CHAPTER 8

Reducing losses during storage of fruit vegetables: regulation of postharvest metabolism

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Abstract

This review article addresses modern strategies for reducing postharvest losses in fruit vegetables by regulating oxidative metabolism during storage. Fruit vegetables such as tomatoes, peppers, eggplants, cucumbers, zucchinis, pumpkins, and melons are highly perishable and susceptible to chilling injury due to their intense postharvest respiration and high moisture content. The article summarizes the physiological and biochemical responses of plant tissues to cold stress, including membrane damage, oxidative stress, and the imbalance of endogenous antioxidants. Emphasis is placed on combined treatment approaches that integrate physical methods (heat treatments, UV irradiation, modified atmosphere storage) with the application of bioactive substances, including phytohormones and natural antioxidants. The review highlights the role of heat-induced stress tolerance, antioxidant defense systems, and nanostructured delivery forms in mitigating cold-related metabolic disorders. It argues that the effectiveness of such strategies depends on species- and cultivar-specific responses, maturity stage, and preharvest conditions. A physiological understanding of tissue metabolism is essential to optimize storage parameters and design effective protective treatments.

Keywords

Fruit vegetables, postharvest metabolism, oxidative stress, chilling injury, antioxidants, bioactive substances, heat treatment, storage technologies, combined treatments.

8.1 Introduction

Fruit vegetables are one of the most popular and valuable groups of vegetable crops, including tomatoes, peppers, eggplants, cucumbers, zucchinis, pumpkins,

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and other fruit-forming plants. They are an essential component of a healthy diet. In 2023, global vegetable production reached 1.2 billion tons, which is 26% higher compared to 2010. Fruit vegetables have high economic profitability and are provided fresh and canned, or as ingredients for food concentrates. Among all fruit vegetables, the highest production volume is attributed to tomatoes (*Solanum lycopersicum*) [1]. Other leading crops include sweet peppers (*Capsicum annuum*), cucumbers (*Cucumis sativus*), and zucchinis (*Cucurbita pepo*), which form the basis for both fresh consumption and processed products.

Fruit vegetables contain sugars, organic acids, polysaccharides, proteins, and lipids, with the percentage ratio of these components depending on breeding and genetic characteristics, as well as biotic and abiotic factors. The value of fruit vegetables lies in their content of bioactive compounds – natural endogenous antioxidants, minerals, dietary fibers, and other phytonutrients capable of addressing the issue of "hidden hunger". In the context of the global transformation of food systems, there is a shift in nutritional approaches with an emphasis on increasing the share of vegetables in the daily diet. This is driven not only by the need for healthier eating but also by the necessity to reduce the carbon footprint associated with the consumption of animal-based products.

However, fruit vegetables are highly sensitive to external factors, exhibit intense postharvest metabolism, and have a short shelf life, which leads to significant losses at all stages of the food supply chain – from harvest to consumption. According to the Food and Agriculture Organization of the United Nations (FAO), fruits and vegetables have the highest loss rate among all food categories – ranging from 40% to 50% of their total volume [2]. These losses have serious economic and environmental consequences, as vegetable production requires substantial natural resource inputs, including water, soil, fertilizers, and energy. Moreover, the loss of such valuable raw materials during storage contradicts the principles of sustainable development, creates additional environmental burdens, and undermines food security.

Ensuring the availability and quality of vegetable products requires comprehensive solutions, including infrastructure modernization, expansion of technological capabilities, the implementation of innovative approaches such as automated systems for monitoring product conditions, alternative methods for extending shelf life, and the adaptation of global experience in the agri-industrial sector [3]. Only an integrated approach will reduce vegetable losses and contribute to the development of sustainable food systems.

Modern storage technologies are based on slowing down postharvest metabolism and maintaining the antioxidant defense system of the fruit [4]. Therefore, the aim of this study was to discuss the mechanisms and strategies for regulating postharvest metabolism, as well as technologies aimed at minimizing oxidative stress, which affects the quality and shelf life of fruit vegetables.

