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Review

Enhancing Calcium Transport in Table Grapes Using Sorbitol: A Sustainable Strategy for Promoting Fruit Quality

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Abstract

Table grapes suffer significant losses due to 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 comprehensive review synthesizes the current scientific understanding and recent studies regarding calcium dynamics and proposes sorbitol as an innovative preharvest solution to enhance table grape quality through improved calcium (Ca) 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 the veraison stage. This review thoroughly discusses the mechanistic hypotheses by which 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. Finally, we outline future directions for investigation, aiming to further clarify the molecular mechanisms involved and explore the potential of sorbitol to form complexes with other poorly mobile nutrients and plant elicitors, opening new avenues for sustainable crop management.

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

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1. Introduction

Table grapes (*Vitis vinifera* L.) are a highly valued fruit in the agri-food sector, appreciated by consumers for their complex flavor and nutritional profile, which includes sugars, organic acids, fiber, minerals, vitamins, flavones, flavanones, volatile compounds, pigments, and anthocyanins, especially in red varieties [1]. As a non-climacteric fruit, grapes must be harvested at a maturity stage that ensures the proper accumulation of sugars, organic acids, and pigments to meet the minimum commercial standards, as well as the development of health-related functional compounds such as polyphenols [2].

Despite their economic importance, table grapes face serious challenges during ripening and storage, leading to significant economic losses and increased food waste. Fungal

infections and physiological disorders, including berry cracking, berry shattering, dehydration of berries and rachis, softening, and loss of color, can disrupt cellular homeostasis, triggering increased enzymatic activity (Polygalacturonase (PG) and Cellulase (Cx)), and the generation of reactive oxygen species (ROS), which compromises cell integrity and reduces shelf-life [3,4]. All these physiological problems are closely related to calcium sufficiency in grape tissues.

Postharvest deterioration due to fungal infection can affect up to 40% of global grape production [5]. Gray mold, caused by *Botrytis cinerea*, is particularly prevalent because it can develop under typical cold storage conditions (0–4 °C) [6]. Maintaining optimal temperature and effective fungal control is therefore essential to minimize fruit loss. The susceptibility of grapes to fungal infection is linked to nutrition; calcium-deficient fruits [7] are more prone to fungal infection since calcium is a key structural component of the cell wall and acts as a signaling agent.

Another important physiological disorder is cracking, defined as the rupture, splitting, or breaking of the berry skin [8–10]. This phenomenon reduces the commercial value of the fruit and makes it more susceptible to biotic infections [11–13]. It typically occurs during the third phase of grape development, when rapid expansion of pulp cells exceeds the mechanical resistance of the cuticle [10,14]. Cracking is induced by environmental factors such as rainfall and high humidity, considered serious constraints for profitable grape production, as well as by increased temperature, which shows a linear relationship with cracking incidence between 10 and 40 °C [10]. The structure and composition of the pericarp cell wall directly influence the mechanical properties and susceptibility to cracking [8,15,16]. Plant hormones such as abscisic acid (ABA), auxins, gibberellins (GA), ethylene, and jasmonic acid are also involved in this process [9,17]. Nutrient deficiencies, particularly of calcium and boron (B), can further increase the incidence of cracking, as calcium is essential for maintaining cell wall integrity [18]

Berry shattering results from the degradation of pectins and celluloses, accompanied by the increased activity of hydrolytic enzymes in the abscission zone (AZ) [19]. Various factors contribute to this disorder, including environmental conditions [18], genetic predisposition [20], and the use of growth regulators such as ethephon and abscisic acid (ABA) [21,22]. Berry abscission occurs in a specific region known as the abscission zone (AZ), located between the pedicel and the berry. Cells within this zone differ physiologically from surrounding tissues, and upon receiving specific signals, usually mediated by plant hormones, hydrolytic enzymes are synthesized that degrade the cell wall, leading to abscission [23,24].

Shattering commonly occurs during handling, harvest, transportation, and storage. However, under extreme conditions such as high temperatures ($\geq$40 °C) during fruit set, this phenomenon may also occur during on-tree ripening, as previously reported [25]. Berry shattering is a frequent postharvest problem during storage, transport, and marketing of table grapes, resulting in significant economic losses [24]. Calcium deficiency, which compromises cell wall integrity, is frequently linked to the weakening of the abscission zone and, consequently, to a higher susceptibility to berry shattering. Conversely, calcium bound to pectins within the abscission zone was found to reduce berry detachment from the clusters [24].

