


Editorial

Postharvest Storage Techniques and Quality Evaluation of Fruits and Vegetables for Reducing Food Loss

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Fresh fruits and vegetables have always made an important contribution to the human diet. Fruits and vegetables provide a variety of colors, shapes, flavors, aromas, and textures, but their full nutritional importance has only been explored and recognized recently as a result of the rising public awareness of food quality and safety. Furthermore, increased consumption of fruits and vegetables has been associated with a reduced risk of cancer and heart diseases in many epidemiological studies, thus highlighting their beneficial health properties.

Traditionally, fruits and vegetables' 'qualities' refer to extrinsic characteristics such as size, shape, color, and firmness. These visual attributes, together with sensorics parameters such as scent and taste, affect consumers' acceptance, and thus have a direct economic implication. However, in recent years there has been a growing awareness of the intrinsic factors of nutritional and functional attributes related to phytonutrient content, such as minerals, vitamins, dietary fibers, and other phytochemicals that determine the nutritional values of fresh produce and directly or indirectly affect consumers' health. These physico-chemical properties are determined by genotypic and agro-environmental factors but they also dynamically change after the product has left the field, and are highly dependent on postharvest handling [1].

Just as fruit and vegetables have always been an important component of the human diet, postharvest losses in produce continue to pose a struggle for modern agriculture. Postharvest losses include any damage to the quantity and quality of produce from the moment of harvest until consumption. The magnitude of postharvest losses in fresh produce is estimated to be 5% to 25% in developed countries and 25% to 50% in developing countries [2,3]. This enormous waste of food poses a significant economic, social, and ecological burden on humanity that prompts an urge to improve the current practices and develop new means to reduce the waste.

In recent years, the field of postharvest handling of fresh produce faced several technological advances. The combination of the online monitoring of the environment or produce state and active modulation of storage conditions with the emerging discipline of modeling based on big data and artificial intelligence (AI) tools introduces both opportunities and challenges to the field. This special issue, titled "Postharvest Storage Techniques and Quality Evaluation of Fruits and Vegetables" presents 20 original research papers that provide new insights, approaches, and advances in pre- and postharvest handling to preserve fresh produce quality and reduce losses.

All fresh horticultural crops are metabolically active organisms, even after harvest, until they are either processed or consumed. Depending on storage conditions, various physiological processes, such as respiration, ripening, and senescence, can significantly impact the quality and shelf life of fruits and vegetables. Since fresh produce is not sterile, the storage time of fresh produce also largely depends on interactions with other organisms in its environment, namely pathogenic microorganisms, insects, and other pests. Consequently, two main processes cause fruit and vegetable deterioration: (1) physiological



Citation: Ziv, C.; Fallik, E. Postharvest Storage Techniques and Quality Evaluation of Fruits and Vegetables for Reducing Food Loss. *Agronomy* **2021**, *11*, 1133. <https://doi.org/10.3390/agronomy11061133>

Received: 13 May 2021

Accepted: 24 May 2021

Published: 2 June 2021

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deterioration, which includes water loss, softening, ripening, and shedding of leaves; and (2) microbial decay, caused by pathogenic bacteria, yeasts, or molds. Both of these processes are highly dependent on environmental conditions and greatly affect one another.

The most prevalent approach to preserve fruit quality and to reduce produce loss after harvest is to delay ripening and senescence. Fruit ripening involves several metabolic processes that differ between 'climacteric' and 'non-climacteric' fruits. During the ripening of climacteric fruit, respiration increases until it reaches a peak, which is accompanied by an increase in ethylene production. In contrast, respiration of non-climacteric fruit does not increase during ripening, and ethylene is not required in order to complete the ripening process. Regardless of the type of ripening, this process, as well as other metabolic processes that lead to deterioration, are driven by respiration. After harvest, the fresh produce continues to respire—utilizing food reserves taking in oxygen, and releasing carbon dioxide and heat from stored carbohydrates. For that reason, postharvest treatments that reduce respiration will delay deterioration processes, prolong shelf life, and help to maintain produce quality.

Cold storage is the most frequently used practice to decrease metabolic activity. However, low-temperature (LT) storage conditions must be adjusted and optimized for each specific type of produce. Additionally, other storage conditions such as humidity [4] and air composition should be adjusted for the best results. Thus, it is necessary to determine the optimal storage conditions to prolong fruit and vegetables' storage time. Specifically, controlled atmosphere (CA) [5] for kiwifruit, as well as dynamic controlled atmosphere (DCA) or ultra-low oxygen (ULO) [6,7] for apples, are increasingly being evaluated as chemical-free applications to prolong storage time.

