

A method to provide end-to-end data visibility in fresh-fruit refrigerated supply chains, deployed for an EU citrus supply chain

Bassem Al Sakhawy^{1,2}, Raphael Sacher⁴, Thijs Defraeye^{2,3}

¹ *Department of Management, Technology, and Economics, ETH Zurich, Weinbergstrasse 56/58, CH-8092 Zurich, Switzerland*

² *Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland*

³ *Food Quality and Design, Wageningen University & Research, P.O. Box 17, 6700 AA Wageningen, the Netherlands*

⁴ *ANYFION GREECE S.A., 6th Km Nafplio-Argos, 21100 Nafplio, Greece*

ABSTRACT

We designed and implemented a data-collection methodology providing comprehensive end-to-end visibility across the refrigerated supply chain of fresh produce. The approach involves two steps: detailed mapping of the supply chain in which the data is gathered and collecting different data in the supply chain. We applied the method for the supply chain of a Greek citrus fruit supplier, shipping to multiple European countries. This study offers a method to gather a comprehensive blueprint of the supplier's supply chain from field to fork. Supply chain stakeholders do not typically undertake such an approach, so there is no standard operating procedure. This data acquisition method serves as a foundation for analyzing the impacts of external factors on fruit quality through the following supply chain stages: cultivation and harvesting, processing, packaging and precooling at the packhouse, refrigerated transportation from the packhouse to the distribution center, storage at the distribution center, and final transportation to the consumers.

- This methodology establishes a replicable method for monitoring perishable goods supply chains
- This methodology enables data-driven analysis and decision-making aimed at reducing spoilage and improving end quality

Keywords

Refrigeration, agricultural cold chains, end-to-end visibility, data collection, fresh fruit, food quality, food transport.

1 Supply chain description and monitored shipments

We describe the supply chain for which the data collection method was applied. The method can be applied to other supply chains as well. This work was done during the Greek supplier's 2023-2024 harvest season (September to March). Four key stakeholders were involved: a Greek supplier, a sensor technology provider, a retailer at the receiving end of the transport, and a Swiss start-up for B2C delivery of citrus fruit. This B2C supply chain is unique because each cardboard box (8 or 13.3 kg) is delivered directly to individual consumers through regional distribution centers (DCs) but not to retailer stores.

A total of 64 citrus shipments were monitored from Greece (Nafplion) to Switzerland (Märstetten / Pratteln), Germany (Singen), and the Netherlands (Maasdijk). The first monitored shipment departed on 14.11.2023, and the last shipment on 17.02.2024.

The cargo consisted mainly of oranges, lemons, and mandarins. In terms of outgoing volumes cleared for dispatch, oranges comprised the majority at 77.65% (1554.86 tonnes), followed by mandarins at 9.83%, lemons at 5.22%, grapefruits at 4.47%, and pomegranates at 1.19%. The remaining percentage accounted for pomegranates, kiwis, and avocados.

Each shipment consisted of multiple lots, with a maximum of 32 pallets per shipment, and could contain mixed fruit loads. A lot is, on average, composed of 6 pallets of 44 cardboard boxes. These lots were meticulously tracked from field to fork. This experiment aimed to comprehensively understand what happens in the entire supply chain and the evolution of the associated fruit quality and enhance end-to-end visibility where necessary. The supply chain stages were categorized into several main phases: cultivation and harvesting, processing, packaging and precooling at the packhouse, refrigerated transportation from the packhouse to the distribution center, storage at the distribution center, and final transportation to the consumers. Each stage is detailed below to overview the entire process comprehensively.

1.1 Description of the monitored fruit species

Pertinent details gathered from the on-field experts regarding the fruit biological species monitored throughout the supply chain, their variety, harvesting season, estimated shelf life, and ideal storage conditions are outlined in Table 1.

Table 1. List of harvested fruit species, varieties, harvesting season, shelf life, and temperature storage conditions

Fruit biological species	Fruit variety	Harvesting season	Shelf life	Ideal storage conditions (°C)
Oranges	Navelina	November - December	4-6 weeks	4-6
	Merlin	January - February	4-6 weeks	4-6
	Lane late	February - April	4-6 weeks	4-6
Mandarins	Clementines	End of November – End of December	6-8 weeks	4-6
	Nova	End of December – End of January	6-8 weeks	4-6
	Ortanique	March-May	6-8 weeks	4-6
Lemons	Interdonato	Mid-November – Mid-March	4-6 weeks	6-8
Grapefruit	Star Ruby	Mid-November – Mid-February	6-8 weeks	6-12
	Pink Marsh	Mid-November – Mid-February	6-8 weeks	6-12
	Yellow Marsh	Mid-November – Mid-February	6-8 weeks	6-12
Blood oranges	Moro	Mid-November – Mid-March	4-6 weeks	4-9
Persimmons	Jiro	Mid of December – Mid of January	2-4 months	0-4

1.2 Pre-harvest

Farmers and farms

The pre-harvest stage of the supply chain includes all activities leading up to the actual harvest of the fruit. The citrus fruit was sourced from 110 farmers situated around the city of Nafplion, Argolia, Greece. The farmers were engaged in the provision of organic fruits for this study. Between mid-September and mid-March, these 110 farmers supplied the Greek company with 2'635 tonnes of fruits.

According to experts interviewed during a field visit in Greece, the agricultural landscape in the region is marked by fragmentation, with farmers adopting a mosaic-style layout comprising small farms. On average, farmers own approximately 1.5 hectares of land they cultivate and harvest. These land holdings are typically divided into several smaller fields or parcels.

This agricultural practice, known as smallholding farming or small-scale farming, involves the cultivation of relatively small plots of land by individual or family farmers. It is often characterized by a high degree of manual labor and traditional farming techniques. In the case of the Argolia region, this practice allows hedging against crop failure risks associated with micro-weather exposure; for instance, while one field may be susceptible to hail danger, another located merely 100 meters away could remain unaffected. This practice is characteristic of Argolia and contrasts the farming practices observed in northern Greece, where farms tend to be larger and less fragmented.

Organic production

The fruits monitored adhere to the standards outlined in the EU Organic Production Regulation (EC) No 834/2007, commonly known as Regulation 0101 (Council of the European Union, 2007). This regulation provides a comprehensive framework for organic farming practices and certification within the European Union, ensuring that organic produce meets strict criteria for environmental sustainability, biodiversity conservation, and natural resource management. Compliance with Regulation 0101 entails prohibiting synthetic pesticides, fertilizers, and genetically modified organisms (GMOs). It also includes stringent soil fertility and management standards, crop rotation, pest and disease control, livestock management, and organic seeds and planting materials. Under this regulation, synthetic fertilizers, pesticides, and GMOs are strictly forbidden in organic farming, promoting environmentally sustainable practices and preserving natural resources. Additionally, Regulation 0101 sets criteria for the processing, storage, and handling of organic products to maintain their organic integrity. This includes rules regarding the use of organic ingredients, food additives, and processing aids in organic food processing to ensure that organic products retain their organic status throughout the processing chain. Labeling and marketing requirements are also established under Regulation 0101. Organic products must bear the EU organic logo, signifying their organic status, the code number of the certifying body, and the percentage of organic ingredients.

