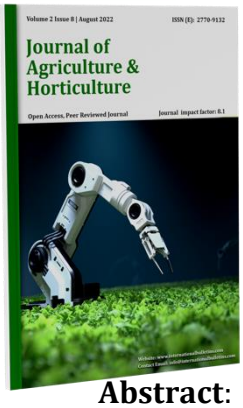

A COMPREHENSIVE REVIEW OF POSTHARVEST TREATMENTS FOR QUALITY RETENTION IN TABLE GRAPES

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Abstract: Table grapes are gaining popularity due to their appealing attributes and nutritional value. In recent years, new seedless varieties and unique flavors have become available worldwide, further increasing their demand. This highlights the need for advanced postharvest treatments to maintain fruit quality. Despite this, our understanding of the biochemical and molecular processes underlying quality improvements remains limited. This review explores the current literature on these mechanisms, focusing particularly on the molecular pathways that influence and regulate the effectiveness of various postharvest treatments aimed at enhancing table grape quality.

Keywords: Vitis vinifera, seedless grapes; fruit quality, postharvest treatments, mechanisms, soluble solid content

1. Introduction

Table grape cultivars, including Vitis vinifera L. and hybrids with V. labrusca L. and V. amurensis Rupr., belong to the Vitaceae family of deciduous woody perennials and rank among the most widely consumed non-climacteric fruits globally. These fruits have a low physiological activity rate and do not continue to ripen after harvest. Table grape quality is defined by various attributes such as appearance, color, texture, flavor, and aroma. The ripening process begins at the "veraison" stage, marked by sugar accumulation, berry softening, anthocyanin synthesis, organic acid metabolism, and the development of flavor compounds. Key indicators of quality include soluble solid content (°Brix) and sugar-to-acid ratios, with specific minimum thresholds set for each cultivar.

Flavor, a crucial quality factor, arises from the synthesis of hundreds of volatile compounds during ripening. However, table grapes are highly perishable postharvest, prone to significant water loss due to rachis and pedicel desiccation, which leads to browning, weight reduction, and berry softening. Additionally, fungal decay—primarily caused by the pathogen Botrytis cinerea—results in substantial losses. This fungus thrives at low temperatures (around 0°C), spreading rapidly among berries. Consequently, the storage and preservation of table grapes are limited, relying on internal factors such as skin and pulp structure, and external conditions like temperature and relative humidity, which play critical roles in maintaining quality.

The growing popularity of table grapes can be attributed to their exceptional organoleptic and nutritional properties, which have driven a significant increase in their consumption in recent years. Data from the International Organization of Vine and Wine (OIV) for 2019 reveals that approximately 36% of global grape production was allocated for fresh consumption, with China leading as the largest consumer, followed by India and the European Union. Over the past two decades, table grape production has doubled, with global output for the 2019/20 season estimated at 23.4 million tons, according to the USDA. While the potential

effects of COVID-19 were factored into this projection, the pandemic's long-term impact on trade and the global economy remains uncertain [1].

China stands as the top producer, yielding 9.5 million tons, followed by Turkey and India, each producing 1.9 million tons (OIV, 2018). On the export front, Chile, Italy, and the USA dominate, collectively accounting for 40% of global table grape exports. Additionally, many developing countries have significantly expanded their exports, recognizing table grapes as a driver of economic growth. This shift, coupled with rising environmental awareness and the push for sustainable development, has spurred research into postharvest technologies. These efforts aim to reduce reliance on agrochemical treatments while ensuring the preservation of fruit quality during storage.

While recent reviews have explored technological advancements in preserving table grape quality during postharvest [2–5], a comprehensive analysis of the mechanisms underlying their beneficial effects is still lacking. This study aims to bridge that gap by examining existing literature on the potential mechanisms involved, with a particular focus on the molecular pathways influenced by postharvest treatments designed to enhance table grape quality. Although an effort has been made to investigate the mechanisms associated with various postharvest methods, it is worth noting that most studies to date have concentrated primarily on modifying the storage atmosphere as the sole postharvest treatment, assessing both its effectiveness and underlying mechanisms.

