Comprehensive REVIEWS in Food Science and Food Safety

Time–Temperature Management Along the Food Cold Chain: A Review of Recent Developments

Samuel Mercier, Sebastien Villeneuve, Martin Mondor, and Ismail Uysal

Abstract: The cold chain is responsible for the preservation and transportation of perishable foods in the proper temperature range to slow biological decay processes and deliver safe and high-quality foods to consumers. Studies show that the efficiency of the cold chain is often less than ideal, as temperature abuses above or below the optimal product-specific temperature range occur frequently, a situation that significantly increases food waste and endangers food safety. In this work, field studies on time–temperature conditions at each critical stage of the cold chain are reviewed to assess the current state of commercial cold chains. Precooling, ground operations during transportation, storage during display at retail and in domestic refrigerators, and commercial handling practices are identified and discussed as the major weaknesses in the modern cold chain. The improvement in efficiency achieved through the measurement, analysis, and management of time–temperature conditions is reviewed, along with the accompanying technical and practical challenges delaying the implementation of such methods. A combination of prospective experimental and modeling research on precooling uniformity, responsive food inventory management systems, and cold chains in developing countries is proposed for the improvement of the cold chain at the global scale.

Keywords: cold chain, food safety, food waste, shelf-life, supply chain

Introduction

Refrigeration, food safety, and food waste are intimately linked. Perishable food, including fruits, vegetables, dairy products, meats, and fish products, needs to be kept in a chilled or frozen state along the entire supply chain. Failing to keep perishable food in the desired temperature range, because of insufficient refrigeration, can stimulate the growth of pathogens and spoilage microorganisms and render the product inedible. When the safety risk is unknown or not reported, the food may be consumed and cause foodborne illnesses, which have a significant societal cost. It is estimated that foodborne illnesses annually cost more than \$50 billion in the United States and cause more than 120000 hospitalizations and 3000 deaths (Scharff 2012; CDC 2016). When insufficient refrigeration of perishable food is known and reported, the food is then discarded, thus mitigating concerns about food safety but creating food waste. The United Nations estimates that each year approximately 1/3 of all food produced for human consumption is wasted, while other reports indicate that food waste accounts for 40% of production (FAO 2011; NRDC 2012). Similar amounts of food waste were reported by Kader (2001), indicating that improvements aimed at reducing food waste have been minimal over the last decade. The annual economic impact of food waste is estimated at \$218 billion in the U.S., \$143 billion in Europe, and \$27 billion in Canada (Young 2012; ReFED 2015; FUSIONS 2016). Such an amount of food waste is unacceptable, especially given the world's growing population, the saturation of land resources used for agriculture, and the already significant concerns about food security in many regions of the world (International Institute of Refrigeration 2009; Young 2012; Jedermann and others 2014a; Gwanpua and others 2015).

The succession of refrigeration steps along the supply chain that are applied to keep perishable food in the desired temperature range is referred to as the cold chain. The efficiency of the cold chain differs significantly between and among countries. In most developing countries, the level of refrigeration applied for the preservation of perishable products is lower than the level applied in developed countries because of the absence of proper refrigeration equipment, reliable sources of electricity, the high energy cost associated with refrigeration, and insufficient awareness of quality and safety concerns associated with improper refrigeration (FAO 2004; International Institute of Refrigeration 2009). It is estimated that the application in developing countries of the same level of refrigeration that is used in developed ones would reduce the amount of perishable food wasted annually by more than 200 million tons, which is approximately 14% of their consumption (International Institute of Refrigeration 2009).

A significant challenge for an efficient cold chain is the different requirements of perishable food product categories (dairy, eggs, fruits and vegetables, fresh-cut fruits, fresh-cut vegetables,

CRF3-2016-0009 Submitted 12/20/2016, Accepted 4/18/2017. *Authors Mercier and Uysal are with Dept. of Electrical Engineering, Univ. of South Florida, 4202 East Fowler Ave., Tampa, FL, 33620, U.S.A. Authors Villeneuve and Mondor are with Saint-Hyacinthe Research and Development Centre, Agriculture and Agri-Food Canada, 3600 Casavant Blvd. West, Saint-Hyacinthe, Quebec, Canada, J2S 8E3. Authors Mercier is also with Dept. of Chemical and Biotechnological Engineering, Univ. de Sherbrooke, 2500 Université Blvd., Sherbrooke, Quebec, Canada, J1K 2R1. Direct inquiries to author Mercier (Email: samuel.mercier@USherbrooke.ca).*

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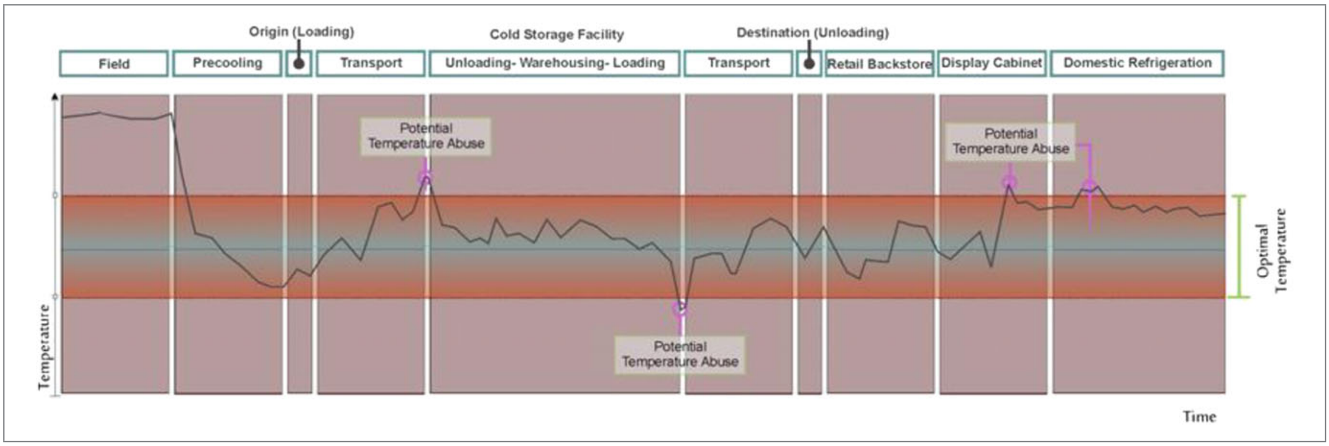

Figure 1–Typical temperature profile of perishable food along the cold chain.

meat and meat products, seafood, and fish) to maximize shelf-life and commercial potential, including different optimal temperature ranges (ambient = 15 °C to 20 °C; cool = 2 °C to 15 °C; cold = −9 °C to 2 °C; and frozen ≤−10 °C) (IATA 2009). As an example, Table 1 presents the optimal storage temperatures for common perishable food products. Although temperature is the most important factor influencing the perishability of a food product, carbon dioxide production, respiratory behavior, ethylene production, and sensitivity are also significant factors (Anonymous 1989, 1990). These factors should also be taken into account to determine the compatibility of different food products when the transportation or storage of mixed loads is considered.