8.2 Biochemical processes in postharvest metabolism

After harvesting, fruit vegetables continue their life cycle, maintaining active metabolism. However, the supply of assimilates, water, and phytohormones from the parent plant ceases, so they rely on previously stored organic compounds. The primary metabolic processes include respiration, ethylene production, and oxidative reactions, which directly affect quality, shelf life, and resistance to stress factors. Respiration is a key process during which organic substances (mainly acids and sugars) are oxidized to produce energy necessary for maintaining cellular activity. After harvesting, the intensity of respiration often increases, leading to faster depletion of nutrient reserves, weight loss, and accelerated aging of the produce. This is particularly characteristic of vegetables with high moisture content and thin skin, such as tomatoes, cucumbers, peppers, and eggplants. Some fruit vegetables (e.g., tomatoes and eggplants) are climacteric, meaning they exhibit a sharp (climacteric) spike in respiratory activity, intense ethylene synthesis, and the ability to ripen postharvest. Ethylene is a phytohormone that activates respiration and regulates ripening and aging processes. During the storage of tomatoes under cooling conditions, respiratory intensity is initially inhibited due to the low temperature. However, after approximately five days of storage, respiratory intensity increases. Subsequently (around 20 days), a climacteric rise occurs, followed by a decline in respiratory activity, during which overripening processes dominate, as indicated by the deterioration of fruit quality [5].

The level of CO_2 emission and the timing of the climacteric phase vary depending on the variety or hybrid of tomatoes and the abiotic factors during cultivation. The climacteric phase is accompanied by physiological changes such as tissue softening, color changes, and aroma development, which make the fruits more appealing for consumption. However, after the onset of the climacteric phase, the fruits quickly lose their properties and degrade. Therefore, delaying the onset of the climacteric phase as much as possible extends the overall storage period.

Non-climacteric fruit vegetables (e.g., peppers, cucumbers, zucchinis) do not exhibit a sharp spike in respiratory activity and are characterized by low levels of endogenous ethylene. In non-climacteric vegetables, ethylene interacts with other phytohormones, such as abscisic acid (ABA) and auxins, which influence ripening and aging processes. These interactions can modulate tissue sensitivity to ethylene and affect product quality during storage. It has been established that the postharvest respiration rate of non-climacteric fruit vegetables is closely correlated with weather conditions during the preharvest period [5, 6]. Non-climacteric vegetables do not have the ability to ripen postharvest and gradually degrade during storage. Lowering the storage temperature slows down metabolic processes accordingly.

During storage, reactive oxygen species (ROS) accumulate in the cells of fruit vegetables, which can damage membranes, proteins, and nucleic acids. This phenomenon is known as oxidative stress. To neutralize ROS, plants utilize endogenous antioxidant systems, which include enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), as well as low-molecular-weight compounds like ascorbic acid (AA), glutathione, phenolic compounds, and carotenoids [4]. The enzymatic and non-enzymatic antioxidant systems work together to neutralize reactive oxygen species, thereby preserving the quality of the fruits. Their activity depends on the type of vegetable, the variety, and the storage conditions. For example, tomatoes are rich in lycopene and ascorbic acid, pumpkins are abundant in β-carotene and phenolic compounds, while peppers contain high levels of ascorbic acid and peroxidase (**Table 8.1**).

Table 8.1 Fruit vegetables and components of antioxidant defense

Fruit vegetable species	Key antioxidant compounds and enzymes	Postharvest action features
Tomato (*Solanum lycopersicum*)	Lycopene, AA, SOD, POD, polyphenols, flavonoids	Reduction of AA content by up to 50%. SOD is activated in response to mechanical damage or over-ripening of the fruit
Sweet pepper (*Capsicum annuum*)	Ascorbic acid, Carotenoids (capsanthin, capsorubin), SOD, CAT, phenolic compounds	Reduction of AA during storage; increase in POD and SOD activity under chilling
Eggplant (*Solanum melongena*)	Chlorogenic acid, anthocyanins, POD, CAT	High phenolic content, which increases under mechanical stress
Zucchini (*Cucurbita pepo*)	Ascorbic acid, polyphenols, SOD, CAT, flavonoids	Activation of phenolics and increase in antioxidant activity under low temperature conditions
Cucumber (*Cucumis sativus*)	Ascorbic acid, POD, flavonoids	Reduction of AA during storage; activation of flavonoid synthesis in response to chilling and mechanical stress
Pumpkin (*Cucurbita maxima*, *C. moschata*)	Carotenoids (β-carotene, lutein), SOD, CAT, polyphenols	Moderate reduction in AA and carotenoid content during storage, SOD activity increases in response to storage-related oxidative stress
Watermelon (*Citrullus lanatus*)	Lycopene, ascorbic acid, β-carotene, SOD, CAT, phenolic compounds,	Reduction of AA and lycopene during storage. SOD, CAT activity decrease as senescence progresses
Melon (*Cucumis melo*)	Ascorbic acid, carotenoids (β-carotene), phenolic acids, flavonoids, SOD, CAT	Gradual decline in ascorbic acid and carotenoid content during storage; antioxidant enzyme activities (e.g., SOD, CAT) decrease with senescence

