Preprint

Solution roadmap to reduce food loss along your postharvest supply chain from farm to retail

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Fresh fruits and vegetables typically have a limited shelf life due to their high moisture content and perishable nature. Notably, long global import and export supply chains can lead to an increased risk of food loss. The main underlying drivers for such food loss are air temperature, relative humidity, but also the ripening gases influenced by the product's postharvest physiology. These factors can lead to quality variation, over-ripening, or microbial decay. Other factors that can cause food loss include supply chain procedures, such as the lack of transparency (i.e., no cold chain or quality monitoring) or unfavorable product inventory management. Optimizing supply chains to minimize postharvest food loss is challenging, as a multitude of individual measures can be taken. A reason is that available strategies work on different food loss drivers, which vary between products and supply chains. Stakeholders, therefore, often do not know where to start. Here we propose a comprehensive collection of 30+ measures for shelf-life prolongation of fresh fruit and vegetables across the food supply chain. This experience-based roadmap was constructed based on our close collaboration with different cold chain stakeholders. The presented 30+ solutions address inefficiencies during storage, packaging, or transport processes by distinguishing hygrothermal food loss drivers. Examples are (1) the adaption of an optimal storage temperature to prevent over-ripening but also chilling injuries; (2) improved packaging ventilation to ensure cooling efficiency and appropriate humidity conditions around the products; or (3) product-related solutions, for instance, by maintaining specific storage or packaging gas composition, acting on the commodities' unique physiology to prolong its shelf life. Furthermore, we included measures for supply chain monitoring or specifically at the retail stage. The easy-to-use solution roadmap is outlined for fresh produce suppliers, distributors, and retailers to accelerate these stakeholders' decision-making and actions and eventually combat postharvest losses.

Keywords: fresh fruits and vegetables, cold chain, cooling, packaging, shelf life

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1 Introduction

Fresh fruits and vegetables are a source of essential nutrients and fibers in the human diet. However, their limited shelf life and high perishability lead to an increased risk for food loss, especially along global food chains. Worldwide, about 20% to 50% of all produced fruits and vegetables are lost or wasted along the supply chain before they reach the consumer stage [1]. Causes for spoiled produce are improper postharvest handling, cold chain mismanagement, and non-optimal packaging, amongst others [2]. Additionally, complex global chains with many engaged stakeholders are susceptible to disruption by sudden events, such as delayed operation processes, extreme weather conditions, or for instance, consequences of the current COVID-19 pandemic [3]. As food loss and waste have a high socio-economic impact on food security and carbon emission globally, this topic is of particular concern [4].

Many recent studies have discussed the reasons for postharvest food loss and how to reduce it [2], [5], [6]. Previously it was described to categorize causes and solutions for food loss and waste on micro-, meso- and macro-levels [7], [8]. Measures tackling the latter include systemic factors usually influenced by governments and policies. Meso-level solutions are fostered by collective actions, such as agreements on good practices, close interaction between stakeholders, or the promotion of efficient food chains. Micro-level solutions are typically processes or technologies for packaging, storage, and transport that individual actors along the supply chain implement. This study will focus on micro-and meso-level solutions, which actors can take downstream of the supply chain (i.e., transporters, suppliers, retailers), excluding the consumer stage.

Today, a multitude of available solutions to tackle food loss are present [9]. However, specific measures are often either discussed in isolation or tailored to particular stages or the fresh produce supply chain. It is challenging for stakeholders to identify which measures are available and decide which actions are optimal to take. This is influenced by the fact that each chain varies due to product type, origin, and specific supply chain standards and protocols. Besides, the product quality is not only affected by preharvest and climate fluctuations, but it is also vulnerable to specific food loss drivers (i.e., temperature, humidity, ripening gases). Consequently, classifying food loss solutions based on those drivers can help to accelerate identifying appropriate measures.