In most developed countries, cold chains are tightly regulated. Refrigeration needs to be applied throughout the entire cold chain, and a HACCP (Hazard Analysis and Critical Control Points) strategy needs to be broadly implemented within the food industry to manage the cold chain and ensure food safety (Jol and others 2007; EUFIC 2013). Nevertheless, it is a significant challenge to maintain the temperature of perishable food in the desired range at all steps of the cold chain. Thus, ensuring the integrity of the cold chain for temperature-sensitive food products involves additional requirements related to proper packaging, temperature protection, and monitoring. Figure 1 illustrates potential temperature abuses induced by 4 typical breaches in the integrity of a cold chain that requires the maintenance of a specific temperature range. In the 1st breach, the temperature has risen above the product's storage temperature specifications. Notable causes of undesirable temperature increases can include inappropriate precooling of the food, poor performance of temperature control systems, temperature fluctuations caused by on–off cycles of the refrigeration unit, local heat sources in trucks or warehouses, and temperature abuses during truck loading and unloading (Villeneuve and others 2002a; Foster and others 2003; Carullo and others 2009; Jedermann and others 2009; Nunes and others 2014). In the 2nd breach, the temperature has fallen below the product's storage specifications, possibly because the product was stored in a refrigerated warehouse at an inappropriate temperature or was left exposed during the unloading process in the winter. The 3rd and 4th breaches, in which the temperature of the food increased again above the storage specifications while it was displayed at retail and after it was purchased by consumers, can occur because of the overloading of display cabinets, the transportation by consumers of food without the protection of an insulated bag, or high temperatures in domestic refrigerators (LeBlanc and others 1996; James and others 2008; Laguerre and others 2013). Each of these breaches can decrease the quality of the food as well as endanger its safety.

Table 1–Optimal storage temperature of common perishable food products (Anonymous 1989, 1990)

Food product	Optimal storage temperature
Deep-frozen food	
Meat	−25 °C or colder
Poultry	−24 °C or colder
Fish	−29 °C or colder
Fruits and concentrated juices	−18 °C or colder
Vegetables	−18 °C or colder
Frozen food	−20 °C or colder
Frozen butter	
Chilled food	
Fresh meat	−1.5 °C
Meat products	−2 °C
Manufacturing meat	−2 °C
Poultry	−1.5 °C
Fish	in melting ice (0 °C to −0.5 °C)
Dairy products	0 °C to 2 °C
Fruits and vegetables	
Low temperature (apple, blueberry, carrot, lettuce, etc.)	0 °C to 2 °C
Moderate temperature (carambola, melon, pumpkin, etc.)	6 °C to 9 °C
High temperature (banana, cucumber, grapefruit, etc.)	12 °C to 16 °C

In the U.S., it is estimated that approximately 12% of food waste occurs during distribution, mainly because of inappropriate refrigeration (NRDC 2012). Monitoring products exposed to intermittent and temporary temperature abuses along the cold chain is critical. Wireless temperature-monitoring technologies, notably radiofrequency identification (RFID) tags, have evolved significantly over the last 2 decades and are now more accurate, more convenient, and available at lower cost (Ruiz-Altisent and others 2010; Ruiz-Garcia and Lunadei 2011; Bollen and others 2015; Musa and Dabo 2016). The application of wireless temperature-monitoring technologies to measure the temperature of perishable food in real time and to adapt cold chain management accordingly is now an accessible strategy to reduce food waste. For instance, if we know the time–temperature history of food from harvesting or processing to storage at the distribution center, then we can avoid shipping a perishable food that has been subjected to temperature abuses to a retailer located too far away given the food's remaining shelf-life (Nunes and others 2014). However, given the high level of temperature heterogeneity inside a truck, refrigerated container, cold room, or warehouse, the proper monitoring of the temperature along the cold chain remains a significant challenge (Raab and others 2008; Pelletier and others 2011). Significant temperature heterogeneity can also be observed inside a single pallet. As an example, Margeirsson and others (2012) reported differences in temperature of up to 8.5 °C depending on the position of fish fillets inside thermally abused pallets. Similarly, Nunes and others (2014) estimated that in a pallet of 1st strike rations subjected to a 24-h summer temperature profile, the remaining shelf-life of the rations at the corner of the pallet was up to 15% shorter than the remaining shelf-life of those at the center of the pallet.

Given that instrumenting each box inside a perishable food pallet to measure its temperature is not realistic, because of cost and practical limitations, modeling has been proposed as the solution to complement the measurement of the temperature from a few sensors, by mapping the temperature where no measurement is taken (Jedermann and others 2009, 2011). Models developed to map the temperature inside pallets can be separated into 2 types: physics-based and data-based. Physics-based models describe momentum, heat, and mass transfer from 1st principles and have been successfully applied to map the temperature inside pallets during precooling (Ferrua and Singh 2009a, 2009b, 2009c), transportation (Defraeye and others 2015b; Han and others 2016), storage inside cold rooms (Hoang and others 2000; Nahor and others 2005), display at retail (Gaspar and others 2012), and storage inside domestic refrigerators (Laguerre and others 2010; Zhang and Lian 2014), among others. An increasing number of physics-based models describing the different steps of the cold chain have been developed over the last decade, in large part because improved computational fluid dynamics (CFD) software has facilitated the numerical implementation of those models' systems of partial differential equations. Physics-based models provide a detailed description of the temperature distribution inside food pallets, promote a fundamental understanding of the underlying physical phenomena, and generally do not require a high number of experimental measurements for their implementation and validation. However, physics-based models remain challenging to implement in a commercial context because of the amount of information required for their development (identification of the main physical phenomena; values of the momentum, heat, and mass transfer properties; proper boundary; and initial conditions), the complexity associated with the conjugated description of airflow, especially in the presence of turbulence, and the significant duration of CFD simulations (Laguerre and others 2013).

