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Rachis browning in grapes: causes, impacts, and advanced strategies for mitigation

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ABSTRACT

Rachis browning is a critical postharvest disorder that adversely affects the visual quality, marketability, and shelf life of table grapes. This phenomenon arises from complex biochemical and physiological processes, including oxidative stress, enzymatic oxidation, cellular degradation, and microbial infection, which collectively result in tissue discolouration and loss of freshness. Conventional control methods such as sulfur dioxide fumigation, controlled atmosphere storage, and modified atmosphere packaging have been widely adopted. Moreover, recent advances in postharvest technologies, including nanotechnology, cold plasma treatment, UV-C irradiation, ultrasound, and the application of natural plant-derived compounds, have demonstrated promising potential for sustainable browning management. This review synthesises current knowledge on the causes and mechanisms of rachis browning, critically evaluates existing and emerging mitigation strategies, and highlights research gaps and future directions. Integrating innovative, eco-friendly technologies offers a pathway toward enhancing grape postharvest quality and sustainability within the global fruit supply chain.

KEYWORDS: water dehydration, chlorophyll degradation, polyphenol oxidase, plant growth regulators, edible coating, nanotechnology

INTRODUCTION

The condition of the rachis critically influences the deterioration of table grapes during postharvest storage, with the green stem structure supporting the berries. Berries are categorised as non-climacteric fruits, exhibiting a minor transient elevation of ethylene during the veraison stage, and they demonstrate a relatively low respiration rate in the postharvest phase (Chervin *et al*., 2004). However, the rachis exhibits a respiration rate significantly higher (between 11 and 28 times) than that of the berries, due to its herbaceous and poorly protected tissue, which predisposes it to rapid dehydration (Li *et al*., 2015). In contrast, grape berries possess a waxy cuticle that provides resistance to moisture loss. After harvest, the rachis becomes susceptible to oxidative processes and enzymatic browning, primarily driven by polyphenol oxidase activity, water loss, and tissue senescence. Physical injuries, microbial infections, chlorophyll degradation, and ethylene-induced physiological changes also contribute to the browning process (Bahar *et al*., 2017; Hamie *et al*., 2022). Although cold storage at around 0 °C and high relative humidity (90–95 %) can extend grape shelf life up to 100 days, this method is not fully effective against fungal infections such as *Botrytis cinerea* and does not entirely prevent rachis browning. Moreover, while fungal decay has been extensively studied, less scientific attention has been directed toward rachis browning despite its considerable impact on grape quality (Rosales *et al*., 2013). Rachis browning, despite involving a small fraction of the cluster's total weight, significantly influences consumer perception (Khandani *et al*., 2026). A green rachis is often equated with freshness, whereas a browned stem suggests poor quality, affecting purchasing decisions and contributing to food waste in developed economies.

The visual and structural condition of the rachis is critical for maintaining grape quality and marketability. As global consumption of table grapes has surged, accounting for approximately 36 % of total grape production, with major markets including China, India, and the European Union, the economic stakes associated with postharvest grape quality have risen sharply. Leading exporters such as Peru, Chile, the Netherlands, Italy, the United States, South Africa, and China, as well as emerging economies, rely heavily on maintaining premium fruit quality for international trade (García Juárez *et al*., 2025). The rachis serves both functional and aesthetic roles: it supports nutrient and water transport during berry development and offers a visible indicator of freshness after harvest. A vibrant green rachis correlates strongly with higher consumer acceptance, while brown or brittle rachises are linked to diminished visual appeal, faster berry detachment, and increased spoilage risks. The rachis's integrity also impacts berry dehydration rates, microbial vulnerability, and overall cluster durability during handling and transportation (Guzmán *et al*., 2021; Romero *et al*., 2022). Consequently, optimising rachis preservation is crucial not only for extending shelf life but also for securing financial returns in the competitive global market. Addressing rachis browning involves strategies ranging from pre-harvest management, such as optimised irrigation and plant growth regulator applications, to advanced postharvest treatments like modified atmosphere packaging (MAP). Comprehensive understanding and targeted intervention strategies are essential for minimising quality loss and meeting stringent export standards.

IMPACTS OF RACHIS BROWNING ON GRAPE QUALITY

1. Effect on visual appeal

Visual appeal is one of the most important quality characteristics for table grapes, as the external appearance of the product predominantly influences consumer purchasing decisions. Among the various visual attributes, rachis colour serves as a key indicator of freshness and overall quality (Figure 1). A green, fresh rachis is often associated with recently harvested, flavourful grapes, while browning or discolouration is commonly perceived as a sign of ageing,



FIGURE 1. Progressive rachis browning in *Vitis vinifera* cv. 'Sultana'. The figure shows increasing severity of browning and necrosis from left to right, indicating deterioration of rachis tissue.

poor storage conditions, or inadequate handling. Even when the berries themselves remain firm, sweet, and palatable, the presence of rachis browning can significantly diminish consumer acceptance, lower perceived quality, and lead to product rejection or price reductions (Ayyub *et al*., 2024; Hamie *et al*., 2022). The aesthetic impact of rachis browning is particularly significant in premium grape varieties marketed primarily for the fresh market. Discolouration disrupts the visual uniformity and vibrancy of the cluster, reducing its market appeal and overall impression of freshness. In retail environments where grapes are displayed under bright lighting, rachis browning becomes even more conspicuous, intensifying negative consumer perceptions (Li *et al*., 2015; Lichter, 2016). As a result, grapes exhibiting visible rachis browning are often discounted, relegated to secondary markets, or discarded entirely, leading to substantial economic losses across the supply chain. With the global expansion of year-round availability of fresh produce, consumer expectations for visually pristine products have become increasingly stringent. Retailers, in turn, have adopted rigorous quality control measures emphasising visual standards. Consequently, maintaining rachis freshness has emerged as a critical factor in postharvest handling, storage, and marketing strategies. Ensuring the visual integrity of grape clusters not only enhances consumer confidence and purchasing behaviour but also safeguards profitability within competitive, high-value produce markets (Wang *et al*., 2023).

2. Relationship with shelf life and overall fruit quality

Primary research shows that rachis browning correlates with multiple physiological changes that undermine shelf life and overall fruit quality. For example, Wang *et al*. (2019) reported that rachis browning significantly reduced total soluble solids and titratable acidity and enhanced berry abscission rate during prolonged cold storage, suggesting that limiting rachis browning is integrally linked with retention of key quality attributes that define shelf life performance. Rachis degradation may also predispose clusters to other quality losses, such as increased berry shattering and susceptibility to mechanical damage. Studies indicate that rachis integrity plays a role in controlling berry drop during handling and storage; clusters with advanced rachis browning often show a higher incidence of berry detachment, which not only reduces commercial yield but also accelerates quality loss through increased exposure to pathogens and dehydration (Zhu *et al*., 2022). Similarly, Li *et al*. (2023) indicated that visual browning increased after 6 d storage at 20 °C and 85–90 % relative humidity and was also associated with altered phenolic metabolism and reduced accumulation of protective flavonols in the rachis, which supports maintenance of chlorophyll and tissue integrity during shelf life. Furthermore, rachis browning reduced oxidative stress markers in rachis tissue, which corresponded to higher browning and may indirectly support reduced shelf life by extending senescence-associated degradation (Ayyub *et al*., 2024).

PHYSIOLOGY AND CAUSES OF RACHIS BROWNING

1. Biochemical and physiological processes involved

Rachis browning is primarily driven by senescence, a cascade of cellular and molecular events triggered immediately after grape detachment from the vine (Figure 2). Water loss and oxidative stress are key initiators, causing turgor loss, tissue dehydration, and collapse (Wu *et al*., 2021). The rachis, vulnerable due to its herbaceous nature, dehydrates faster under low humidity or improper storage, promoting enzymatic activity that accelerates browning. Oxidative stress, caused by reactive oxygen species (ROS), further damages cellular components and speeds up senescence.

Chlorophyll degradation is another central factor, regulated by enzymatic processes involving chlorophyllase, pheophytinase, pheophorbide a oxygenase, and red chlorophyll catabolite reductase (Figure 2). Stress-induced breakdown of chlorophyll exposes underlying pigments and oxidised phenolics, leading to visible browning (Li *et al*., 2025; Zou *et al*., 2023). Although grapes are non-climacteric, the rachis shows relatively higher ethylene production than berries. Ethylene accelerates senescence, chlorophyll loss, and tissue deterioration. Treatments with 1-methylcyclopropene (1-MCP), an ethylene inhibitor, have been shown to delay rachis browning, confirming ethylene's involvement (Ye *et al*., 2017).

Furthermore, other plant growth regulators such as abscisic acid (ABA) also contribute by promoting ROS accumulation, enhancing oxidative stress, and weakening cell walls, exacerbating browning (Figure 2). Conversely, auxin (IAA), gibberellins (GAs), and cytokinins (CKs) delay senescence by maintaining chlorophyll content, promoting vascular health, and enhancing antioxidative defences (Li *et al*., 2025; Lichter, 2016). Research has shown that hormonal imbalance is one of the main causes of rachis browning (Khandani *et al*., 2026). Thus, hormonal balance critically influences rachis physiology postharvest.