Here, we present a selection of actions for product suppliers, distributors, and retailers to minimize postharvest loss of fresh produce. First, we discuss the different drivers of fruit and vegetable quality deterioration and antagonizing methods. Second, we address additional categories, including the retailer's operation system and supply chain monitoring leading to food spoilage favoring conditions. Based on each of these categories, we propose a roadmap of 30+ individual solutions that increase the shelf life of fresh produce. Finally, we discuss how these measures fit different product types and supply chain scenarios.

2 Food loss drivers along the supply chain and possible antagonizing solutions

2.1 Temperature abuse in the cold chain

It is well known that temperature is the key driver of postharvest losses. The main reasons are temperature-dependent processes, such as respiration or transpiration leading to over-ripening and senescence, but also the growth of pathogenic microbes [10]. Therefore, it is crucial to continuously maintain an optimal temperature range with proper ventilation along the whole supply chain to minimize or decelerate those undesirable processes [11]. It should be ensured that cooling is implemented as soon as possible after harvest. Also, the precooling technology needs to be optimized for each commodity to prevent damage through temperature shocks [12]. Where access to electricity and refrigeration is lacking, low-energy cooling systems (e.g., evaporative or solar-driven coolers) are possible options for short-term cold storage [13], [14]. On the other hand, temperature control is also essential to prevent chilling or freezing injuries of cold-sensitive products typically with (sub)tropical origin [10].

2.2 Low humidity and increased moisture loss

Transpiration-induced water loss is de facto a loss in marketable weight and consequently leads to quality reduction through symptoms including wilting, shriveling, or softening. Different fresh produces (fruits, tubers, roots, leafy vegetables) show a wide range of susceptibility to transpiration due to morphological and anatomical variation, including surface area, water content, or skin permeability [15], [16]. For most fresh produce, humidity in the storage atmosphere or packaging headspace should typically be maintained high (>90%). Nevertheless, packaging and storage specifications must be adjusted separately for each product to achieve optimal quality. Next to traditional plastic packaging (e.g., trays, bags, foils), several recent and more sustainable solutions are available for enhancing a high humidity environment around the products. Examples are biodegradable polymers, (edible) coatings, and humidifying systems [17]–[21]. Furthermore, it should be noted that for certain products, including roots or tubers, postharvest washing steps can significantly reduce shelf life by removing natural protective layers (minimizing moisture loss) or by increasing the risk of microbial infection by contaminated water [22], [23].

2.3 High humidity and related condensation and microbial decay

Another cause of food loss is postharvest diseases induced by various microbial pathogens, including fungi and bacteria. These organisms mostly show advanced growth under moist and warm conditions [24]. Elevated humidity levels or the presence of tiny water droplets from condensates favors the germination and growth of pathogenic fungal spores. Temperature fluctuations in the cold chain can lead to such condensation on the fruit's surface or packaging films [25]. It is, therefore, crucial to optimize packaging for each product to control moisture and minimize condensation films. This can be achieved by optimal ventilated packaging (positions, size, amount of ventilation holes) [26], active or modified atmosphere packaging [27], humidity regulating trays [28], [29], or moisture absorbers in the packaging [30].

2.4 Ripening gases accelerating over-ripening and senescence

Different species and cultivars have a unique postharvest metabolism that influences the onset and duration of ripening and decay processes. Climacteric fruits (e.g., mango, avocado, apple, avocado), which continue to ripen after harvest, are of specific concern since their postharvest shelf life is often short [31]. After harvest, these fruits produce the plant hormone ethylene, which influences their ripening and senescence reactions but also of other surrounding horticultural products. Other ripening gases, such as O_2 or CO_2, in the product's surrounding atmosphere additionally influence its respiration rate and related shelf life. Suitable postharvest technologies, such as controlled atmosphere storage or active packaging, modify the surrounding gas composition to maintain the product's freshness longer [16], [32], [33]. Furthermore, ethylene absorption, prevention of mixed loaded cargo, and well-ventilated storage and transport can help control and slow down ethylene-related processes [34]–[36].

