salts during fruit development limits the breakdown of cell walls, preventing softening and delaying fruit ripeness, as high presence of Ca inhibits polygalacturonase activity, an enzyme responsible of pectin degradation [130]. In peaches, some authors [131] observed higher accumulation of polyphenol content as well as antioxidant activity, but a lack of modifications in fruit firmness, sugars, and acids content which gives peaches their main quality attributes, whereas others reported a 34.2-44.7 % firmness increase in Ca treated canned peaches cv. 'Andross' [132]. Ca applications also proved to improve storability of peach fruits. Ca chloride ($CaCl_2$) solutions at 1 % improved weight loss, cell membrane ion leakage (IL), and brown rot incidence as increased phenolic content, antioxidant activity, and enzymatic activity after 30 days of storage at 8 ± 2 °C, 50 % RH [133]. In 'Fengtangly' variety, $CaCl_2$ applications delayed softening by regulating cell wall metabolism during storage at 4 ± 1 °C and 90 ± 5 % RH for 70 days [134]. In cherry fruit, applications of 1 mM of $CaCl_2$ during tree dormancy effectively improved Ca nutrition, cracking incidence, and sweet cherry fruit quality characteristics [135]. When treatments applied 30 days before harvest, Ca caseinate, $CaCl_2$, Ca hydroxide ($Ca(OH)_2$),and Ca nitrate ($Ca(NO_3)_2$) were effective to reduce cracking, with $CaCl_2$ and $Ca(OH)_2$ being the most effective compounds, reducing cracking by 62 % and 66 % respectively but only $CaCl_2$ improved cherry firmness, and none of Ca treatments modified sugars or organic acids [136].

Table 1. Effects of Ca nutrition on plant products.

Fruit	Ca Products	Effects	References
Apple	Prohexadione-Ca $CaCl_2$ $CaCO_3$	-Alleviates bitter pit incidence	[121,137,138]
Tomato	$CaCl_2$	-Reduced blossom-end rot incidence and severity	[122,123]
Pineapple	$CaCl_2$ Ca gluconate Ca oxide (CaO) $Ca(NO_3)_2$ Ca-boron	-Reduced IL -Reduced MDA content -Reduced internal browning incidence	[124,126]
Loquat	$CaCl_2$	-Reduced IL -Reduced MDA content -Reduced internal browning incidence -Promoted accumulation of proline, GABA and polyamines	[127,128]

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Mango	$CaCl_2$	-Enhanced antioxidant enzymatic activity	[139]
Peaches	Calcium-silicate $CaCl_2$ $Ca(NO_3)_2$ Calcium sulphate ($CaSO_4$)	-Improved firmness -Reduced weight loss -Promoted bioactive compound content -Delayed softening -Limited rise of PG, PME, Cx, and β-Gal activities	[131–134]
Sweet cherry	$CaCl_2$ $Ca(OH)_2$ $Ca(NO_3)_2$ Calcium caseinate	-Improved firmness -Enhanced bioactive compounds content and antioxidant activity -Reduced cracking incidence	[135,136]
Table grapes	$Ca(NO_3)_2$ $CaCl_2$ CaAs	-Reduced weight loss -Reduced berry shattering -Reduced malic acid degradation -Reduced *Botrytis cinerea* incidence -Higher activity of antioxidant enzymes -Enhanced bioactive compounds content -Reduced MDA -Reduced IL -Inhibed ABA synthesis - Increased fruit firmness and Ca pectate -Inhibed ethylene production by supressing *VvACO1* expression -Reduced cracking incidence	[25,30,140–146]

MDA- Malondialdehyde; ABA- Abscisic Acid; PG- Polygalacturonase; PME- Pectin Methylesterase; Cx- Cellulase; β-Gal- β-Galactosidase; GABA- Gamma-Aminobutyric Acid; VvACO1- 1-aminocyclopropane-1-carboxylate oxidase 1.

4.4. Effect of Ca Application on Table Grapes Quality

Preharvest Ca treatments strengthened the cell wall of grape berries, retaining turgor and delaying cellular lipid catabolism, thereby prolonging shelf-life [141]. The activities of PG and PE enzymes have also been reduced, delaying pectin degradation and alleviating weight loss, decay incidence, MDA content, and relative conductivity [143].