Citrus cultivation

The standard cultivation regime for oranges encompasses a series of carefully timed interventions to optimize tree health and fruit yield. Beginning in February, growers are advised to administer multi-compound fertilizers at a rate of 2 kg per tree. This initial nutrient boost sets the stage for robust growth and development in the coming months. In March, attention turns to pruning activities, vital for maintaining tree shape and removing dead or diseased branches. Following pruning, applying copper or copper sulfide serves as a preventive measure against fungal diseases, bolstering tree resilience.

From February to April, tree trunks are painted with Bordeaux paste—this protective measure shields against pests and pathogens, safeguarding the integrity of the trees. During May, the focus shifts to sulfur application through spraying or dusting methods. This step aids in disease prevention and ensures optimal fruit development.

In June, the emphasis turns to foliar fertilization, an essential practice involving the application of trace elements, potassium, and amino acids directly to the leaves. This targeted approach enhances nutrient uptake and promotes overall tree vigor. Finally, as November arrives, growers undertake a strategic spraying regimen, incorporating a mixture of copper, silicon, and calcium. This combination fortifies the trees against common stressors and primes them for future challenges.

Beyond these seasonal interventions, adherence to a rational watering schedule is paramount, with trees typically receiving hydration weekly for 2 to 3 hours. This approach to irrigation helps maintain soil moisture levels and supports healthy root development. Moreover, growers remain vigilant for signs of pest infestation, with particular attention paid to leaf miner, mealybug, and mite activity. Prompt detection and targeted intervention are essential for mitigating potential damage and ensuring the ongoing health of the orchard.

1.3 Harvesting

A few days before harvesting, a field visit is conducted in collaboration with the producer to assess the general condition of the produce. A random selection process is employed, wherein 5 fruits of the same variety from 5 distinct trees are chosen to measure their juice percentage and sugar content value. For oranges, harvesting is initiated solely if the juice percentage exceeds 35% and the sugar content value surpasses 10 °Brix, guaranteeing that the fruits adhere to the predetermined quality benchmarks before being harvested and transported to the processing facility. °Brix, also referred to as '°Br,' is a unit of measurement used to quantify the sugar content of a solution commonly found in fruit juices or other liquids. It indicates the percentage of total soluble solids in the liquid, with one degree Brix equivalent to 1 gram of sucrose per 100 grams of solution. Meanwhile, the juice content percentage represents the proportion of juice relative to the total weight of the fruit.

1.4 Sorting

Upon reaching the warehouse, fruits are stored outside under a shelter on the side of the warehouse in pallets of 36 large plastic boxes (size was not measured). It is common to see two pallets stacked atop each other, totaling a height of 3.6 m and a width of 1.2 m. Outside-facing pallets are exposed to sunlight and other potential environmental conditions (e.g., rain, wind, hail). Usually, fruits arriving from the farm are processed on the same day. If the fruits arrive at the processing facility Friday afternoon, the time until processing gets typically longer as they are stored outside the warehouse until Monday.

Quality control of the fruits involves monitoring various characteristics to ensure they meet specified standards. The sample size for quality control is determined based on the square root of the total number of boxes in the lot, with a minimum of 10 boxes (dimensions: 0.6 x 0.3 x 0.16 m or 0.4 x 0.3 x 0.19 m depending on the product, c.f. section 1.5) and a maximum of 30. This approach ensures that a representative sample is obtained for evaluation.

Controlled quality characteristics include the absence of diseases, insects, frost/hail damage, wounds, or puffiness. Fruits exhibiting any of these symptoms are deemed unacceptable, as they pose a risk to shelf life and overall quality. Fruit aroma, color, taste, and overall appearance are controlled: an employee checks whether these characteristics are typical of the variety. Coherence or firmness is evaluated for persimmons, with a minimum weight-to-diameter ratio specified. Persimmons must weigh at least 2.5 kg per 8 mm diameter to ensure proper ripeness and texture.

Following this quality check, the products are moved into the warehouse for further processing stages. Initially, they undergo pre-sorting on a conveyor belt, followed by a brushing process to remove soil, dust, and other impurities without using water or fungicides, as the products are organic. Subsequently, a calibration process is conducted to separate fruits with a diameter smaller than 61 mm or larger than 92 mm from the conveyor belt. Manual sorting, performed by a team of up to 8 individuals, is the final processing stage before packaging. The sorting criteria include size, injuries, infections, pathogens, softness, ripeness, and adherence to proper harvesting practices. The standards for these criteria follow those specified in the aforementioned quality check. This is the only documentation or standard practice detailing the exact sorting criteria found in this supply chain. Instead, the experience of the deployed workers seemed more prevalent. Fruits failing to meet these standards are diverted for processing into juice rather than being shipped to end customers.

1.5 Packaging

After the fruits are selected, they are sent to the packaging line. Oranges were packaged in customer-specific (0.6 x 0.3 x 0.16 m) 13 kg open-top cardboard boxes and, on a few occasions, in IFCO 6416 14 kg boxes. Mandarins, lemons, and persimmons were packaged in smaller customer-specific (0.4 x 0.3 x 0.19 m) 8 kg open-top cardboard boxes.

All customer-specific boxes were arranged on wooden Euro-pallets at 1.2 m x 0.8 m x 0.144 m. For the pallets containing oranges, each layer accommodated 4 boxes. The pallets were stacked 11 or 12 layers high (Figure 1a.), depending on the total cargo weight, with a maximum load capacity of 21.5 tons of the refrigerated trailer, which can hold 32 pallets. Clementine and lemon pallets, on the other hand, comprised 10 layers with 8 boxes per layer. Notably, the cardboard boxes featured a single large vent hole on the long side, while the short side contained no vent holes. The bottom face of each cardboard box featured four triangular vent holes (Figure 1b). The rationale behind these vent holes is to facilitate airflow, aiding in the following precooling and refrigerated cooling processes.

a) Typical pallet, short side facing**b) Bottom vent holes**

Figure 1a) Pallet of customer-specific cardboard boxes for oranges; Figure 1b) Bottom vent holes of the cardboard boxes.