3 Current strategies and trends to optimize supply chain operations

In addition to the main underlying food loss drivers, supply chain protocols and product standards influence food loss and waste accumulation. In the following, we discuss relevant improvements for individual supply chain operations.

3.1 Adequate quality and packaging standards

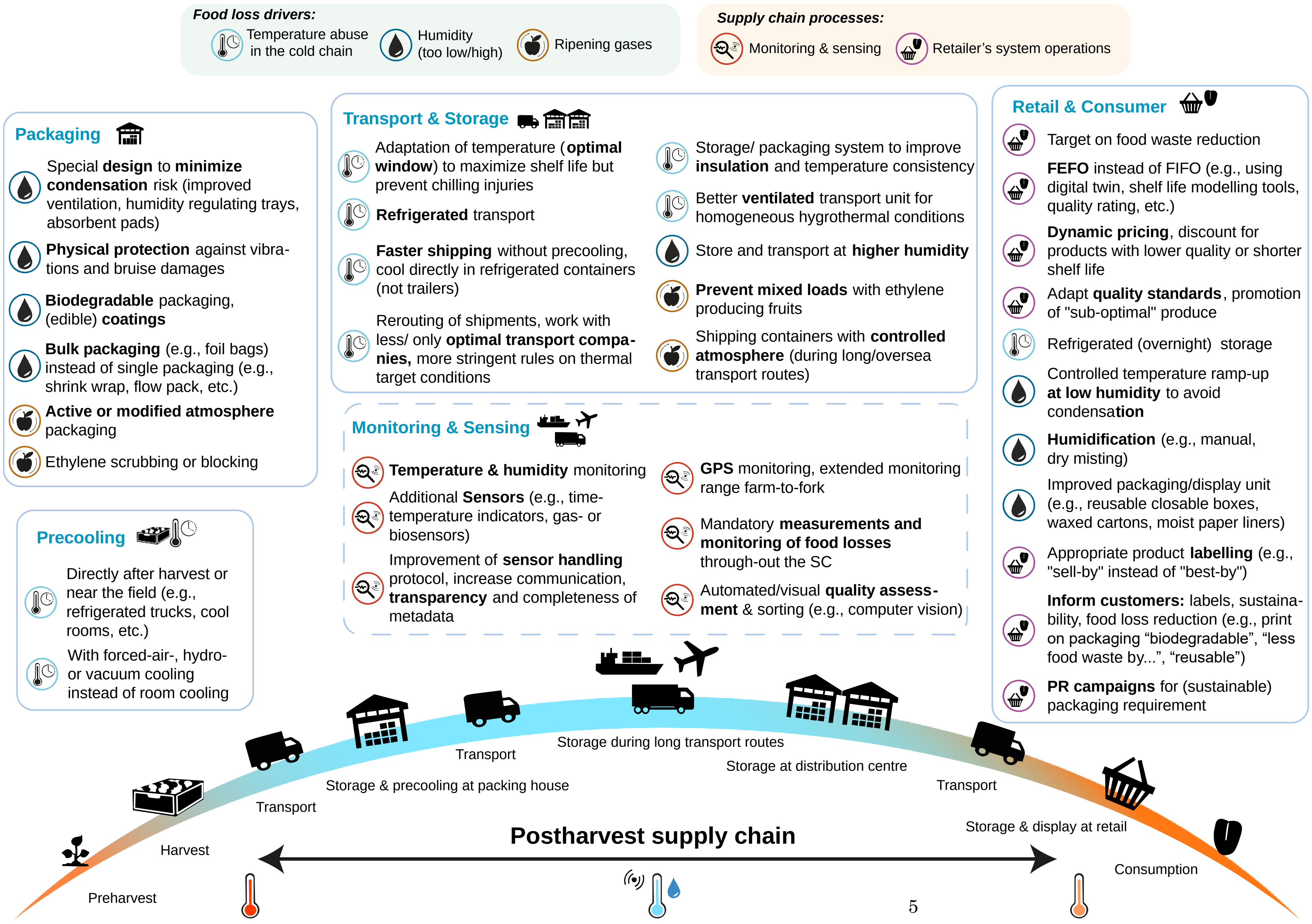
While quality standards help maintain product uniformity and thereby reduce food loss during long supply chains, they can also induce food loss due to "imperfect" and out-sorted products [37]. Thus, to decrease this avoidable loss, the possibility of purchasing products with non-conform size, shape, or increased maturity should be encouraged. Recent studies have shown that consumers are willing to buy such products when discounted [38], [39]. Another option is dynamic pricing for different product qualities incentivizing customers to buy not only perfect products without any blemishes [40]. Furthermore, communication in stores helps to improve the perception of suboptimal food and motivation for purchase [41]. Product labels should inform customers clearly, such as "best-before" instead of "sell-by" dates which are usually misleading [42]. In addition, information on the product can also be used to inform the customer about how food loss is currently prevented. An example is the required use of packaging for imported products with long transport routes [43]. Nevertheless, recyclable and reusable packaging units should be preferred to reduce greenhouse gas emissions, especially for domestic products.