Ethylene is the plant hormone best-known for its effect on fruit ripening. The inhibition of ethylene synthesis is advantageous because inhibiting ethylene production delays processes related to fruit ripening, i.e., softening, chlorophyll degradation, and the breakdown of complex sugars, e.g., starch, into simple sugars. Reducing ethylene synthesis by LT/CA storage and/or by application of the competitive ethylene antagonist, 1-methylcyclopropene (1-MCP), which blocks the response of plants to ethylene, can greatly delay the ripening of climacteric fruits, and additionally alleviate physiological disorders such as scald in apples [7]. However, treatment of 1-MCP for late-harvested apples stored in CA increased flesh browning [8], indicating that more work is required to optimize performance of this treatment. Interestingly, co-regulation of methionine biosynthesis, ethylene production, and respiration in 1-MCP-treated tomatoes has shed new light on the effect of this treatment on fruit physiology [9] and may facilitate the improvement of its implementation. While manipulating ethylene production is a common practice, the increase in applications of other growth regulators, such as salicylic acid and the polyamine putrescine, holds great promise to extend the repertoire of postharvest treatments and resultantly prolong the storage time of non-climacteric fruits, such as mandarins [10].

Ripening, senescence, and mechanical injuries not only affect fruit quality but also significantly increase the susceptibility of fresh produce to microbial attacks that cause decay. Chemical treatments with synthetic or natural pesticides are used for fresh produce preservation, as they are highly efficient practices to inhibit microbial activity and to reduce losses. However, this practice may pose negative implications on human and environmental health, due to possibly harmful by-products and residues. For that reason, there is a growing public demand to reduce the use of these chemicals. Furthermore, several health and environmental concerns for hazardous food contamination due to preharvest application of pesticide, as shown for cherry tomatoes [11], also render this practice questionable.

As a result, a growing effort has been made in recent years to develop alternatives to fungicides. Such efforts are comprehensively reviewed and summarized for avocados [12]. Both physical means (ozone, electrolyzed water, and modified/controlled atmospheric packaging) and natural compounds (chitosan, essential oils, biocontrol agents, antifungal

edible coatings, and organic acids) are attracting research interest as alternative, safe, and efficient means for preservation in the fresh-produce industry.

Specifically, physical treatments including hot-water rinsing and brushing (HWRB) of acorn squash [4], light-emitting diode (LED) treatment to reduce anthracnose decay via inducing a resistance mechanism in avocados [13], microperforated plastic bags (Xtend®) combined with sub-optimal LT storage of peppers [14], and high-temperature wound-healing treatment of potatoes [15] were all shown to efficiently extend the shelf life and inhibit the deterioration of produce.

In addition, the use of natural components for edible coating applications is referenced as a safer option for extending the shelf life of perishable produce and improving food appearance [16,17]. Edible coatings (ECs) of fresh produce with semipermeable film can prolong postharvest fruit life through reducing moisture loss, respiration, gas exchange, and additionally delaying changes related to ripening such as fruit softening, color changes, loss of organic acids, and the breakdown of starches into sugars. Thus, ECs are increasingly gaining attention as alternative storage methods for fresh agricultural produce to extend storage time and shelf life. For example, the application of polysaccharide-based edible coatings for plums was shown to prevent shriveling—an economically important postharvest disorder [16]. In some cases, edible coatings are applied in combination with additional natural compounds that serve as antimicrobials to increase the efficiency of a treatment [17]. Nevertheless, more research is required to fully understand the specific effects of different coatings on fruit physiology and postharvest performance.

Essential oils (EO) from the aromatic plant species are an economic source of unsaturated fatty acids, posing antimicrobial and antioxidant activities that can aid in postharvest preservation. Such natural extracts as citrus [18] and sage essential oil [17] were found to delay microbial activity and to extend the shelf lives of strawberries and tomatoes, respectively. EO can be applied alone or as an additive for the edible coating of fresh produce. In tomatoes, the combined application of aloe vera gel coating with sage EO decreased fruit ethylene emission and decay symptoms, maintaining fruit firmness [17].