Following packaging, another quality check ensues. This process involves the selection of one sample comprising five fruits randomly chosen from different boxes within the lot. The weight of each fruit is measured, and juice is extracted from the sampled fruits, with the weight of the juice also recorded. A calculation is then made to determine the ratio of juice to fruit weight. The result is the fruit's 'juice content.' The juice content percentage is assessed to gauge the fruit's juiciness and suitability for consumption. The average juice content reading of the five fruits must exceed a certain threshold. For Navelina oranges, the average minimum acceptable juice content level is 33%, while for other oranges, it is 35%. Clementine mandarins must have a minimum level of 40%, Ortanique mandarins a minimum of 35%, and other mandarin varieties a minimum of 33%. Lemons, grapefruits, and blood oranges have their respective thresholds, with minimum juice content level requirements of 25%, 35%, and 30%, respectively. Additionally, a refractometer was used in the experiment. A portable refractometer DIGIT - 032 ATC (Thermo Fisher Scientific, Massachusetts, United States) (Brix scale: 0 - 32%, precision: 0.2%) measured the sugar content (in °Brix). Different minimum thresholds were established for different fruit species. Each sample of oranges, blood oranges, and mandarins (Clementine and Ortanique varieties) had to meet an average minimum sugar content of 10 °Br to be cleared for shipping. In contrast, pomegranates and persimmons had to meet a minimum sugar content of 15 °Br. Finally, acidity is often assessed by combining one spatula (1g) of juice with 50 ml of distilled water, though this measurement was not logged in the retrieved datasets.

1.6 Precooling

Boxes are weighed before being placed onto standard Euro Pallets (EUR/EPAL 0.8 x 1.2 x 0.144 m) and sent to the pre-cooling facilities. Time-to-precooling was not precisely tracked; however, information obtained from field visits and discussions with process specialists revealed that fruits are typically received from the farm, processed, and packaged on the same day before being transferred to the precooling room. Exceptions occur for lots arriving on Friday afternoons, necessitating waiting until Monday for precooling, resulting in a time-to-precooling ranging from the same day to two days occasionally.

In principle, the rooms used for precooling are cold storage rooms where the design and refrigeration power have been optimized to induce fast cooling. The precooling will, therefore, not occur in a commercial precooling facility and will be somewhat slower.

The small room is 3.2 x 6.4 x 5 m and can accommodate 64 pallets (i.e., two full shipment cargo). Its refrigeration unit has a cooling power of 8 kW with 2 fans (volume flow rate 300 m³ h⁻¹) loaded against the ceiling on the back wall and faces the pallets. As a comparison, refrigerated trailers have specifications ranging from a cooling power of 6 kW with a volumetric flow rate of 2,500 m³ h⁻¹ such as the Carrier Supra HE 6 trailer refrigeration unit (Carrier, Palm Beach

Gardens, United States), to a cooling power of 15kW with a volumetric flow rate of 5,500 m³ h⁻¹ such as for the Carrier Vector series (Carrier, Florida, United States)

A newer room was built at the beginning of the season and has a dimension of 5.2 x 11.5 x 4.5 m. It can accommodate a total of 96 pallets. The new refrigeration unit has two fans with a higher power (12 kW) and a higher volume flow rate (500 m³ h⁻¹). The unit was loaded against the back wall ceiling facing the pallets (Figure 2).

a) Back wall refrigeration unit

b) Pallets facing the refrigeration unit

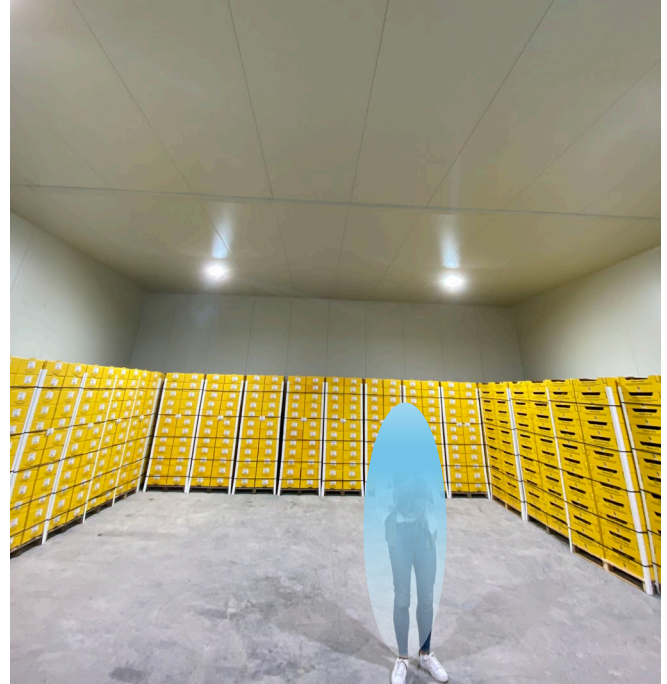


Figure 2a) New pre-cooling room refrigeration unit 2b) Pallet view inside the new pre-cooling room.

The precooling process was done at a set temperature of 4-6 °C for about 10 hours on average. Ideally, the core temperature of the fruits reaches the target temperature within 2 to 3 hours. However, this is often only possible during winter when the fruits are stored outside at approximately 5°C Celsius before further storage. Precooling times are often longer.

It is important to note that the room’s setpoint temperature of 4-6 °C accommodates various types of fruits with differing ideal storage conditions, although they overlap within the 4-6 °C range, as shown in Table 2. These guidelines were set in place by the UNECE standard FFV-14 (UNECE, 2023).

Table 2. Summary of fruit varieties and their ideal storage temperatures.

Fruit variety	Ideal storage and transport temperature (°C)
Oranges, all	4-6
Mandarins, Clementines and Ortanique	4-6
Mandarins, other	5-10
Lemons, all	6-8
Grapefruits, all	6-12
Blood Oranges, Moro	4-9
Persimmons, Jiro	0-4
Pomegranates, Ermionis	4-6

1.7 Refrigerated transport

The cargo consisted of 32 pallets loaded into the trailer following standard procedures. Cooled pallets are loaded into a trailer (width: 2.49 m, height: 2.70 m, length: 13.60 m) and transported to the end destination using the setpoint temperature of 4-6 °C. The temperature in the loading hall during loading was estimated to vary between 14 and 18 °C; however, exact daily readings were unavailable in time for the experiment.

Two distinct types of sensors were employed in the study. Two TempTale GEO Ultra sensors (Sensitech Inc., Beverly, United States) were utilized to measure air temperature and relative humidity in real-time. These sensors have a temperature range of -10 to 55 °C with an accuracy of ± 0.5 °C and a relative humidity range of 10 to 100%, with an accuracy of $\pm 3.0\%$ (RH: 10-90%) and $\pm 4\%$ (RH: 90-100%). Additionally, it measured light intensity within the range of 0 to 400 lux, which was instrumental in detecting door openings during transport. The sampling interval for this sensor was set at 15 minutes.