2. Role of oxidative stress and enzymatic activities

Biochemically, rachis browning is largely mediated by oxidative enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) (Figure 2). PPO catalyses phenolic oxidation into quinones, which polymerise into brown pigments upon tissue injury or dehydration (Ghorbani *et al*., 2025). Similarly, POD accelerates brown pigment formation by oxidising phenolics during stress responses. Increased PPO and POD activities are strongly associated with storage-related browning. For instance, CA storage with low oxygen reduces PPO activity and browning severity. Peroxidase-mediated lignin deposition, while strengthening tissues, visually darkens the rachis and reduces flexibility, further compromising postharvest quality (Nath *et al*., 2022).

Lignin deposition in plant tissues is a defence response to both biotic and abiotic stresses. The biosynthesis of lignin involves the enzymatic action of phenylalanine ammonia-lyase (PAL) and other downstream enzymes that convert phenylalanine into monolignols, the building blocks of lignin. Although lignin strengthens cell walls, its accumulation in the rachis can lead to visual browning and loss of flexibility. Moreover, PAL plays a regulatory role in the phenylpropanoid pathway, leading to the synthesis of phenolic compounds, which serve as substrates for oxidative enzymes such as PPO and POD (Zeng *et al*., 2025).

Moreover, oxidative stress during postharvest storage induces lipid peroxidation, where ROS attack unsaturated fatty acids in cell membranes. ROS, including superoxide anions (O_2^-), H_2O_2, and hydroxyl radicals (•OH), are highly reactive molecules that can damage cellular components such as lipids, proteins, and nucleic acids (Kakaei *et al*., 2024; Wang *et al*., 2019). This process leads to the generation of malondialdehyde (MDA), a marker of oxidative damage, and causes membrane destabilisation, exacerbating browning. ROS not only cause direct cellular damage but also activate enzymes such as PPO, POD, and PAL, thereby intensifying the browning process. Simultaneously, enzymatic oxidation generates additional ROS, perpetuating oxidative stress, which triggers senescence pathways, accelerating tissue degradation and predisposing the rachis to browning (Romero *et al*., 2020).

3. Environmental and postharvest factors contributing to browning

Pre-harvest environmental conditions strongly influence rachis browning susceptibility. High growing-season temperatures induce oxidative stress and activate browning-related enzymes. Water stress compromises vascular function, promotes phenolic metabolism, and predisposes tissues to browning (Chacón-Vozmediano *et al*., 2021; Kaur *et al*., 2019).

Nutrient availability, especially nitrogen, potassium, and calcium, is critical for maintaining tissue integrity. Deficiencies or imbalances in these nutrients can weaken cells, increase susceptibility to mechanical damage, and promote enzymatic browning during postharvest storage. Moreover, fungal infections, such as *B. cinerea*, and other pests can compromise the integrity of grapevine tissues, facilitating oxidative damage and enzymatic browning (Li *et al*., 2022).

Postharvest factors such as storage temperature, humidity, mechanical injuries, and atmospheric composition critically determine browning progression (Hamie *et al*., 2022; Zhao *et al*., 2025; Zhu *et al*., 2023). Inadequate cooling or high vapour pressure deficits exacerbate water loss and oxidative reactions. Mechanical damage during handling exposes phenolics to enzymatic oxidation. Atmospheric composition, particularly oxygen and carbon dioxide levels, also affects browning dynamics. Elevated oxygen levels accelerate respiration and ROS generation, fuelling enzymatic browning. Conversely, increased carbon dioxide

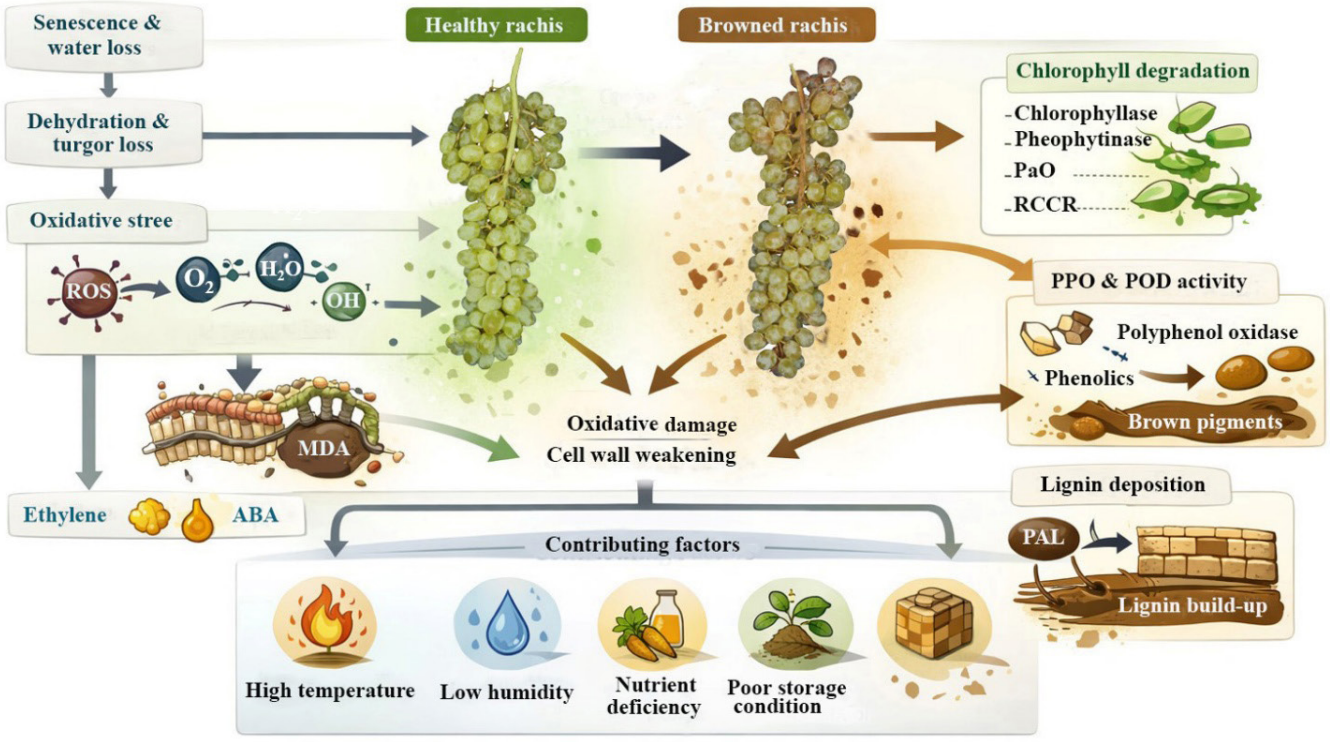


FIGURE 2. Physiology and causes of rachis browning. Rachis browning is primarily associated with senescence, water loss, chlorophyll degradation, hormone synthesis and functionality, oxidative stress, and enzymatic activities (PPO and POD). PaO: Pheophorbide a oxygenase, RCCR: Red chlorophyll catabolite reductase.

levels under controlled atmospheres can suppress PPO/POD activity, slow respiration, and mitigate browning. However, excessively high CO_2 concentrations risk inducing anaerobic metabolism and off-flavours. High CO_2 storage can differentially modulate the expression of ethylene-related genes like *ACS* and *ACO* (Becatti *et al*., 2010), influencing rachis senescence trajectories.

CONVENTIONAL STRATEGIES TO ADDRESS RACHIS BROWNING

1. Optimal storage conditions (temperature, humidity, and atmosphere)

Managing postharvest rachis browning primarily relies on controlling temperature, humidity, and atmospheric composition. Low-temperature storage, ideally between 0–2 °C, slows metabolic processes, respiration, and enzymatic activities such as those of PPO and POD, which are involved in browning reactions. Moreover, cool conditions reduce water vapour pressure deficits, thus minimising dehydration of the rachis tissue. However, sensitivity to chilling injuries in some cultivars necessitates careful monitoring (Lichter *et al*., 2011).

Relative humidity (RH) is equally critical. Storage at 90–95 % RH preserves rachis turgor, prevents shrivelling, and delays oxidative damage. Environments that are too dry hasten water loss, leading to rachis collapse, while excessively high humidity fosters fungal growth, particularly *B. cinerea* infections (Meena *et al*., 2024).

Atmospheric modifications further enhance rachis preservation. Reducing oxygen levels and enriching carbon dioxide concentrations through controlled atmosphere storage (CA) or MAP suppresses oxidative metabolism and enzymatic browning. Elevated CO_2 levels can inhibit PPO activity, slow senescence, and maintain rachis and berry integrity. Ethylene inhibitors like 1-MCP are also utilised to delay senescence, reduce ethylene sensitivity, and prolong rachis freshness (Wang *et al*., 2019; Yun *et al*., 2024). Pre-cooling immediately after harvest remains a vital step, rapidly removing field heat to preserve grape cluster quality during subsequent storage. As highlighted by de Aguiar *et al*. (2023b), precooling at 0–1 °C minimises water loss, maintains berry firmness, and prevents chilling injuries. Proper packaging with adequate perforations facilitates rapid and uniform cooling.

