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Review

Opportunities for Prediction Models to Reduce Food Loss and Waste in the Postharvest Chain of Horticultural Crops

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Abstract: Significant losses occur in the fresh produce supply chain, spanning from the harvest to postharvest stages, with considerable wastage during production and consumption. Developing predictive models for overall postharvest losses is crucial to inform growers and industry stakeholders, facilitating better decision-making and resource management. These models play a pivotal role in supporting governments, as well as global food and agricultural organizations, in their efforts to alleviate poverty and ensure food and nutrition security for the growing human population. This review discusses opportunity targets for predicting total postharvest losses and addresses strategies for effective waste management with the aim of promoting sustainable agricultural production and enhancing global food security.

Keywords: supply chain; food security; global hunger; harvest; storage; shelf life; consumer demand

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1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) estimates that about one-third of food produced for human consumption is lost or wasted globally, amounting to approximately 1.3 billion tons per year [1]. Providing food for the global population, predicted to reach a peak at 11.2 billion in 2100, will be a challenge [2]. Furthermore, the United Nations Intergovernmental Panel on Climate Change has cautioned that the current global warming of 1.09 °C could exceed 1.5 °C and 2 °C during the 21st century unless greenhouse gas emissions are substantially reduced and decline to 'net-zero' around or after 2050 [3]. The inefficient utilization of natural resources such as land and water due to crop loss and waste hampers progress in vital endeavors such as eradicating hunger and poverty, ensuring nutritional sufficiency, and fostering economic growth. Within subsistence farming systems, the loss of crop quantity not only diminishes the physical supply of sustenance but also exacerbates food insecurity [4].

In today's interconnected world where food supply chains are increasingly globalized, the repercussions of food loss in one region reverberate across borders, impacting food availability and prices elsewhere. This underscores the intricate interdependence of international markets, where disruptions in one segment can reverberate throughout the entire system, affecting communities far removed from the point of origin [5]. Interestingly, reducing food loss and waste can contribute to climate change mitigation strategy and food security [6].

In the horticultural crop production chain, crop loss and waste can occur at various stages, beginning in the field and continuing through harvest, storage, transportation, wholesale, and retail markets, and in consumers' possession. The US Natural Resources Defense Council (NRDC) estimates that 40% of food in the US is never consumed [7]. Over 21% of water, 19% of fertilizers, and 18% of cropland contribute to the production of unconsumed food, an amount equivalent to the cropland area of the US states of Kansas,

Nebraska, and North Dakota combined [8]. Recent studies have placed particular emphasis on understanding on-farm crop loss and waste. Farm-level food loss encompasses food that remains unharvested or is lost between the time of maturity and its sale [7]. These studies provide valuable insights for accurately estimating total loss and expected waste based on empirical trials and observations [9]. Economic and environmental challenges are the main drivers for the on-farm crop loss and waste. In the 2023 season, Schweitzer Orchards, situated near Sparta, Michigan, faced a significant challenge as they did not harvest approximately 10% to 15% of their apple crop, while 80% of the apple fruit were left on trees in one farm in West Virginia due to lacking market. These responses to conditions were influenced by marketing concerns related to apple size, as well as fruit damage due to the temperature in the field dropping to ≈ -7 °C, ultimately resulting in a surplus of unconsumed apples left hanging on the trees. One of the primary factors driving this response was a substantial increase in labor costs, which escalated by about 40% over the past five years, placing considerable financial strain on the orchard [10]. In response to this economic issue, the United States Department of Agriculture (USDA) announced a purchase program to relieve the apple surplus in different states around the country. This was the largest government buy of apples and apple products to date. However, with the harvest window coming to an end, many growers had already left their apples to drop and rot, which increased the total loss and waste in the apple industry [11].

The postharvest chain experiences both calculated losses and unexpected waste, which necessitate a comprehensive understanding in relation to various factors influencing modern agricultural production [12]. These factors include those contributing to improved crop quality, effective harvest management, and the extension of storability, longevity, shelf life, and consumer demand [13]. The extent of total loss and waste varies depending on postharvest technologies, which exhibit high variability between countries and are often correlated with governmental support, external markets, and agricultural policies. Utilizing different treatments to maintain fruit quality stands out as a significant factor in reducing total loss. However, consumer purchasing power plays a crucial role in determining total waste in the latter stages of the postharvest chain [14]. An estimated 931 million tons of food is wasted every year, of which 60% occurs in households, indicating there are clear environmental, monetary, and societal benefits for households to reduce food waste [15]. In developing countries, limited financial resources hinder the ability to purchase commodities at competitive prices, leading to comparatively higher levels of waste when compared to developed countries.

Recently, a vast array of cultivars has emerged through breeding programs, alongside breeding efforts for new varieties, including those generated through gene editing. In spite of proof of the importance of these new cultivars in enhancing crop quality and productivity [16], this likely surge in diversity presents a potential risk for increased total crop loss, as there may not be sufficient understanding of the handling of these novel crops. Furthermore, the unchecked expansion of farm cultivation with specific cultivars, without a comprehensive grasp of market dynamics, can result in substantial losses and waste in production. Understanding the intricacies of both the crops themselves and the market demands is essential for mitigating such risks [17].

The objective of this review is to expose the interactions within the postharvest chain, facilitating predictive models that will forecast loss and waste, which can then be avoided through harvest decision-making or marketing.

2. Total Loss and Waste on Farm and at Harvest

Depending on the choice of definition used for 'food loss', this can include crops that have reached maturity in the field and were grown for the purpose of human consumption but are never harvested due to a number of interdependent factors. These losses, occurring at harvest, rather than pre- or postharvest, can be considered harvest losses, and are sometimes left out of discussion (Figure 1, [18]).