A recent study indicates that Ca ascorbate (CaAs), a Ca salt containing ascorbic acid, "significantly improved berry firmness and reduced browning and colour change indices at harvest and during storage" in 'Thompson Seedless' table grapes [145]. It also significantly decreased weight loss and reduced berry abscission and decay spread rates during storage [145].

Cracking is "closely related to the strength and elongation of the peel" [147,148]. Changes in the composition of cell wall components and the activities of metabolic enzymes regulated by cell wall–related genes may affect the occurrence of fruit cracking [23,148–150]. Enzymes such as PG, PME, beta-galactosidase (β-Gal), cellulase (Cx), and expansins (EXP) are involved in cracking. Elevated

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activities of PG, β-Gal and Cx in genotypes prone to cracking indicate a role in the breakdown of the cell wall [15,23,151]. Ca treatments can reduce PG and Cx activities, slowing down pectin and cellulose degradation and resulting in higher peel integrity [15]. The cuticle is a "protecting barrier against external or internal stresses" and pathogens [18,152–154]. Cuticle thinning, especially during the last stages of fruit development makes it vulnerable to microcracks [18,155]. Preharvest foliar spraying of Ca is a promising strategy to reduce fruit cracking, as Ca is essential for strengthening and stabilizing the structure of the cell wall and membrane [20]. $CaCl_2$ has been shown, particularly at the flowering stage, to reduce cracking incidence by approximately 4-to-10 fold compared with the control group [15]. This effect is attributed to increased Ca absorption during this period, leading to higher Ca content in the peel, improved mechanical properties, fruit hardening, and reduced internal pressure [15]. A research study in 'El-Bayadi' table grapes showed that 1 % $CaCl_2$ preharvest spraying "significantly reduced rotting incidence during storage compared to the control" [156]. $CaCl_2$ also reduced the extracellular PG activity of Botrytis cinerea by up to 90 % [12,157]. Furthermore $CaCl_2$ "had a direct influence on the conidia and hyphae of Botrytis cinerea, causing conidial malformation and cytoplasmic disorganization" [12].

Ca transport to the berries decreases drastically post-veraison due to a reduction in transpiration rate and xylem functionality [12,141]. This suggests that Ca deficiency in some grape varieties is more common than previously thought, and that the post-veraison period offers the greatest opportunity to artificially modify berry Ca content.

Foliar treatments were also effective to preserve postharvest life and quality. In 'Thompson Seedless' variety, concentrations of 5 and 10 % enhanced phytochemicals, including the berry total acids, total phenolics, flavonoids and carotenoids contents, and total antioxidant activity, as well as ascorbate peroxidase (APX), superoxide dismutase (SOD), and catalase (CAT) enzyme activities. They also decreased total soluble solids content, malondialdehyde (MDA), ion leakage (IL), and pH. After 2 months of storage at 1 ± 1 °C, treated fruit showed lower decay, weight loss, colour change, IL, and browning [142]. This advantage of spraying Ca on leaves was also previously observed [140]. Fruit treated with $Ca(NO_3)_2$ at 2 % and stored at 1 °C were found to have a higher activity of antioxidant enzymes (SOD, CAT, APX, and guaiacol peroxidase (GPX)), and lower weight loss, chilling injury (CI), MDA, IL, and fungal incidence compared to untreated fruit. In addition, combined treatments of $Ca(NO_3)_2$ at 2 % and zinc sulfate at 1 % achieved the highest performance. Combined treatments of $CaCl_2$ at 0.016 % with magnesium oxide (MgO) at 0.056 % significantly reduced weight loss, berry shattering, and decay percentage of 'Flame seedless' variety after 12 days at 10 °C [142]. Moreover, Ca applications were observed to stimulate genes related to the biosynthesis of anthocyanins in table grapes [158], facilitating the accumulation of antioxidant compounds.