Source: compiled from data [7–12]

Fluctuations or reductions in temperature and humidity, changes in storage atmosphere, and postharvest treatments can either activate or suppress the antioxidant defense systems of fruit vegetables. When the production of substances necessary to maintain normal cellular homeostasis is disrupted, the cell's ability to counteract reactive oxygen species (ROS) is only effective for a limited time. As the cell ages, these compounds begin to accumulate, and the defense system becomes depleted. This leads to metabolic disturbances and, ultimately, cell death.

The biochemical processes occurring in vegetables during storage are closely linked not only to physiological processes (e.g., respiration) but also to physical processes, such as moisture transpiration. After harvest, fruit vegetables continue to lose moisture through transpiration, which results in reduced cell turgor, wilting, and surface wrinkling. Dehydration leads to a decline in enzyme activity, inhibition of respiration, protein synthesis, and other metabolic processes. This is a protective response of the organism, allowing it to preserve cellular structure under unfavorable conditions. On the other hand, moisture loss stress can activate certain enzymes, such as those associated with aging or tissue oxidation.

Moisture loss is the second most significant cause of deterioration during storage, following overripening, particularly in physiologically immature vegetables such as cucumbers, zucchinis, and eggplants. Moisture loss negatively affects the appearance and consumer properties of the vegetable production. The rate of moisture loss depends on storage conditions, particularly temperature and relative humidity. Lowering the storage temperature significantly slows transpiration, which is a critical factor in maintaining the commercial appearance and weight of the product.

However, while reducing temperature is beneficial for limiting transpiration and suppressing metabolism, it also poses a risk of cold-induced damage, especially for vegetables of tropical and subtropical origin. Such temperature reductions can lead to the development of a complex of metabolic disorders that degrade the quality.

8.3 Metabolic disorders induced by cold exposure

For fruit and vegetable products of tropical and subtropical origin, cold storage often leads to the development of a complex of metabolic disorders that negatively affect quality. This set of changes is collectively known as chilling injury (CI). Fruits sensitive to CI typically have a short storage life because low temperatures, which are effective in delaying aging and suppressing the development of pathogenic microorganisms, cannot be used for their preservation. The storage life of chilling-sensitive produce increases as the storage temperature decreases, but only to a certain threshold, referred to as the critical chilling temperature. For subtropical plant species, this critical temperature is approximately 8°C, while for tropical species, it is around 12°C. The approximate critical temperatures at which signs of chilling injury begin to appear in fruit vegetables are provided in **Table 8.2**.

Table 8.2 Chilling sensitivity of fruit vegetables

Crop		Chilling injury threshold, °C	Estimated time to onset of chilling injury symptoms, days
Cucumber		≤ 10	2–3
Zucchini		≤ 5	2–3
Melon		≤ 7	4–7
Watermelon		≤ 10	5–10
Pumpkin		≤ 10	14–28
Sweet pepper		≤ 7	4–10
Eggplant		≤ 10	2–5
Tomato	Green mature	≤ 13	4–7
	Breaker	≤ 13	3–5
	Pink-light red	≤ 10	7–10
	Red ripe	≤ 7	10–14

Source: compiled from data [13–15]

Sensitivity to CI strongly depends on the duration of exposure to suboptimal temperatures, the variety, growing conditions, the developmental stage of the fruit, and the storage environment.