2. Packaging innovations and their role in browning reduction

Advancements in packaging have become central to improving postharvest grape quality by creating microenvironments that control gas exchange, humidity, and moisture retention (Figure 3). MAP is among the most widely adopted innovations. By adjusting O_2 and CO_2 levels inside the package, MAP reduces oxidative stress, slows respiration, and decreases PPO/POD activity, thereby mitigating rachis browning (Yang *et al*., 2022).

Polyethylene and polypropylene liners are common materials used for grape packaging (Figure 3). They help retain moisture but must be optimised for permeability to avoid condensation and fungal infections. Innovations such as microperforated films allow for fine-tuned ventilation, balancing gas exchange and humidity, thereby extending shelf life and reducing disease risks (Maryam *et al*., 2021).

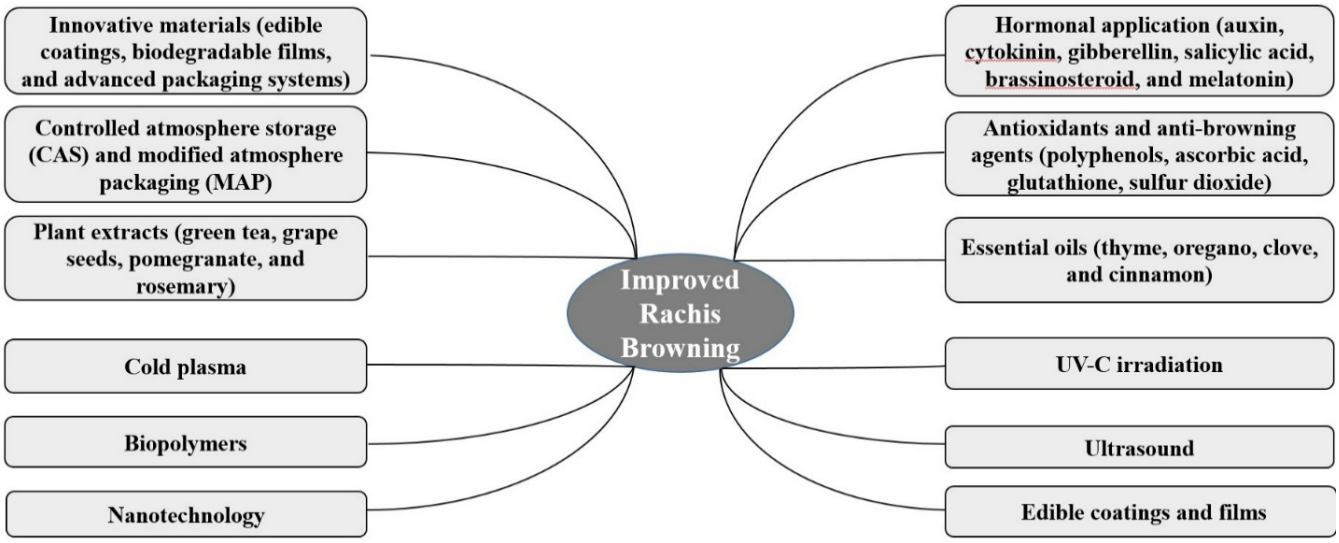


FIGURE 3. Approaches to mitigating rachis browning: hormonal application (auxin, cytokinin, gibberellin, salicylic acid, brassinosteroid, and melatonin), edible coatings and films, antioxidants and anti-browning agents (polyphenols, ascorbic acid, glutathione, sulfur dioxide, plant extracts (green tea, grape seeds, pomegranate, and rosemary), essential oils (thyme, oregano, clove, and cinnamon), Innovative materials (edible coatings, biodegradable films, and advanced packaging systems), UV-C irradiation, ultrasound, controlled atmosphere storage (CA) and modified atmosphere packaging (MAP), cold plasma, nanotechnology, and biopolymers.

Elevated oxygen storage, using atmospheres with 70–80 % O_2, has also been shown to inhibit microbial growth and preserve berry firmness and rachis integrity during storage (Deng *et al*., 2007). Meanwhile, mild CO_2 enrichment (15–20 %) helps suppress browning enzymes and control fungal infections without inducing off-flavours (Pretel *et al*., 2006).

Edible coatings represent an emerging strategy, providing a semi-permeable barrier that reduces water loss, maintains rachis freshness, and delays oxidative degradation (Figure 3). Coatings formulated with pectin, polyvinyl alcohol, or salicylic acid have demonstrated potential in extending shelf life and reducing rachis browning (Lo'ay *et al*., 2021). These coatings not only slow moisture loss but can also incorporate natural antioxidants, further strengthening their protective effects. Ultimately, integrating optimised packaging technologies with careful handling practices ensures improved rachis and berry quality throughout storage and transportation. Various treatments have also been reported to reduce rachis browning in some grape cultivars (Table 1).

HORMONAL APPROACHES TO MITIGATING RACHIS BROWNING

1. Role of plant growth regulators such as auxin, cytokinin, gibberellin, salicylic acid, brassinosteroid, and melatonin

Plant growth regulators regulate an array of physiological and developmental processes, including stress responses. Among these, auxins, cytokinins, gibberellins, brassinosteroids, and melatonin play distinct roles in determining the susceptibility or resistance of plant tissues to postharvest disorders (Figure 4).

Auxins are fundamental phytohormones involved in processes such as cell elongation, vascular development, and the modulation of antioxidant systems (Khandani *et al*., 2024a; Khandani *et al*., 2024b). A decline in auxin levels during cold storage is associated with increased rachis browning, potentially through the promotion of senescence and vascular dysfunction. Enhancing auxin concentrations, particularly via indole-3-butyric acid (IBA) applications, has been shown to sustain vascular integrity, delay senescence, and stimulate antioxidant defences, collectively mitigating browning symptoms (Guzmán *et al*., 2021). Experimental applications of IBA at different phenological stages improved rachis mass, vascular development, and berry firmness without inducing cluster compactness (Pugliese *et al*., 2022). Additionally, IBA treatments during full bloom enhanced the rachis' vascular area and hydraulic conductivity, correlating with delayed browning during storage (Guzmán *et al*., 2021). Furthermore, postharvest application of indole-3-acetic acid (IAA) at concentrations of 50 and 100 mg L^{-1} to the rachis abscission zone was shown to reduce rachis browning (Figure 5) by enhancing hormonal balance within the rachis, maintaining IAA and gibberellin (GA_3) levels, and decreasing abscisic acid (ABA) content (Khandani *et al*., 2026). These findings emphasise the potential of auxin-based strategies in enhancing grape postharvest longevity.

Cytokinins such as forchlorfenuron (CPPU) are known to stimulate cell division and delay senescence. CPPU application results in increased berry size, rachis thickness, and vascular bundle development, enhancing the structural integrity necessary to resist browning (Zoffoli *et al*., 2009). Furthermore, CPPU plays a role in modulating the antioxidant defence mechanisms in plants. By augmenting antioxidant activity within the rachis, CPPU may counteract oxidative stress, a key factor in cellular damage and senescence. Balic *et al*. (2012) reported that applying 400 mg L^{-1} benzyladenine to the rachis of 'Red Globe' 1 day before harvest conferred supplementary protection and influenced the expression profiles of three specific genes: *TL1*, *CBS*, and *ERF*. This observation implies a hypothetical cellular regulatory mechanism governing water loss and senescence in the rachis, which likely encompasses the metabolic pathways associated with ethylene and oxidative stress. Postharvest application of 6-Benzyladenine (BAP) at concentrations of 50 and 100 mg L^{-1} can delay rachis browning during postharvest storage by maintaining the relative water content and chlorophyll content of the rachis (Khandani *et al*., 2026).

Gibberellins (GA) regulate critical growth processes and contribute significantly to maintaining rachis vitality by delaying senescence and preventing vascular deterioration. Increased GA levels help sustain vascular function and reduce oxidative stress by regulating antioxidant-related gene expression. While commercial GA applications at fruit set had no clear impact on rachis pigmentation (Raban *et al*., 2013), GA applications during berry enlargement phases enhanced rachis chlorophyll content and reduced browning (Lichter *et al*., 2015). Khandani *et al*. (2026) demonstrated that postharvest application of GA_3 at concentrations of 50 and 100 mg L^{-1} reduced oxidative stress by enhancing enzymatic and non-enzymatic antioxidant activities, ultimately leading to better chlorophyll retention and maintenance of rachis greenness. These findings highlight the importance of application timing and concentration in harnessing GA benefits for postharvest management.