Calcium content in fruit tissues plays a crucial role in controlling decay caused by *B. cinerea*. The activity of *B. cinerea* on the cell wall of apple tissues with low calcium levels leads to a decrease in non-cellulosic polysaccharides, coupled with increases in cellulose, wall-bound phenolics, proteins, and mineral elements. Conversely, in infected tissues of high-calcium fruits, changes in cell wall composition are generally less pronounced than those observed in low-calcium fruit [26]. In this regard, calcium treatments have

been shown to maintain low carboxymethyl cellulase (CMCase) activity and suppress the activity of cell wall–degrading enzymes produced by *B. cinerea*, thereby reducing infection in grapes [27].

ColorColour is a key factor in consumer acceptance [28]. Browning during postharvest storage is a common issue in table grapes and can result from both enzymatic and non-enzymatic reactions [29]. Irregularities and poor coloration have been associated with low expression of ripening-related genes involved in ABA biosynthesis [21,30], particularly under high temperatures [31,32] and limited sunlight exposure [32] during the ripening season. In this regard, calcium has also been shown to stimulate the biosynthesis of anthocyanins, making its deficiency an important factor contributing to color loss [33,34].

Finally, rachis browning and color loss are indicators of senescence or degradation of grape clusters. A green rachis is a sign of freshness, while a brown rachis is a major cause of consumer rejection and fruit loss [28]. The rachis is particularly susceptible to dehydration and enzymatic browning due to its high metabolic rate, with a respiration rate estimated to be 11 to 28 times higher than that of the berries [35,36]. Rachis browning has been associated with tissue dehydration, chlorophyll degradation, and the activity of cell wall–related enzymes involved in both the synthesis and degradation of polyphenols. In this context, preharvest calcium applications in vineyards have been shown to effectively preserve rachis freshness by reducing water loss and chlorophyll degradation [37]. Moreover, calcium has been reported to suppress the formation of brown pigments. The enzymatic activities of polygalacturonase, xylanase, cellulase, and pectinase in the cell wall were significantly reduced, whereas the contents of phenols and flavonoids increased. At the same time, the activities of polyphenol oxidase and phenylalanine ammonia-lyase were decreased [38].

To overcome these challenges, a variety of quality control strategies have been developed. Among preharvest practices, girdling is a common technique [39–41] that interrupts the downward phloem flow, leading to the accumulation of sugars, auxins (IAA), and abscisic acid (ABA) in the berries, thereby accelerating ripening [41–43]. However, girdling often reduces cuticle thickness, which may increase susceptibility to berry cracking. Alternatively, preharvest application of elicitors represents a robust and environmentally friendly strategy [44–47]. Elicitors such as salicylates (SA, ASA, MeSA) have shown strong efficacy against *B. cinerea* by stimulating the antioxidant system of the plants, enhancing the activities of enzymes such as ascorbate peroxidase (APX), Catalase (CAT), and peroxidase (POD) [44,48]. Oxalic acid (OA) has also been shown to improve fruit quality, particularly color, by increasing endogenous ABA levels, a key ripening regulator, through the upregulation of the *VvNCED1* gene [44,49].

In postharvest handling, Modified Atmosphere Packaging (MAP) is commonly used to maintain fruit quality and reduce the respiration rate [50–52]. Sulfur dioxide (SO_2) remains the standard fungicidal treatment for controlling gray mold [53]. SO_2 promotes defense mechanisms and increases tissue firmness by inducing pectin demethylation [54]. However, SO_2 has significant limitations, as excessive exposure can cause fruit damage such as bleaching, discoloration, and spotting [55]. In addition, it is strictly regulated, with the European limit set at 10 mg kg^{-1} for fresh table grapes (European Regulation (EC) N° 1333/2008) [56]. These restrictions, together with the growing demand for sustainability and the reduction in food waste, have encouraged the search for alternative, innovative, and environmentally friendly solutions.

In this context, this review highlights the potential of calcium (Ca), a vital macronutrient that contributes to cell wall integrity and fruit firmness. Preharvest calcium applications strengthen the berry cell wall, improving fruit quality attributes such as firmness, and reducing weight loss, rachis browning, decay incidence, and cracking. However, calcium accumulation in both skin and flesh tissues stops after veraison. Calcium treatments in

table grapes are effective only when applied between fruit set and veraison, a period during which the stomata are still functional and calcium that is not directly absorbed by the berries can be redistributed through xylem transport [57]. This feature limits its effective translocation to developing fruits (sink organs) after veraison, when the transpiration rate decreases and xylem functionality in the berries is drastically reduced [7,57]. Consequently, fruits that fail to accumulate sufficient calcium in their tissues may develop physiological disorders.

To overcome this transport limitation, this review proposes the use of sorbitol, a natural sugar alcohol that acts as a "carrier". Sorbitol, due to its multiple hydroxyl (-OH) groups, enhances the solubility of calcium salts by forming stable and soluble calcium–sorbitol complexes. This vectoring process helps associate compounds with limited mobility, such as calcium, with a carrier that facilitates their controlled distribution through the phloem. In this way, as observed with boron in sorbitol-producing species, calcium complexed with sorbitol is expected to achieve greater mobility through the phloem, allowing it to reach sink organs more efficiently. Therefore, this review explores how preharvest application of calcium–sorbitol complexes may amplify the benefits of optimal calcium nutrition, offering a sustainable solution to improve the quality, firmness, and resistance of table grapes to both biotic and abiotic stress.