In this way, it can be confirmed that the use of foliar Ca on fruit is a useful tool to strengthen the plant's resistance and activate defense mechanisms against both biotic and abiotic stresses. In general, the authors report improvements in firmness, weight loss, phenolic content, antioxidant activity and enzymatic activity, while fruit quality parameters related to sugars and organic acids remain unaffected by Ca application alone. Due to calcium's low mobility, applying sorbitol, which promotes translocation of nutrients through the plant can be an important strategy to enhance calcium's optimal nutrition benefits, as well as to boost the synergistic effects of sorbitol, in a suitable nutrient-polyol preharvest treatment.

5. Polyols as Physiological Tools and Nutrients Vector

Polyols, or sugars alcohol, are sugar-like carbohydrates that mainly have hydroxyl groups (-OH) groups attached. Polyols are widely used in food products, are Generally Recognised as Safe (GRAS) by the U.S. Food and Drug Administration and are included in the European Food Safety Agency food additive list (EC Nº 1333/2008). By their structural complexity, they can be found in monosaccharides forms (sorbitol, mannitol, and xylitol), disaccharides (maltitol and isomalt) and oligosaccharides, such as hydrogenated starch hydrolysates [159,160].

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Furthermore, polyols have been repeatedly stated to be naturally present in higher plants [161]. They are a reduced form of ketose and aldose sugars, being sorbitol, mannitol, and galactitol the most abundant in plants. Besides the common hexitol structure among these three polyols, only mannitol and sorbitol are photosynthesis products, as is sucrose. Polyols are related to primary metabolism and possess several physiological functions, including nutrient transportation, energy source, and signalling modulation, increasing tolerance against drought, saline stress, and both biotic and abiotic stresses [162]. Salinity is one of the major environmental challenges to plants, as it is known to repress plant development and production in the first instance, followed by osmotic stress and water loss caused by the severe ion imbalance produced by Na^+ and Cl^- accumulation. In response, plants develop a succession of metabolic mechanisms in order to restore homeostasis, which encompasses the production of antioxidant enzymes, polyamines, NO, and osmoprotectants such as sorbitol [162].

5.1. Sorbitol: Properties and Role in Plant Physiology

Sorbitol is a 6-carbon sugar-alcohol derived from its sugar aldose, glucose. This polyol can naturally be found in fruits from Rosacea family, such as apples [163], pears [164], nectarines [165], apricots [166], plums [167], or peaches [168], as well as other plant species in lower contents [169]. Besides the known role of sorbitol as a carbon source in apples, pears peaches, apricots and cherries among other fruits, enzymes and genes of sorbitol metabolism has been found in other species initially not regarded as sorbitol-producers, like table grapes [170], as well as physiological effects when sorbitol is externally applied in blood oranges [171,172]. Sorbitol is photosynthesized mainly in matured leaves, in contrast to younger ones, which do not have enough photosynthetic capability to fully generate this metabolite, as well as sucrose [173]. In fruit that naturally accumulate sorbitol, its biosynthesis involves two key enzymes: sorbitol-6-phosphate dehydrogenase (S6PDH), which reduces glucose-6-phosphate (G6P) to sorbitol-6-phosphate (S6P) using NADPH, and sorbitol-6-phosphate phosphatase (S6PP), which converts S6P into free sorbitol. Its activity highly dependent on Mg^{+2} [161]. Then, sorbitol can be metabolized in either fructose or glucose. The main pathway involves sorbitol dehydrogenase which is NAD^+-dependent (NAD-SDH), catalysing the reversible conversion of sorbitol to fructose. Sorbitol dehydrogenase, which is $NADP^+$-dependant (NADP-SDH), also contributes to sorbitol transformation, producing glucose instead. Although this enzymatic reaction has a lower affinity for sorbitol, it is still reversible, whereas sorbitol oxidase (SOX), while still less active than NAD-SDH, irreversibly converts sorbitol to glucose. The activity of both SDH enzymes are induced by Ca^{2+} and Mg^{2+} availability [174].