2. Mechanisms Associated with Effectiveness of the Postharvest Treatments Applied to Maintain Table Grape Quality

2.1. Effect on the Cell Wall of Table Grape

The cell wall plays a pivotal role in determining the postharvest quality of table grapes, influencing attributes such as firmness, texture, and overall structural integrity. Postharvest treatments can significantly impact the cell wall by modulating its composition and the activity of cell wall-degrading enzymes. Dynamic changes in the chemical composition of the cell wall and tissue structure during fruit ripening, senescence, and postharvest storage significantly influence the sensory, chemical, and physical properties of table grapes. The plant cell wall is a complex network composed of polysaccharides (pectin, cellulose, and hemicellulose), proteins, and polyphenols. In grape berries, the cell wall serves as a protective barrier, shielding the fruit from external factors and restricting the diffusion of key compounds, including aromas and polyphenols [2].

Firmness is a critical quality attribute for consumers, as excessive softening can result in postharvest decay or rejection. Fruit softening primarily arises from modifications to the cell wall caused by the degradation of cell wall polymers. This process is driven by various enzymes, including cellulase (CL), polygalacturonase (PG), β-galactosidase (β-GAL), pectate lyase (PL), and xyloglucan endotransglycosylase/hydrolase (XTH) [8,9]. Changes in cell wall composition and enzyme activity have been observed during grape ripening. Additionally, research has shown that berry firmness during ripening is regulated by a complex network of genes [3].

Two key pectin-degrading enzymes play a significant role in the softening of fruit. In other fruits, such as strawberries, exposure to 30% CO_2 for 3 hours at 25°C has been shown to delay cell wall degradation. This treatment preserves the integrity of the middle lamella and down-regulates the expression of genes associated with cell wall-degrading enzymes. Similarly, short-term high CO_2 treatments have been effective in alleviating flesh gelling

during the cold storage of persimmons by maintaining the structural integrity of cell walls and the plasmalemma [4].

In table grapes, low-temperature scanning electron microscopy has been employed to investigate the microstructure of epidermal and hypodermal cells in the skin, comparing CO_2-treated and non-treated samples. Grapes stored in ambient air exhibited significant cellular compression and volume loss [20]. Additionally, cell wall-plasma membrane separation was observed in non-treated "Husayni" grapes after 41 days at 0°C. Conversely, a double application of short-term high CO_2 treatment enhanced the quality of table grapes, ensuring that the membrane remained fully attached to the cell wall throughout the cold storage period [5].

2.2. Impact on the Plasma Membrane.

The mechanisms through which plants detect cold temperatures remain incompletely understood. It is believed that multiple primary sensors are involved in the initial signaling response to cold stress. Each sensor may detect a particular aspect of the stress and participate in a specific branch of the signaling cascade. Plants are thought to sense low temperatures through alterations in membrane fluidity, permeability, and fatty acid composition, which results from an increase in polyunsaturated lipid content [5].

Given the importance of preserving cell membrane integrity during the postharvest storage of table grapes at low temperatures, various treatments have been examined for their effects. Storing table grapes in controlled atmospheres with elevated oxygen levels helped maintain the quality of the fruit by delaying ion leakage, a sign of compromised membrane integrity, compared to grapes stored in normal air. High CO_2 levels also notably reduced ion leakage in "Husayni" table grapes stored at 0°C, as compared to untreated samples. Similar results were observed with polyamine treatments, which likely helped preserve membrane integrity by promoting the accumulation of unsaturated fatty acids. Additionally, short-term high CO_2 treatments on "Husayni" grapes preserved the structural integrity of energy-related organelles, crucial for repairing metabolic damage and restoring cell membranes. These gaseous treatments also enhanced the unsaturation of 18-carbon fatty acids, increasing the lipid unsaturation ratio and the unsaturated fatty acid index in the membranes of polar lipids [6].

Additionally, it has been proposed that a 2-day CO_2 treatment in strawberries can alter fruit metabolism, leading to the accumulation of α-linolenic acid, which may help stabilize membranes during low temperature storage. Given the crucial role of membranes and their lipid composition in preserving fruit quality during postharvest storage, researchers have focused on uncovering the molecular mechanisms involved in lipid metabolism. However, there is limited information regarding table grapes in the postharvest phase. Phospholipase D, a key enzyme in membrane lipid metabolism, showed significant increases in enzyme activation, mRNA accumulation, and new protein synthesis during the early stages of heat acclimation. This suggests that phospholipase D may play a role in the grape's response to heat stress postharvest. Temperature-induced lipocalin (TIL) facilitates the transport of sterol molecules to the plasma membrane in response to stress, enhancing membrane fluidity at low temperatures. TIL gene expression has also been induced in citrus fruits stored at low temperatures, indicating a potential role of these genes in improving cold stress tolerance. A comprehensive transcriptional analysis comparing the responses of table grapes to low temperatures and high CO_2 levels revealed that the activation of TIL and LTP gene expression

in response to cold storage may be linked to mechanisms in untreated grapes that help them adapt to low-temperature storage [5].