On the other hand, fruit core temperature was monitored using the TempTale Ultra probe sensors (Sensitech Inc., Beverly, United States). These sensors have a temperature range of -30 to 70 °C with an accuracy of ± 0.5 °C. The probe attached to the sensor was inserted into the fruit until it reached the core. The sampling interval for the probe sensors was set at 40 seconds.

The placement, measurements, and rationale behind the sensors installed in the trailer are detailed below, and an illustration is presented in Figure 3.

Firstly, one of the two real-time sensors (GEOsensor) positioned on the pallet near the trailer door tracks air temperature, relative humidity, and light levels. This sensor was placed atop the last pallet, typically near the trailer door and centrally within the trailer. Light measurements are a crucial indicator of potential door openings within the trailer's cargo space, offering valuable insights into temperature and humidity fluctuations and when the cargo is in the trailer. By monitoring light levels, the sensor can detect instances when the trailer doors open, allowing outside air to enter the cargo area. Such door openings can lead to abrupt changes in temperature and humidity levels, which may adversely affect the quality and freshness of the transported fruits. When coupled with temperature and humidity data, light measurements provide context for interpreting any detected drops in these parameters. For example, a sudden decrease in temperature or humidity recorded by the sensor during the trip may coincide with a spike in light levels, indicating that the doors were opened and external environmental conditions impacted the cargo. This correlation helps distinguish between natural fluctuations and external influences, enabling more accurate assessment and interpretation of the sensor data.

Additionally, a pulp sensor monitors the core temperature of the fruits. It is adjacent to the real-time sensor described above. This measurement is essential for assessing the effectiveness of refrigeration systems in maintaining optimal fruit storage conditions throughout the journey. By tracking fruit core temperature, conclusions can be drawn regarding the impact of the cargo's temperature fluctuations on fruit quality. Insights into how core fruit temperature correlates with the cargo's internal temperature could lead to recommendations or adjustments on ensuring fruit freshness and preventing spoilage.

Furthermore, another real-time sensor (GEOsensor) is positioned atop the last pallet, near the driver, and centrally within the trailer. It records air temperature, air relative humidity, and light levels. This setup played a pivotal role in enhancing the end-to-end visibility aspect of this research, eliminating any blind spots during the journey. It also facilitated the collection of airflow data within the trailer. This research did not monitor the internal airflow, which is helpful for cargo modeling research (Defraeye et al., 2024). The data provided by these sensors proved to be exceptionally valuable for shipments with multiple destinations, especially considering the uncertainty surrounding the exact quantity of cargo offloaded at the first stop. In such scenarios, maintaining visibility into the conditions the remaining fruits experienced throughout their journey became paramount. The sensor data allowed the monitoring of the remaining cargo and the internal conditions to which it was subjected. Finally, precooled fruits are loaded into trailers in a centreline-turned-loading pattern, meaning all pallets are organized in columns parallel to the length of the trailer. On average, the loading of the trailer lasts around 15 minutes.

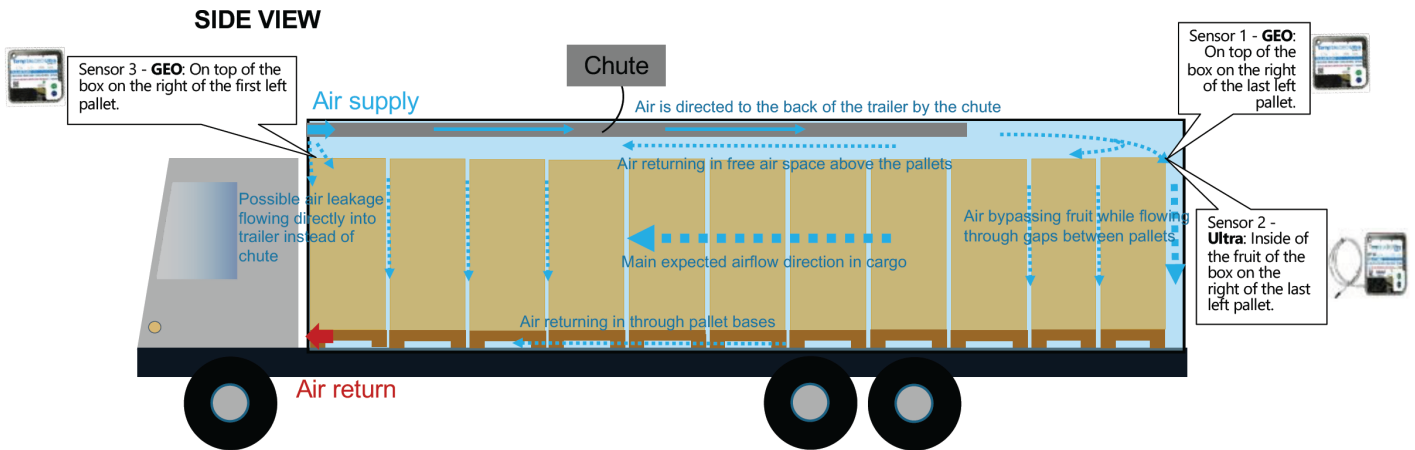


Figure 3. Schematic Diagram of Sensor Placement in a Trailer. This figure illustrates the placement of three different sensors within a freight trailer for monitoring purposes. Sensors 1 and 2 are situated next to the rear of the trailer (the door). Sensor 1 (GEO) is located atop the box on the right of the last left pallet. Sensor 2 (Ultra) is placed inside the fruit of the box on the right of the last left pallet. Sensor 3 (GEO) is positioned atop the box closest to the driver, on the right of the first left pallet. In addition to the sensor placement, the figure shows the expected airflow within the trailer. Air is directed to the back of the trailer by the chute, with the main expected airflow direction traveling through the cargo. There is air return from the pallet bases, while air bypasses fruit and flows through gaps between pallets. Possible air leakage is also illustrated as it may flow directly into the trailer instead of following the intended path. Figure adapted from Verreydt et al. (2024).

Once the pallets are loaded and the trailer's door is closed, the refrigeration system is activated to maintain a supply air set temperature ranging from 4 to 6 °C. The trailers depart from Nafplion, Argolia, Greece, and head to Patras port, where they await loading onto a ship bound for one of the following ports in Italy before continuing their journey: Venice, Ancona, or Bari. These shipments are ultimately destined for Switzerland, the Netherlands, or Germany, with the potential for two stops within Switzerland. The transportation journey concludes upon the trailer's arrival at the customer's distribution center. Table 3 provides an overview of the number of shipments per destination.