Salicylic acid (SA) has been widely recognised for its role in enhancing postharvest grape quality by inhibiting ethylene biosynthesis, reducing water loss, and suppressing oxidative enzyme activities. The pre-harvest spray of 1.5 mM SA reduced weight loss, rachis browning and decay incidence of 'Flame Seedless' table grape (Champa *et al*., 2015). Moreover, postharvest treatments combining SA with pectin and polyvinyl alcohol at varying concentrations (0, 1, and 2 mM) showed significant reductions in cell wall-degrading enzyme activities, lipid peroxidation, and electrolyte leakage (Lo'ay *et al*., 2021). Additionally, 2 mM SA applications were most effective in preserving berry firmness, appearance, rachis browning, taste, and overall shelf life (Hazarika & Marak, 2021). Thus, SA emerges as a critical postharvest intervention for minimising rachis deterioration.

Brassinosteroids (BRs), particularly 24-epibrassinolide (EBR), have demonstrated remarkable efficacy in enhancing postharvest fruit resilience due to their roles in antioxidant activation and stress tolerance (Álvarez *et al*., 2024).

TABLE 1. Various treatments improved rachis browning in different grape cultivars during storage. Part 1/2.

Treatment	Cultivar	Storage condition duration	Traits	Reference
Melatonin (50 and 100 μmol L^{-1})	'Kyoho'	4 °C and 80 % RH for 25 d	Decrease: rachis browning index, decay development, weight loss rate, berry abscission rate, respiration rate, and terpenes content. Increase: total phenolics, total flavonoids, accumulation of esters, aldehydes, and alcohols. Delay: reduction of anthocyanins and TSS.	(Ban *et al.*, 2023)
IBA (20 mg L^{-1}) + GA_3 (10 mg L^{-1}) at full bloom	'Superior Seedless'	0 °C and 95 % RH for 60 d	Produced looser bunches with larger berries. Improved: total vascular bundle area (xylem and phloem) and rachis hydraulic conductivity rachis and berries firmness, and freshness appearance.	(Guzmán *et al.*, 2021)
GA (20 mg L^{-1}), CK (2 mg L^{-1})	'Mystery', 'Superior', 'Red Globe', and 'Crimson Seedless'	2.5 ± 1 °C and 90–95 % RH	Increase: berry weight and diameter, and rachis diameter. Decrease: rachis browning, browning scale, rachis dry weight, and weight loss.	(Kakaei *et al.*, 2024)
CK (50 and 100 mg L^{-1})	'Fakhri'	2 ± 0.5 °C and 92 ± 2 % RH for 7 d	Maintain: RWC, chlorophyll, antioxidant enzyme, IAA, GA_3 in rachis. Suppress: rachis browning, MDA, H_2O_2, total phenolic compound, PPO, POD, weight loss in rachis.	(Khandani *et al.*, 2026)
CA (15 % CO_2 and 5 % O_2) and CK (400 μL L^{-1})	'Red Globe'	long-term cold storage (90 days at 0 °C) and after shelf-life (90 days at 0 °C plus 2 d at 20 °C)	Delay: development of browning, water loss, and senescence. CK affected the expression profiles of *TL1, CBS* and *ERF*.	(Balic *et al.*, 2012)
Nitric oxide (NO) (100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1500 μL L^{-1})	'Thompson Seedless'	25 days at 0 ± 0.5 °C and 90 ± 2 % RH and 3 d at 8 ± 0.5 °C or 20 ± 0.5 °C	Prevented rachis browning by delaying water loss, reducing phenols accumulation, inhibiting PPO activity, and inducing POD activity. Down-regulated *PPO1*, up-regulated *POD3*, and affected the expression of *PAL2* and *PAL3* in grape rachis.	(Wu *et al.*, 2021)
1-MCP and ethylene	'Thompson Seedless', 'Mystery', and '3003'	0 °C and 92.5 % RH for 6 d	1-MCP delayed rachis browning, whereas ethylene tended to enhance it. 1-MCP reduced respiration and ethylene production, while enhanced auto-fluorescence properties of rachis.	(Li *et al.*, 2015)
1-MCP and 1-MCP + 80 % O_2, 1-MCP + 20 % CO_2	'Kyoho' and 'Yongyou NO.1'	4 ± 1 °C for 32 d	Prevent rachis browning and chlorophyll degradation, maintained the cellular microstructure integrity and promoted esters and terpenes synthesis. Downregulate: transcriptional expression of genes involved in ethylene biosynthesis and genes expression related to softening.	(Wang *et al.*, 2019)
Aloe vera gel coating (50 %)	'Sundarkhani', 'Khismishi', and 'Shaghali'	2 ± 1 °C and 90 ± 5 % RH for 20 d	Reduce: rachis browning, weight loss, electrolyte leakage, respiration rate and POD activity. Increase: total phenolic content, total antioxidant, and enzyme activities (SOD and CAT) in berries.	(Ayyub *et al.*, 2024)
CO_2 (20 %) + O_2 (20 %) + N_2 (60 %)	'Cardinal'	0 ± 0.5 °C and 95 % RH for 33 d	High CO_2 levels reduce: *GPO* and *VcPAL* mRNA levels (contributed to the appearance of browning rachis) and lipid peroxidation levels.	(Rosales *et al.*, 2013)
High O_2	'Kyoho'	0 ± 1 °C and 95 % RH for 65 d	Improve: berry hardness, springiness, chewiness, flavors and membrane integrity. Reduce: fruit decay, berry drop, rachis browning and weight loss. Delay: decrease of SSC, TA and ascorbic acid. High O_2 resulted in a firmer berry, better texture, berry adherence strength, and sensory scores.	(Deng *et al.*, 2005)

TABLE 1. Various treatments improved rachis browning in different grape cultivars during storage. Part 2/2.

Treatment	Cultivar	Storage condition duration	Traits	Reference
kPa CO_2 (20 %) + kPa O_2 (20 %) + kPa N_2 (60 %)	'Red Globe' and 'Superior Seedless'	0 °C and 95 % RH for 28 d	Improve: rachis browning and non-enzymatic antioxidant system. Reduce: total phenolic content, antioxidant activity, expression of different stilbene synthase genes, and lipid peroxidation levels. Corroborate: important role of ethylene-responsive factors in the beneficial effect of the gaseous treatment, not only in the berries but also in the rachis. Avoid: induction of cell wall-degrading enzyme-related genes.	(Romero *et al.*, 2022)
SO_2 (1200 µL L^{-1})	'Shine Muscat'	20 °C and 85–90 % RH for 6 d	Inhibited rachis browning and affected endogenous phenolic metabolism and sulfur assimilation, at both transcriptional and metabolic levels. Promote: accumulation of major phenolic compounds, such as (+)-catechin, (-)-epicatechin, (-)-epicatechin gallate, and proanthocyanidins, by increasing the transcript levels of *VvLAR* and *Vv3GT* genes involved in flavonoid pathway. Activate: gene expression involved in sulfite assimilation, resulting in the accumulation of sulfur-containing metabolites (including cysteine, hydrogen sulfide, and glutathione).	(Li *et al.*, 2023)
Chlorine dioxide (ClO_2) (1, 1.2, 1.5, and 2 mg L^{-1})	'Kyoho'	0.5 °C for 90 d	Reduce: berry decay and rachis browning. Improve: microbial safety of grapes and is a promising nonthermal pathogen reduction technique for fresh table grape	(Chen *et al.*, 2018)
Chitosan (0.5 and 1 %)	'Shahroudi'	0 °C for 60 d	Reduce: weight loss, decay, browning, shattering, and cracking. Increase: TSS, TA, and TSS/TA ratio levels. Delay: changes of the total phenolics, catechin, and antioxidant capacity.	(Shiri *et al.*, 2013)