Data-based models rely on the selection of a mathematical model structure, the calibration of the model input parameters from a training set of measurements, and the validation of the model using a validation set. Data-based models generally do not provide a fundamental understanding of the underlying physical phenomena governing the cold chain like physics-based models do; data-based models also have many unknown parameters to be estimated from experimental measurements and may be prone to a greater extent to overfitting problems. However, data-based models provide greater flexibility given that their mathematical structure is not limited to those imposed by 1st principles, are easier to implement for complex and highly coupled operations, and are well positioned to take advantage of the vast amount of experimental measurements available in this era of big data.

In this review, the key aspects related to the control of the temperature of perishable food along the cold chain, as well as the potential improvements to the cold chain provided by real-time temperature monitoring of perishable food, are investigated. More specifically, field studies conducted on the measurement of the temperature of chilled food products along the cold chain are reviewed, with each step from precooling to storage in domestic refrigerators taken into consideration. From the analysis of the field studies, the current efficiency of the cold chain in maintaining the temperature of perishable food is established, and the most pressing weaknesses that need to be corrected for better food quality and safety are identified. Potential management systems to improve the cold chain based on the measurement of perishable food temperature are then discussed, and challenges related to the implementation of such systems are identified. Finally, relevant prospective research projects for global and inclusive improvements to the cold chain are proposed.

Temperature Conditions along the Cold Chain

Overview of the cold chain

Figure 2 presents an overview of the steps in a typical cold chain. The cold chain generally starts right after harvesting for fresh fruits and vegetables and right after processing for processed fruits and vegetables, meat, and dairy products, when the food is precooled to bring its temperature to the appropriate food-specific storage temperature. Unless food wastage occurs at an earlier step, the cold chain ends when the food is placed in a domestic refrigerator by the consumer. In between, depending on market demand, the food may transit through 1 or more storage and distribution centers before being shipped to retailers, as well as through a packaging center and cross-docking sites where shipments from small suppliers are combined to reduce transportation costs (Mack and others 2014). The total duration of the cold chain is highly dependent on the specific product and the target market, with some cold chains being as short as a few hours and others lasting several months or even years, especially for frozen food products (Mack and others 2014; Gogou and others 2015). The distribution center is a critical control point in many cold chain management systems, as it provides the opportunity to sort and combine shipments received from many suppliers and to schedule the shipments' departure according to retailer demand, food arrival time, and the food's current quality. Nevertheless, each step in the cold chain has a significant impact on the final quality of the food, and temperature abuses that exceed the food tolerance level may occur at any point, leading to food waste or raising safety concerns.

Precooling

Precooling is critical for removing heat from perishable food after harvesting or production, especially given that refrigeration systems used during transportation are generally designed to preserve the temperature of the load, and not to remove additional heat (James and others 2006). Reducing the delay from harvesting to precooling has been shown to improve the shelf-life of perishable food significantly, as this is generally the period when perishable food is at its highest temperature and loses shelf-life at the highest rate (Nunes and others 2014). As an example, Pelletier and others (2011) monitored the quality of strawberries along the cold chain and reported that a delay of 4 h between harvesting and precooling increased water loss by approximately 50% and significantly decreased the visual quality of the food at its arrival at the distribution center. Nunes and others (1995) reported similar results for delays of 6 and 8 h before precooling.

There exists a variety of precooling techniques, including forced-air cooling (Thompson 2002), hydrocooling (Reina and