Table 3. Overview of shipment destinations. Shipments 3, 32, 49, 56, and 62 stopped in Oberarth before arriving in Pratteln (Switzerland). Shipments 17, 19, 28, and 66 stopped in Oberarth before Märstetten. Shipment 67 was the only shipment with two stops in two different countries (Märstetten CH, then Singen DE). Shipments 3 and 30 did not have accessible data.

Destination		Total number of shipments	Shipment numbers
Country	City		
Switzerland	Pratteln	25	3, 5, 6, 10, 15, 18, 21, 25, 29, 32, 33, 34, 36, 38 39, 41, 44, 45, 47, 49, 52, 54, 56, 62, 65
	Märstetten	20	1, 7, 9, 14, 17, 19, 20, 23, 26, 28, 40, 46, 48, 55, 58, 60, 63, 64, 66, 67
	Oberarth	9	3, 11, 17, 19, 28, 49, 56, 62, 66
Netherlands	Maasdijk	13	4, 8, 16, 22, 24, 30, 31, 35, 42, 50, 53, 59, 61
Germany	Singen	9	2, 12, 13, 27, 37, 43, 51, 57, 67

1.8 Fruit handling at the distribution center

Upon arrival at the destination, a secondary quality assessment is conducted. The number of sample boxes selected for inspection varies depending on the total number of boxes in the trailer. If multiple lots are delivered, the sample boxes are chosen randomly, ensuring representation from different pallets and layers within each pallet (top, middle,

bottom). The quantity of sample boxes selected is determined according to Table 4, which outlines the sampling criteria based on the total number of boxes. The evaluated quality metrics are: weight at arrival, sugar content at arrival, and various sensory properties, including appearance, odor, taste, and firmness.

Table 4. Quality check guidelines. Depending on the number of boxes in the shipment (1st column), the minimum number of boxes to use for quality check is provided, and the percentage range of the sampled boxes per total number of boxes.

Total number of boxes per shipment	Minimum number of sample boxes	Percentage of total
100	5	5%
101 to 300	7	2%-7%
301 to 500	9	2%-3%
Above 501	12	< 2%

Upon receipt of goods, the net weight of each box is meticulously checked so it complies with the target weight. To ensure precision, the scale is tared with an empty box, adhering strictly to the instructions provided by the scale manufacturer. Notably, the empty box used for taring must be sourced from the delivery itself, as it may retain moisture compared to a reserve box. The recorded net weight of each box is documented in the quality report.

Additionally, the qualitative properties of all sampled boxes are thoroughly assessed, encompassing criteria such as wholeness, healthiness, cleanliness, freedom from pests and pest damage, absence of skin and cold damage, and appropriate degree of development and ripeness. To aid in this evaluation, DC workers utilize an image catalog provided for reference.

Furthermore, to gauge sugar content, one fruit is extracted per sample box, and its sugar content (°Brix) is measured using a hand refractometer provided for this purpose. The model and specifications of the refractometer used were not collected. This measurement is conducted using the sugar content measurement instructions. The sugar content values obtained for the following fruits should meet or exceed the specified thresholds at the distribution center (Table 5), otherwise, the fruits will not be dispatched to the end user. Core temperature at the time of arrival is also logged, albeit these data already exist on the sensor dataset.

Table 5. Minimum requirements for sugar content values per fruit at departure and upon arrival.

Fruit	Minimum sugar content (°Br) at arrival	Minimum sugar content (°Br) at departure
Orange	10	10
Clementine	10	10
Pomegranate	15	15
Grapefruit	9	10

One fruit is examined from every second sampled box for the sensory test. During this test, the fruits are cut open and assessed for various sensory properties, including appearance (e.g., color, size, visual abnormalities), odor (e.g., fruity, sweet, sour, fermented, herbaceous), taste (e.g., sweet, sour, bitter, characteristic of fruit), and consistency (e.g., firm, soft, melting, floury, sandy, crunchy). For instance, if there are 12 sampled boxes, 6 are selected for sensory testing. From each of these boxes, one fruit is chosen for sensory analysis. This results in a total of 6 fruits being evaluated. It is important to note that the fruits removed from the boxes for sensory testing are replaced with another fruit. Only full boxes meeting quality standards are sent downstream in the supply chain. In instances where the produce quality is significantly compromised, the distribution center workers (DC) notify the retailer, who may then

instruct them to sort the low-quality fruits before dispatching them to the customers. However, such occurrences are infrequent. In a prior season, the Greek company encountered only one instance where an entire cargo trailer was rejected out of the 500 trailers previously dispatched to the distribution centers (DCs). The detailed procedures of these extreme cases were not gathered as they were not encountered during this experiment.

1.9 Transport to the consumers

After the quality check, the cardboard boxes are closed with a cardboard lid. Fruits are typically stored for an average of 1-3 days at the distribution centers at room temperature (around 20 °C). During a field visit to a Swiss distribution center in Märstetten, it was observed that in Swiss facilities, the distribution center sends the boxes to the correct addresses via the postal service. The processing and delivery times between the post office and the customer typically range from 1 to 3 days, and delivery is conducted by unrefrigerated trailers. Therefore, upon arrival at the distribution center, one should account for a total last-mile delivery time of 2-6 days at ambient temperatures.

Each package received by the end customers is accompanied by an information sheet containing detailed instructions tailored to the specific fruit variety. These guidelines are designed to assist end-customers in prolonging the shelf life of the fruits and minimizing food spoilage. For all citrus fruits, including oranges, lemons, grapefruits, and mandarins, customers are advised that storing them in a cool environment can preserve freshness for up to 4 weeks, with mandarins having a slightly shorter duration of 2 weeks. Customers were recommended to utilize Styrofoam containers or wool blankets to shield the fruits when stored outdoors during colder seasons. Alternatively, storage in a cool cellar or the refrigerator's vegetable drawer, but no recommended temperatures were specified. Regular inspection of the fruits for any signs of damage or dark spots is encouraged, with customers instructed to consume fruits showing visible imperfections first and promptly remove any moldy specimens from the storage container. Furthermore, customers are informed that ripe citrus fruits may still exhibit a green hue, contrary to common misconceptions associating green fruits with being unripe or bitter. Citrus is a non-climacteric which implies it does not ripen after harvest. Fruit, therefore, needs to be harvested sufficiently ripe, but the peel color is not an indicator of ripeness. The peel color can change after harvest, though. End-customers can also offer feedback on the received packages, facilitating continuous improvement in service quality.

2 Data collection, processing, and supply chain monitoring

All data described below was collected in the period spanning between September 2023 and March 15th 2024.