The symptoms of chilling injury vary depending on the type of produce. Some common symptoms for tropical plants include the appearance of lesions, discoloration, sliminess, internal breakdown, inability to ripen, loss of taste and aroma, and decay. Spots, round or irregularly shaped depressions on the fruit surface, as well as uneven coloration, are the most common forms of chilling damage and the first symptoms observed in many vegetables (including cucumbers, zucchinis, sweet peppers, and tomatoes) (**Fig. 8.1**).

At the microscopic level, the symptoms of chilling injury are similar across all plant organisms. These symptoms include swelling and disorganization of mitochondria and chloroplasts, where thylakoid expansion and granum disassembly occur, a reduction in the size and number of starch granules, accumulation of lipid droplets inside mitochondria, and condensation of nuclear chromatin [15]. The first physiological response to low-temperature exposure is changes in the conformation and structure of the cell membrane. Due to reduced solubility and depolymerization of pectin, the permeability of cell walls changes significantly. The most critical changes occur in the lipid composition of membranes, which are similar to those observed during aging. These changes include lipid peroxidation, an increase in the saturation index of fatty acids, degradation of phospholipids and galactolipids, and an increased sterol-to-phospholipid ratio. If the storage period at low temperatures is excessively long, the cell membrane loses elasticity, ruptures, and water, ions, and cellular metabolites leak out. As a result, a cascade of secondary reactions occurs, such as loss of turgor, electrolyte leakage, loss of metabolic energy, disintegration of photosynthetic systems, and ultimately, cell lysis. Prolonged exposure to low temperatures makes it impossible to restore the original cellular organization upon warming. Moreover, the symptoms of CI become more pronounced when vegetables are transferred to room temperature.

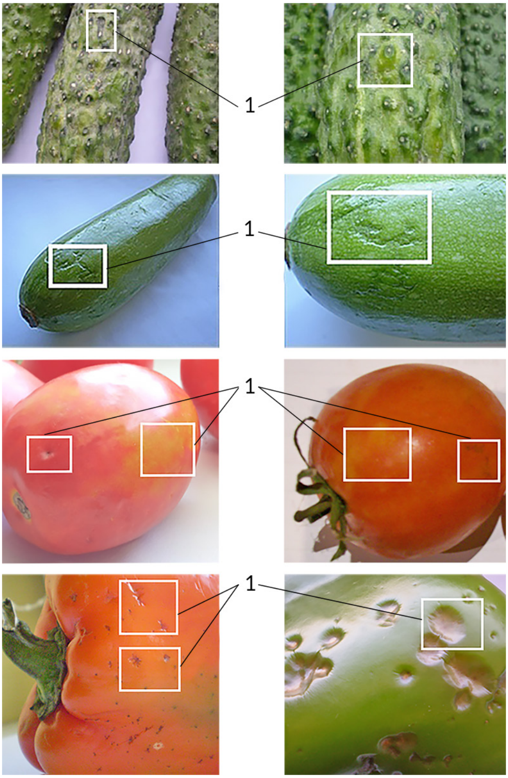

Fig. 8.1 Symptoms of chilling injury in various vegetables: 1 – area showing chilling injury
Source: author's photo

In addition to the direct impact of low temperatures on the molecular organization of membrane lipids, membrane integrity is further compromised by oxidation. Low-temperature stress is accompanied by the generation of high levels of reactive oxygen species (ROS). Excessive ROS production occurs in chloroplasts, which are involved in photosynthesis and have an oxygen surplus. Another source of ROS is the activation of NADPH oxidases localized in cell membranes, which leads to massive production of superoxide anions. This also results in lipid peroxidation of membranes. Oxidative stress is exacerbated by the inhibition of antioxidant enzyme activity, which is responsible for ROS removal. Overall, researchers agree that oxidative stress plays a leading role in the induction of chilling injury.

8.4 Physical methods for regulating postharvest metabolism

Various postharvest technologies are available to delay the development of chilling injury during the storage of sensitive produce. Some of these technologies are physical in nature and primarily involve modifying temperature, relative humidity, or the gas composition of the storage atmosphere for fruits and vegetables. However, controlled atmosphere storage, depending on the type of produce, can be beneficial, ineffective, or even harmful in reducing chilling injury. For example, controlled atmosphere storage has advantages for zucchinis, does not affect tomatoes, and exacerbates chilling symptoms in cucumbers and sweet peppers [14]. It is known that the use of modified atmosphere storage can effectively reduce chilling injury symptoms in tomatoes and zucchinis, especially when the correct combination of temperature, oxygen concentration, and fruit maturity stage is applied. Pre-treatment with 10% CO_2 for 24 hours, combined with a modified atmosphere, reduces CI symptoms in sweet peppers, including calyx darkening and loss of firmness [16]. However, considering the principles of sustainable production, the use of film materials for creating a modified atmosphere raises significant concerns regarding their application.