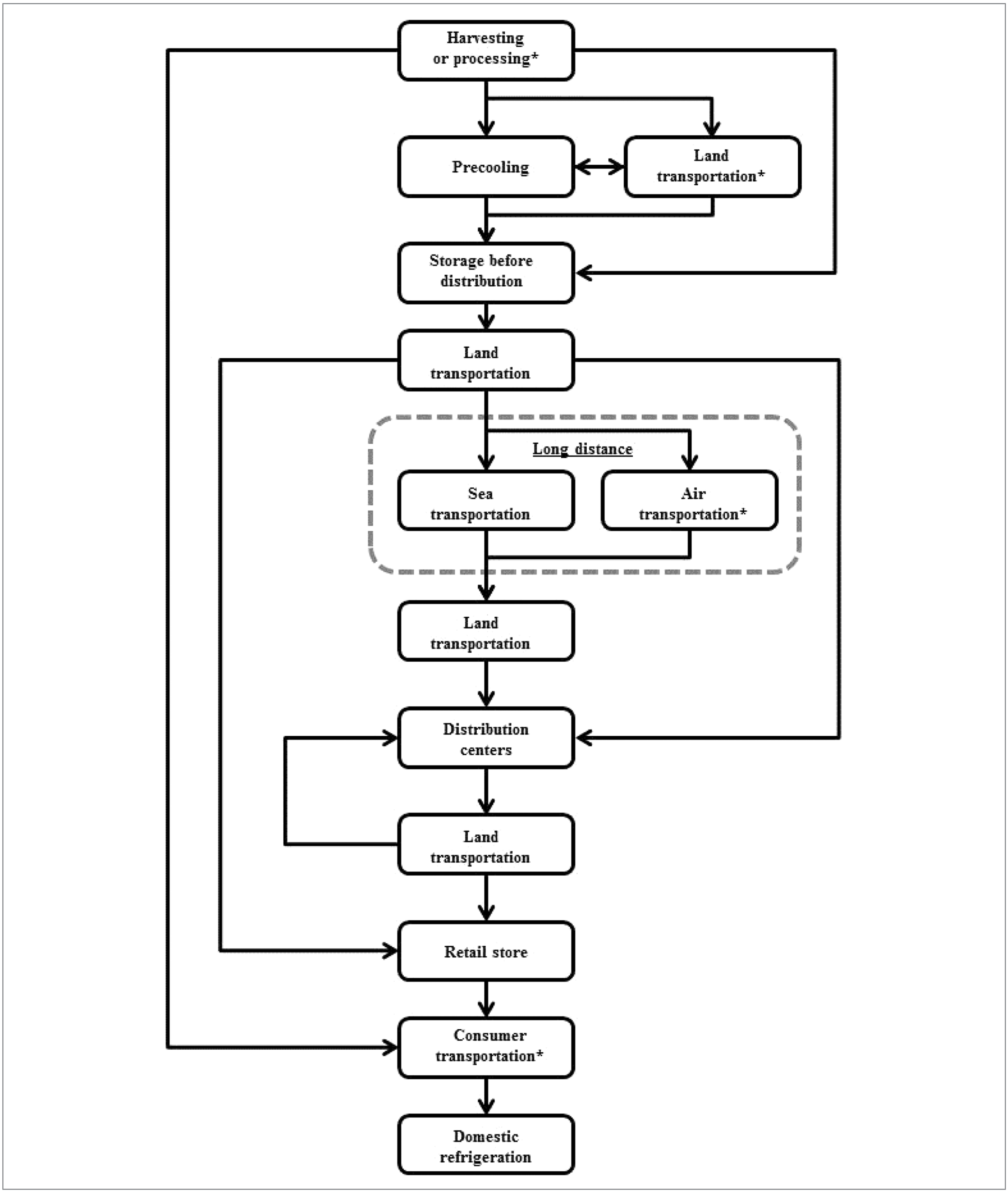

Figure 2–Overview of the main steps in a typical cold chain. The asterisks denote steps where no refrigeration is generally applied.

others 1995), room cooling (Thompson 2004), vacuum cooling (McDonald and Sun 2000), and cryogenic cooling (Curtis and others 1995). Forced-air cooling is usually accomplished by creating an air pressure differential on 2 sides of a stacked pallet tunnel. The air pressure allows the cooled air to circulate from the outside through the warmer product and back into the room after going through the refrigeration unit for recooling. Hydrocooling uses chilled or cold water to lower the temperature of the product in pallets or large containers prior to further packaging. Room cooling is a relatively older technique in which the product is placed in either boxes or pallets inside a cold room and exposed to cooler temperatures. Room cooling takes longer and is sometimes used after other precooling techniques for temperature stabilization. Vacuum cooling is used in situations where rapid cooling of the product is required or desired: significant temperature drops are achieved in a short time frame by evaporating the moisture from the product. In vacuum cooling, the pressure is dropped to the point where water can boil at a very low temperature, in order to encourage faster evaporation. Cryogenic cooling is accomplished by using liquid nitrogen or dry ice, which produce boiling temperatures as low as −196°C. As the product moves along a conveyor belt through a tunnel where liquid nitrogen is evaporating, the product's temperature drops rapidly. If this conveyor tunnel is designed to be vertical, it is called a spiral chiller and is generally used for frozen products.

The choice of cooling method for a specific food product depends on a number of factors, including the product's mechanical properties and its sensitivity to chilling or freezing injuries. As an example, strawberries lend themselves well to forced-air cooling methods at temperatures around freezing (0 °C to 2 °C), as the freezing point of strawberries is below that of water. However, other products such as tomatoes may be more susceptible to low temperatures and can get bruised easily. Other circumstantial factors, such as harvest volume (which determines the flow of the product into the facility) and economic considerations, also play a role, as the choice of cooling method must be justified by a better return on investment or higher customer satisfaction.

Uniform precooling of food products poses a significant challenge. For instance, during forced-air cooling, the perishable food products near the side of the pallet facing the fan in a precooling tunnel are in contact with warmer air than the products on the opposite side and generally cool down at a slower rate. Consequently, cooling at the pallet surface on the side facing the fan may be insufficient if precooling is stopped based on the measurement of the temperature on the opposite side, or some foods may suffer cold injuries if precooling is performed until the products facing the fan reach the desired temperature. The variability of each load's properties after harvesting also increases the complexity of precooling. The desired temperature profile during precooling is obtained when the temperature at every point inside the pallet reaches a temperature range that promotes the preservation of the food (Figure 3A). However, if harvest conditions are particularly warm (Figure 3B) or cold (Figure 3C), if the load is subjected to solar radiation (Figure 3D), if the number of pallets (Figure 3E) or bins per pallet (Figure 3F) differ, or if a different crop is precooled (Figure 3G), failure to properly adjust the precooling time and operating conditions can lead to insufficient or excessive temperature decreases.

The quality of precooling is strongly dependent on the packaging. Both the design and the material of the packaging need to be considered when choosing the optimal cooling method (Stanley 1988). The design of the package vent areas directly affects the flow of the cold fluid inside the pallet as well as the heat and mass transfer rates at the surface of the food (Defraeye and others 2015a; Zhao and others 2016). However, the package cannot be designed only from the perspective of optimal precooling: sufficient protection against mechanical damage along the cold chain also needs to be considered. Many current packages have been designed with greater consideration given to the mechanical protection of the food rather than proper precooling, with the result that precooling uniformity and efficiency are decreased (Pathare and others 2012)

Pelletier and others (2011) monitored the temperature of strawberries along the cold chain and reported a high variability in precooling efficiency, as indicated by temperature differences of up to 2 °C between the pallets before they were loaded for transportation. Similarly, Nunes and others (2014) investigated the cold chain for blackberries and reported that the temperature at the center of some pallets did not decrease sufficiently during precooling. Both of the aforementioned studies revealed the need for a more effective precooling step to improve the preservation of food, as insufficient precooling can have a lasting effect on the food temperature along the cold chain even if the subsequent steps are performed at the correct ambient temperature (Nunes and others 2014).

Commercial transportation

Land transportation. Land transportation by cars or trucks is the most common mode of food transport. In the U.K. it is estimated that more than 90% of food is transported by land (AEA Technology 2005). A survey of the cold chain for yogurt and meat products in France by Derens and others (2006) indicated that those foods, transported by refrigerated trucks, travel nearly 1000 km from production to retail. In the U.S. it is estimated that food transported by land travels more than 2000 km before it arrives at the retailer (Pirog and others 2001). In Canada, McKellar and others (2014) reported that the average total transportation time for fresh-cut lettuce from production to retail was approximately 38 h, which, assuming an average speed of approximately 65 km/h, corresponds to a distance of nearly 2500 km.