In table grapes, sorbitol has a major role in cellular homeostasis. Under abiotic stress conditions such as high salinity and drought, polyols function as regulators thanks to their osmotic potential and capability to retain water, mitigating damage risk and stabilizing proteins and enzymes [175]. Furthermore, polyols also have a scavenging function against ROS, which are formed under certain moments of stress, preventing oxidative damage and subsequent plant deterioration and reduced productivity [176]. In grapevines, an increase in the VvPLT1 transporter was observed in response to salt and water stress, which has significantly higher affinity to sorbitol and mannitol resulting in polyol accumulation in grown berry tissue, therefore establishing a causal link between abiotic stress, polyol accumulation, and genetic response [177]. Sugar alcohol applications have also been proven to stimulate plant growth regulators [3], as well as PAL and UFGT activity, with the subsequently increase in anthocyanin, stilbenes, and total polyphenols content [3,172].

Regarding foliar fertilization, the presence of smaller particles, surfactants that reduce surface tension, and the use of optimal pH and concentration levels further enhance nutrient penetration and absorption, ultimately improving the overall efficiency of foliar fertilization [178]. In particular, sorbitol has proven to be an effective surfactant for foliar fertilization, as it modifies the morphology, the vapor pressure values and the distribution of fertilizer droplets through shape, gravity, vapor pressure and salt aggregation modulation [179].

The European Union´s (EU) strict regulation of fertilizers makes polyols a preharvest treatments interesting strategies to control issues aggravated by climate-change and environmental changes. In

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the EU, polyol regulations are encompassed in the legislation on fertilizers and additives, Regulation (EC) Nº 2003/2003, establishing the basis for the authorization of fertilizer products, including chelating and complexing agents, a description that fits polyols well. Although this regulation does not specifically mention polyols, their inclusion in the list of chelating agents may be an important step torward regulating these compounds. These directives promote the use of sustainable agricultural practices and the reduction of the environmental impact of chemical products. Nevertheless, the individual agricultural policy of each country could include modifications regarding the use of chelating agents that fit within the framework of these directives.

5.2. Complexation Mechanism and Transport of Sorbitol

Foliar applications of these nutrients complexed with sorbitol have been to improve resistance to various physiological stresses and disorders (Table 2). In this context, some authors refer to polyols as "vectors" [115,180] due to their role in forming carrier-mediated complexes with nutrients, thereby enhancing the transport of agrochemical products into specific targeted plant organs. In grapes, phloem transportation of nutrients may be an important way to improve fruit quality with preharvest treatments, as transport via xylem is non-functional after veraison berry growth [181]. Although the detailed mechanism by which sorbitol enhances nutrient transportation through phloem is still a subject of study [182], some researchers suggest that polyols facilitate mobility of other nutrients as they are able to behave as reducing agents, dissolving inorganic compounds and preventing particle aggregation through the process of dissolving minerals at high temperatures, thanks to theirs high dielectric constants [183,184]. Sorbitol's multiple -OH groups could enhance the solubility of Ca salts by facilitating the formation of calcium-sorbitol complexes. These complexes are stabilized within a hydration sphere through hydrogen bonding in an aqueous medium (Figure 1). This process of cation stabilization is favoured by the redox potential of Ca^{2+} (-2.87 V) [185], small ionic radius (1.00 Å) [186], and the high enthalpy of complexation [187], which is promoted under acidic conditions, particularly at pH levels below 4. A temperature of 50 °C, pH 4, and a duration of 45 min, were shown to be the optimum conditions for stabilizing the chelating reaction of inorganic Ca with sorbitol, along with a specific mass ratio of sorbitol with Ca ion of 1.45-1.94 [188]. Computational modelling [187] and experimental data [189] both confirm that the presence of sorbitol increases Ca salt solubility, likely due to the formation of energetically favourable and highly hydrated complexes.

In order to overcome the low mobility of Ca in the phloem, the vectorization process is employed [115]. Vectorization involves associating compounds with limited translocation within the plant to a 'vector' that facilitates and controls their distribution. Commonly used vectors include amino acids, carboxylic acids, phenolic acids, sugars, and polyols (such as sorbitol, mannitol, and xylitol) [115]. It has been shown that calcium-sorbitol complex treatments on vegetables increased the total Ca concentration, especially the pectin-bound Ca, in basal, intermediate, and young leaves, as well as in fruits (up to 76% in pepper fruits) [115]and table grapes [25]. This is crucial, as pectin synthesis and the binding of Ca to these structures are closely linked to the total Ca concentration in plant tissues.