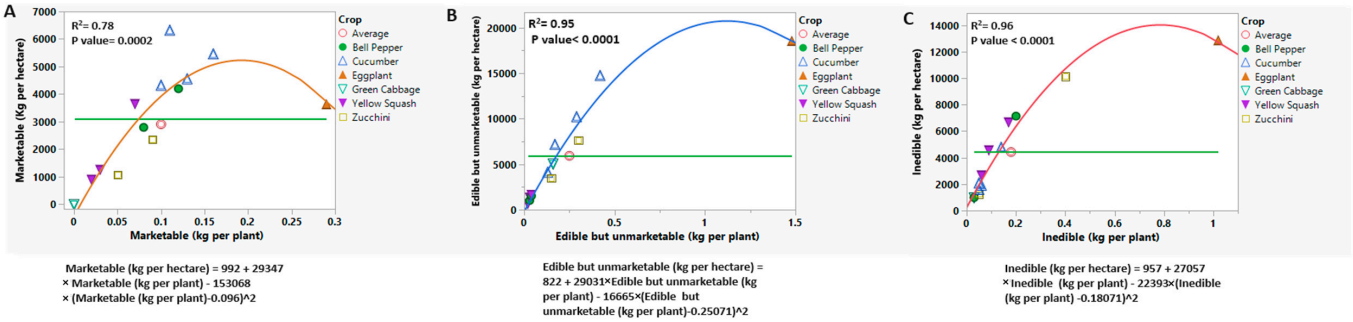

Figure 1. Prediction of on-farm marketable (**A**), edible but unmarketable (**B**), and inedible crops (**C**). Crops are used as model to explain on-farm loss and waste, and this might be applicable for any other crop. Modified from [18].

Edible, fresh vegetables in an amount equivalent, on average, to 34% to 42% of the total harvested crop remain in the field after the primary harvest in the US [9,19]. This amount can exceed 100% of the harvested crop in individual fields, because the amount not harvested can exceed the amount that was harvested. The vast majority of specialty crop yield data that are collected and reported reflect the harvested yield, rather than the total yield.

Several factors can determine whether a crop is harvested or not, and they are driven by market and environmental fluctuations, some of which can be forecasted. Growers weigh whether or not they are connected to a buyer that has an interest in purchasing the crop, the appearance and maturity of the crop in the field, the price available to them, the risk of a rejected shipment with the associated economic burden, and whether or not another crop in their purview requires attention at the same time (see Figure 2, [19]).

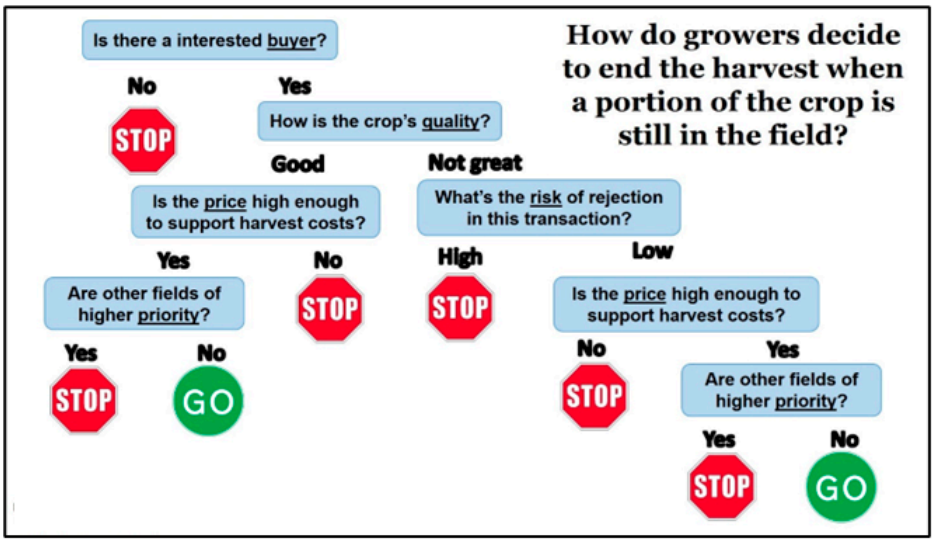

Figure 2. Growers' decision on ending the harvest when a portion of the crop is still in the field [19].

A strong point of leverage within this decision-making is the price. Ultimately, if the price growers are offered does not exceed the cost of harvesting the crop, the result is the loss of food available in the field at that time. Without accurate forecasting, growers are subjected to prices that fluctuate daily, and sometimes within a day, resulting in uncertain conditions for decision-making.

Nassar et al. [20] found that simple and compound deep learning models—the long short-term memory and the convolutional long short-term memory recurrent neural network—were more effective at predicting wholesale prices for fresh produce than machine learning types. Additionally, Noboa et al. [21] found that compound deep learning

models (convolutional long short-term memory multi-layer perceptrons) forecasted avocado prices well in Ecuador.

The focus on fresh produce pricing in this type of analysis and prediction is just beginning and is important to expand. Further, ensuring that price prediction can be used by growers at the production level will prevent and reduce losses resulting from price-driven decision-making at harvest. A crop at maturity in the field can sometimes be held there for one or two days, while a harvested crop in storage will rapidly lose shelf life if a grower is waiting for prices to improve in order to sell.

3. Loss and Waste in Postharvest Chain

Strategies aimed at bolstering food security through the mitigation of postharvest losses and waste involve a multifaceted approach. This includes the adoption of cultivars (varieties) known for their extended postharvest lifespan, implementation of integrated crop management systems to optimize both yield and quality, and adherence to meticulous harvesting and postharvest handling protocols, all of which are essential for preserving the quality and safety of horticultural crops and their derived products [22]. Various factors can influence the overall loss and waste of fresh produce, spanning from initial production planning to meeting market demand [23]. In developing countries, over 39% of postharvest losses happen during handling and storage, contrasting sharply with less than 6% in developed countries. Conversely, consumption waste takes an opposite trajectory, surging to over 61% in developed countries while remaining at 5% in developing ones (Figure 3).