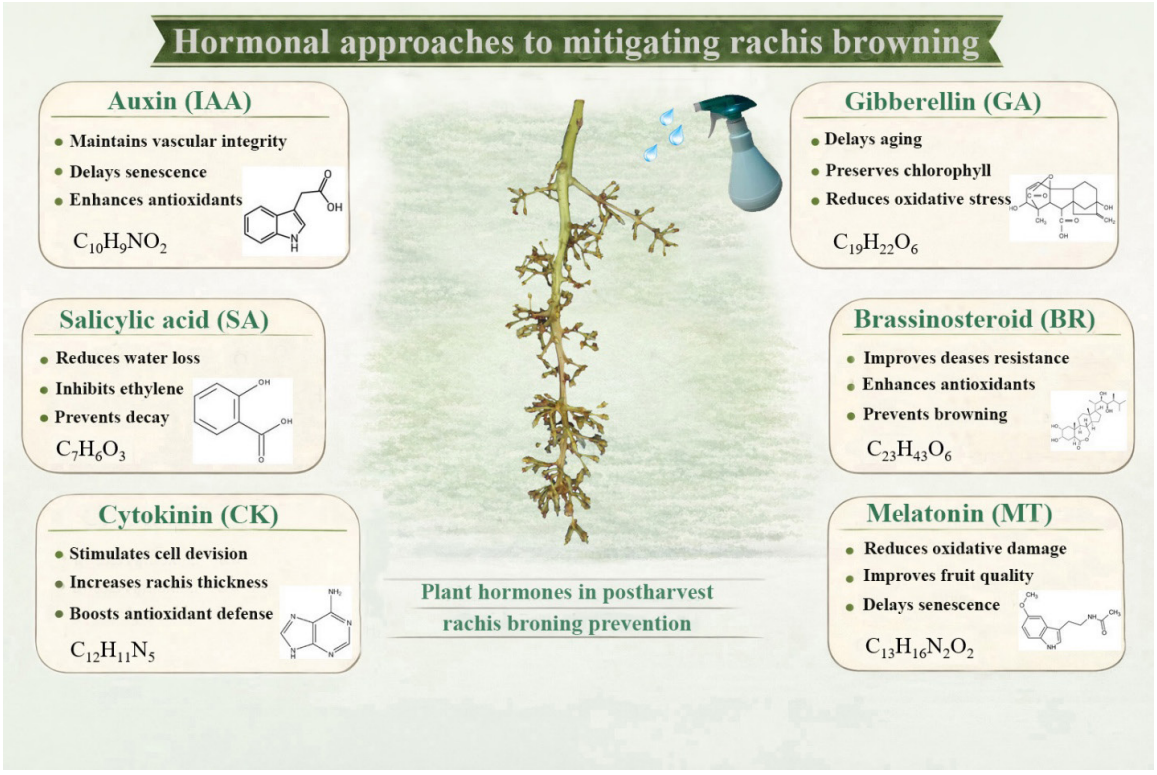


FIGURE 4. Hormonal approaches (auxin, cytokinin, gibberellin, salicylic acid, brassinosteroid, and melatonin) to mitigating rachis browning.

The treatment of grapes with a concentration of 5 µmol L^{-1} EBR resulted in a marked reduction in both the deterioration and threshing rates, postponed the accumulation of MDA and the onset of odour degradation, and sustained elevated antioxidant capacity; furthermore, it promoted the activities of SOD, CAT, cinnamate-4-hydroxylase (C_4H), and 4-coumarate:CoA ligase (4CL), in addition to enhancing the expression levels of genes such as *VCHI*, *VGNS*, and *VPAL*-like, thereby mitigating the incidence of postharvest grey mould and bolstering disease resistance (Zeng *et al*., 2025). Moreover, applications of BRs at 0.5–1 mg L^{-1} concentrations effectively delayed rachis browning by suppressing PPO and POD enzyme activities and maintaining chlorophyll levels (Champa *et al*., 2015). Therefore, BRs present a viable strategy for improving the postharvest stability of table grapes, contributing to extended storage life and enhanced marketability.

Melatonin (N-acetyl-5-methoxytryptamine), an indoleamine with potent antioxidant properties, significantly ameliorates oxidative stress and delays fruit senescence (Kakaei *et al*., 2024). Its role extends to regulating critical developmental processes and enhancing resistance against chilling and waterlogging stresses (Zhang *et al*., 2019). In grapes (*Vitis labrusca* × *vinifera* 'Kyoho'), exogenous melatonin application at 50–100 µmol L^{-1} concentrations reduced rachis browning, berry decay, and weight loss while enhancing phenolic and flavonoid accumulations (Ban *et al*., 2023). Melatonin can serve as an effective postharvest treatment for reducing rachis browning by decreasing phenolic compounds and suppressing the activities of PPO and POD enzymes (Khandani *et al*., 2026). These treatments also delayed declines in anthocyanin content and total soluble solids, further highlighting melatonin's multifunctionality in preserving postharvest grape quality.

2. Applications of ethylene inhibitors (*e.g.*, 1-MCP)

Ethylene, despite grapes being classified as non-climacteric fruits, plays a significant role in rachis browning by promoting chlorophyll degradation, tissue senescence, and oxidative stress. 1-MCP is an ethylene action inhibitor that binds to ethylene receptors, preventing ethylene perception and its associated ageing processes (Koushesh Saba & Watkins, 2020). Post-harvest 1-MCP applications have been shown to significantly delay rachis browning by reducing respiration rates, decreasing oxidative damage, and enhancing the activities of antioxidant enzymes. In particular, 1-MCP treatment preserves chlorophyll content and structural integrity in rachis tissues during cold storage (Li *et al*., 2015). Transcriptomic analyses have further revealed that 1-MCP downregulates genes associated with carotenoid biosynthesis and lysine degradation, pathways linked to senescence (Li *et al*., 2015; Zhang *et al*., 2022). These molecular adjustments contribute to delaying rachis discolouration and structural weakening during prolonged storage.

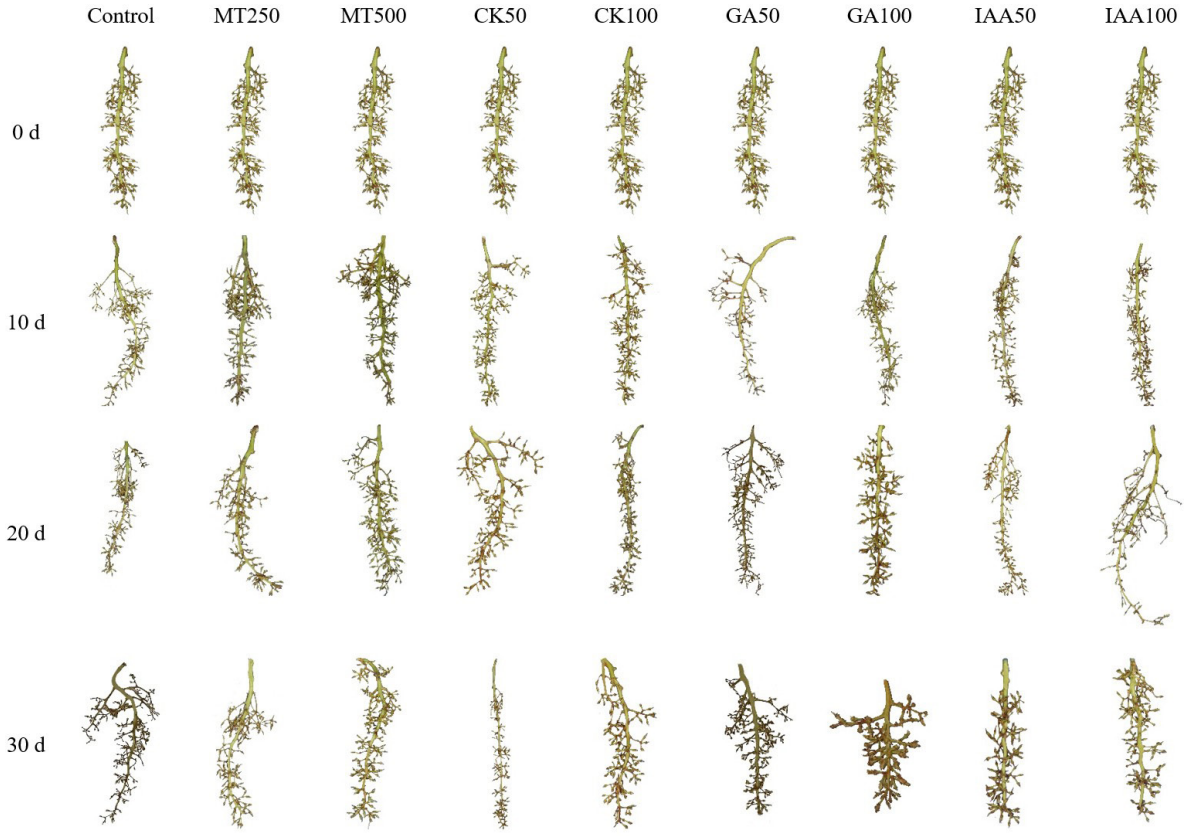


FIGURE 5. Rachis browning of 'Fakhri' table grape treated with melatonin (MT: 250 and 500 µM), cytokinin (CK: 50 and 100 mg L^{-1}), gibberellin (GA: 50 and 100 mg L^{-1}), and indole-3 acetic acid (IAA: 50 and 100 mg L^{-1}) during cold storage (Khandani *et al.*, 2026).

Integrating 1-MCP treatments with innovative packaging solutions, such as laser microporous films (LMF), provides additional benefits by controlling humidity and oxygen levels, thereby further extending grape shelf life and maintaining quality (Tong *et al*., 2024). Thus, the use of hormonal treatments and ethylene inhibitors represents a powerful strategy for controlling rachis browning, offering sustainable solutions for the grape industry's postharvest challenges.

MATERIAL-BASED SOLUTIONS FOR RACHIS PRESERVATION

1. Use of edible coatings and films

The development of edible coatings and films has emerged as a sustainable and effective strategy to extend the postharvest life of table grapes and mitigate rachis browning and originally inspired by ancient preservation techniques, modern edible coatings are now designed using biodegradable and non-toxic materials such as polysaccharides (*e.g.*, chitosan, alginate, pectin), proteins (*e.g.*, gelatin, soy protein), and lipids (*e.g.*, waxes and oils). These coatings create a semi-permeable barrier over the fruit surface, reducing moisture loss, limiting oxygen diffusion, and slowing down oxidative reactions associated with browning (Divyashri *et al*., 2024; Eshghi *et al*., 2022; Saeedi *et al*., 2025).