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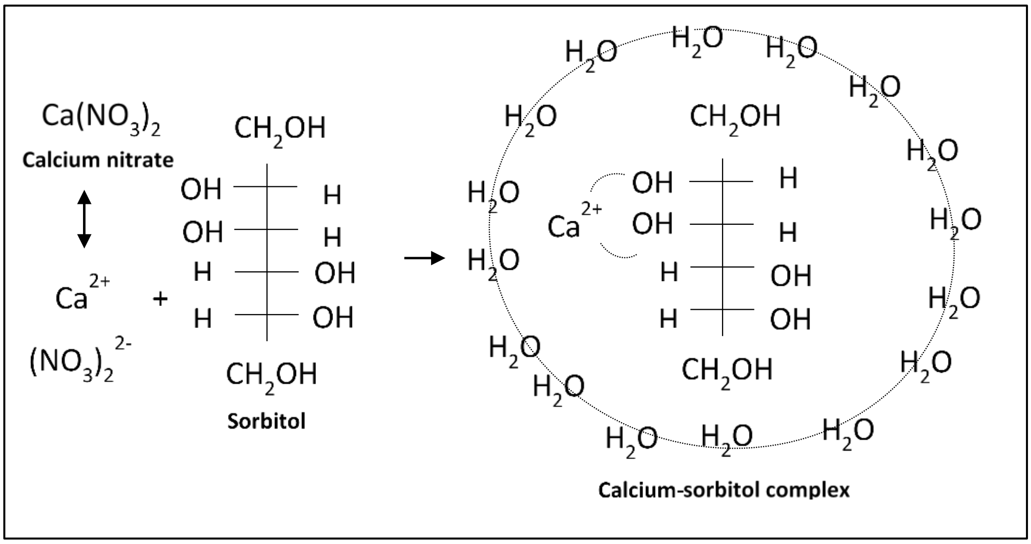

Figure 1. Stabilisation of the calcium-sorbitol complex structure in an aqueous medium.

6. Applications and Effect of Calcium-Sorbitol Complexes in Table Grape Quality

6.1. Enhancing Ca Transport and Other Nutrients

Spraying foliar fertilizers and phytosanitary products to the aerial parts of plants is an effective tool for crop management and sustainability [178]. Applying fertilizers directly to the aerial parts of the plant can be beneficial in minimizing nutrient loss and preventing soil contamination. However, to achieve an adequate supply of macronutrients, foliar fertilization should be considered a supplementary strategy which can be particularly effective in specific situations, such as poor soil conditions, nutrients with limited phloem mobility, or to improve compatibility for nutrient distribution, thereby avoiding sole reliance on root uptake. For instance, in acidic soils, P solubility can be significantly restricted, whereas in alkaline soils, the availability of micronutrients such as Zn, F, and Mn is often diminished. Under arid conditions, foliar feeding becomes especially valuable, as the uptake of macronutrients like K is limited during drought-induced water stress [190]. Foliar application is also advantageous when nutrient uptake through roots is compromised by competitive interactions. For example, the use of urea to supply N when its absorption competes with polysaccharides at the root level [191]. Additionally, foliar fertilization can be used for the bio-fortification of the nutritional quality of crops in order to improve human health and nutrition by increasing the content of essential elements such as zinc [192] and selenium [193]. Furthermore, foliar nutrient enrichment can be used to alleviate physiological disorders in plants.

This expanded agronomic practice has been successfully used to apply methyl jasmonate [194], algae-based fertilizers [195], amino acids [196], and minerals [144,197], among other phytoproducts [198]. A different approach toward transportation has been proposed by Zhang et al. (2021) [199], who applied glycinebetaine in rice (Oryza sativa L.), chelating Al^{3+} in the plant roots, which is a detrimental element for plant function, and increasing Ca^{2+} concentrations up to 25 and 28 % in shoots and roots, respectively.