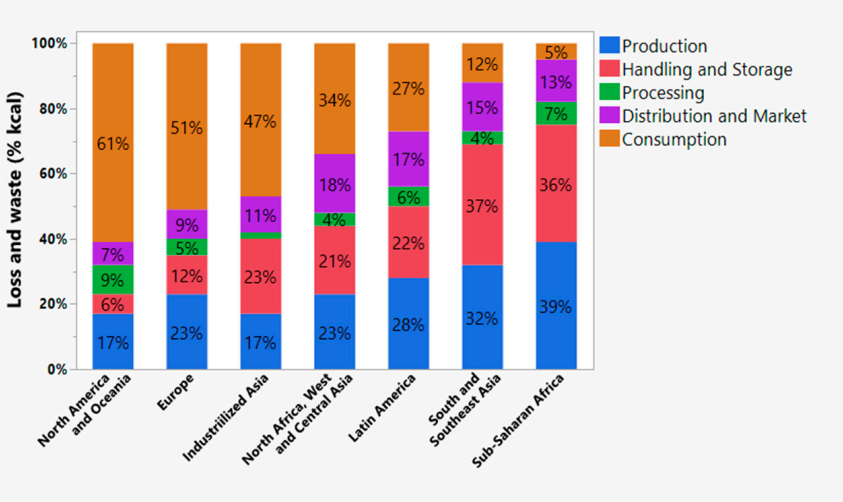

Figure 3. Global food loss and waste from farm to consumer by area. Modified from [1].

Matar et al. [24] showed that within the postharvest journey of fresh strawberries cultivated in southern Spain and distributed to France, the most substantial fruit loss was observed at the retail stage post-export, surpassing a 10%. Conversely, at the consumer level, the loss fluctuated between 2 and 30%, indicating a variable impact. The temperature during shelf life and durations was the main factor driving the fruit deterioration. At the distribution stage, prior research from the same research group has shown that a strawberry tray with more than 13% of the fruit surface spoiled would be rejected by consumers, resulting in complete discarding by the distributor [25]. The study confirms the complicated factors that lead to fruit and vegetable loss and waste during different postharvest stages and conditions.

3.1. Managing Postharvest Loss and Waste for Horticultural Crops

The United States Environmental Protection Agency (EPA) introduced the wasted food scale (Figure 4), outlining pathways to mitigate food waste and promote sustainability [26].

In a survey included 1010 consumers, the majority of respondents claimed to waste less food than the average American, mainly driven by saving money and setting a good example for children. Environmental concerns were of lesser importance. The most cited reasons for discarding food included worries about foodborne illnesses and a preference for fresher items. While there were some slight variations based on factors like age, parental status, and income, no significant differences were found across racial, educational, or residential demographics [27].



Figure 4. The wasted food scale prioritizes actions that prevent and divert wasted food from disposal. Tiers of the scale highlight different pathways for preventing or managing wasted food, arranged in order from most preferred on the top left to least preferred on the top right. Within a given tier, pathways are ranked equally. Source [26].

Postharvest losses in fruits and vegetables stem from various stages including harvesting, postharvest handling, storage, processing, distribution, and consumption.

In addition, weight loss can vary between cultivars from the same species. In a study on ten potato cultivars harvested at optimal harvest time and stored at 2–3 °C for 2–7 months without controlling the storage humidity, it was observed that some cultivars experienced lower weight loss compared to others in the same study [28]. Hence, employing suitable postharvest handling, packaging, transportation, and storage practices is crucial for minimizing these losses. Here are some causes of postharvest loss and waste along with strategies to mitigate them in the postharvest chain.

3.1.1. Optimum Harvest Time

The timing of harvest plays a critical role in determining the quality and shelf life of fruits and vegetables. Numerous factors impact their nutritional content and quality, from color development to the concentration of antioxidants and nutrients. Harvesting too early or too late can compromise stability and exacerbate water loss in crops, while also potentially leading to physiological disorders during storage. Stem end flesh browning in 'Gala' apples (Figure 5F), a physiological disorder causing severe losses during storage and shelf life, increased with late harvest. Employing precise methods to manage harvest timing can significantly reduce overall postharvest losses and waste [29].

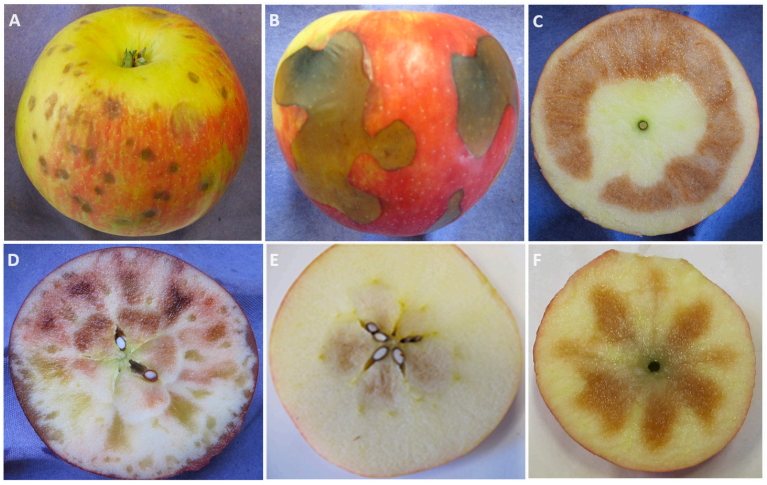

Figure 5. Fruit loss from physiological disorders development. Bitter pit (**A**), soft scald (**B**), soggy breakdown (**C**), watercore breakdown (**D**), core browning (**E**), and stem end flesh browning (**F**) in different apple cultivars. Modified from [30].

3.1.2. Storage Temperature and Relative Humidity

The ideal storage temperature can vary not only between different species but also among cultivars within the same species. Failure to maintain the correct storage temperature can lead to significant losses, with potential losses reaching 100% due to chilling injuries or freezing damage [31]. Additionally, maintaining the appropriate relative humidity is crucial for horticultural crops during storage and handling, given that the water content ranges from 76% to 94% across various fruits and vegetables. Any loss of water translates directly to weight loss and ultimately diminishes the economic value of the produce. In a preliminary study on two lettuce cultivars grown under controlled hydroponic system and stored after harvest at 20 °C for 10 h, the weight loss ranged from 14.5 to 27% and this variation was highly varied between the two cultivars (Figure 6).