Given the long distances traveled and, therefore, the long duration of land transportation, keeping the temperature of perishable food in the desired range during this step in the cold chain is critical. Derens and others (2006), Morelli and Derens-Bertheau (2009), and Derens-Bertheau and others (2015) reported that the temperature of perishable food was efficiently kept in the desired range during commercial transportation in France and that average temperatures during this step in the cold chain were 2.9 °C, 3.1 °C, and 2.4 °C, respectively. Gogou and others (2015) reported an average temperature of 3.9 °C during the transportation of meat products in Greece.

Higher temperatures have also been observed during land transportation. Koutsoumanis and others (2010) measured the time–temperature profile of milk along the cold chain in Greece and reported an average temperature during land transportation of 6.7 °C. In that study, more than 85% of the temperature measurements during land transportation were above 6.0 °C. Temperatures above those recommended have also been reported during truck loading and unloading. Abad and others (2009) reported temperature increases of 2.0 °C during loading of fish boxes in a truck before their transportation from Germany to Spain and of 3.0 °C during unloading. Pelletier and others (2011) monitored the temperature of strawberries during a 4-d shipment from California and reported temperature increases from 1.5 °C to 6.0 °C for some pallets. McKellar and others (2014) measured the time–temperature profiles of fresh-cut lettuce in Canada during the summer and winter and reported temperature increases to above 10.0 °C when the truck was loaded or unloaded for measurements taken during the summer. The average temperatures reported for transportation from production to the distribution center and from the distribution center to retail during the summer were 6.3 °C and 5.9 °C, respectively (McKellar and others 2014). During the winter, the average temperatures reported for transportation from production to the distribution center and from the distribution center to

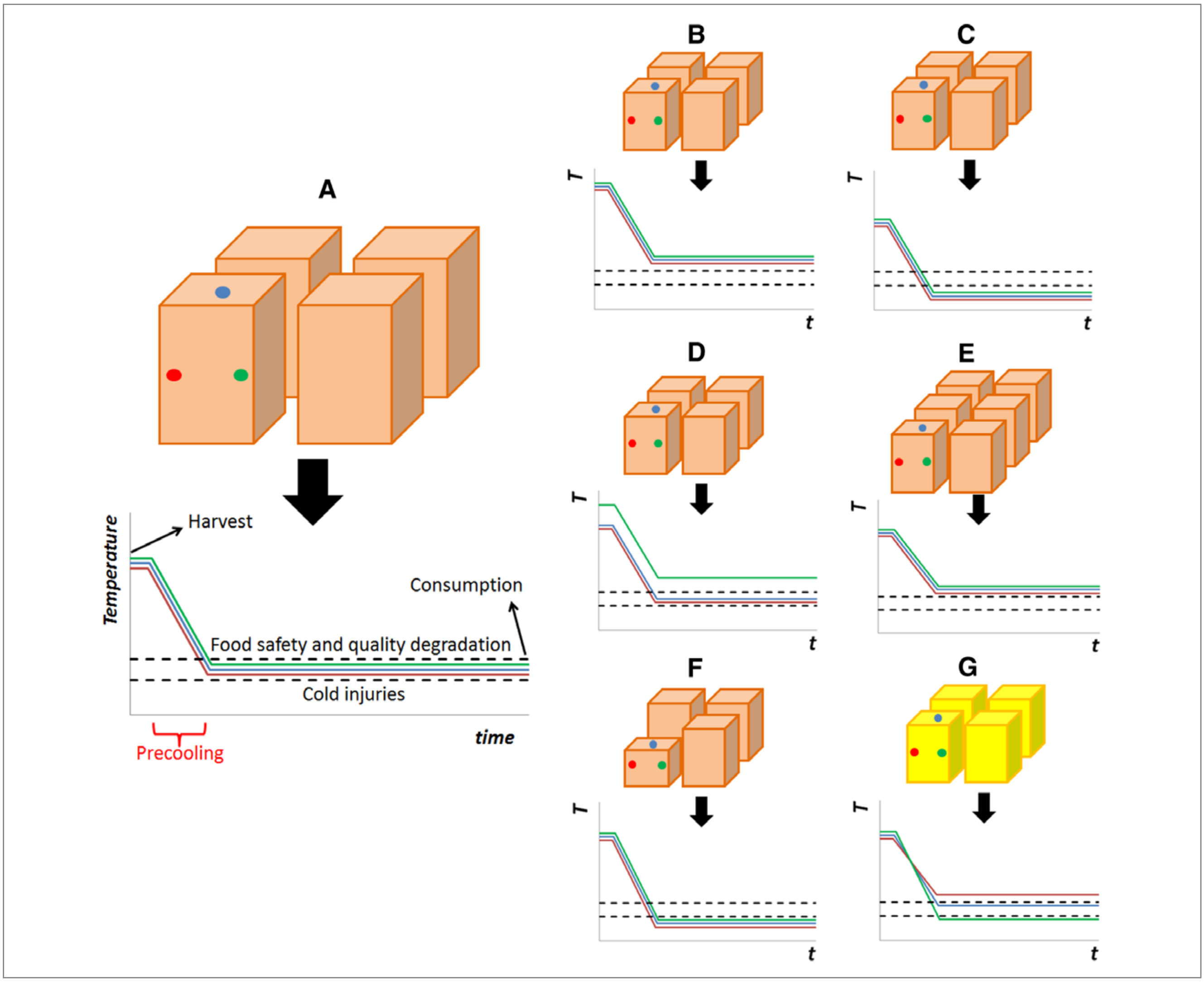

Figure 3–Temperature at 3 positions inside a pallet (represented by the blue, green, and red dots) along a cold chain depending on the success (A) or failure (B–G) of forced-air precooling. T, temperature; t, time.

retail were lower, 2.3 °C and 2.9 °C, respectively (McKellar and others 2014). Those lower average winter temperatures could be attributed to a smaller increase (or even a decrease) in the food temperature during truck loading and unloading.