LTPs (lipid transfer proteins) are among the most functionally significant classes of plant proteins, as they not only bind lipids but have also been shown to transfer them between membranes in in vitro studies [33]. Furthermore, LTPs have been demonstrated to stabilize membranes under stress, particularly in response to cold stress [6].

Another crucial aspect in the study of biomembranes is the effect of water on them. Although grapes exhibit low respiration rates after harvest and the cuticular wax layer regulates water movement between the epidermal cells and the surrounding atmosphere [35], even slight changes in water content or its state can cause significant alterations in the metabolism of grape bunches. Additionally, water loss equivalent to about 5–10% of the fruit's fresh weight can render the grapes commercially unacceptable. In contrast, the rachis, lacking the thick epidermis and cuticular wax found on the berries, is more susceptible to dehydration. As a result, a 2% to 3% water loss can cause the rachis to show browning symptoms. This is important in markets where the condition of the rachis, in terms of color and turgidity, serves as a key indicator of postharvest quality. It has been observed that storing grapes at 0–1°C with 95% relative humidity is not sufficient to prevent water loss from the bunches, leading to an increase in rachis browning [40–42]. However, postharvest treatments that modify the composition of storage atmospheres, such as Modified Atmosphere Packaging (MAP), Controlled Atmosphere (CA), and 3-day short-term high CO_2 treatment, have been effective in reducing water loss and controlling rachis browning during storage.

The availability of water plays a crucial role in determining the properties of membrane lipids, which in turn can influence the biophysical characteristics of membranes. During cold storage of tulip bulbs, the conversion of bound water into free water was observed. Similarly, in “Husayni” table grapes, the levels of unfreezable water in various tissues (skin, pulp, seeds, and rachis), measured using a differential scanning calorimeter, increased significantly when exposed to high CO_2 levels. In contrast, these water levels either remained stable or decreased in grapes stored in air. Additionally, cold acclimation in vegetative apple buds appears to involve processes such as an increase in unfreezable water levels.

Blanch et al. found that storing strawberries at 0°C in air resulted in a noticeable decrease in unfreezable water content, accompanied by an increase in cellular water leakage, cell structural disorganization, and a decrease in water potential. However, a 3-day CO_2 treatment helped maintain the water status similar to that of freshly harvested fruit. Unfreezable water content is closely associated with membranes, proteins, and other macromolecules [7]. According to Goñi et al., increases in unfreezable water content could serve as a sensory parameter that reflects metabolic adjustments in CO_2-treated tissues, which are influenced by the changes caused by air storage at extremely low temperatures.

3. Conclusions and Future Perspectives

Today, various postharvest technologies are utilized to enhance the quality of table grapes during storage. Growing consumer concerns about the use of chemicals on agricultural products have led to the increased adoption of physical treatments. These treatments primarily involve controlling the gaseous composition surrounding the grape bunches during storage at temperatures near 0°C. As a result, much of the current research focuses on

understanding the mechanisms behind the beneficial effects of gaseous postharvest treatments. These treatments help preserve grape firmness by regulating the expression of genes responsible for cell wall degrading enzymes. Additionally, several postharvest treatments have been shown to maintain membrane integrity, with water status being a critical factor in evaluating the effectiveness of these treatments.

However, there are no consistent trends regarding the modulation of the antioxidant system through postharvest treatments, as the effects often depend on the specific type of tissue analyzed. In contrast, most treatments have been effective in controlling lipid peroxidation by reducing MDA content, which is activated during cold storage. The phenylpropanoid pathway, which is important for the health-promoting properties of table grapes, has been extensively studied. These studies suggest that different treatments can increase the levels of beneficial compounds such as anthocyanins, stilbenes, and flavanols by modulating gene expression. However, some responses vary depending on the grape cultivar.
Advancements in molecular tools, such as microarrays and RNA-seq, have revealed the role of various transcription factors in the effectiveness of postharvest treatments for table grapes. These transcription factors are not only regulated at the transcriptional level by the treatments but also play a role in the in vitro activation of target genes, such as those encoding pathogenesis-related proteins (PRs) and dehydrins.

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