3.2 Improved monitoring to identify temperature abuse and food loss hotspots

Various incidents, including power cuts, weather, or cooling delays, can cause interruptions in the cold chain leading to accelerated decay and eventually food loss. To close these gaps, monitoring air temperature and other environmental factors (relative humidity or ripening gases) help identify weak points and optimize cold chains [44]. Today, several sensor technologies, including (hygro)thermal loggers or Time-Temperature Integrators (TTI), are currently available for sensing conditions of packed or transported products [45]–[47]. Additionally, shelf life models and digital twins of fruits and vegetables connected to real-time sensor data can predict the product quality evolution until the retailer [48]–[50]. By the use of this information, product inventory management can be improved to first sell products with a reduced shelf life, so by implementing "first-expired-first-out" (FEFO) instead of the "first-in-first-out" (FIFO) system [40], [46]. Next to monitoring environmental conditions, measurements of fruit quality at different stages along the supply chain (e.g., by hyperspectral imaging) can further help implement a FEFO inventory system. Finally, it is required to measure food loss and waste from farm to fork transparently. By linking product quality and loss data, it is possible to identify food loss hotspots, enabling optimal reduction intervention. Hence, transparency along the supply chain through data collection and sharing amongst stakeholders is needed, and consequently, communication technologies and close collaborations through effective partnerships reduce postharvest losses due to improved structural efficiencies [2], [51]. Thus, investments in new technologies for intelligent labels logistics, such as gas sensors or remote quality monitoring, can significantly accelerate the retailer's food loss impacts [45], [52], [53].

4 Specific solutions for reducing food loss from farm to retail

In the following, we present the solution roadmap to help reduce food loss at different stages in the supply chain (Figure 1). The proposed solutions antagonize specific food loss drivers (i.e., temperature, humidity, ripening gases) (section 2) or inefficiencies in the retailer's operation system (i.e., standards, labels, inventory management) (section 3.1). In addition, we list actions for plastic reduction, supply chain monitoring processes (i.e., cold chain, product quality, food loss) that improve problem identification, as well as transparency and communication between stakeholders (section 3.2). In the subsequent Table 1, the solutions are outlined together with relevant references.