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

2.1. 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 of 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 [58]. Nevertheless, a defining characteristic of Ca is its low mobility through the phloem [59–61]. 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 to stimuli, such as hormones, biotic and abiotic stresses, and developmental factors [62]. In response to external signals, an early event in the signaling process consists of a translocation of Ca^{2+} from the 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 encountered [63].

2.2. 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 disorders caused by the mineral shortage. Among Ca^{2+} deficiency symptoms, bitter pit is commonly observed in apples [64,65] as dark circular lesions beneath the skin surface of the fruit. The affected spots are brown, dry, and porous in texture, tending to appear as necrotic tissue, and are commonly located at the calyx area. In tomatoes and peppers, deficiency may lead to BER, showing a sunken dark area at the apical end of the fruit [65,66]. In pineapples [67–69] and loquat [70,71], 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 [72]. Nevertheless, preharvest exogenous foliar treatments with Ca solutions have proven to be an effective solution to alleviate these symptoms.

2.3. 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 a high presence of Ca inhibits PG activity, an enzyme responsible for pectin degradation [73]. In peaches, some authors [74] observed higher accumulation of polyphenol content as well as antioxidant activity, but a lack of modifications in fruit firmness, sugars, and acids content, key parameters defining peach quality attributes, whereas others reported a 34.2–44.7% firmness increase in Ca-treated canned peaches cv. 'Andross' [75]. Ca applications also proved to improve the storability of peach fruits. Ca chloride ($CaCl_2$) solutions at 1% improved weight loss, cell membrane ion leakage (IL), and brown rot incidence, as well as increased phenolic content, antioxidant activity, and enzymatic activity after 30 days of storage at 8 ± 2 °C, 50% RH [76]. In the '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 [77]. 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 [78]. When the treatments were 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 the Ca treatments modified sugars or organic acids [79].

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	[64,80,81]
Tomato	$CaCl_2$	−Reduced blossom-end rot incidence and severity	[65,66]
Pineapple	$CaCl_2$ Ca gluconate Ca oxide (CaO) $Ca(NO_3)_2$ Ca-boron	−Reduced IL −Reduced MDA content −Reduced internal browning incidence	[67,69]
Loquat	$CaCl_2$	−Reduced IL −Reduced MDA content −Reduced internal browning incidence +Promoted accumulation of proline, GABA and polyamines	[70,71]
Mango	$CaCl_2$	+Enhanced antioxidant enzymatic activity	[82]
Peaches	Calcium-silicate $CaCl_2$ $Ca(NO_3)_2$ Calcium sulfate ($CaSO_4$)	+Improved firmness −Reduced weight loss +Promoted bioactive compound content −Delayed softening −Limited rise in PG, PME, Cx, and β-Gal activities	[74–77]
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	[78,79]

Table 1. *Cont.*

Fruit	Ca Products	Effects	References
Table grapes	$Ca(NO_3)_2$ $CaCl_2$ CaAs	−Reduced weight loss −Reduced berry shattering −Reduced malic acid degradation −Reduced *B. cinerea* incidence +Higher activity of antioxidant enzymes +Enhanced bioactive compounds content −Reduced MDA −Reduced IL −Inhibited ABA synthesis −Increased fruit firmness and Ca pectate −Inhibited ethylene production by suppressing *VvACO1* expression −Reduced cracking incidence	[18,23,57,83–88]

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. The symbol '+' indicates an increase or improvement, and '−' indicates a decrease or reduction in the respective trait.

2.4. 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 [57]. The activities of PG and pectin methylesterases (PME) enzymes have also been reduced, delaying pectin degradation and alleviating weight loss, decay incidence, malondialdehyde (MDA) content, and relative conductivity [85]. A recent study indicates that Ca ascorbate (CaAs), a Ca salt containing ascorbic acid, significantly improved berry firmness and reduced browning and color change indices at harvest and during storage, in 'Thompson Seedless' table grapes [87]. It also significantly decreased weight loss, reduced berry abscission and decay spread rates during storage [87].