2.1 Pre-harvest data

For data collection pre-harvest, we primarily utilized a weather dataset containing daily readings from 01/01/2023 to 16/04/2024 for the city of Nafplion, Argolia, Greece. The dataset was collected from the OpenWeather API. The primary objective was to investigate potential correlations between relevant weather parameters during the harvesting season and any subsequent quality issues in the harvested fruits upon arrival for processing.

The dataset included the following columns: latitude, longitude, event time, sunrise time, sunset time, temperature (K), sensible temperature (K), pressure (mbar), humidity (%), dewpoint (K), UV index, clouds(%), visibility (m), wind speed (km/h), wind degree, wind gust (km/h), weather type (e.g., clear, clouds, drizzle, dust, mist, rain, smoke, snow), weather description (e.g., broken clouds, clear sky, dust, few clouds, heavy intensity rain, light intensity drizzle, light rain, light snow, mist, moderate rain, overcast clouds, scattered clouds, smoke, snow), minimum temperature (K), minimum temperature time, maximum temperature (K), and maximum temperature time.

After cleaning the initial data, which involved converting temperatures to degrees Celsius, the dataset and information from our production records were analyzed. By merging the weather data with the merged data frame from the processing stage (described later in section 2.2), these data enable us to assess the impact of weather conditions on the harvest.

Statistics such as average historical temperature, humidity, UV index, and sun exposure for critical periods leading up to the inspection date of each produced lot were then incorporated into our analysis. This can enable to identify any patterns or correlations between weather conditions and the observed quality of the harvested fruits. Data on the rain precipitation in mm needed to be included. However, we used the weather type column (which would mention rain or drizzle) to determine if there was any rainfall during critical pre-harvest periods, which could also influence fruit quality. By assigning a numerical value to drizzle, rain, and other possible values, one could correlate these variables to the different parameters.

2.2 Packhouse

Packhouse temperature data

TempTale Ultra probe sensors (Sensitech Inc., Beverly, United States) collected temperature sensor data, including ambient temperature measurements. These sensors have a temperature range of -30 to 70 °C with an accuracy of ± 0.5 °C. They were strategically placed at key points in the packhouse in Greece. One sensor was positioned outdoors at the intersection of two trusses, shaded from direct sunlight, and located approximately 2.30 meters above the ground and 3.13 meters from the back wall of the warehouse. This placement aimed to capture the temperature experienced by the fruits upon arrival at the supplier's location and before processing. The storage duration was a few hours, at most, over the weekend, as discussed in a previous section (c.f. section 1.4). Another temperature sensor was placed inside the warehouse, positioned 2.40 meters above the ground and directly facing the caliber sorting line of the conveyor belt at 5.45 m from the back wall. This placement ensured a close representation of the temperature inside the warehouse, specifically at the nearest point to the fruits.

These sensors operate with a specified sampling time and have a battery life lasting around 3 months. The primary objective is to enhance end-to-end visibility by examining the temperature conditions experienced by the fruits at the Greek supplier's facility before precooling.

Fruit quality data

The Greek supplier also collects data on the fruits at this stage, focusing on each lot. This data collection process involves three distinct methods. Initially, they recorded this information by hand in a physical ledger located in Greece. Subsequently, the data are transcribed into an Excel file. Finally, the supplier shares this dataset with a Swiss Data Insights company, which offers an online platform serving as a virtual database.

To ensure data consistency and accuracy, we applied a 3-sigma approach. The 3-sigma approach is a statistical method commonly applied in quality control to identify and remove outliers from a dataset. This approach sets control limits based on the dataset's mean and standard deviation. Specifically, we calculate the dataset's mean (average value) and standard deviation (which measures how spread out the values are). Then, control limits are defined at three standard deviations above and below the mean, expressed as $\mu \pm 3\sigma$, where μ is the mean and σ the standard deviation.

In a dataset that follows a normal distribution, roughly 99.7% of values should fall within this range, meaning only about 0.3% of data points would lie outside these limits. Therefore, data points beyond the $\pm 3\sigma$ limits are flagged as potential outliers. These outliers may represent data entry errors, anomalies, or extreme variations that do not reflect normal process conditions. In this study, outliers identified through the 3-sigma approach were reviewed and excluded from further analysis to ensure data consistency and accuracy in evaluating the following fruit quality metrics: sort-out rate, juice content, and sugar content. Identified outliers indeed pertained to typing errors and not out-of-control events.

Initially, external quality scores (the appearance and condition scores) were denoted by alphabets (A to D) but were subsequently mapped to numeric rankings (1 to 4, where A corresponds to 4 and D to 1). The overall inspection score was derived from the combined condition and appearance scores (an AA rating has the optimal score of 120, while a DD rating has the lowest score of 5). This transformation facilitated the analysis of correlation factors between the overall inspection score and other variables.

Dataset integration with other datasets

The dataset used for analysis consisted of a merge between the Excel file and the online datasets. A key identifier was established to facilitate the merge. Since a unique key was not readily available, a composite key was created by combining the last 7 digits of a unique numerical code found on the product label, summed to the volume of the lot, which was converted to string format. This composite key ensured a reliable linkage between the datasets. The merge aimed to enrich the dataset with the qualitative rating of the appearance and condition of the fruits, which are present only in the online datasets.

Consolidated dataset

The resulting dataset comprises essential information, including the lot identifier, arrival date at the facility, producer details, total lot volume, post-sorting volume, sort-out rate, species, variety, sugar content value, juice content, box weight, precooling status, storage temperature, appearance score (ranging from 1 to 4, with 4 indicating the best), condition score (similarly ranging from 1 to 4), and overall inspection score (ranging from 5 to 120, with 120 being optimal). Each row corresponded to a lot. However, the condition, appearance, and overall inspection scores were not present for all the lots (rows) in the resulting dataset.

2.3 Precooling

To ensure visibility at this stage of the processing, temperature sensors were installed inside the precooling rooms. In the small cold room, a sensor (TempTale Ultra probe sensors (Sensitech Inc., Beverly, United States), temperature range [-30 °C, 70 °C], ± 0.5 °C accuracy) was positioned 2 meters above the ground, on the back wall, centrally situated, and hidden behind the pallets that face the refrigeration unit. Meanwhile, in the large cold room, another sensor with the same specifications was positioned 3.30 meters above the ground, centrally below the refrigeration unit. Specifically, this sensor was situated behind the cooling unit. These sensors were not retrieved in time for the analysis.

Since each shipment disposed of two real-time sensors, and these sensors were deployed as soon as the packaging was complete, we can also access specific shipment precooling data by examining the real-time sensor measurements up to the indicated ‘trip departure’ timestamps.