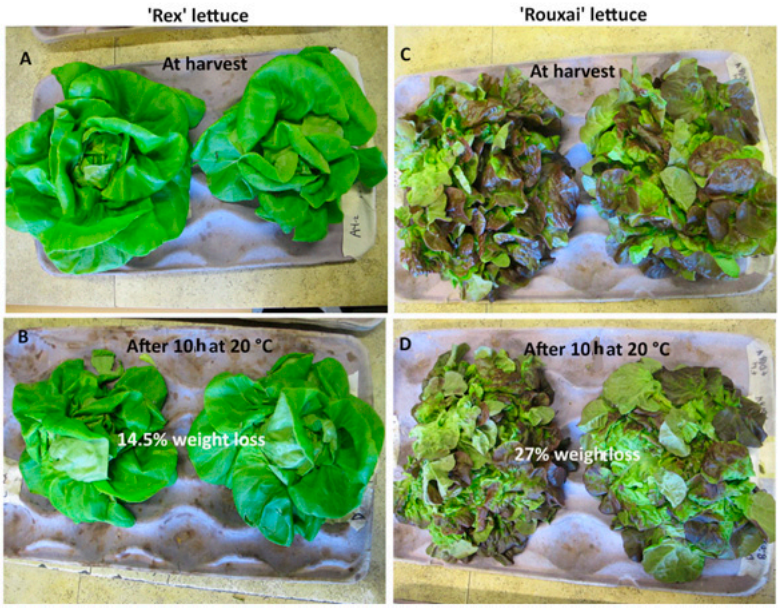

Figure 6. Weight loss in 'Rex' (**A**,**B**) and 'Rouxai' (**C**,**D**) lettuce grown in a hydroponic controlled system and stored after harvest at 20 °C for 10 h.

Wang et al. [32] developed a model that can be applied to predict the shelf-life of strawberry from 4 °C to 35 °C in range of 1 to 16 days.

3.1.3. Storage System

Fruits are distinct from vegetative tissues in that they evolved primarily as structures to attract consumers. In postharvest management, various storage systems can be utilized, including regular air storage, modified-atmosphere packaging (MAP), controlled atmosphere storage (CA), and dynamic controlled atmosphere storage (DCA) (Figure 7). Besides storage temperature, factors such as relative humidity, oxygen levels, and carbon dioxide concentration play crucial roles in these systems (Figure 7A). These factors influence the mechanisms that reduce respiration rates, suppress ethylene production in climacteric fruit, manage physiological disorders, maintain fruit quality, and minimize total loss and waste in the postharvest chain. Additionally, the tolerance of fruits and vegetables to low oxygen storage varies significantly (Figure 7B,C). Gil and Beaudry [33] discussed the main factors which cause fruit loss in postharvest (Table 1). Based on this table, it is evident that a prediction model for loss and waste is essential for every crop. However, this model may also need to be cultivar-specific and should be comprehensive, accounting for all factors that contribute to loss and waste. The DCA technique is based on the use of oxygen levels that are kept at extremely low values, at $\leq$1 Kpa, close to the anaerobic compensation point (ACP). These hypoxic conditions, which are considered the lowest oxygen limit (LOL) tolerated by fruit, are, in general, effective in retaining fruit quality compared with those in oxygen concentrations above the LOL [34]. In addition, a reduced incidence of physiological disorders in apple, such as superficial scald, stem end flesh browning, and senescent breakdown, has been reported in DCA-stored fruit [35,36]. These results can vary greatly in relation to apple genetic background [37].

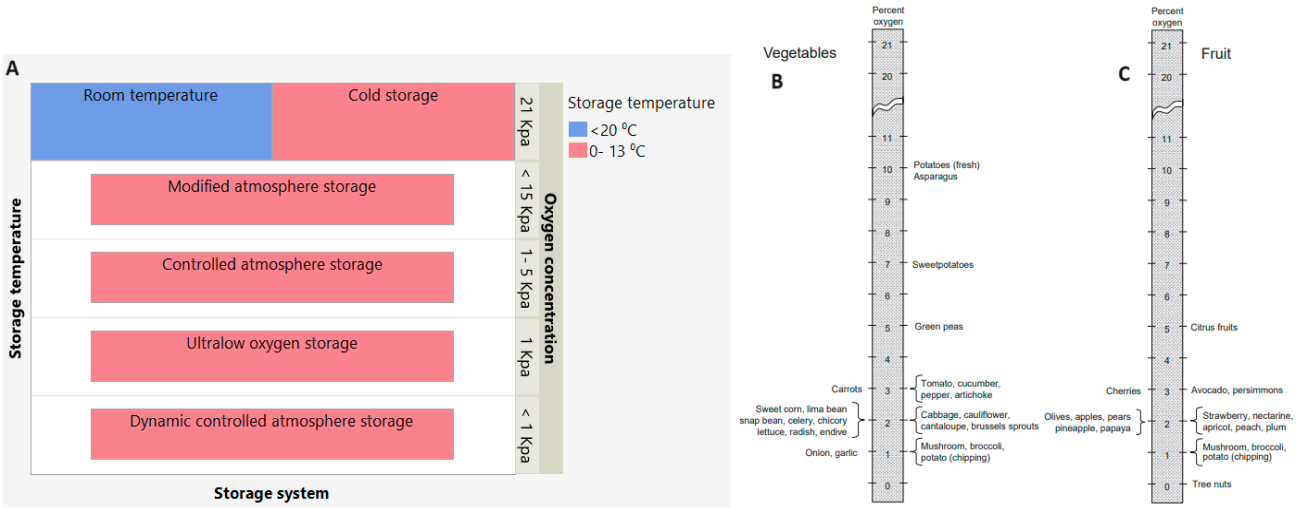

Figure 7. Storage systems based on storage temperature and oxygen level (**A**); vegetable and fruit tolerance to oxygen level in the storage (**B**,**C**). (**B**,**C**) are modified from [38].