Some studies suggest that ultraviolet (UV) irradiation of fruits can reduce chilling sensitivity by stimulating defense mechanisms, including increased activity of antioxidant enzymes. UV treatment induces the formation of phenolic compounds and flavonoids, which help combat oxidative stress and may extend shelf life by strengthening cellular structures and enhancing immune responses. It is known that UV irradiation increases the chilling resistance of tomatoes. Recent studies have shown that UV irradiation of zucchinis enhances their resistance to chilling by increasing flavonoid accumulation and antioxidant capacity, thereby reducing oxidative stress during low-temperature storage [17].

At the industrial level, the most commonly used methods include conditioning at moderate temperatures, pre-storage heat treatments at high temperatures, or interrupting cold storage with temporary warming of the produce (either once or periodically). This approach aligns with the requirements of the European Green Deal. The positive effects of heat treatments are associated with the formation and protective action of heat shock proteins (HSPs). HSPs play a role in regulating ROS production and protecting cellular compartments from oxidative stress. Heat-induced thermotolerance can also provide protection against cold stress. Postharvest heat treatments alter the normal protein synthesis program and cellular metabolism. Under heat stress, rapid dissociation of polyribosomes occurs, and protein synthesis temporarily halts. It then resumes with a new set of proteins, including HSPs. As a result, normal ripening processes are blocked, and if the product is stored at low temperatures, this inhibition persists for some time. Thus, postharvest heat treatments can not only delay the development of chilling injury, but also modulate the rate of ripening and aging of the produce [18].

Heat conditioning procedures are typically carried out in hot air at temperatures ranging from 30°C to 40°C, with durations ranging from a few hours to several days. Higher temperatures are used for insecticidal and fungicidal purposes. In industrial settings, the most common methods include hot water dipping (HWD) and hot water rinsing and brushing (HWRB) or spraying [19]. Heat treatment also directly reduces the number of pathogenic microorganisms by destroying or inactivating spores. The temperature and duration of exposure can vary significantly (from 33°C for several days to 63°C for a few seconds) and are typically determined experimentally for specific plants and purposes (**Table 8.3**).

Table 8.3 Postharvest heat treatment regimens for fruit vegetables

Treatment method	Temperature, °C	Duration	Target application	Crops
1	2	3	4	5
Hot air (conditioning)	35–39	12–72 h	Reduction of chilling injury symptoms, delay of ripening	Tomato, Eggplant, Pepper
HWD	42–50	3–10 min	Reduction of chilling injury symptoms, control of fungal pathogens	Eggplant, Pepper, Cucumber
	45	15 min	Reduction of chilling injury symptoms	Tomato
	55	1 min	Prolonged storage life, reduced fusarium disease and fruit decay, improved fruit quality	Melon

Continuation of Table 8.3

1	2	3	4	5
HWRB	59°C	15 s	Control of fungal pathogens, improved fruit quality	Melon
	54°C	15 s	Control of fungal pathogens, improved fruit quality	Pumpkin
	55°C	12 s	Maintaining fruit quality after prolonged storage	Pepper
	52°C	15 s	Enhancing cold tolerance, maintaining quality during storage	Red tomato
Steam treatment	50–55°C	5–15 min	Reducing water loss, controlling pathogens	Tomato, Pepper
Combined conditioning + cooling	38°C → 12°C	24 h + storage	Enhancing cold tolerance, maintaining quality during storage	Tomato, Eggplant

Source: compiled from data [6, 12, 13, 18–22]

Fruits and vegetables with green coloration may experience yellowing when exposed to high temperatures. This phenomenon is explained by the activation of chlorophyllase, which leads to chlorophyll degradation. Therefore, for cucumbers and zucchinis, heat treatments at temperatures not exceeding 45°C are recommended.