It is important to note that while the shelf lives of horticultural commodities is dependent on postharvest handling, shelf life is also significantly affected by a wide range of pre-harvest factors. Both genetic background and environmental parameters can significantly affect postharvest performance. Genotypic background and pre-harvest climatic conditions were found to affect the head quality and post-harvest performance of freshly cut broccoli [19]. Similarly, cultivars and cultivation seasons were found to have a significant effect on the postharvest quality and shelf lives of baby leaves (spinach and 'wild' rocket) [20], while maturity at harvest, the weather during the growing season, and orchard management greatly affected the flesh-browning of apples stored at CA [7]. Another example of the genetic effect on shelf life was demonstrated in the fruit quality of six different cultivars of mangoes [21], as well as for three acorn squash cultivars that were found to differ in susceptibility to cold storage temperatures and fungal decay [4]. In addition, agrotechnical practices such as the grafting of Cucurbitaceae vegetables such as watermelons [22], or the training and pruning of fruit trees such as mangoes [23] were shown to significantly affect fruit quality and postharvest performance [24,25]. Furthermore, the pre-harvest application of prohydrojasmon (PDJ) or abscisic acid (ABA) induced a red color in mango fruits that were exposed to sunlight at the orchard, which consequently reduced their susceptibility to fungal decay during storage [23]. All of these parameters for preharvest handling play important roles and affect the postharvest performance of fresh produce; thus, methods for controlling and manipulating these parameters have great potential to be used as part of an integrated management system.

Last but not least, it is important to note that each measure taken to reduce postharvest losses has a direct impact on the nutritional and sensory quality of fresh produce. All pre- and postharvest practices directly affect produce quality and therefore should be evaluated from a plant physiology and pathology point of view in addition to food chemistry and food nutrient aspects. Specifically, as integrated approaches increasingly become a common

practice, a standard evaluation of fruit and vegetable sensory and nutritional quality is essential, in parallel with the development of high-throughput evaluation means for the chemical composition of fresh produce. Two examples demonstrating such efforts include the evaluation of mineral (calcium) content in apples by the use of X-ray fluorescence [7], and the use of an ultrasound-assisted extraction method for extracting antioxidants in chokeberries [26] to provide a more accurate quality evaluation.

Finally, while many of these pre- and postharvest approaches to reducing produce loss that are described here (Figure 1) hold great potential as new practices for sustainable postharvest management, more research is required before they can be successfully applied commercially.

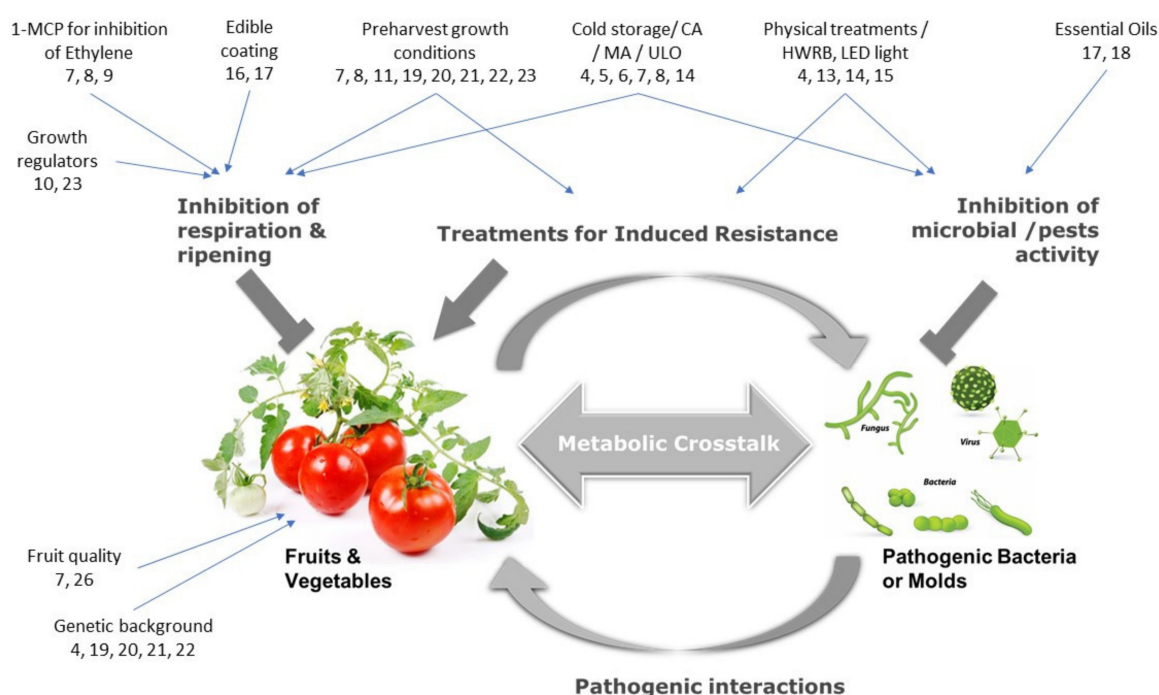


Figure 1. Current and emerging approaches to preventing postharvest deterioration of fresh produce (for more details, see text). Specified numbers refer to the relevant references cited along the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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