Air storage plays a crucial role in managing fruit and vegetable postharvest in important crops such as the potato. Potato is an important crop for food security, nutrition, and the economy. However, reducing losses and waste in potato tubers during cold storage can be challenging. While low-temperature storage (4–10 °C) is effective in preserving the quality of potato tubers by inhibiting sprouting, weight loss, rotting, and greening, it also leads to the accumulation of reducing sugars such as fructose, glucose, and sucrose in a process known as cold-induced sweetening [39,40]. Managing storage temperature and relative humidity can reduce the total loss and waste in potato significantly. Nevertheless, the retail price of potatoes after storage might fluctuate daily and range from USD 0.23 to USD 2.36 per pound (Figure 8D), varying based on the cultivar, consumer preference, and the agricultural production system (conventional or organic) (Figure 8A–C). Prediction models of marketing prices might contribute to reducing the total losses and waste in potato postharvest.

Table 1. Main causes of postharvest loss for wide range of fruit. Modified from [33].

Fruit	Main Causes of Postharvest Loss
Apple	High respiration rate, high storage temperature, physiological disorders, softening
Pear	Physiological disorders, softening, CO_2 injury, O_2 injury during CA storage
Peaches, nectarines, plums, apricots	Physiological disorders, chilling injury, softening
Sweet cherries	Water loss, shriveling, pitting, stem browning, softening
Strawberries	Bruise, decay, water loss
Raspberries, blackberries, blueberries	Bruise, decay, water loss, shriveling
Table grapes	Berry shatter, water loss, decay, rachis, peduncle browning
Bananas	Physiological disorders, delay ripening, rapid ripening, decay
Mangoes	Chilling injury, delay ripening, decay
Papayas	Mechanical injury, chilling injury, decay
Pineapples	Mechanical injury, translucency, chilling injury, postharvest diseases
Avocados	Fruit ripening, water loss, storage temperature, decay
Cherimoyas	Chilling injury, mechanical damage, splitting, decay
Citrus	Chilling injury, physiological disorders, water loss, decay
Dates	Sunburn, fruit maturity, chilling injury, water loss
Figs	Decay, mechanical damage, weight loss
Guavas	Rapid ripening, water loss, mechanical damage, chilling injury, decay
Kiwifruit	Physical damage, physiological disorders, decay
Melons	Chilling injury, mechanical damage, decay
Persimmons	Chilling injury, flesh discoloration, decay, softening
Prickly pear	Water loss, pericarp thickness, maturity, decay
Pomegranates	Chilling injury, fruit cracking, physiological disorders, sunburn, water loss, aril browning, decay
Fresh-cut fruits: apples and pears	Browning, water loss, microbial growth
Fresh-cut fruits: mangoes	Browning, water loss, microbial growth
Fresh-cut fruits: melons	Microbial growth, water loss

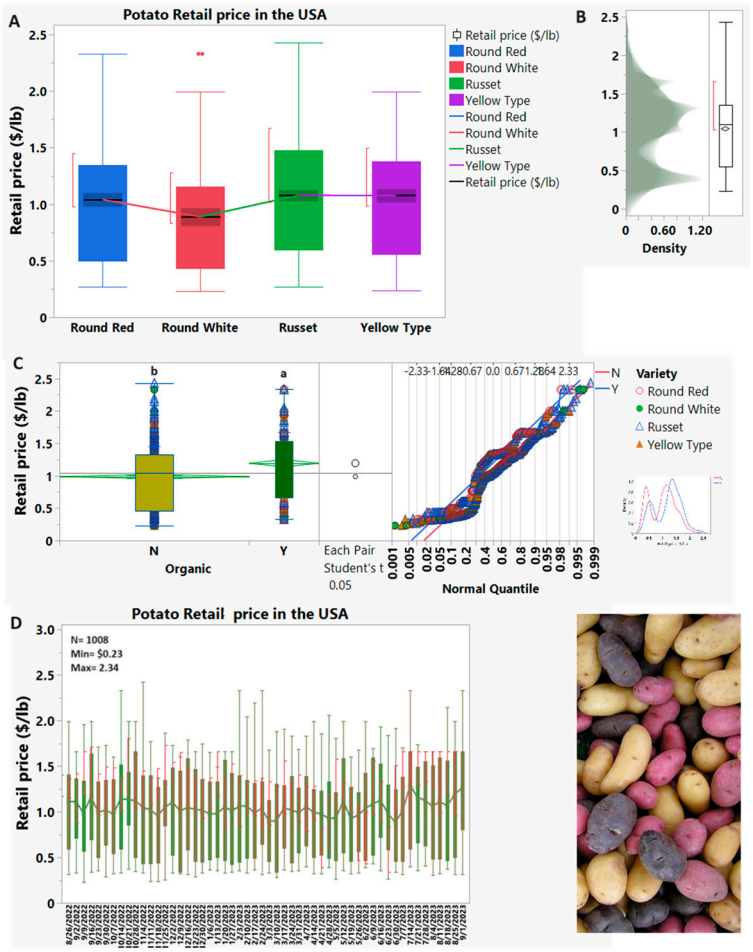

Figure 8. Potato retail price in the USA in 2022–2023 based on variety (**A**), agricultural system (**B**,**C**), and daily price (**D**). Modified from [41].

In apple fruit storage, using the appropriate system can increase total income and help meet market demand and sustainable production. Apples can be stored at room temperature for 1 week. In modified-atmosphere packaging (MAP), the storage time can be extended by reducing water loss, respiration, and ethylene production, even at room temperature. Storing apples in cold storage at temperatures ranging from 0 to 4 °C can extend their storage life to 4 to 6 months, depending on the cultivar. Moreover, using controlled atmosphere (CA), ultra-low-oxygen (ULO), and dynamic controlled atmosphere (DCA) technologies can prolong storage life to 9 to 11 months, based on the cultivar and its susceptibility to low-oxygen storage [33]. These advances in storage systems will not only reduce total losses but also maintain the highest fruit quality and help achieve competitive market prices. However, the retail price after storage can be dynamic and might change daily, ranging from USD 0.2 to USD 5 per pound (Figure 9C), and different factors control its value (Figure 9A,B,D). This price fluctuation drives losses and waste.