Cracking is "closely related to the strength and elongation of the peel" [89,90]. 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 [16,90–92]. Enzymes such as PG, PME, beta-galactosidase (β-Gal), Cx, and expansins (EXP) are involved in cracking. Elevated activities of PG, β-Gal, and Cx in genotypes prone to cracking indicate a role in the breakdown of the cell wall [8,16,93]. Ca treatments can reduce PG and Cx activities, slowing down pectin and cellulose degradation and resulting in higher peel integrity [8]. The cuticle is a "protective barrier against external or internal stresses" and pathogens [12,94–96]. Cuticle thinning, especially during the last stages of fruit development, makes it vulnerable to microcracks [12,97]. 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 [10]. $CaCl_2$ has been shown, particularly at the flowering stage, to reduce cracking incidence by approximately 4- to 10-fold compared with the control group [8]. 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 [8]. A research study in 'El-Bayadi' table grapes showed that 1% $CaCl_2$ preharvest spraying significantly reduced decay incidence during storage compared to the control [98]. $CaCl_2$ also reduced the extracellular PG activity of *B. cinerea* by up to 90% [7,99]. Furthermore, $CaCl_2$ "had a direct influence on the conidia and hyphae of *B. cinerea*, causing conidial malformation and cytoplasmic disorganization" [7].

Ca transport to the berries decreases drastically post-veraison due to a reduction in transpiration rate and xylem functionality [7,57]. 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 the berry Ca content. Foliar treatments were also effective in preserving postharvest life and quality. In the '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 the APX, SOD, and CAT enzyme activities. They also decreased total soluble solids content, MDA, ion leakage (IL), and pH. After 2 months of storage at 1 ± 1 °C, treated fruit showed lower decay, weight loss, color change, IL, and browning [84]. This advantage of spraying Ca on leaves was also previously observed [83]. 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 incidence of decay of 'Flame seedless' variety after 12 days at 10 °C [84]. Moreover, Ca applications were observed to stimulate genes related to the biosynthesis of anthocyanins in table grapes [34], facilitating the accumulation of antioxidant compounds.

Thus, it can be confirmed that the use of foliar Ca on fruit is a useful tool to strengthen the resistance of the plants and activate their 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 the low mobility of calcium, the application of sorbitol, which promotes nutrient translocation in plants, can be an important strategy to enhance the optimal nutritional benefits of calcium. It can also boost the synergistic effects of sorbitol in a suitable nutrient-polyol preharvest treatment.

3. Polyols as Physiological Tools and Nutrients Vector

Polyols, or sugar alcohols, are sugar-like carbohydrates that primarily have attached hydroxyl (-OH) groups. Polyols are widely used in food products, are Generally Recognized as Safe (GRAS) by the U.S. Food and Drug Administration [100], and are included in the European Food Safety Agency food additive list (EC N° 1333/2008) [56]. By their structural complexity, they can be found in monosaccharide forms (sorbitol, mannitol, and xylitol), disaccharides (maltitol and isomalt), and oligosaccharides, such as hydrogenated starch hydrolysates [101,102]. Due to their similar structure and functional hydroxyl groups, polyols such as mannitol and xylitol also possess potential for acting as nutrient transport vectors.

Furthermore, polyols have been repeatedly reported to be naturally present in higher plants [103]. They are a reduced form of ketose and aldose sugars, being sorbitol, mannitol, and galactitol being the most abundant in plants. Besides the common hexitol structure among these three polyols, only mannitol and sorbitol are photosynthetic products, as is sucrose. Polyols are related to primary metabolism and possess several physiological functions, including nutrient transportation, energy source, and signaling modulation, and contribute to increased tolerance against drought, saline stress, and both biotic and abiotic stresses [104]. Salinity is one of the major environmental challenges to plants, as it is known to repress plant development and production initially, 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 [104].

3.1. 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 the Rosaceae family, such as apples [105], pears [106], nectarines [107], apricots [108], plums [109], or peaches [110], as well as other plant species in lower contents [111]. 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 have been found in other species initially not regarded as sorbitol-producers, like table grapes [112], as well as physiological effects when sorbitol is externally applied in blood oranges [113,114]. Sorbitol is photosynthesized mainly in mature leaves, in contrast to younger ones, which do not have enough photosynthetic capability to fully generate this metabolite, as well as sucrose [115]. 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 is highly dependent on Mg^{2+} [103]. Then, sorbitol can be metabolized into either fructose or glucose. The main pathway involves sorbitol dehydrogenase, which is NAD^+-dependent (NAD-SDH), catalyzing the reversible conversion of sorbitol to fructose. Sorbitol dehydrogenase, which is $NADP^+$-dependent (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 is induced by Ca^{2+} and Mg^{2+} availability [116].

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 [117]. Furthermore, polyols also have a scavenging function against ROS, which are formed under specific stress conditions, preventing oxidative damage and subsequent plant deterioration and reduced productivity [118]. In grapevines, an increase in the *VvPLT1* transporter was observed in response to salt and water stress, which has a significantly higher affinity to sorbitol and mannitol, resulting in polyol accumulation in developed berry tissue, therefore establishing a causal link between abiotic stress, polyol accumulation, and genetic response [119]. Sugar alcohol applications have also been proven to stimulate plant growth regulators [120], as well as PAL and UFGT activity, with the subsequent increase in anthocyanin, stilbenes, and total polyphenols content [114,120].