2.4 Refrigerated transport

Sensor measurement per shipment

In every shipment, three sensors were included. Two of these sensors, known as the GEO sensors, were responsible for real-time monitoring of the air temperature, air relative humidity, location, and light intensity. Meanwhile, a pulp temperature sensor was inserted into a fruit adjacent to one GEO sensor to monitor the temperature of the fruit core. The two adjacent sensors were positioned atop the last pallet, typically near the trailer door and centrally within the trailer. The other GEO Sensor was positioned in the front, on top of the central pallet closest to the driver. An explanation of the rationale behind the choice of using three sensors and their specifications was provided in section 1.7.

Note that the sensors were placed on top of the pallets as they entered the precooling rooms. Therefore, their readings include both precooling conditions and transport conditions. An identification process of the precooling, transport, and post-arrival stages was put in place based on the dataset's indication of a trip departure or arrival.

The datasets related to the core temperature sensor were accessed after their arrival at the distribution centers.

Data extraction

To streamline the extraction of the real-time sensor datasets, a web automation tool was devised utilizing Python's Selenium library. The tool operates using a spreadsheet provided by the sensor company, containing metadata about each shipment. Upon execution, the tool autonomously accesses the designated platform, logs in, and extracts the relevant data associated with each sensor's serial number. The tool dynamically generates a dedicated folder for every shipment, utilizing the shipment's name as the folder's identifier. Subsequently, the extracted data were organized within these folders, each stored as an Excel file for ease of access and management.

Data cleaning

Duplicate entries were identified and removed from all datasets during the data validation process. A few datasets lacked departure or arrival time indicators. To address this, departure and arrival times were manually assigned based on observed temperature fluctuations, cross-referenced with estimated shipment departure/arrival times provided in the metadata.

Data augmentation: trailer movement

The datasets collected from the real-time sensors provide real-time measurements at 15-minute intervals. However, the location data these sensors capture is contingent upon signal availability. As a result, the exact location is not consistently visible due to potential signal loss at sea or in low-signal coverage areas.

The location and timestamp columns from the dataset were used to better understand the trailer movement status. The objective was to determine whether the trailer was in motion or stationary at any given time. To achieve this, the following approach was adopted: If the calculated distance between two consecutive data points' coordinates was below 7 kilometers, the trailer was assumed not to be in motion. The distance calculation between consecutive coordinates was performed using the Haversine formula (3). The Haversine formula calculates the shortest distance between two points on a sphere, given their latitudes and longitudes. It takes into account the curvature of the Earth's surface. It provides accurate distance calculations even for relatively short distances, such as those encountered in trailer movements, making it suitable for determining distances between GPS coordinates.

$$a = \sin^2(\Delta lat) + \cos(lat1) \cdot \cos(lat2) \cdot \sin^2(\Delta lon) \quad (1)$$

$$c = 2 \cdot \text{atan2}(a, 1 - a) \quad (2)$$

$$d = R * c \quad (3)$$

Where:

Δlat is the difference between two latitudinal values

Δlon is the difference between two longitudinal values

a is the square of half the chord length between two coordinates

c is the central angle between the two points

R is the radius of the Earth in km

d is the distance between two coordinates in km

The rationale behind setting the threshold at 7 kilometers is as follows: within a 15-minute timeframe, this distance corresponds to a speed of approximately 28 kilometers per hour. Considering that Ro-Ro (Roll-on/Roll-off) ships transporting trailers typically maintain an average speed of 16 knots, equivalent to roughly 30 kilometers per hour, selecting a higher threshold could lead to incorrect assumptions about the trailer's motion status. A higher threshold might erroneously indicate that the trailer is stationary when it is actually in motion at sea. Moreover, on the ground, trailers rarely travel at such low speeds, further supporting the appropriateness of the 7-kilometer threshold for accurately distinguishing between stationary and moving states.

Merging the shipment-specific location dataset with the temperature, humidity, and light datasets is avoided at this point, as the timestamps associated with location data vary depending on the signal. To address the issue of mismatched timestamps between the location data frame and the other data frames, we propose a solution that uses a time window approach. Given that two consecutive data points in the merged data frame are 15 minutes apart, we create a time window of 7.5 minutes. Suppose the difference between the timestamp of a location and the timestamp in the merged data frame falls within this time window. In that case, we include the location information for that specific timestamp. If not, *NaN* values are fed to the corresponding cells. The rationale behind using a 7.5-minute time window is to ensure that the location information is associated with the most relevant timestamp in the merged data frame. For example, if we have two consecutive timestamps in the merged data frame at 10:00 and 10:15, and a location timestamp is recorded at 10:10, it is more logical for the location information to be closer to the second timestamp (10:15) than the first (10:00). Therefore, by using a 7.5-minute time window, we aim to align the location data more accurately with the corresponding timestamps in the merged data frame, minimizing potential discrepancies.

A binary value was assigned to each row with location data to represent whether the trailer was in motion or stationary. A value of 1 indicates that between two consecutive data points with non-*NaN* coordinates, the location remains within a 7 km radius. This implies that the trailer is assumed to be stationary. Conversely, a value of 0 indicates that the trailer was in motion. This distinction is essential because there have been instances where we observed a temperature increase despite no door openings detected by the light sensor. In such cases, the trailer was stationary, as the driver had temporarily halted and turned off the refrigeration unit and/or the engine to minimize noise during his mandated break. Therefore, visually identifying periods when the trailer was stationary despite no door openings, one can attribute significant temperature changes to instances where the refrigeration unit was turned off.

For each shipment, transportation data spreadsheets obtained from the sensor company platform were processed. Subsequently, the temperature, humidity, and light datasets associated with the front and back real-time sensors (GEOsensors) were merged using the timestamp column.

Data augmentation: absolute humidity

We also calculate the absolute humidity, as it provides a more precise indication of the moisture content in the air, regardless of temperature, compared to the relative humidity measured. For fruit transportation, absolute humidity is crucial because it directly affects the rate of moisture loss from the fruits. We use the Clausius-Clapeyron relation equation (4) to derive the absolute humidity, given the relative humidity and temperature values, at ambient pressure conditions.

$$AH [g/m^3] = \frac{2.1764 * RH * 6.112 * e^{\frac{17.67 * T}{243.15 + T}}}{T + 273.15} \quad (4)$$

Where:

AH represents absolute humidity in grams per cubic meter (g/m^3).

RH represents relative humidity as a percentage (%).

T represents temperature in degrees Celsius ($^{\circ}C$).

Statistics per shipment

Key statistics for each shipment are extracted to analyse the precooling, transportation, and post-arrival stages of the data. Metrics such as the minimum, maximum, mean, median, standard deviation, variation, and percentiles (25th and 75th) are calculated. Event indicators ('trip departure' and 'trip arrival') from the sensor datasets are used to segment the data into these stages.