Food loss drivers:

- Temperature abuse in the cold chain
- Humidity (too low/high)
- Ripening gases

Supply chain processes:

- Monitoring & sensing
- Retailer's system operations

Packaging

- Special **design** to **minimize condensation** risk (improved ventilation, humidity regulating trays, absorbent pads)
- **Physical protection** against vibrations and bruise damages
- **Biodegradable** packaging, (edible) **coatings**
- **Bulk packaging** (e.g., foil bags) instead of single packaging (e.g., shrink wrap, flow pack, etc.)
- **Active or modified atmosphere** packaging
- Ethylene scrubbing or blocking

Precooling

- Directly after harvest or near the field (e.g., refrigerated trucks, cool rooms, etc.)
- With forced-air-, hydro- or vacuum cooling instead of room cooling

Transport & Storage

- Adaptation of temperature (**optimal window**) to maximize shelf life but prevent chilling injuries
- **Refrigerated** transport
- **Faster shipping** without precooling, cool directly in refrigerated containers (not trailers)
- Rerouting of shipments, work with less/ only **optimal transport companies,** more stringent rules on thermal target conditions
- Storage/ packaging system to improve **insulation** and temperature consistency
- Better **ventilated** transport unit for homogeneous hygrothermal conditions
- Store and transport at **higher humidity**
- **Prevent mixed loads** with ethylene producing fruits
- Shipping containers with **controlled atmosphere** (during long/oversea transport routes)

Monitoring & Sensing

- **Temperature & humidity** monitoring
- Additional **Sensors** (e.g., time-temperature indicators, gas- or biosensors)
- Improvement of **sensor handling** protocol, increase communication, **transparency** and completeness of metadata
- **GPS** monitoring, extended monitoring range farm-to-fork
- Mandatory **measurements and monitoring of food losses** through-out the SC
- Automated/visual **quality assessment** & sorting (e.g., computer vision)

Retail & Consumer

- Target on food waste reduction
- **FEFO** instead of FIFO (e.g., using digital twin, shelf life modelling tools, quality rating, etc.)
- **Dynamic pricing**, discount for products with lower quality or shorter shelf life
- Adapt **quality standards**, promotion of "sub-optimal" produce
- Refrigerated (overnight) storage
- Controlled temperature ramp-up **at low humidity** to avoid condensation
- **Humidification** (e.g., manual, dry misting)
- Improved packaging/display unit (e.g., reusable closable boxes, waxed cartons, moist paper liners)
- Appropriate product **labelling** (e.g., "sell-by" instead of "best-by")
- **Inform customers:** labels, sustainability, food loss reduction (e.g., print on packaging “biodegradable”, “less food waste by...”, “reusable”)
- **PR campaigns** for (sustainable) packaging requirement

Figure 1. Food loss and waste-reducing strategies mapped for different drivers and grouped for several stages along the postharvest supply chain of fresh produce. Abbreviations: SC, Supply chain; GPS, Global positioning system; FEFO, "first-expired-first-out"; FIFO, "first-in-first-out"; PR, Public relations.

Table 1. Postharvest measures to reduce food loss and waste along the supply chain (SC) of fresh produce.

Category/ driver	**Impact**	**Solution**	**SC segment**	**References**
Temperature	Increased temperature-related shelf life	*Precooling directly after harvest or near the field (especially relevant for very perishable products, such as berries). e.g., refrigerated trailers, cool rooms, etc.*	Precooling	[54]
		Faster precooling with forced-air-, hydro- or vacuum cooling instead of room cooling	Precooling	[12], [55]
		Better ventilated (reusable) packaging container for homogenous cooling *e.g., corrugated fiber boxes with ventilation holes, containers from " IFCO Systems"*	Packaging	[56]–[63]
		Improved packaging system / insulation for better temperature control *e.g., phase change material for insulated containers*	Packaging	[64], [65]
		Faster shipping so shorter transit time and food precooling inside refrigerated containers instead of a-priori precooling (but in most refrigerated trailers not yet feasible)	Transport	[54]
		Rerouting of shipments, selection of less & only optimal transport companies *more stringent rules on thermal target conditions, mandatory monitoring of hygrothermal conditions*	Transport	[48]
		Refrigerated transport (no interruptions in the cold chain) *e.g., from field to the packing house (before precooling) or from distribution center to the retail*	Transport	[48], [50]
		Adaption of target temperature to the optimal range for maximizing shelf life *e.g., by reducing the target temperature, preventing chilling-inducing storage temperatures*	Transport & Storage	[16], [33]
		Refrigerated (overnight) storage or display *e.g., instead of leaving fresh produce overnight on the shelf*	Retail	[50], [66]
Humidity	Reduced microbial induced decay	*Specially designed packaging to decrease condensation or contamination risk* *e.g., humidity regulating trays, the addition of absorbent pads, improved ventilation, packaging material with incorporated antimicrobial compounds*	Packaging	[26], [28]–[30], [67]