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 [121]. 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 [122]. The strict regulation of fertilizers in the European Union (EU) makes polyols an interesting preharvest treatment strategy to mitigate stress factors aggravated by climate and environmental changes. In the EU, polyols are not specifically regulated as such; however, when used in agricultural formulations, they can act as complexing agents. The European Parliament and Council Regulation (EU) 2019/1009 [123] establishes the framework for the authorization of EU fertilising products, including the classification of chelating and complexing agents, a category under which polyols could potentially be considered. Although this regulation does not explicitly list polyols, their recognition among complexing agents would represent an important step towards the formal regulation of these compounds. These directives promote the use of sustainable agricultural practices

and the reduction in 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.

3.2. Thermodynamic, Chemical, and Practical Rationale for Preferring Sorbitol as a Vector

The selection of sorbitol as a calcium complexing agent is justified by its superior chemical and thermodynamic performance compared to other common polyols, such as mannitol and xylitol. Sorbitol (D-glucitol) and mannitol (D-mannitol) are six-carbon open-chain isomers (hexitols), and they share the same molecular weight of 182.17 g mol^{-1}. In contrast, xylitol is a lighter pentitol, having a molecular weight of 152.15 g mol^{-1}. The crucial difference between sorbitol and mannitol resides in their stereochemistry, specifically the orientation of the hydroxyl (-OH) group at the C2 position of sorbitol relative to mannitol. This stereochemical difference drastically influences the capacity of sorbitol to interact with divalent cations like Ca^{2+} [124].

Aqueous solubility is a determining practical factor for formulating concentrated treatments. Sorbitol is exceptionally soluble in water (~2350 g L^{-1}). Xylitol also exhibits very high solubility (~1690 g L^{-1}). In marked contrast, mannitol has a significantly lower solubility (~180–220 g L^{-1}). This pronounced solubility difference (sorbitol is approximately 10 to 15 times more soluble than mannitol) is attributed to the flexible conformation of sorbitol, which favors the formation of hydrogen bonds with water, whereas mannitol tends toward crystallization due to a favored internal molecular packing arrangement [101]. Consequently, the low solubility of mannitol restricts its practical utility as a complexing agent in concentrated solutions. Quantitatively, the affinity of Ca^{2+} for these polyols follows the order: sorbitol > xylitol > mannitol [124,125]. In dilute aqueous solutions at 25 °C, the 1:1 formation constant (CaL^{2+}) for sorbitol (log K ≈ 0.0) is slightly higher than that for xylitol (log K ≈ −0.1 to −0.2), and considerably greater than that for mannitol (log K ≈ −0.3 to −0.5).

This difference in stability is explained by molecular geometry. Optimal Ca^{2+} chelation requires coordination with a cis-cis vicinal triol. Sorbitol, being derived from glucose (D-glucitol), can adopt conformations where its hydroxyl groups (-OH) are favorably oriented to satisfy this geometrical requirement [125]. Sorbitol can act as a polydentate ligand, specifically a tetradentate ligand, coordinating with four -OH groups (at C1, C2, C4, and C6) [126]. This enveloping configuration explains the greater capacity of sorbitol to stabilize the cation in solution. In contrast, the stereochemistry of mannitol imposes steric restrictions that limit its effective denticity to bidentate or tridentate coordination, resulting in less stable complexes. Xylitol, being a pentitol, has a shorter chain and lacks a sufficient -OH segment to achieve the complete tetradentate potential of sorbitol, reaching a maximum coordination of bidentate or tridentate. Superior complexing ability of sorbitol is reflected in its capacity to keep Ca^{2+} soluble and prevent the precipitation of insoluble salts (such as phosphates or carbonates). Classic studies demonstrated that sorbitol and xylitol are effective at significantly delaying calcium phosphate precipitation. Conversely, the presence of mannitol has only a weak effect, as Ca^{2+} tends to precipitate promptly, similar to control conditions. Moreover, in highly alkaline media, sorbitol increases the solubility of calcium hydroxide [$Ca(OH)_2$] by forming stable Ca-sorbitol-hydroxide complexes [124].