Polysaccharide-based coatings, particularly chitosan, have been extensively studied for their antimicrobial properties and their ability to maintain fruit firmness and appearance. Chitosan coatings help reduce microbial spoilage, limit oxidative stress, and delay senescence by enhancing antioxidant defences such as SOD, CAT, and APX activities (Shiri *et al*., 2013). In grape storage, chitosan treatments have been shown to significantly reduce weight loss, berry shattering, and rachis browning while maintaining the sensory quality of the fruit (Eshghi *et al*., 2021). Moreover, Youssef *et al*. (2019) reported that chitosan nanoparticles, silica nanoparticles, and chitosansilica nanocomposites effectively prevented the deterioration of table grape quality during postharvest storage, without any negative effects on fruit parameters.

When applied to table grapes, edible coatings function by minimising water loss from the rachis, thus preserving its turgor and green appearance. Moreover, the reduction in oxygen permeability offered by coatings curbs the activities of browning-related enzymes, such as PPO and POD, thereby limiting pigment formation and tissue degradation (Moghadas *et al*., 2024). Some advanced coatings incorporate natural antioxidants or antifungal agents, further enhancing their protective effects and extending grape shelf life (Al-Meshal *et al*., 2024).

Notably, combined formulations of polysaccharides and other bioactive compounds have demonstrated synergistic effects. For example, coatings based on pectin and polyvinyl alcohol (PVA) enriched with salicylic acid not only reduced rachis browning but also improved overall fruit antioxidant capacity and reduced enzymatic activity associated with senescence (Lo'ay *et al*., 2021). Thus, edible coatings and films represent a promising, environmentally friendly alternative to synthetic packaging methods, providing dual protection against physiological and microbial deterioration in table grapes during storage.

2. Application of antioxidants and anti-browning agents

The application of antioxidants and anti-browning agents is a well-researched strategy to reduce rachis browning in grapes, preserving their postharvest quality. Antioxidants such as ascorbic acid, glutathione, and polyphenols mitigate oxidative damage by scavenging ROS and enhancing the activity of endogenous antioxidant enzymes, including SOD, CAT, and APX (Farouk *et al*., 2022; Liang *et al*., 2024). Meanwhile, anti-browning agents like calcium-based compounds, sulfur dioxide (SO_2), and natural plant extracts inhibit enzymatic browning by suppressing PPO and POD activities (Li *et al*., 2023).

Ascorbic acid, a natural antioxidant, inhibits PPO activity by acting as a reducing agent, scavenging oxygen, and converting o-quinones back to phenolic precursors before polymerisation occurs. Its efficacy depends on concentration, application method, and storage conditions. For instance, 2 mM ascorbic acid effectively reduces rachis browning in 'Flame Seedless' grapes stored at 0 °C with 95 % RH for 1–2 weeks, extending shelf life by two days at 20 °C (Farouk *et al*., 2022). Additionally, combining ascorbic acid with chitosan enhances its anti-browning effect by stabilising phenolic compounds. Ascorbic acid lowers the fruit surface pH, suppressing PPO activity, which thrives in neutral to alkaline conditions (Yin *et al*., 2022; Zhou *et al*., 2022). It may also interact with PPO's active site, reducing catalytic efficiency. Beyond browning inhibition, ascorbic acid preserves vitamin C content, reinforcing the fruit's antioxidant capacity (Eshghi *et al*., 2021).

Glutathione (GSH), a tripeptide antioxidant, maintains cellular redox homeostasis by neutralising ROS and regenerating other antioxidants like ascorbic acid. Its thiol group scavenges ROS, preventing lipid peroxidation and chlorophyll degradation. GSH also inhibits enzymatic browning by maintaining a reducing environment, preventing phenolic oxidation, and possibly modulating PPO activity (Liang *et al*., 2024). Furthermore, GSH supports sulfur metabolism and detoxification, preserving cellular integrity during storage (Chen *et al*., 2022). By stabilising metabolic functions, GSH extends grape shelf life.

Polyphenols, including flavonoids and tannins, reduce rachis browning via ROS scavenging, metal chelation, and PPO/POD inhibition. They competitively bind to PPO's active site or reduce o-quinones, delaying browning (He *et al*., 2023). Grapes with higher endogenous polyphenol levels exhibit greater resistance to browning (Romero *et al*., 2020). Exogenous polyphenol-rich extracts (*e.g.*, grape seed or green tea) further enhance antioxidant capacity. Polyphenols also stabilise cellular membranes, reducing permeability and leakage caused by oxidative stress (Efenberger-Szmechtyk *et al*., 2021). This preserves rachis turgor and delays senescence.

SO_2, widely used in grape storage, combats browning through antimicrobial, antioxidant, and enzyme-inhibitory mechanisms. It suppresses microbial growth, preventing cellular decay, and inhibits respiratory enzymes, prolonging rachis freshness. Beyond its antimicrobial effects, SO_2 acts as an antioxidant, slowing down respiration and enzymatic browning, thus maintaining stem greenness, berry turgidity, and overall freshness (Zhang *et al*., 2024). Higuchi *et al*. (2024) demonstrated that the association of an ultra-fast SO_2-generating pad (FieldSO_2) with a dualrelease pad effectively controlled grey mould and extended the shelf life of 'Italia' table grapes up to 90 days under cold storage. In 'Shine Muscat' grapes, SO_2 treatment enhances phenolic accumulation by upregulating genes in the flavonoid biosynthesis pathway (*VvLAR* and *Vv3GT*), while also preserving cellular structure and membrane integrity in the rachis (Li *et al*., 2023). Moreover, SO_2 stimulates the GABA shunt pathway, increasing levels of GABA, glutamate, and related enzyme activities, alongside the expression of *VvGAD1*, *VvGAD4*, and *VvGABA-T1*. It also boosts polyamine synthesis, specifically putrescine, spermine, and spermidine, by enhancing arginine decarboxylase (ADC) activity and suppressing ornithine decarboxylase (ODC) expression. Finally, SO_2 improves energy metabolism, as shown by elevated ATP levels and increased activity of key enzymes like H^+-ATPase, Ca^{2+}-ATPase, succinate dehydrogenase (SDH), and cytochrome c oxidase (CCO), with corresponding gene upregulation (Zhang *et al*., 2024).

Essential oils (*e.g*., thyme, clove) and plant extracts (*e.g*., green tea, pomegranate) are emerging as eco-friendly anti-browning agents. Their polyphenols and volatile compounds (*e.g*., thymol, eugenol) exhibit antimicrobial and antioxidant properties. They inhibit PPO/POD activity and reduce oxidative damage. For example, clove oil-based edible coatings reduce weight loss by 76 % and retain phenolics in grapes (Divyashri *et al*., 2024). Thyme and cinnamon oils suppress *B. cinerea* and lower PPO/POD activity, delaying browning (Elsayed *et al*., 2022).

3. Innovative materials for moisture retention and browning prevention

Recent advances in postharvest technologies have led to the development of innovative materials such as edible coatings, biodegradable films, and advanced packaging systems that effectively mitigate rachis browning in table grapes. These materials maintain the physiological and structural integrity of the rachis by regulating moisture levels, reducing oxidative stress, and inhibiting enzymatic activity, thereby preserving grape quality during storage (Divyashri *et al*., 2024).

Edible coatings, formulated from polysaccharides (*e.g*., chitosan, alginate), proteins (*e.g*., gelatin, whey protein), or lipids (*e.g*., beeswax, carnauba wax), create semi-permeable barriers that reduce water loss and prevent desiccation (Wu *et al*., 2024). They also maintain turgor pressure, which is key to delaying rachis browning. Enrichment with antioxidants, such as ascorbic acid, citric acid, and plant extracts, further enhances their ability to inhibit oxidative and enzymatic browning (Eshghi *et al*., 2021). Notably, Ayyub *et al*. (2024) reported that *Aloe vera* gel coatings significantly increased antioxidant enzyme activity and bioactive compound levels in grapes, reducing browning and preserving freshness.

Biodegradable films, derived from natural polymers like starch, polylactic acid (PLA), and polyhydroxyalkanoates (PHA), offer another sustainable solution. These films regulate gas exchange, maintaining optimal oxygen and carbon dioxide levels to slow metabolic processes and oxidative reactions, effectively delaying browning (Omerović *et al*., 2021; Yun *et al*., 2024). In this context, de Aguiar *et al*. (2023a) assessed biobased and SO_2-generating plastic liners for extending the shelf life of 'Benitaka' table grapes, demonstrating the potential of such materials in postharvest applications. Additionally, infusion with antimicrobial agents or antioxidants provides added protection against microbial spoilage and oxidative stress.

Advanced packaging systems, including active and smart packaging, represent the next frontier in postharvest grape preservation. Active packaging technologies incorporate humidity regulators and oxygen scavengers to extend shelf life (Bodbodak & Rafiee, 2016), while smart packaging systems offer real-time monitoring of storage conditions, allowing for timely interventions.