Significant heterogeneity of the temperature of pallets according to their position inside refrigerated trucks has been reported. Raab and others (2008) investigated the transportation of chicken breasts from the producer to the distribution center and reported differences in temperature of up to 10 °C between the air near the doors of the truck and the air near the cooling device. Nunes and others (2014) observed differences of up to 5 °C for pallets of blackberries placed at different positions and transported from Mexico to California. Studies conducted on time–temperature measurements inside pallets subjected to ambient conditions representative of a cold chain indicate that significant heterogeneity of the temperature inside a pallet can also be expected. Margeirsson and others (2012) reported that the temperature of fish fillets varied by up to 8.5 °C depending on their position inside thermally abused pallets. Nunes and others (2014) estimated that the remaining shelf-life was up to 15% shorter for 1st-strike rations placed at the corner of a pallet subjected to a 24-h summer temperature profile than for those placed at the center of the pallet. Significant heterogeneity was also observed inside pallets of yogurt (Sivakumar and others 2015) and fruits (Hoang and others 2015; Defraeye and others 2016).

A significant factor explaining the heterogeneity of food temperature during land transportation is the heterogeneity of the airflow. The airflow is affected by factors such as the type of air delivery system (top-air delivery compared with bottom-air delivery) and the load patterns used in truck trailers (Figure 4), which will affect the amount of product warming or freezing that can occur. In top-air delivery trailers, all products should be placed on pallets or racks to provide adequate return air space under loads, while in bottom-air delivery trailers, special care should be taken to cover any vertical air channels left in a load from varying package sizes, shapes, or numbers, in order to prevent short-cycling of the circulating air and inadequate air circulation through and around the rest of the load. Maintaining the necessary air circulation channels to promote a uniform temperature is easier in straight loads of a single commodity. However, for mixed loads, which are common for short-distance transportation, the differences between the packages in terms of size, shape, design, required temperature, and

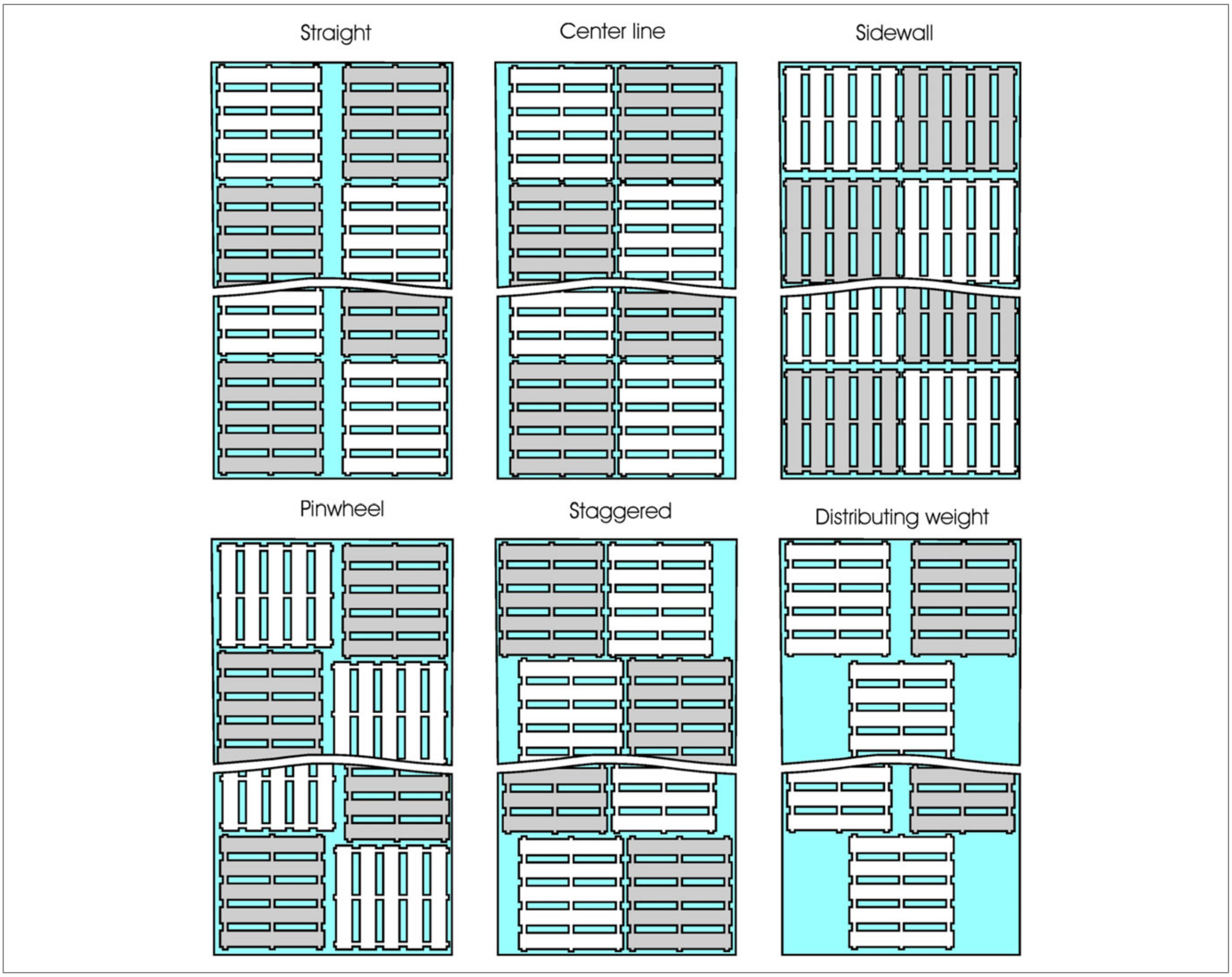

Figure 4–Diagrams of common loading patterns in a refrigerated truck.

number will contribute to the heterogeneity of food temperature during land transportation. Whenever possible, only temperature-compatible commodities should be loaded in mixed loads. When that practice is not possible, a temperature suited to the most valuable or most perishable products should generally be used (Kasmire and Hinsch 1987). Additional factors explaining the heterogeneity of food temperature during land transportation are different initial pallet temperatures as a result of nonuniform precooling and greater sensitivity of pallets near the back of the truck to door opening (James and others 2006; Pelletier and others 2011; Nunes and others 2014; Lafaye de Micheaux and others 2015).