Minerals are important nutrients for plants though some of them are known to have low mobility through the phloem. Physicochemical factors restrict the efficient long-distance transport of Ca. Due to cation exchange within the xylem, Ca competes with other ions including H^+ for binding sites on the walls of xylem vessels and pit membranes, making pH a determinant factor in modulating Ca mobility. Moreover, Ca is able to form low soluble or insoluble compounds, such as Ca oxalate, which restricts its translocation. Due to its limited mobility in the phloem, Ca primarily accumulates in transpiring aerial tissues (leaves). Thus, Ca transport to low transpiration sink organs, such as

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developing fruits, is often restricted, particularly after the fruit has evolved beyond the fruit set stage [114].

B is an essential micronutrient required for the growth of higher plants with an essential role in cell wall expansion. Most of B content is located in the cell wall and was considered phloem-immobile, meaning it could not be effectively redistributed within the plant. In 1996, Brown and Hu observed that despite being considered phloem-immobile, B was free and mobile in Pyrus, Malus, and Prunus species [200], which are major sorbitol producers, and later in celery (Apium Graveloens L.) [201], a mannitol producer specie. Proposed models for B polyol-dependent transport are attributed to the structural and chemical properties of B. Most of B within the plant can be found in the form of cis-diol esters complexed in cell wall pectins and polygalacturonans, being functionally immobile. In contrast, free B is primarily present as boric acid (H_3BO_3) in the cytoplasm and as the anion borate $B(OH)_4^-$ (Figure 2), as it is the main reaction in aqueous solutions [202], where the pH of 7.5 favours this molecular form. The small molecular size and high membrane permeability of H_3BO_3 enable its diffusion from the phloem to near xylem vessels, returning to the leaves and preventing B from reaching sink organs [203]. H_3BO_3 naturally reacts with esters with polyhydroxy compounds like polyols (Figure 1), forming stable complexes [201] that are phloem mobile. This finding suggests that polyols are crucial for B mobility through the phloem and for reaching sink organs in plants.

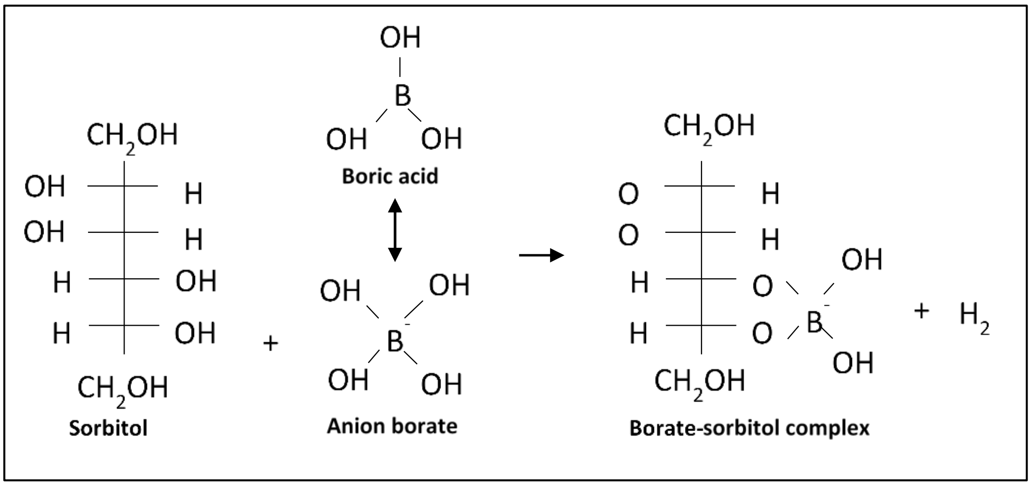

Figure 2. Formation of the borate-sorbitol complex.

Nevertheless, treatments of B have been reported as effective when applications are made from early stages of fruit setting, as treated almond trees were observed to achieve a higher concentration in flower buds, flowers, and bulbs. Will et al. (2012) [204] reported that foliar absorption B is significantly greater when applied to the abaxial (lower) leaf surface compared to the adaxial (upper) surface in both lychee and soybean, highlighting the importance of targeting the correct leaf side to enhance uptake, especially considering the thick and waxy characteristics of lychee leaves acknowledged by the authors. Also, the application of both sorbitol and $CaCl_2$ enhanced foliar B absorption, likely by reducing relative humidity. This humectant effect is particularly valuable for fertilizers like boric acid, promoting better nutrient uptake through prolonged leaf surface wetness [204]. In a similar way as B, Ca is expected to achieve higher mobility through the phloem when complexed with sorbitol (Figure 3).