PHYSICAL METHODS

1. Effects of UV-C irradiation on rachis browning

Ultraviolet-C (UV-C) irradiation has gained attention as a non-chemical, eco-friendly method for mitigating rachis browning and extending grape shelf life. UV-C light (200–280 nm) exerts germicidal and physiological effects, primarily by reducing microbial decay, oxidative stress, and enzymatic activity (Sabir & Sabir, 2019). Its antimicrobial action is central: UV-C damages microbial DNA, inhibiting fungal and bacterial growth, thereby preserving rachis integrity. Additionally, UV-C triggers the synthesis of secondary metabolites such as phenolic compounds and flavonoids, which serve as antioxidants that scavenge ROS and curb oxidative damage (Sheng *et al*., 2018). Enhanced antioxidant capacity helps maintain cell structure and delay senescence. Furthermore, the phenolic compounds induced by UV-C can inhibit PPO and POD activities, limiting enzymatic browning.

2. Effects of ultrasound on rachis browning

Ultrasound treatment, employing high-frequency sound waves (20–100 kHz), has also emerged as a sustainable, non-thermal technology to tackle postharvest grape issues. Through acoustic cavitation, ultrasound physically disrupts microbial cells and enzymatically inactivates PPO and POD, crucial players in enzymatic browning. Moreover, ultrasound enhances the diffusion of antioxidants, like ascorbic acid, into rachis tissues, further minimising oxidative reactions (Shi *et al*., 2024).

Ultrasound also reduces microbial load by physically damaging the membranes of spoilage fungi and bacteria, such as *B. cinerea* and *Penicillium* spp. (Fan *et al*., 2021). In addition, controlled ultrasound stress can stimulate grape defence responses, boosting the synthesis of phenolics, flavonoids, and glutathione, which delay senescence and preserve nutritional quality (Ma *et al*., 2020). Treatment efficacy is highly dependent on ultrasound frequency, power, and exposure time: low-frequency, moderate-intensity, short-duration applications yield optimal results, whereas excessive exposure risks tissue softening (Bal *et al*., 2017).

When combined with edible coatings or MAP, ultrasound's effectiveness is further enhanced. Ultrasound pre-treatment can improve the adhesion and performance of chitosan-based coatings, leading to a controlled release of antimicrobials and antioxidants (Barış Kavur & Yemenicioğlu, 2024). Similarly, ultrasound-assisted MAP can optimise gas dynamics to better control oxidative stress and enzymatic activity during storage (Moradinezhad *et al*., 2023).

3. Role of CA and MAP

CA and MAP have proven highly effective in extending grape shelf life by creating optimal gaseous conditions that slow metabolism, reduce oxidative stress, and inhibit enzymatic browning (Cukrov *et al*., 2019). CA maintains precise O_2, CO_2, and N_2 concentrations at low temperatures, typically reducing O_2 while elevating CO_2 levels. These conditions suppress respiration and ethylene production, slowing senescence and minimising oxidative stress by limiting oxygen for ROS formation. Furthermore, high CO_2 concentrations inhibit PPO and POD activities (Tian *et al*., 2005), effectively delaying browning.

MAP works on a smaller scale by enclosing grapes in selective-permeability films that allow controlled gas exchange. MAP reduces metabolic rates, oxidative stress, and microbial growth. Active packaging enhancements, such as oxygen scavengers and CO_2 emitters, can further improve MAP performance. However, improper gas concentrations can lead to anaerobic respiration, causing off-flavours or tissue damage (Cukrov *et al*., 2019; Czerwiński *et al*., 2021). Therefore, precision in gas regulation is crucial.

Combining CA and MAP with antioxidant treatments or edible coatings yields even better results. For instance, chitosan-based coatings enriched with ascorbic acid or essential oils, when used with MAP, enhance antioxidant defences and further inhibit enzymatic browning (Perumal *et al*., 2021). CA integration with UV-C treatment or SO_2 fumigation provides additional protection against microbial spoilage and oxidative degradation (Souza *et al*., 2022).

4. Effects of cold plasma on rachis browning

Cold plasma technology, based on the generation of ionised gases containing ROS, reactive nitrogen species (RNS), electrons, and photons, offers a novel, non-thermal solution for postharvest grape preservation. Cold plasma's strong antimicrobial activity stems from the oxidative damage it inflicts on microbial membranes and DNA, preventing rachis decay (Alaguthevar *et al*., 2024).

Cold plasma also effectively combats oxidative stress. Reactive species produced by plasma neutralise ROS like superoxide anions and hydrogen peroxide, thereby preserving membrane lipids and chlorophyll. Plasma exposure can also induce the synthesis of endogenous antioxidants such as phenolic compounds and flavonoids (Lin *et al*., 2024). Importantly, cold plasma suppresses enzymatic browning. It modifies the structure of PPO and POD, reducing their activity, and can degrade phenolic substrates necessary for enzymatic oxidation (Mayookha *et al*., 2023). The slight acidity induced by cold plasma further inhibits PPO, which favours neutral to alkaline pH. Treatment optimisation, including voltage, exposure time, and gas composition, is critical. Low to moderate plasma doses effectively reduce browning without damaging grape tissues, while overexposure can cause phytotoxic effects.

5. Integration of physical and biochemical approaches

Rachis browning results from complex interactions among oxidative stress, enzymatic reactions, microbial decay, and physiological senescence (Wu *et al*., 2021). Therefore, a multifaceted strategy combining physical and biochemical methods is the most effective. Integration of CA, MAP, UV-C, ultrasound, cold plasma, and antioxidant applications provides comprehensive protection. For example, combining CA or MAP with antioxidant-enriched edible coatings can simultaneously control the storage environment and deliver bioactive compounds directly to grape tissues (Das *et al*., 2023). Similarly, combining UV-C or cold plasma with MAP or CA synergises antimicrobial and antioxidative mechanisms, offering superior preservation of rachis quality.

ADVANCES IN POSTHARVEST TECHNOLOGIES FOR RACHIS BROWNING CONTROL

1. Role of nanotechnology and biopolymers

Recent advances in nanotechnology and biopolymers offer promising strategies for mitigating rachis browning in grapes, addressing key factors such as oxidative stress, enzymatic activity, and microbial decay (Hussein *et al*., 2023). Nanotechnology enables the development of precise and effective postharvest treatments by manipulating materials at the nanoscale. Nanoemulsions, consisting of oil dispersed in water, encapsulate antioxidants, antimicrobials, or plant extracts, enhancing their stability, solubility, and bioavailability (McClements *et al*., 2021). These nanoemulsions improve the stability, solubility, and bioavailability of active ingredients (Barradas & de Holanda e Silva, 2020). These nanoemulsions, incorporating agents like thymol and carvacrol, inhibit PPO activity, scavenge ROS, and curb microbial growth, thus delaying browning.

Nanocomposite coatings represent another nanotechnological approach, combining biopolymers such as chitosan or alginate with nanoparticles like clay, silver, or zinc oxide. These composites enhance mechanical strength, barrier properties, and functional performance, lowering oxygen permeability and providing antimicrobial and antioxidant protection (Al-Meshal *et al*., 2024; Jamali *et al*., 2024).

Biopolymers, derived from renewable natural sources, have become crucial in postharvest management due to their biodegradability and non-toxicity. Edible coatings from materials like chitosan, alginate, pectin, and starch form semi-permeable barriers that minimise water loss, maintain turgor pressure, and prevent desiccation, key factors in mitigating rachis browning (Al-Meshal *et al*., 2024). Functionalisation of these coatings with bioactive compounds such as ascorbic acid or plant extracts further boosts antioxidant and anti-enzymatic activities. For instance, chitosan coatings enriched with green tea extract have demonstrated significant reductions in PPO activity and ROS levels (Moghadas *et al*., 2024). Beyond conventional coatings, the development of biocompatible nanocomposites has also gained attention; for example, Youssef *et al*. (2019) reported that a silica and chitosan nanocomposite effectively preserves freshness, highlighting the potential of such hybrid materials in postharvest applications.

Integrating nanotechnology and biopolymers yields synergistic benefits. Nanocomposite biopolymer coatings combine structural strength with functional capabilities, while embedding nanoemulsions into biopolymer matrices enhances active compound delivery (Rehman *et al*., 2021; Youssef *et al*., 2019). Such approaches not only improve postharvest preservation but also reduce dependence on synthetic chemicals, aligning with the growing consumer demand for natural, eco-friendly solutions. The success of these strategies, however, hinges on optimising formulations, application methods, and storage conditions (Hussein *et al*., 2023).

2. Future prospects for sustainable postharvest solutions

Looking ahead, sustainable postharvest solutions will emphasise innovations like gene editing (*e.g.*, *CRISPR-Cas9*) for developing browning-resistant grape varieties and the continued evolution of nanotechnology for precise antioxidant delivery. Smart packaging equipped with sensors and active compounds will enable real-time quality monitoring, while non-thermal treatments like UV-C, cold plasma, and ultrasound offer chemical-free alternatives to combat microbial decay and enzymatic browning (Lin *et al*., 2024; Sheng *et al*., 2018; Shi *et al*., 2024). Moreover, advances in biopolymer technology and circular economy practices, such as using agricultural waste for packaging materials, will further promote sustainability. Achieving widespread adoption of these solutions will require interdisciplinary collaboration, consumer education, and supportive policy frameworks, ensuring long-term fruit quality preservation with minimal environmental impact.