Air transportation. Transportation of perishable food by air offers considerable advantages for a year-round supply of perishable food in regions that are distant from the harvesting or production site. Yet air transportation of perishable food remains limited because of the high economic and environmental costs of this mode of transportation. As an example, in the U.K., it is estimated that less than 1% of food is transported by air, while air transportation accounts for 11% of the CO_2 emissions associated with food transportation (AEA Technology 2005).

Nevertheless, air transportation is required for high-value perishable food and perishable food with a short shelf-life that have to arrive at their destination quickly. Air transportation is also critical to the economy of many regions, notably fruit- and vegetable-producing countries in Africa that ship most of their food to developed markets (MacGregor and Vorley 2006). Air transportation may become a more significant link in the cold chain worldwide, as the overall amount of goods transported by air, after a few years of stagnation or decrease, is once again increasing (Pelletier 2010; Boeing 2014; Eurostat 2015).

Although scarce, studies measuring time–temperature profiles during air transportation of perishable food indicate poor control of the temperature. It is estimated that approximately only half of the transit time attributed to air transportation is actually spent in flight; during the other half, the perishable food is being transported to or from the airport, stored at the airport, or loaded in or unloaded from the plane (Figure 5) (Pelletier and others 2005). More specifically, airport operations are divided into 2 categories: operations inside cargo terminals and operations on the tarmac. Inside cargo terminals, perishables are weighed, identified, labeled, and placed into unit load devices (ULDs). Then, the ULDs are assigned to either a cargo flight or a passenger flight based on the volume and destination and are placed on the tarmac for cargo operations. After a flight, the ULDs are unloaded from aircraft cargo holds, brought to the cargo terminals to be inspected and cleared by customs, and placed back on regular pallets. High

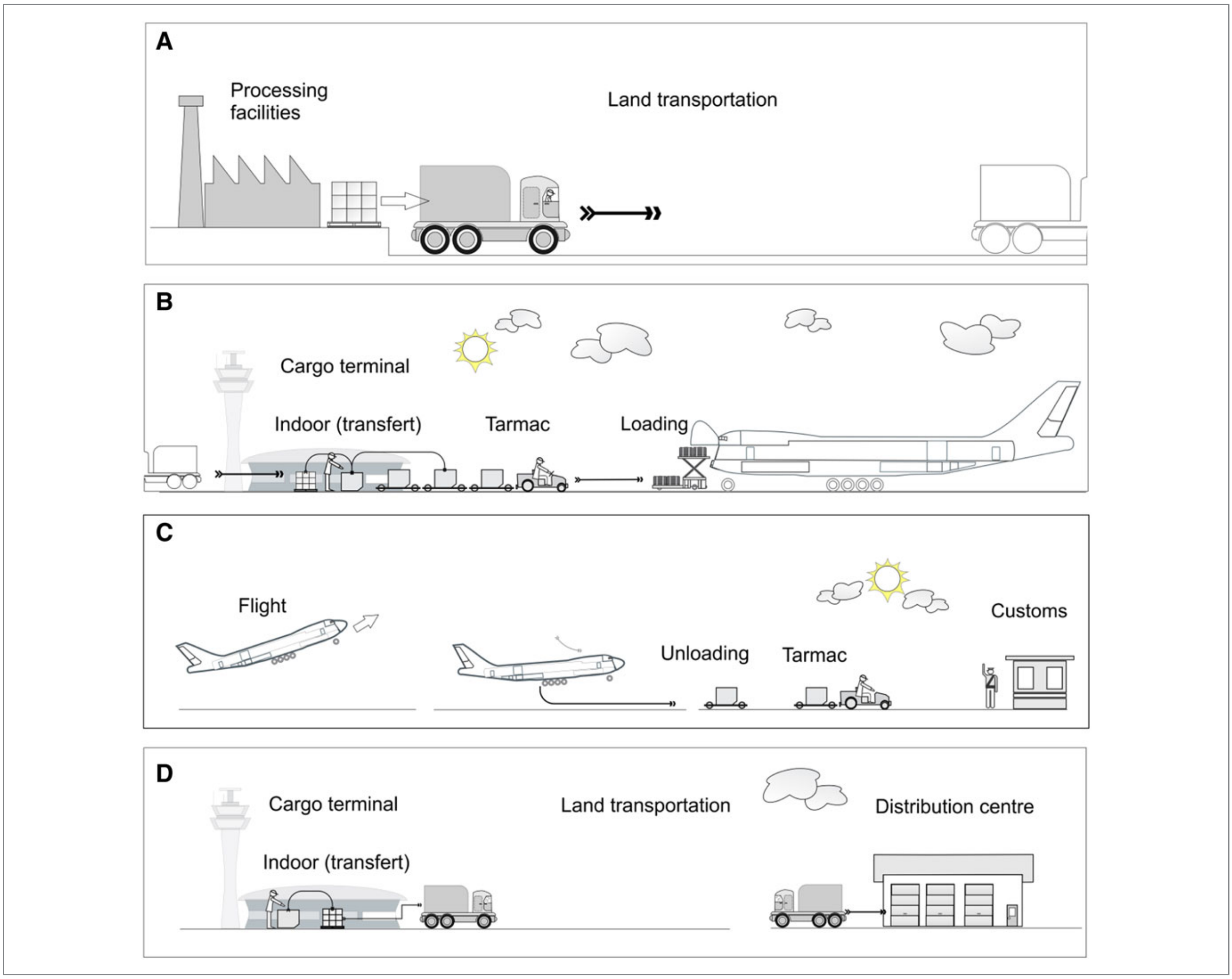

Figure 5–Transit of perishable food through an airport: Land transportation to the airport (A); operations inside cargo terminals and operations on the tarmac before the flight (B); flight and airport operations after the landing of the aircraft (C); and airport operations prior to the land transportation to the distribution center (D).