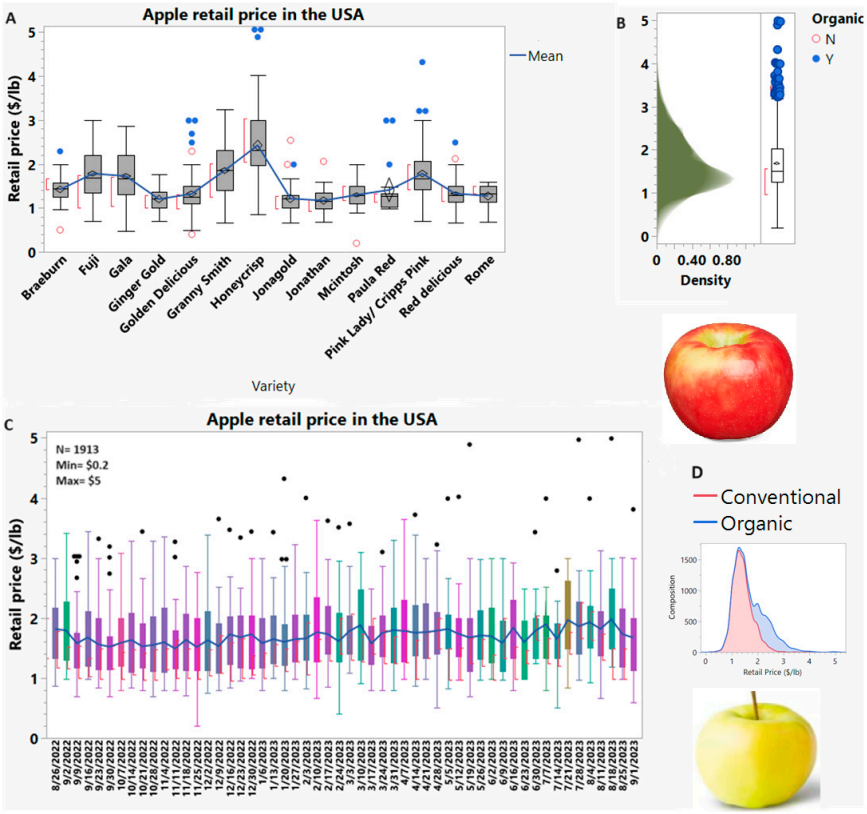

Figure 9. Retail price of apple fruit in the USA in 2022–2023 based on variety (**A**), Agricultural system (**B**,**D**), and daily price (**C**). Modified from [41].

Weight loss in baby spinach stored at 4 °C for 12 days was reduced by 1.3% in leaves stored in modified-atmosphere packaging (MAP) with 5% O_2 and 15% CO_2 compared to those stored in 78% N_2 and 21% O_2 [42].

Selecting the optimal storage system based on horticultural crop physiology, storage time target, market demand, and consumer preference is a key factor in reducing total loss and waste during storage.

3.1.4. Physiological Disorder Management

The total loss in fruit and vegetables from postharvest physiological disorder development might reach 100%. Postharvest physiological disorders are a result of the abiotic stress [29]. However, different pre- and postharvest factors might influence physiological disorder development in horticultural crops [43]. Identifying the physiological disorders in every crop and even at the cultivar level is critical to reduce total loss and waste in the

postharvest chain. The prediction models based on the fruit maturity, fruit nutrient content, the response to storage temperature, and different kinds of postharvest biotic and abiotic stresses are strong tools to mitigate total loss and waste and manage the marketing plans.

A comprehensive examination of prediction models for bitter pit in 'Honeycrisp' apples has illuminated a promising avenue for mitigating postharvest losses by over 30% [44].

3.1.5. Managing Postharvest Pathogens

Losses stemming from pests and diseases impacting fresh fruits and nuts throughout the supply chain—from harvest to commercialization—are notoriously difficult to gauge accurately. In regions with robust postharvest infrastructure and storage facilities, these losses are estimated to hover around 25% of total production. However, in developing countries, where storage facilities and postharvest handling chains are often insufficient, losses can skyrocket, surpassing 50% [45]. Crafting an integrated strategy encompassing decay management, preharvest, harvest, and postharvest practices is paramount. These components play pivotal roles in shaping the intricate interplay among hosts, pathogens, and environmental factors. Romanazzi et al. [46] conclude that integrated management program where adoption of a holistic approach is the key for meeting the challenge of minimizing postharvest losses caused by gray mold, incited by *Botrytis cinerea*.

The control of postharvest decay usually relies on synthetic fungicides. Fungicides are widely used due to their effectiveness, persistence, and cost efficiency in managing decay losses, even under suboptimal storage conditions [47]. However, future use of postharvest fungicides will be restricted or banned by many countries [48]. The approval of fungicides for horticultural products warrants careful scrutiny because their residues, which inhibit pathogens, are present on products consumed by the public. Fungicides are often used in combination with other strategies, such as sanitizers, heat treatments, and coatings. Modeling to predict losses could help limit fungicide use to when it is truly needed, reducing unnecessary applications. Despite the introduction of new fungicides, their use on horticultural crops is generally declining. For instance, fungicide use in California decreased from 1,300,000 pounds in 2007 to 700,000 pounds in 2018 [49]. On the other hand, employing biocontrol agents as a substitute for synthetics faces numerous constraints and hurdles, making it challenging to integrate them effectively into practical control strategies.

Recently, reducing total loss, waste, and ensuring food safety and sustainability in postharvest chain from pathogens has become highly imperative and can be achieved through various means: marker-assisted selections [50,51], understanding the relationship between the pathogen and fruit defense system [52], identifying the endophytic and epiphytic microbiome and their interaction and mechanisms in fruit [53–55], developing postharvest biological control strategies [56,57], an adopting integrative approaches for postharvest pathogen management.

3.1.6. Fruit and Vegetable Quality in the Packing Line

Fruit loss and waste after harvest and during handling in the packing line can be significant and unpredictable. Ait-Oubahou et al. [58] explained that different protocols can be adopted for fresh produce handling and packing and that they differ by crops. Injuries caused by improper handling tend to increase respiration rate, weight loss, ethylene production, senescence, and decay in horticultural crops. Water loss will increase if the outer skin of the produce is damaged and/or when it is kept at high temperatures associated with low moisture content in the air. Water loss from produce is the principal cause of weight loss, poor appearance such as shriveling and wilting, loss of textural quality, firmness, crispness, and juiciness, and overall loss of nutritional value.