Overall, the effects of heat treatments on fruits and vegetables mitigate cold stress through the following factors [13]:

– enhancing membrane integrity by increasing the ratio of unsaturated fatty acids to saturated fatty acids;

– increasing the expression of heat shock protein (HSP) genes and their accumulation;

– boosting the antioxidant activity of the system;

– enhancing arginine synthesis pathways, leading to the accumulation of signaling molecules (polyamines, nitric oxide, and proline) responsible for improving cold tolerance;

– altering the activity of phenylalanine ammonia-lyase and polyphenol oxidase enzymes;

– enhancing carbohydrate metabolism.

8.5 Regulation of postharvest metabolism using biologically active substances

One of the effective approaches to controlling metabolism and enhancing cold tolerance is the use of biologically active substances (BAS), which can modulate the physiological state of vegetable, reduce metabolic intensity, stabilize cellular structures, and strengthen antioxidant defenses.

Bioregulation through phytohormones. Phytohormones (such as auxins, gibberellins, cytokinins, abscisic acid, ethylene, and others) are natural substances produced by plants that regulate their growth, development, and responses to stress factors. Researchers studied the synthetic first-generation cytokinin, 6-benzylaminopurine (6-BA), also known as benzyl adenine or BA, as a postharvest treatment for cucumbers to mitigate chilling injury [23]. They found that exogenous 6-BA allows fruits to maintain higher levels of chlorophyll, ascorbic acid, phenolic compounds, and overall antioxidant capacity. Additionally, this treatment increases the activity of superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and glutathione reductase (GR) under cold stress. The results demonstrate that 6-BA alleviates CI symptoms in cucumbers by enhancing the activity of antioxidant enzymes and overall antioxidant activity.

Cytokinins have also been shown to reduce cold sensitivity in zucchini [17]. To mitigate chilling symptoms, treatments with phytohormones such as methyl jasmonate and methyl salicylate have been proposed. Methyl jasmonate reduces CI in zucchini [17], however is ineffective in reducing CI symptoms in peppers [24]. Other phytohormones, such as salicylic acid, melatonin, and brassinosteroids, demonstrate the ability to strengthen the fruit's antioxidant system, increasing the activity of SOD, CAT, and polyphenol oxidase (POD), which aids in adaptation to low temperatures and limits the development of CI.

Postharvest metabolism can also be regulated by influencing the phytohormones of fruits. Retardants and ethylene inhibitors are widely used to control ripening and aging processes. For example, 1-methylcyclopropene (1-MCP), an ethylene receptor inhibitor, effectively reduces tissue sensitivity to ethylene, delays fruit softening, slows chlorophyll loss, and extends the shelf life of vegetables, including zucchinis, tomatoes, and eggplants. However, it does not affect chilling injury in peppers [24]. It is likely that the use of 1-MCP only alleviates CI symptoms and requires additional protective measures against low temperatures. When plants are treated with growth regulators that induce cold tolerance, the fruits generally become less sensitive to chilling during storage. The use of phytohormones stimulates the production of endogenous antioxidants. However, the antioxidant defense of tissues can also be supplemented by using exogenous BAS with antioxidant properties.

Antioxidant protection and regulation of oxidative stress. Treatment of fruits and vegetables with compounds that act as antioxidants and reduce oxidative damage induced by chilling is widely applied during the storage of vegetables. The advantage of synthetic antioxidants over natural ones lies in their higher free radical scavenging activity, greater stability, slower degradation by cellular monooxygenase systems, and prolonged action. Numerous synthetic compounds, including butylated hydroxytoluene (BHT), ethoxyquin, and diphenylamine, have been recognized as highly effective in preventing oxidative browning in various fruits and vegetables. However, concerns about the environmental impact of chemical compounds have driven increased attention toward natural antioxidants.