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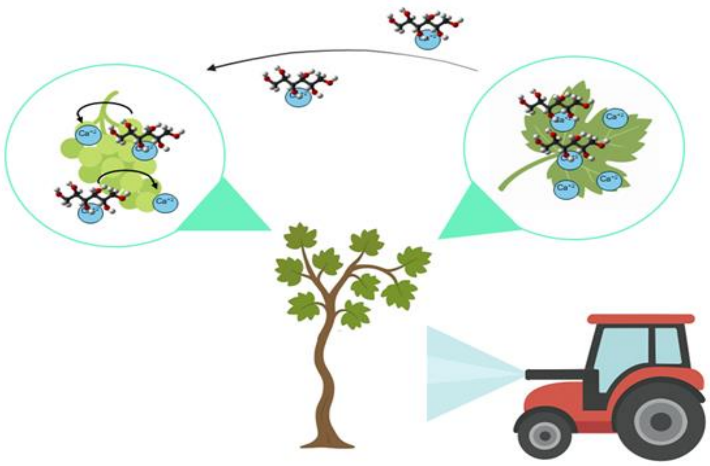

Figure 3. Proposed transport mechanism of the calcium-sorbitol complex through the phloem.

6.2. Effects on Fruit Quality and Stress Resistance

In potatoes, chelated calcium-sorbitol fertilizer revealed better performance than solely inorganic Ca fertilizers, promoting yield as well as the absorption and utilization of N, P and K nutrients [188]. When Ca, zinc and sorbitol were sprayed individually, quality and yield traits in potato increased, including total soluble solids, dry matter, protein, and starch content. Furthermore, the three solutions combined resulted in the plants with the highest quality values [205]. This effect has also been observed when sorbitol is mixed with B and Ca applied to mangoes [129], achieving higher yield and quality traits. However, other authors observed a higher absorption rate of B but less translocated content of the mineral, probably due to a high B application, inducing toxicity in the soybean plants [206]. In peanuts, dose ranging from 1.5 to 1.8 g L^{-1} of chelated calcium-sorbitol treatments significantly increased yield production by up to 28.6 %, and fat content by 5.0 %, potassium and Ca content in peanut kernels by 98.6 and 55.3 %, respectively, and dry matter accumulation by 37.9 % in comparison to untreated peanut plants [207]. In wheat, sorbitol spray treatments with nanoparticles of Cu in addition to zeolite fertilizer contributed to a higher nutrient uptake and accumulation of the plants, leading to higher yield rates [208], highlighting the importance of symbiotic strategies with polyols in order to maximize crop performance.

The chelated calcium-sorbitol complex has been applied to white seedless table grapes of the ‘Doña María’ variety, which is included in a Protected Designation of Origin (PDO) and is required to achieve a minimum of 12.5 °Brix in total soluble solids [25]. Foliar applications during on-tree ripening improved the mobility of Ca intro the fruit as calcium-pectate, or ‘bound calcium’, resulting in increased fruit firmness and reduced ABA and MDA contents. Polyphenols synthesis was stimulated, leading to higher antioxidant activity. In chelated calcium-sorbitol treated grapes, malic acid degradation was preserved while greater amounts of glucose and fructose were shown [25]. Overall, these changes resulted in a superior maturity index while preserving good storability traits.

Calcium-sorbitol chelated treatments promoted anthocyanin biosynthesis in ‘Sanguinelli’ blood oranges through stimulation of the phenylpropanoid pathway, of which the PAL enzyme is key to triggerimg the synthesis of flavonoids [172]. After 17 days of the first treatment and during the on-tree ripening stage to harvest date, total phenolic and antioxidant activity was higher in treated fruits in every fraction: juice, flavedo, albedo, and pulp. The same behaviour was observed for anthocyanin content, minerals content, individual sugars, and individual acids. When blood oranges were stored at 8 °C, anthocyanin levels significantly increased. However, this increase was more prominent in treated fruits as well as hesperidin and narirutin. Overall, chelated calcium-sorbitol treatment

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preserved bioactive compounds in blood oranges, such as sugars and acids, resulting in an improved sensory quality after 30 days of storage [171].