Adopting new technologies for assessing fruit quality and sorting the fruit based on specific parameters relevant to the crop and market demand is critical for reducing total loss in the packing line.

3.1.7. Coating and Reducing Weight Loss during Shelf Life

The transition of fresh produce from cold storage temperatures to uncontrolled market temperatures, which varies during transportation and exhibiting for sale, can significantly influence respiration rates and fruit metabolism. Ultimately, this can lead to increased water loss, fruit shriveling, wilting, and alterations in sensory attributes. To reduce fruit loss and waste, various coating materials are applied. These coatings, composed of food additive compounds, protect the fruit's surface and reduce water loss, thereby maintaining fruit quality during storage and shelf life.

Edible coatings serve as thin layers of edible material applied to food surfaces, either in addition to or in lieu of natural protective waxy coatings [59,60]. They act as barriers against moisture, oxygen, and solute movement. These coatings are typically applied directly onto food surfaces through dipping, spraying, or brushing techniques, effectively creating a modified atmosphere [59].

Given that they are consumed, materials used in the preparation of edible films and coatings must be generally regarded as safe (GRAS) by the FDA, and they must adhere to relevant regulations concerning the specific food product [61]. The impact of these coatings on fruits and vegetables varies significantly based on factors such as temperature, alkalinity, coating thickness, and type, as well as the variety and condition of the produce [62].

Shah et al. [63] found that hypobaric treatment and chitosan coating either alone or in combination significantly reduced weight loss compared to untreated fruit. The industrial application of carrageenan coating with calcium on fresh fruit improved external firmness and reduced quality loss in fresh strawberries [64]. Peach fruits treated with rhubarb–sodium alginate coating maintained their quality, sensory attributes, and reduced decay loss compared with untreated fruits [65]. Edible coating application contributed to maintaining quality, reducing weight loss, delaying physiological disorder development, and extending the shelf life of pear fruit [66].

An integrative approach is necessary to comprehend the interactions among cultivar, fruit maturity at harvest, storage temperature, fruit microbiome, fruit quality during storage, and the effectiveness of coatings in reducing overall loss and waste in specific crops.

3.1.8. Consumer Preference

According to United Nations statistics, nearly one-third of the total international output of food is wasted every year, and the annual cost of food waste disposal is as high as 940 billion US dollars [67]. Food waste is closely linked to the final stage of the postharvest chain, largely dependent on consumer acceptability and preference. Individuals vary in their tastes and behaviors, and generally, consumers are keen to explore new cultivars and crops, with a focus on healthy produce on the market. However, purchasing decisions can be influenced by economic factors and individual purchasing power. A multitude of complex factors can impact the overall loss and waste of horticultural crops at the consumer level.

Huang et al. [68] show that consumers who prefer suboptimal citrus fruit with a freshness indicator and traceability certification are willing to pay more for the purchase. To reduce total loss and waste of fruits and vegetables in the postharvest stage at the consumer level, developing and adopting innovative approaches such as smart logistics management, as well as active and intelligent packaging, apps, and software, is highly encouraged [69].

Efforts to reduce total loss and waste at the consumer level should be grounded in holistic approaches and strategies that correlate fruit quality with consumer acceptability. Prediction models can be instrumental in guiding governments and policymakers toward an effective management of total loss and waste, thereby contributing to the fight against global hunger and promoting sustainable resource management.

3.2. Prediction of Loss and Waste in Postharvest Chain

In recent years, artificial neural networks, genetic algorithms, fuzzy logic, and adaptive neuro-fuzzy inference systems have become integral tools across various domains of food science [70–72]. Integrative prediction models for total loss and waste are necessary. These models should be specific, taking into account factors such as cultivar, growing region, pre- and postharvest technologies, postharvest disease management, marketing plans, shelf life, and consumer preferences. Various parameters need to be considered to accurately assess total loss and waste, enabling the development of solutions to reduce losses and manage waste effectively.

Many models have been developed to reduce loss during the postharvest chain, including validation. Examples include prediction models of bitter pit in 'Honeycrisp' apples to reduce physiological disorder development during storage and to manage marketing [44]; prediction models of gray mold risk in pear fruit in long-term cold storage [73]; prediction models of physiological disorders in apple fruit based on maturity indices at harvest [74]; integrative prediction models for potato dormancy and sprouting to reduce loss during storage [75]; prediction models for strawberry quality in relation to postharvest decay and modified-atmosphere storage [76]; and prediction models of potato tuber quality based on maturity indices [77]. Furthermore, the advanced utilization of nondestructive prediction models for assessing fruit and vegetable quality parameters at harvest, as well as during storage, packing line, and transportation, contributes to reducing losses and waste. These models enable easy monitoring of fruit quality, facilitating the attainment of consumer acceptability [78–84]. However, more research is needed to develop holistic models for individual crops to connect environmental data with fruit physiology.

Many factors contribute to fruit loss and waste prediction models. Fruit loss from culls was about 14% in 'Gala' apples, and various factors affected the estimation of fruit loss, starting from the use of plant growth regulators (PGRs) to manage harvest and prevent fruit drop, to the costs associated with picking, handling, and storing the fruit. Other factors include the use of postharvest PGRs such as ethylene inhibitors, fungicides, post-storage handling, and fruit packaging (Figure 10) (personal communication with Ryan Hess, Hess Brothers' Fruit Company, Lancaster County, PA, USA).