From a formulation standpoint, sorbitol (and to a lesser extent, xylitol) is preferable to mannitol due to several interconnected reasons: (i) Sorbitol exhibits greater compatibility and stability with calcium salts in solution, a factor which ensures a higher proportion of soluble and mobilizable Ca^{2+} remains available after foliar application. Mannitol has a lower capacity for complexation and stabilization under typical agronomic conditions. (ii) Sorbitol functions effectively as a wetting agent and surfactant, thereby enhancing

foliar penetration and prolonging the time of contact on the leaf surface [127]. (iii) Sorbitol offers favorable cost-effectiveness and industrial availability. Field trials in crops such as potato and peanut have backed the finding that formulations containing Ca^{2+}-sorbitol surpass inorganic Ca^{2+} when measured by the criteria of foliar incorporation and quality improvement. For example, studies demonstrated that sorbitol-chelated calcium significantly improved yield and calcium nutrient absorption in peanuts [127]. Therefore, sorbitol is established as the most efficient and cost-effective choice for foliar applications designed to enhance the mobility and content of Ca within the fruit.

3.3. Complexation Mechanism and Transport of Sorbitol

Foliar applications of these nutrients complexed with sorbitol have been reported to improve resistance to various physiological stresses and disorders (Table 2). In this context, some authors refer to polyols as "vectors" [61,128] 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 the veraison stage of berry growth [129]. The mechanism of action of sorbitol as a Ca^{2+} vector relies on the stabilization of the cation. Multinuclear Nuclear Magnetic Resonance (^{1}H, ^{13}C, and ^{43}Ca NMR) studies provide direct evidence that Ca^{2+} forms complexes with sorbitol in aqueous solution. These analyses have identified the preferred Ca^{2+} binding sites on sorbitol as the O-H groups of C1, C2, C4, and C6, suggesting a 1:1 tetradentate complex where the Ca^{2+} is partially enveloped by the organic molecule. Fourier-Transform Infrared (FT-IR) spectroscopy also confirms the complexation, showing shifts in the O–H and C–O stretching bands and confirming that the metal links via the hydroxyl groups. Angyal (1973) [130] indicated that the presence of cis sequences of hydroxyl groups is key for sugars/polyols to form stable complexes with metals.

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

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	[72,131]
Table grapes	Ca	+Total soluble solids +Total soluble solids/acidity ratio +Total Phenols +Color and anthocyanidins −Berry shattering +Improved firmness −Respiration rate	[18,119,132,133]
Wheat	Cu	+Enhanced nutrient uptake	[134]
Peanut	Ca	+Higher crop yield +Fat content +Mineral content +Dry matter	[135]

Table 2. *Cont.*

Plant	Minerals Applied	Effect	References
Blood oranges	Ca	+Red color of peel and pulp +Anthocyanin content + Naruritin and hesperidin content +Individual sugar accumulation +Enhanced organoleptic properties −K:Ca ratio	[113,114]
Potatoes	Ca Zn	+Tubers per plant +Tuber weight +Total yield +N, P, and K content	[136,137]
Rice	Zn	+Yield +Protein synthesis +Seed production +Dry matter	[138]
Melon	B	+Plant growth +Dry matter	[139]
Lychee	B	+B absorption	[140]
Soybeans	B	+B absorption	[140,141]

The symbol '+' indicates an increase or improvement, and '−' indicates a decrease or reduction in the respective trait.

Multiple -OH groups of sorbitol 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 favored by the redox potential of Ca^{2+} (−2.87 V) [142], small ionic radius (1.00 Å) [143], and the high enthalpy of complexation [144], 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 calcium ion of 1.45–1.9 [137]. Computational modeling [144] and experimental data [125] both confirm that the presence of sorbitol increases Ca salt solubility, likely due to the formation of energetically favorable and highly hydrated complexes. To overcome the low mobility of Ca^{2+} within the phloem, the formation of the Ca^{2+}-sorbitol complex operates based on several mechanistic hypotheses, which are supported by experimental evidence:

1. Maintaining Solubility:

In the majority of plant species, calcium is a nutrient characterized by very low phloem mobility. Unlike nutrients such as potassium, Ca^{2+} is not easily retranslocated from older leaves to younger tissues via the phloem [145]. This phenomenon is attributed to its strong tendency to precipitate or to be sequestered in the form of insoluble salts (oxalates, Ca pectates in cell walls) and to its rapid immobilization in cellular compartments (e.g., vacuoles) within the source leaves. In fact, abundant calcium oxalate crystals are observed in grapevine leaves as a mechanism for immobilizing excess Ca [146]. Furthermore, free Ca^{2+} tends to interact with membranes and signaling proteins (such as calmodulin), hindering its persistence in the phloem sap [147]. In *Vitis vinifera*, calmodulin (CaM) and calmodulin-like (CML) proteins function as intracellular Ca^{2+} sensors and sequestrators, binding to calcium ions using EF-hand motifs and modulating Ca^{2+}-dependent signaling in response to environmental and stress stimuli [148]. These factors explain why the transfer of Ca via the phloem is naturally highly restricted, leading to Ca deficiencies in distal organs (fruits, apices) even when the plant possesses sufficient Ca in mature leaves. The Ca-

sorbitol complex maintains Ca^{2+} in soluble form and prevents its precipitation as $Ca(OH)_2$, oxalate, or other salts in the sap. For example, in model solutions, the presence of sorbitol at neutral pH was observed to stabilize Ca, preventing the formation of solids for long periods [127,137]. Analogously, inside the phloem, the complexed Ca would be "protected" from anions such as oxalate or phosphate, reducing the formation of insoluble deposits in the vessels.