	Reduced mass loss	*Packaging for physical protection against vibrations and bruise damages* *e.g., package design with improved mechanical strength, prevention of over-loading*	Packaging	[26]
	Reduced mass loss & reduced plastic usage	*(edible) Coatings* *e.g., coating matrix from protein, lipid (oil, waxes), polysaccharides or composites*	Packaging	[68], [69]
	Reduced plastic usage	*Biodegradable or bio-based packaging material* *e.g., polylactic acid, starch, cellulose*	Packaging	[18], [20], [70]
	Reduced plastic usage	*Bulk packaging of entire crates or pallets instead of single product packaging (shrink wrap, flow pack, etc.), e.g., foil bags*	Packaging	[71]
	Reduced mass loss	*Store and transport at higher humidity using humidifiers* *e.g., ultrasonic dry misting that provides a higher humidity while also evaporative cooling the product*	Whole SC	[19], [21]
	Reduced microbial induced decay	*Controlled temperature ramp-up at low humidity to reduce condensation when shifting products from refrigerated conditions to ambient conditions (e.g., at the retailer stores)* *e.g., by a portable or desiccant dehumidifier*	Transport & distribution	
	Reduced mass loss & plastic usage	*Improved packaging or display unit to minimize transpiration induced-mass loss* *e.g., use of reusable closable boxes or lids that match package containers instead of "open"/unpacked display, use of waxed cartons or moist paper liners reducing product moisture evaporation*	Retail	[26], [57], [72]
Ripening gases	Reduced mass loss & slower ripening/decay	*Active or equilibrium modified atmosphere packaging*	Packaging	[73]–[75]
	Slower ripening/ decay	*Additives or treatments for ethylene absorption or blocking* *e.g., $KMnO_4$, 1-Methylcyclopropen (1-MCP)*	Packaging & Transport	[34]–[36]
		Shipping containers with controlled atmosphere (for long/oversea transport routes)	Transport	[16], [33]
		Prevention of mixed loads with ethylene producing/ climacteric fruits	Transport	[16]
Retail system		*Adaption of quality standards and promotion of "sub-optimal" produce*	Retail & Packaging	[37]

	Consumer awareness	*Appropriate product labeling* *e.g., "sell-by" instead of "best-by"*	Retail & Packaging	[2]
		PR campaign demonstrating the need for plastic packaging, explaining how it helps to save food by its protective function (reduction of moisture loss and shriveling, softening, or bruise symptoms)	Retail & Packaging	[76]
		Print informative messages on packaging *e.g., " I help to keep you more fresh", "biodegradable packaging", "reusable packaging"*	Packaging	
		Better inform customers about food loss reduction strategies *e.g., label, sticker, sustainability score, "less food loss by…"*	Packaging	
	FEFO instead of FIFO	*Discount for products with lower quality and shorter shelf life, dynamic pricing system*	Retail	[40]
	Awareness	*Food waste limit or reduction target and donation of saved food to food banks*	Retail	[77]
Monitoring & Sensing	*Increased transparency*	*Time-Temperature Integrators, gas- or biosensors for quality monitoring*	Logistics	[45], [46]
		Hygrothermal and GPS sensors, extended monitoring range "from-farm-to-retail	Logistics	[48]
		Inventory management with FEFO instead of FIFO *e.g., based on automated quality rating, digital twins, etc.*	Logistics	[46], [50], [78], [79]
		Improvement of the sensor handling protocol & communication, completeness of the metadata	Logistics	[48]
		Automated visual quality assessments and product sorting *e.g., computer vision, hyperspectral imaging*	SC checkpoints	[80]–[82]
		Mandatory monitoring and measurements of food losses across the SC	Whole SC	

Abbreviations: SC, supply chain; CC, cold chain; GPS, geographical position system; FEFO, "first-expired-first-out"; FIFO, "first-in-first-out".