CHALLENGES AND OPPORTUNITIES IN RACHIS BROWNING MITIGATION

1. Limitations of current methods

Despite various strategies to mitigate rachis browning in grapes during storage, significant limitations persist, restricting their overall effectiveness and commercial adoption. Current techniques, including chemical treatments, CA, MAP, and natural compound applications, face critical challenges that necessitate new and sustainable solutions.

One major limitation is the reliance on synthetic chemicals such as SO_2, which, although effective, presents risks to human health and the environment. SO_2 can cause phytotoxic effects, leading to tissue damage and bleaching in grapes, and must be carefully regulated to meet food safety standards (Torres-Díaz *et al*., 2025). Furthermore, alternative natural compounds, including plant extracts and essential oils, although safer, often suffer from instability, high production costs, and difficulties in scalability (Elsayed *et al*., 2022).

Another issue is the inconsistency of treatment effectiveness across grape varieties and storage conditions. Methods like CA and MAP demand precise environmental control; any deviation in gas composition, temperature, or humidity can trigger anaerobic respiration, cause off-flavours, or fail to prevent browning (Souza *et al*., 2022). Physical treatments such as UV-C irradiation and cold plasma show promise but require specialised equipment and careful calibration to avoid phytotoxicity. Moreover, the absence of standardised protocols for these technologies complicates their application on a commercial scale.

Economic and logistical barriers also hinder the adoption of advanced postharvest technologies. Innovations like nanotechnology-based coatings, smart packaging systems, and gene-edited grape varieties involve high costs that small-scale producers often cannot afford. Moreover, the infrastructure needed for CA and other sophisticated methods may not be readily available worldwide (Ucar *et al*., 2021).

2. Gaps in research and need for interdisciplinary approaches

In addition to practical challenges, several research gaps impede progress in mitigating rachis browning. A major gap is the limited understanding of the molecular mechanisms behind browning. Although the roles of enzymes like PPO, POD, and ROS are known, the genetic and metabolic regulation of these processes remains unclear (Romero *et al*., 2022). Advanced omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, offer new opportunities to identify biomarkers and regulatory pathways critical to rachis browning (Romero *et al*., 2016).

Furthermore, inconsistent experimental conditions across studies, involving different grape varieties, storage setups, and treatment parameters, make it difficult to compare results. Standardised evaluation protocols are urgently needed to

ensure reproducibility and consistency (Bahar *et al*., 2017). Additionally, long-term studies simulating commercial storage conditions are lacking, limiting the practical applicability of many proposed solutions (Li *et al*., 2015).

Another critical and often overlooked research gap concerns the increasing number of newly released seedless table grape cultivars developed by private breeding companies over recent decades. Several of these cultivars exhibit a heightened susceptibility to rachis dehydration, which in turn exacerbates the severity of stem browning symptoms (Piarulli *et al.*, 2024). Unlike well-studied traditional varieties, the physiological and biochemical responses of these new cultivars to postharvest treatments remain largely unexplored. Given their growing commercial importance and inherent vulnerability, single-strategy interventions are unlikely to be sufficient. Therefore, future research should prioritise the development and evaluation of combined, multi-target approaches tailored specifically to the unique characteristics of these emerging cultivars.

CONCLUSION

1. Summary of key findings

In conclusion, rachis browning in grapes during storage is a multifaceted postharvest challenge driven by oxidative stress, enzymatic activity, microbial decay, and physiological changes. Key findings demonstrate that current mitigation strategies, such as CA, MAP, and the application of natural compounds like ascorbic acid and plant extracts, are effective but face limitations, including chemical dependency, variability across grape varieties, and economic constraints. Emerging technologies, such as nanotechnology, cold plasma, and smart packaging, offer promising alternatives by providing targeted, sustainable, and eco-friendly solutions (Figure 6). However, gaps in research, such as a limited understanding of molecular mechanisms and the lack of standardised protocols, hinder their widespread adoption.

2. Recommendations for practical applications

For practical applications, it is recommended to adopt integrated approaches that combine physical treatments (*e.g.*, UV-C, cold plasma) with biochemical interventions (*e.g.*, antioxidant-enriched edible coatings) to enhance efficacy. Standardised protocols should be developed to ensure consistency and reproducibility across studies and commercial practices. Additionally, small-scale producers should be supported by cost-effective, scalable technologies, such as biodegradable films and low-cost smart packaging systems. Collaboration between researchers, industry stakeholders, and policymakers is essential to facilitate the translation of innovative solutions into real-world applications.

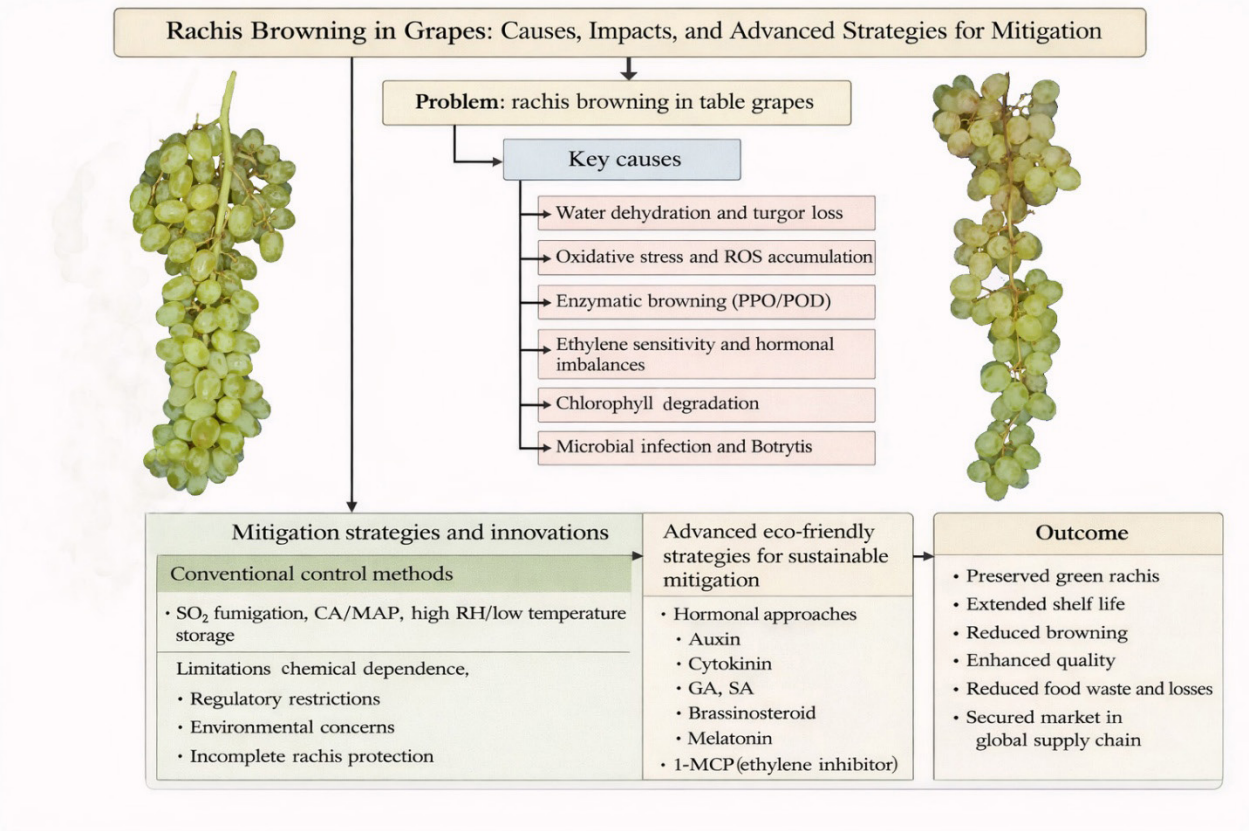


FIGURE 6. Overview of the main causes and mitigation strategies of rachis browning in table grapes. The figure highlights physiological and biochemical factors involved in browning, conventional postharvest treatments, and emerging eco-friendly approaches aimed at preserving rachis quality and extending shelf life.

3. Future directions for research and innovation

Future research should focus on advancing interdisciplinary approaches to address gaps in knowledge and technology. This includes leveraging omics technologies to elucidate the molecular mechanisms of browning, optimising emerging technologies like nanotechnology and cold plasma for scalability, and exploring circular economy principles to develop sustainable solutions from agricultural waste. Long-term studies under commercial storage conditions are needed to validate the effectiveness of new strategies. By prioritising innovation, collaboration, and sustainability, the grape industry can overcome current challenges, improve postharvest management practices, and ensure the long-term preservation of fruit quality in alignment with global sustainability goals.

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