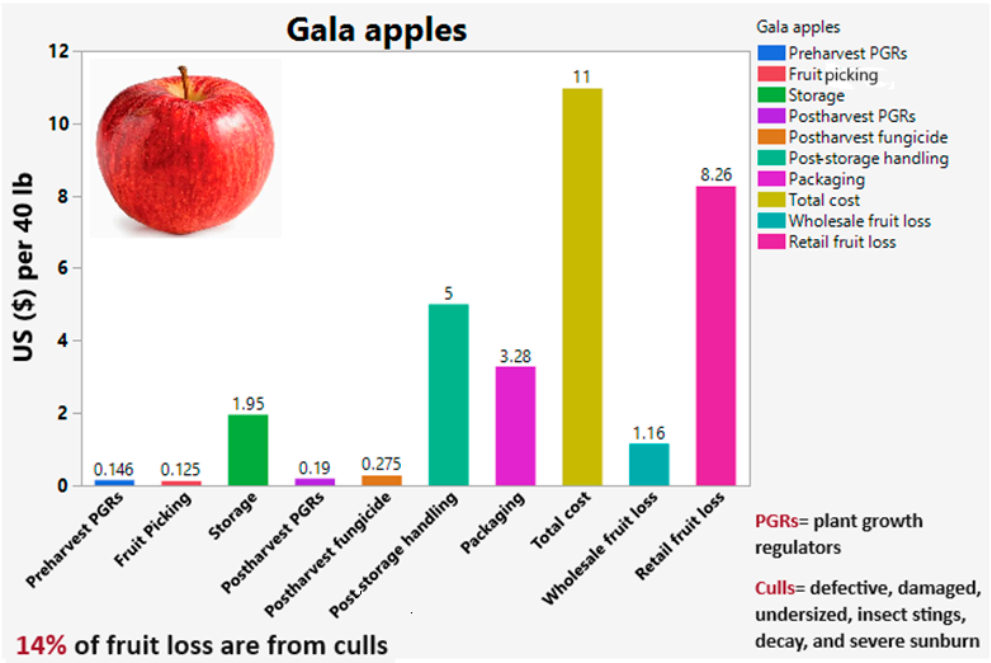

Figure 10. Fruit loss in 'Gala' apples in postharvest chain after long-term storage. (Personal communication with Ryan Hess, Hess Brothers' Fruit Company, Lancaster County, PA, USA).

4. Interaction between Total Loss and Crop Waste on the Farm and in Postharvest

The quality of fruit is regarded as the primary factor influencing the interaction between harvested fruit and fruit within the postharvest chain. Recent strides in artificial intelligence, particularly in machine learning, have ushered in a new era of efficiency across pre- and postharvest tasks, catalyzing a profound metamorphosis within the food value chain. By seamlessly integrating machine learning into horticultural practices, not only have operations been revolutionized, but the pace and precision of myriad processes have also been elevated to unprecedented heights [85]. Machine learning is used to assess preharvest fruit quality, fruit maturity, yield prediction, postharvest handling and processing, fruit sorting and grading, prediction of consumer behavior, and prediction of sales.

Based on the model developed by Johnson et al. [19], prediction models for fruit quality, storage economic performance, consumer preference, and marketing strategies are required for integrated decision-making by growers, stakeholders, government, and policymakers to minimize total losses on farms and during postharvest and to pave the way toward sustainable agricultural production.

5. Global Strategies to Manage Loss and Reduce Waste in the Postharvest Chain

The FAO has pioneered the development of the Global Food Loss Index (GFLI), a groundbreaking tool designed to empower policymakers by providing comprehensive insights into both the positive strides and concerning patterns regarding food loss trends over time [86]. In addition, the wasted food scale released by the US Environmental Protection Agency prioritizes actions that prevent and divert wasted food from disposal (Figure 5).

Different strategies can influence reducing total food loss and preventing food waste globally, such as the following:

1. Connecting growers worldwide through international grower associations can educate, manage, guide, and explore new integrative technologies and markets to reduce losses and enhance economic and sustainable profitability.
2. Fighting global hunger by implementing strategies to ship unharvested and unused crops from some parts of the world to other countries in need.
3. Training growers and stakeholders on the latest storage technologies for every crop.
4. Building an integrative prediction model to reduce loss and prevent waste for every individual crop, supporting global food security through new and existing international organizations such as the FAO.
5. Educating people about food safety regulations and rules in both developed and developing countries.
6. Using databases from research centers and universities worldwide to build strong and reliable estimates of actual food loss and waste globally.

6. The Effects of New Agricultural Technologies on Crop Loss and Waste on Field and in the Postharvest Chain

Sophisticated breeding programs have contributed significantly to enhancing crop quality, increasing productivity, prolonging shelf life, and improving consumer preference [87–89]. However, the gap between breeding programs and postharvest science needs to be filled to avoid losses that may occur due to a lack of industry knowledge regarding the stability of these new cultivars. Additionally, the large number of new cultivars released annually, especially for perennials, might negatively impact marketability and consumer acceptability.

The novel approaches in crop gene editing, such as clustered regularly interspaced short palindromic repeats (CRISPR) technology, provide a powerful tool for editing genomes, allowing researchers to easily alter DNA sequences and modify gene functions. This technology has the potential to enhance crop nutritional value, prolong shelf life, and improve quality and reduce crop total loss [90]. Arctic apples, pink pineapple, and GMO papaya are examples of commercialized GMO horticultural crops.

Digital agriculture, robotics, artificial intelligence, smart packaging [91–93], spectroscopy [94], imaging, nanotechnology [95], nanoparticles, and mechanization are excellent tools for managing postharvest loss and waste. They also help reduce labor and costs during the postharvest chain [96,97].

7. Conclusions

Managing postharvest loss and waste is a critical factor for food security, sustainable agricultural production, and combating global hunger. Various factors can impact horticultural crop loss and waste in the postharvest chain. These factors are complex and need to be integrated into prediction models that can connect all these elements to guide growers, distributors, industry professionals, policymakers, and governments in making informed decisions regarding storage and marketing.

The identification of the drivers of food loss and waste in horticultural crops and the interacting factors that contribute to losses allows predictive analytics to target these areas individually, or, more usefully, as a collection, which will act to forecast losses in time for their prevention.

Building integrative global strategies to reduce loss and waste in the postharvest chain is essential. This can be achieved by supporting growers and farms on a global scale. Adopting new postharvest technologies and integrating pre- and postharvest efforts to improve and maintain quality will significantly reduce total loss. Effective marketing strategies and consumer education will also help reduce losses and waste in the final stages of the postharvest chain, contributing to better global health and wealth distribution.

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