5 Decision-making strategies for solution evaluation and identification of optimal measures

5.1 Identification of product-specific solutions

Since fresh products derive from various plant tissue at different stages in development, they need specific packaging and storage adjustments to counteract related decay drivers. In Figure 2, product types or commodities are mapped based on the different causes of food loss, including (1) respiration-related decay (temperature-induced); (2) ethylene-related over-ripening (induced by temperature or ripening gases); (3) transpiration-related moisture loss (humidity-induced); and (4) pathogen-related decay (humidity-induced). For each category, we proposed specific solutions. Products that are mapped in overlapped areas are susceptible to more than one food loss driver and should especially be considered. These include young and immature plant parts, such as sprouts (e.g., asparagus), seeds (e.g., beans), or inflorescence (e.g., broccoli). Ethylene-sensitive products are also mapped to this area. These products show increased senescence or discoloration symptoms when stored with ethylene-producing products (i.e., climacteric fruits) [16]. Both optimized packaging and storage methods can help reduce those symptoms. Small products, including berries, are of specific concern as they are prone to condensation and microbial decay. This is due to their large surface area to volume ratio, which increases the risk of transpiration and condensation occurrences. Leafy vegetables (e.g., salads, herbs) also having a large tissue area are prone to transpiration-induced wilting. Various packaging and refrigerated storage at retail help reduce symptoms due to moisture loss. Most "real" and particularly climacteric fruits show increased respiration, ripening, and eventually senescence after they are harvested. Ethylene scrubbers in packaging or during storage decrease those autocatalytic processes [34]–[36].