2.5 Arrival at DC and last-mile delivery to the consumer

Fruit quality data collected at the distribution centre, as elaborated in section 1.9, were manually recorded by warehouse employees on paper-format documents. These documents needed to be transcribed into digital Excel files to facilitate further automation of analysis tasks.

The customer feedback datasets were provided in Excel format and included feedback gathered between October 2023 and April 2024. Feedback was categorized into one of five categories: damage to the packaging, delivery time, very high temperatures, very low temperatures, or miscellaneous issues. Additional uncategorized complaints were related to spoilage upon arrival or over-ripeness, occasionally involving taste-related concerns. During data pre-processing, only rows with lot identifiers consisting of 13 digits were selected, as these are reliably traceable to the original datasets. Lot identifiers with more than 13 digits were considered erroneous and untraceable.

2.6 Summary table

A summary of all datasets is provided below.

Table 6. Summary List of All Datasets.

Supply chain step	Dataset	Provider	Description
<i>Pre-harvest</i>	Weather Nafplion	Sensor company	Nafplion weather data. Includes 1-3 daily temperature, humidity, UV, rain readings, and sunrise and sunset times.
<i>Warehouse processing</i>	Traceability report	Greek supplier	Includes: batch ID, date, packaging date, export date, farmer ID, product, variety, number of crates, net weight (kg), quantity in kg, weight per packaged box, number of packaged boxes, total packaged quantity, loss quantity (kg, %), trailer arrival week trailer, diseases, insects, frost/hail symptoms, °Brix, juice content (%), precooling temperature (°C)
	Inspections sheet	Swiss data insights co.	Contains: batch ID, inspection date, inspection type and location, sugar content and juice content, number and volume (kg) of boxes inspected, appearance, and condition scores
	Temperature outside warehouse	Sensor company	Regular readings of ambient temperature in the shaded section of the warehouse. Not yet retrieved
	Temperature inside warehouse	Sensor company	Regular readings of ambient temperature inside the warehouse. Not yet retrieved
<i>Precooling</i>	Temperature precool 1	Sensor company	Regular readings of temperature in the first precooling room. Not yet retrieved
	Temperature precool 2	Sensor company	Regular readings of temperature in the second precooling room. Not retrieved
<i>Transport (includes shipment-specific precooling data)</i>	Metadata - sensors	Sensor company	Metadata per shipment, including sensor serial numbers, dates of trip departure and arrival, trailer number
	Metadata - shipments	Sensor company	Metadata per shipment, including product shipped, packaging, pallet positioning, and other
	Front humidity	Sensor company	Regular readings per shipment sensor
	Front light	Sensor company	Regular readings per shipment sensor
	Front location	Sensor company	Readings dependent on signal strength
	Front temperature	Sensor company	Regular readings per shipment sensor
	Back humidity	Sensor company	Regular readings per shipment sensor
	Back light	Sensor company	Regular readings per shipment sensor
	Back location	Sensor company	Signals dependent on signal strength
	Back temperature	Sensor company	Regular readings per shipment sensor
	Core temperature	Sensor company	Core temperature recurrent readings for each sensor
	Digital twin temperature	Sensor company	DT core temperature readings for each sensor
<i>DC and last mile</i>	Quality sheets	Main retailer	Contains: sugar content, weight, qualitative gradings, date
	Customer feedback sheet	Main retailer	Contains: customer remarks on lots
	Quality sheets	Small retailer	Contains: weekly qualitative grading (scale 1-5) and storage temperature/humidity readings. Use: shelf life

Acknowledgments

This work was supported by Sensitech. We acknowledge the support of Dr. Rafael Sacher, George Stergiou, Dr. Martin Meckesheimer, and Elvira Zing for their collaboration in structuring the experiment. We acknowledge the support of Ana Mikler, Nikos Prountzos, Vagelis Kyriakou, Anastasia Biniari, and Rebecca Näf for organizing the data collection and supply chain information. Additionally, we acknowledge the support of Celine Verreydt, Elisabeth Tobler, and Jörg Schemminger for sharing their insights.

Author Contributions

Bassem Alsakhawy: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Writing - Original Draft.

Raphael Sacher: Conceptualization, Supervision, Project Management, Review.

Thijs Defraeye: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly to improve the spelling, grammar, and style of the text. No additional original content was generated using these AI-assisted technologies. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

UNEP, 2021. Food Waste Index Report 2021. Nairobi.

FAO, 2019. The state of food and agriculture: moving forward on food loss and waste reduction. Rome.

FAO, 2023. The State of Food and Agriculture 2023 – Revealing the true cost of food to transform agrifood systems. Rome.

FAO, 2021. The State of Food and Agriculture 2021. Making agrifood systems more resilient to shocks and stresses. Rome.

Rejeb, A., Keogh, J. G., Rejeb, K. (2022). Big data in the food supply chain: a literature review. *Journal of Data, Information and Management/Journal of Data, Information and Management*, 4(1), 33–47. <https://doi.org/10.1007/s42488-021-00064-0>

Council of the European Union, 2007. Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91.

Defraeye, T., Verreydt, C., Gonthier, J., Lukasse, L., Cronje, P., Berry, T. (2024). Building a physics-based virtual refrigerated container filled with fruit in ventilated packaging. <https://doi.org/10.31224/3527>

UNECE, 2023. UNECE Standard FFV-14 concerning the marketing and commercial quality control of Citrus fruit, Geneva.

Hofman, H., 2011. Management of internal dryness of Imperial mandarin. Project Number: CT04002 Department of Employment, Economic Development & Innovation, Kalkie.

Zhou, Y., He, W., Zheng, W., Tan, Q., Xie, Z., Zheng, C., et al. (2018). Fruit sugar and organic acid were significantly related to fruit Mg of six citrus cultivars. *Food Chemistry*, 259, 278–285. <https://doi.org/10.1016/j.foodchem.2018.03.102>

Khalid, S., Malik, A. U., Saleem, B. A., Khan, A. S., Khalid, M. S., Amin, M. (2012). Tree age and canopy position affect rind quality, fruit quality and rind nutrient content of 'Kinnow' mandarin (*Citrus nobilis* Lour × *Citrus deliciosa* Tenora). *Scientia horticulturae*, 135, 137–144. <https://doi.org/10.1016/j.scienta.2011.12.010>

Verreydt, C., Cobbinah-Sam, E., Mikler Celis, A., Meckesheimer, M., Prountzos, N., Sacher, R., Tobler, E., Defraeye, T. (2024). Identifying cooling heterogeneity during precooling and refrigerated trailer transport for the citrus supply chain by extensive temperature monitoring within full-scale experiments. *Food Control*, 165, 110672 (18 pp.). <https://doi.org/10.1016/j.foodcont.2024.110672>