Natural antioxidants have become an alternative to synthetic ones because they are fully biodegradable and environmentally safe. However, natural exogenous compounds are not as universally effective as synthetic ones, meaning they may only be beneficial for specific vegetables. Additionally, for antioxidant components to be effective, they must easily reach the target site of oxidative damage, which is typically achieved by lipophilic compounds. Extensive research has been conducted on treating fruits and vegetables with ascorbic acid, tocopherol, glutathione, polyphenolic compounds (quercetin, resveratrol, rutin), and chitosan. Single-component antioxidants are generally less effective than compositions containing two or more antioxidants [21]. Each year, hundreds of studies are published on the antimicrobial and other functional properties of extracts from higher plants. The use of higher plants and their components as antioxidants, bactericides, or fungicides provides such advantages as better systemic action, non-phytotoxicity, and biodegradability. These compounds can be applied continuously year after year without any negative impact on the environment. A wide range of available spices and herbs exhibit fungicidal, bactericidal, and antioxidant properties, including marjoram, cumin, savory, basil, coriander, mustard, and horseradish. Understanding their characteristics and specific mechanisms of action will help evaluate their contribution to regulating the metabolic processes in fruit tissues. It has been demonstrated that such treatments reduce the intensity of lipid peroxidation in cellular membranes [12]. This, in turn, decreases cellular damage, delays turgor loss, and prevents premature tissue breakdown.

Modern approaches involve the use of bioactive compounds in the form of nanomaterials, encapsulation in polymer carriers, or incorporation into active packaging films. For example, applying edible coatings with the addition of horseradish extracts and lecithin as an antioxidant delays the development of chilling injury in tomatoes by 2 weeks during storage at 2°C [21].

Treatment with bioactive substances is a promising approach for extending the storage life of fruit vegetables, reducing chilling injury, and maintaining nutritional value. The combination of phytohormonal regulators, antioxidants, and protective natural compounds effectively regulates postharvest metabolism. However, optimal concentrations, application methods, and combinations of bioactive substances must be tailored to specific vegetable types and storage conditions.

8.6 Combined methods for protecting fruit vegetables from oxidative damage

Numerous approaches proposed to reduce chilling injury do not completely prevent the appearance of chilling symptoms in most vegetables. However, oxidative stress-induced damage can be mitigated by combining different measures. Various external stressors trigger similar mechanisms to enhance resistance to oxidative stress. This explains why many different postharvest treatments can reduce physiological disorders induced by oxidative stress. When two or more stressors are applied simultaneously, plant tissues develop broader stress cross-tolerance [25].

It has been established that combining heat treatment with antioxidant application reduces the severity of chilling injury in red tomatoes [21]. The low-temperature damage index in treated fruits, depending on the tomato variety and antioxidants used, was 7.0–14.7 times lower compared to untreated fruits and 3.3–7.7 times lower than in tomatoes treated with hot water alone. Similar results were obtained when combining heat treatment with antioxidant solutions for two varieties of peppers. Pre-storage treatment with a solution of a complex natural-synthetic antioxidant at 45°C for 15 minutes extended the storage life of peppers by 2 weeks. This postharvest treatment reduced the sensitivity of peppers to low-temperature storage: the level of chilling damage decreased by 7–9 times, and the severity of low-temperature injuries in treated fruits was reduced by 9–12 times. Heat treatment combined with antioxidants significantly affects the level of lipid peroxidation products during zucchini storage [12]. This treatment stabilizes the level of malondialdehyde throughout the storage period, indicating the full activation of antioxidant defense mechanisms and timely utilization of ROS.

Despite researchers' efforts, no universal solution has been found to prevent metabolic disorders during the storage of fruit vegetables. Slowing tissue oxidation can be achieved by combining antioxidants with heat treatment. However, strategies for combined protection measures must be developed with a clear understanding of the biochemical responses of tissues. Species and varietal specificity, developmental stage, and growing conditions significantly influence tissue responses to storage-induced stress factors. For example, the ability to activate the endogenous antioxidant system or the effectiveness of exogenous biologically active substances varies not only between crops but also among varieties within the same species.

The successful implementation of combined technologies is possible only with the targeted selection of physiologically justified parameters, such as temperature and duration of heat treatment, antioxidant concentration, and the sequence and method of application (e.g., spraying, dipping, or vapor treatment). Additionally, potential negative effects of excessive metabolic inhibition, such as delayed ripening or loss of flavor, must be considered. Thus, a promising direction is the integration of physiological monitoring (e.g., malondialdehyde content, antioxidant enzyme activity) with practical storage technologies. Such approach allows the adaptation of protection systems to the specific properties of each batch of vegetable produce, ensuring optimal storage outcomes.

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