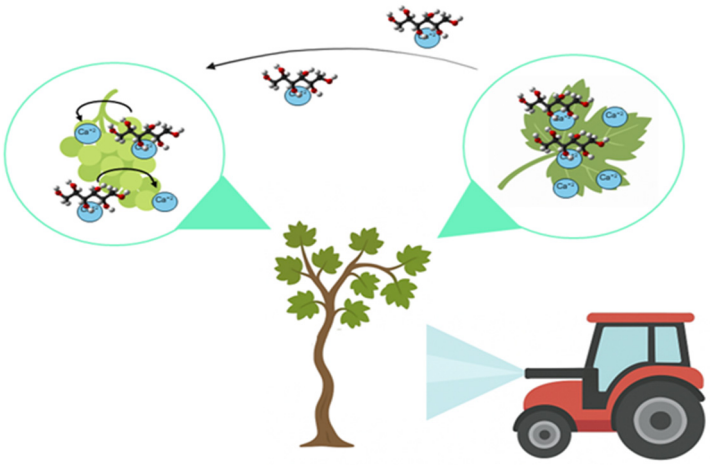

Figure 1. Proposed transport mechanism of the calcium-sorbitol complex through the phloem.

2. Reduction in Electrostatic Interaction:

Although the Ca^{2+}-sorbitol complex probably maintains a net positive charge (given that sorbitol is a neutral ligand), the coordination with multiple -OH groups reduces the effective exposed charge of the Ca^{2+}. The cation becomes partially "wrapped" by the sorbitol, decreasing its electrostatic interaction with cell walls and cation exchange sites in the phloem. This makes the chelated Ca^{2+} less susceptible to being withdrawn by the Ca^{2+} transporters of the cellular membranes, allowing it to remain in the sieve tube and be displaced with the flow of photoassimilates [149].

3. Use of Polyol Transport Systems:

In plants that naturally translocate polyols (sugar alcohols) through the phloem, specific transporters for these compounds exist in the membranes of source and sink cells. For example, in the apple tree (*Malus domestica*), phloem sorbitol transporters (*MdSOT3*, *MdSOT4*, and *MdSOT5*) have been identified, which are responsible for sorbitol loading and unloading [150]. It is conceivable that if the Ca^{2+} is bound to sorbitol, it may utilize these existing transport systems. Sorbitol would thus act as an "encapsulating vehicle": its transporters mobilize the molecule (which is recognized as a transport nutrient), carrying the complexed Ca with it. It is worth noting that a similar mechanism has been demonstrated for boron (B), a micronutrient that is analogous to calcium in terms of phloem immobility. In species that naturally synthesize sorbitol, B forms neutral borate-polyol complexes that allow it to move freely through the phloem [149,151]. This suggests that sorbitol can form stable compounds with other metabolites, facilitating their transportation through the phloem, even in plant species where sorbitol is not present. This has been reported for poorly mobile nutrients like Zn, B, and salicylic acid [141,152,153] and is applicable by analogy to Ca^{2+} [71,113,114,135]. In this regard, although sorbitol is not typically present in table grapes, Conde et al. (2015) [119] and Afoufa-Bastien et al. (2010) [154] characterized polyol transporters, (*VvPLT1*) and (*VvPMT5*) in grape cells, responsible for sugar alcohol absorption. This mechanism could be crucial under stress conditions where sugar alcohols are rapidly oxidized to reducing sugars by sorbitol dehydrogenases [119].

This implies that the grape plant possesses a mechanism to facilitate the transport of the sorbitol-calcium complex.

In order to overcome the low mobility of Ca in the phloem, the vectorization process is employed [61]. 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) [61]. 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) [61] and table grapes [18]. 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.

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

4.1. Enhancing Ca Transport and Other Nutrients

Spraying foliar fertilizers and phytosanitary products onto the aerial parts of plants is an effective tool for crop management and sustainability [121]. 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, phosphorus (P) solubility can be significantly restricted, whereas in alkaline soils, the availability of micronutrients such as zinc (Zn), iron (Fe), and manganese (Mn) is often diminished. Under arid conditions, foliar feeding becomes especially valuable, as the uptake of macronutrients like potassium (K) is limited during drought-induced water stress [155]. Foliar application is also advantageous when nutrient uptake through roots is compromised by competitive interactions. For example, the use of urea to supply nitrogen (N) when its absorption competes with polysaccharides at the root level [156]. 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 Zn [157] and selenium (Se) [158]. 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 [159], algae-based fertilizers [160], amino acids [161], and minerals [86,162], among other phytoproducts [163]. A different approach regarding transport has been proposed by Zhang et al. (2021) [164], 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, although 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 determining 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 developing fruits, is often restricted, particularly after the fruit has developed past the fruit set stage [60].