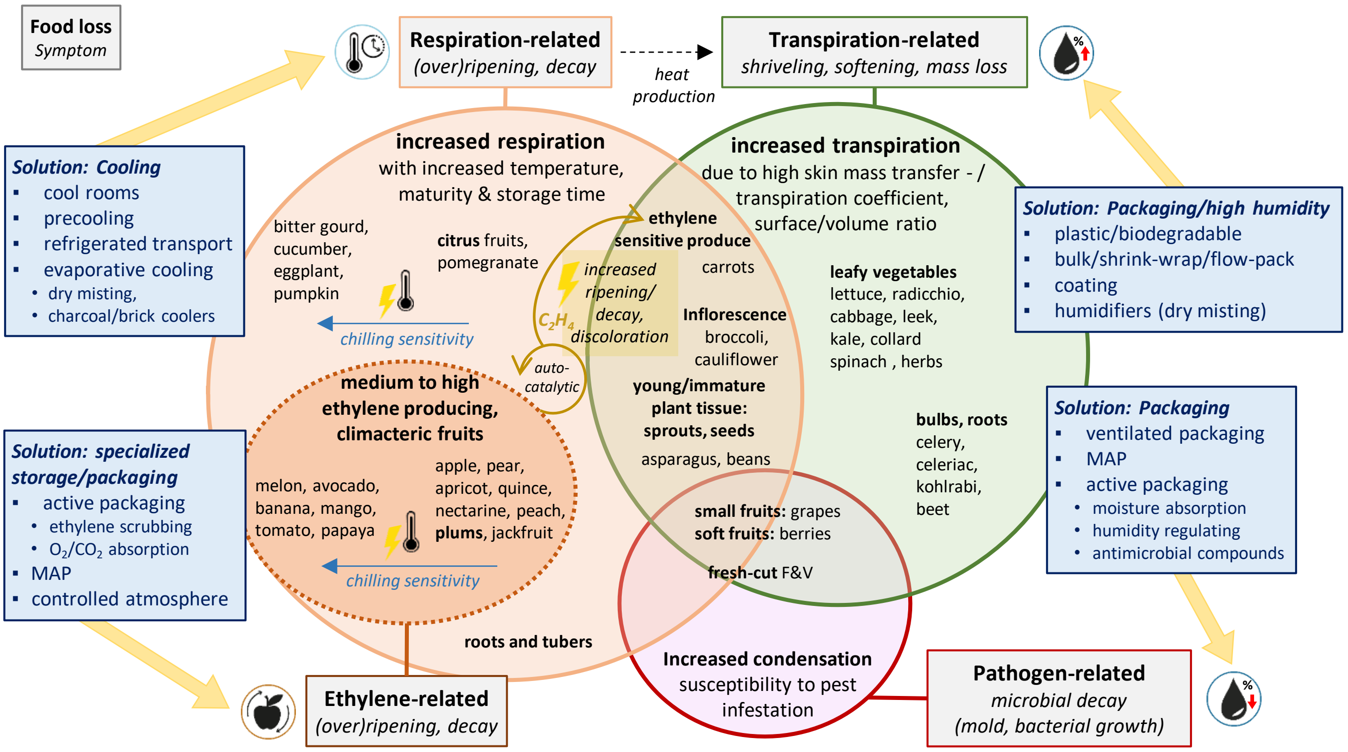


Figure 2. Plant product groups mapped to different physiological (respiration-, transpiration-, ethylene-related) or pathological food loss categories and related symptoms (grey shaded) plus antagonizing postharvest solutions (blue shaded). Abbreviations: F&V, fruits and vegetables; MAP, modified atmosphere packaging.

5.2 Trade-offs between the value of food loss and the impact of reduction solutions

Several trade-offs arise during the decision-making of implementing food loss and waste reduction strategies. Examples are the (short term) costs for new measures versus the possible increased revenues of saved food that usually only occur later [83]. Furthermore, when new standards are established, their environmental impact must not outweigh the emissions of the accumulated food loss. For example, refrigeration, transport, or storage solutions are high energy-intensive. In contrast, the packaging is typically overestimated in relation to the whole supply chain's emissions [84]. Nevertheless, it is often challenging to precisely quantify the total carbon footprint along the supply chain, and studies comparing the environmental impact of different food loss solutions are generally scarce [9]. Therefore, life cycle analyses (LCA) of the whole value chain and each operation are helpful in receiving the relevant information for decision-making processes [5], [85]. For instance, an LCA of the entire value chain driven by food loss compared to that caused by food loss reduction strategies would provide valuable insight to identify the trade-offs and optimal measures. That way, we could determine how different criteria score in saving food, reducing the environmental footprint as well as saving (energy) costs. In conclusion, the measurement of food loss cannot be circumvented when evaluating these trade-offs in order to gain all the required information.

6 Conclusions

This study composed a collection of food loss and waste reduction strategies for postharvest supply chains of fruits and vegetables. We addressed the main food loss drivers, as well as unfavorable supply chain processes leading to inefficiencies and spoilage. We presented the results in a roadmap list of 30+ individual measures for suppliers, distributors, and retailers to improve different supply chain segments. These 30+ measures included conditions during packing and precooling, transport, storage and retail. This available easy-to-use solution roadmap will support the decision-making and actions of stakeholders. It provides them with an overview and a starting point for optimizing their postharvest supply chain and minimizing food loss.

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Author contributions

T.D. conceptualized the study and wrote the project outline, T.D did project administration and was the Principal Investigator (PI) in the project; S.S., K.S., C.S., D.O., and T.D. developed the methodology; S.S. and performed the interpretation and visualization of the results; T.D. supervised S.S.; S.S. wrote the original draft with key inputs from T.D.; T.D, K.S., C.S. and D.O. critically reviewed and edited the manuscript; S.S revised the manuscript based on these suggestions.

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