Table 2. Physiological effects of applying mineral-sorbitol complexes to different plant.

Plant	Minerals Applied	Effect	References
Mango	B Ca	+ Total soluble solids +Carotenoids +Ascorbic acid +C: N ratio +Shelf-life +Yield -Acidity - Total soluble solids /acidity ratio	[129,209]
Table grapes	Ca	+ Total soluble solids + Total soluble solids /acidity ratio +Total Phenols +Colour and anthocyanidins -Berry shattering +Improved firmness -Respiration rate	[3,25,177,210, 211]
Wheat	Cu	+Enhanced nutrient uptake	[208]
Peanut	Ca	+Higher crop yield +Fat content +Mineral content +Dry matter	[207]
Blood oranges	Ca	+Red colour of peel and pulp +Anthocyanin content +Naruritin and hesperidin content +Individual sugars accumulation +Enhanced organoleptic properties -K: Ca ratio	[171,172]
Potatoes	Ca Zn	+Tubers per plant +Tuber weight +Total yield +N, P, and K content	[188,205]
Rice	Zn	+Yield +Protein synthesis +Seed production +Dry matter	[212]
Melon	B	+Plant growth +Dry matter	[213]
Lychee	B	+B absorption	[204]
Soybeans	B	+B absorption	[204,206]

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Other sugar alcohols, such as inositol, have shown positive effects in wine grapes by enhancing yield, soluble solids, tannin, and anthocyanin contents when applied at doses between 2.4 and 3.6 L hm^{-2}. These results suggest that polyols may contribute to improved Ca absorption; however, higher doses have been associated with detrimental effects on leaf photosynthetic performance [211]. In honeydew melons, chelated Ca with mannitol resulted in elevated mesocarp Ca concentrations, elevated fruit firmness, and enhanced marketability without a modification in the sugar content of fruit [214].

7. Conclusions and Future Perspectives

Adverse conditions for growing table grapes in certain regions caused by climate change and the poor suitability of arid soils highlight the need for more sustainable solutions. Ca has proven to be an effective tool in preventing physiological disorders in table grapes and other crops. Additionally, sorbitol has shown the ability to promote defense mechanisms against both biotic and abiotic stresses, while also improving fruit quality. Combining sorbitol with Ca may offer beneficial effects, not only due to their individual properties, but also thanks to sorbitol's synergistic role in enhancing Ca transport, helping it reach sink organs more efficiently. Furthermore, sorbitol complexation with other low-mobility nutrients and elicitors could enhance their effects, opening new research opportunities involving polyols. Therefore, calcium-sorbitol treatments contribute to reducing postharvest food losses and generate economic benefits for producers and farmers by improving marketable yield and extending shelf-life. At the same time, it provides affordable, sustainable, and environmentally friendly treatment that is most likely compatible with global agricultural practices. In conclusion, calcium-sorbitol treatments represent an alternative tool, offering a nutrient-based fertilization option when fruit development or specific conditions require a complementary approach to ensure and enhance fruit quality and preservation.

Author Contributions: Conceptualization, D.M-R. and A.G.; writing—review and editing, A.G, A.S-G., M.E.G-P. M.H.D., J.M.V. and D.M-R.; funding acquisition, J.M.V. and D.M-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by MICIU/AEI /10.13039/501100011033 and by FEDER, UE, grant number PID2022-137282OB-I00

Acknowledgments: The authors thank the Generalitat Valenciana, the Conselleria of Education, Universities and Employment, for the funding Alberto Guirao Carrascosa´s PhD-scholarships (CIACIF/2022/270), which enable him to undertake doctoral studies, and to the European Social Fund for co-financing these grants.

Conflicts of Interest: The authors declare no conflicts of interest, financial or otherwise, that could have influenced the research outcomes or conclusions presented in this work.

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