Boron (B) is an essential micronutrient required for the growth of higher plants, with an essential role in cell wall expansion. Most of the 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 [151], which are major sorbitol producers, and later in celery (*Apium graveloens* L.) [165], a mannitol producer species. 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 $B(OH)^{4-}$, as it is the main form in aqueous solutions [166], where the pH of 7.5 favors 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 [167]. H_3BO_3 naturally reacts with polyhydroxy compounds like polyols, forming stable complexes [165] that are phloem mobile. This finding suggests that polyols are crucial for B mobility through the phloem and for reaching sink organs in plants.

Nevertheless, B treatments have been reported as effective when applications are made from the early fruit-set stages, as treated almond trees were observed to achieve a higher concentration in flower buds, flowers, and bulbs. Will et al. (2012) [140] reported that foliar absorption of 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. Moreover, 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 [140]. In a similar way to B, Ca is expected to achieve higher mobility through the phloem when complexed with sorbitol (Figure 1).

4.2. Effects on Fruit Quality and Stress Resistance

Evidence from other crops demonstrates the broad applicability of calcium-sorbitol complex treatments: in potatoes, chelated calcium-sorbitol fertilizer revealed better performance than inorganic Ca fertilizers applied alone, promoting yield as well as the absorption and utilization of N, P, and K nutrients [137]. 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 [136]. This effect has also been observed when sorbitol is mixed with B and Ca applied to mangoes [72], 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 high B application rates, inducing toxicity in the soybean plants [141]. In peanuts, doses ranging from 1.5 to 1.8 g L^{-1} of chelated calcium-sorbitol treatments significantly increased yield by up to 28.6%, and fat content by 5.0%, K 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 [135]. In wheat, sorbitol spray treatments with nanoparticles of copper (Cu) in addition to zeolite fertilizer contributed to a higher nutrient uptake and accumulation of the plants, leading to higher yield rates [134], 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 [18]. Foliar applications during on-tree ripening improved the mobility of Ca into the fruit as calcium-pectate, or 'bound calcium', resulting in increased fruit firmness and reduced ABA and MDA contents. Polyphenol 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 observed [18]. Overall, these changes resulted in a superior maturity index while preserving good storage potential life. 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 triggering the synthesis of flavonoids [114]. After 17 days of the first treatment and during the on-tree ripening stage to harvest date, total phenolic and antioxidant activity were higher in treated fruits in all fractions: juice, flavedo, albedo, and pulp. The same behavior was observed for anthocyanin content, mineral 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 preserved bioactive compounds in blood oranges, such as sugars and acids, resulting in an improved sensory quality after 30 days of storage [113].

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 [132]. In honeydew melons, chelated Ca with mannitol resulted in elevated mesocarp Ca concentrations, elevated fruit firmness, and enhanced marketability without modification in the sugar content of fruit [168].

4.3. Potential Limitations and Application Considerations

Although Ca–sorbitol applications show promising results, their effectiveness is conditioned by several physiological and agronomic factors. Calcium has intrinsically low phloem mobility, and its movement into berries decreases sharply after veraison due to reduced xylem functionality and transpiration [57,129,145]. Therefore, application timing is critical, with the highest efficiency reported when foliar sprays are applied between fruit set and veraison [57]. Likewise, environmental conditions strongly influence uptake, since factors such as humidity, surface wetness, and stomatal behavior determine foliar absorption [155]. Although Ca–sorbitol complexes improve Ca solubility and mobility [71], application dose must be carefully managed, as excessive polyol sprays may adversely affect leaf physiology [120]. Finally, varietal differences in cuticle traits, transpiration rate, and sensitivity to cracking result in heterogeneous responses among cultivars; consequently, Ca-based treatments may require variety-specific adjustment [8,34].

5. 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. A combination of sorbitol and Ca has been shown to offer beneficial effects. These effects can be attributed to the properties of both substances, as well as to the synergis-

tic role of sorbitol in enhancing Ca transport. This effect helps Ca to 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. Calcium-sorbitol treatments thus represent an affordable, sustainable, and readily compatible solution for global agricultural practices. By enhancing calcium efficiency and mitigating key physiological disorders, these applications significantly reduce postharvest food losses, extend shelf life, and generate economic benefits through improved marketable yield and enhanced fruit quality. Ultimately, calcium-sorbitol complexes provide a crucial nutrient-based alternative, offering a complementary strategy to ensure fruit quality and preservation under challenging developmental or environmental conditions.

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