temperatures can be encountered, especially when the perishable food is on the tarmac before being loaded in the plane: on the tarmac, temperatures as extreme as −50 °C or +50 °C can be observed, depending on the season or location (Nunes and others 2006; Pelletier 2010). Depending on airport operations, a difference of about 14 °C inside ULDs was observed between the worst and best scenarios studied by Villeneuve and others (2000). Bollen and others (1998) measured the temperature inside pallets of asparagus shipped by air from Auckland to Tokyo and reported that the temperature of the asparagus increased from 4 °C to 14 °C within 30 min of ground operations in Auckland. Abad and others (2009) reported increases of 5 °C in fresh fish shipped by air from South Africa to Spain during loading and unloading of the plane. Mai and others (2012) monitored the temperature of fresh fish during air transportation from Iceland to the United Kingdom or France and reported that poor temperature control occurred during storage and ground operations at the airports before and after the flights, with the pallets of food subjected to ambient temperatures above 10 °C as well as solar radiation for several hours. However, the high ambient temperature resulted in a relatively moderate increase in the temperature of the fish (less than 2 °C), which is explained by the transportation of the fish inside polystyrene boxes, which provide high resistance against heat transfer by conduction, and by the presence of ice inside the boxes. Many factors, such as the availability of cooling and handling equipment at the airport, the type of ULDs used for transportation of perishables (plastic, metal, or insulated), flight delays, solar radiation on the tarmac, and the geographical location of the airport, can result in temperature variations inside ULDs during airport operations (Villeneuve and others 2000, 2001; IATA 2009). As a result of the possible increase in perishable food temperature before or while the food is being loaded in the plane, onsite recooling may be required to ensure that food safety is maintained (Laurin and others 2003; Pelletier and others 2005; Villeneuve and others 2005). At certain major air hubs, such as Singapore and Dubai, some of the aforementioned effects are mitigated by on-airport cool storage capacity (dnata Singapore 2014; Emirates SkyCargo n. d.).

During flight, maintaining the perishable food temperature is made more complicated by the presence of mixed loads with different temperature requirements (Pelletier and others 2005). Émond and others (1999) measured the temperature at different positions inside the holds of a Boeing 747-400 Combi during a

6-h flight. The temperature was significantly heterogeneous, and differences of more than 10 °C from the set temperature were observed. The authors concluded that additional protection, for instance, in the form of insulated packaging, is required to properly preserve perishable food that decays quickly at temperatures above 4.0 °C. Heap (2006) reported that the temperature of a load shipped by air from Europe to the U.S. varied from −1 °C to 26 °C, despite instructions to maintain the temperature between 2 °C and 8 °C. There is also a risk that perishable food will freeze or suffer chilling injuries in situations where the pressure is not controlled in the cargo hold of the plane. Fruits and vegetables native to tropical or subtropical regions are particularly at risk. A survey of the air transportation industry indicated that the majority of the complaints filed regarding perishable food are related to bad odors, poor color or texture, and rotted products. These issues are generally related to inadequate temperatures and support the need for better temperature management during air transportation of perishable food (Villeneuve and others 2002b). To prevent some of the issues mentioned above, it is increasingly common for lucrative industries to arrange for charter planes to transport perishable foods to their destination (Fresh Plaza 2016; Cropp 2017). Moreover, advances in refrigeration systems, such as the development of active temperature-controlled ULDs during the past decade, have enhanced the ability of key stakeholders to ensure unbroken cold chains (Baxter and Kourousis 2015).

Sea transportation. Sea transportation is much slower than transportation by air and may thus not be appropriate for perishable food with a short shelf-life. Nevertheless, sea transportation may be more cost-efficient than air transportation and is an important mode of transportation for fruits, vegetables, dairy products, meats, and fish products that are produced at a location far from the market and whose shelf-life exceeds the transportation time. Sea transportation is generally performed in specialized vessels or refrigerated containers (Smale 2004). Although transportation in specialized vessels remains significant for products such as bananas, refrigerated containers are the most frequent choice because they provide greater logistical flexibility and cost-efficiency for smaller shipments (Jedermann and others 2014b; Arduino and others 2015). For both specialized vessels and refrigerated containers, the most typical airflow pattern is the delivery of cold air through floor gratings, and the air then flows vertically through the pallets before being returned to the cooling unit through the ceiling (Smale 2004).

Amador and others (2009) monitored the temperature inside a refrigerated container of pineapples shipped from Costa Rica to Florida, a trip that took 3 d. Defraeye and others (2016) investigated sea transportation of citrus in refrigerated containers during a 21-d trip. Both Amador and others (2009) and Defraeye and others (2016) reported that the temperature was lower (by as much as 3 °C to 4 °C) near the bottom of the pallets than near the top, a difference that is explained by the vertical airflow pattern inside refrigerated containers. Tanner and Amos (2003) monitored the temperature inside a refrigerated container and a specialized vessel during the shipment of kiwifruits from New Zealand to Belgium. Those authors reported a significant temporal and spatial heterogeneity of the temperature inside the container. Because of this heterogeneity, the temperature control system, which operated based on measurement of the temperature at a single position within the container, was inefficient. For instance, when the sensor measured a temperature above the set point of 0.5 °C, a decrease in the delivery air temperature down to −5 °C was observed, increasing the likelihood of freezing injuries for the pallets near the air delivery. Tanner and Amos (2003) also reported that the temperature was more uniform for transportation inside the hold of the vessel, although the number of kiwifruits outside the recommended range of temperature remained significant. The heterogeneity of the temperature can be attributed to a number of factors related to the operation and design of the container or the vessel as well as the properties of the food product and packaging (Tanner and Smale 2005). Mai and others (2012) measured the temperature along the cold chain of fresh fish transported from Iceland to the United Kingdom or France by sea or by air. Those authors reported that the temperature remained more stable during sea transportation than during air transportation, as transportation by sea using refrigerated containers reduced the number of handling operations during which the pallets could be exposed to high ambient temperatures. For instance, refrigerated containers can be transferred directly from the ship to a truck on deck, while pallets have to be unloaded from a plane and loaded back in a refrigerated truck after air transportation.

Rail transportation. Rail transportation is used mainly for long distances (exceeding approximately 400 km) and for delivery times greater than 2 d between markets that are connected by a railroad system (Tsamboulas 2008). As such, rail transportation is a minor component of perishable food transportation, and the literature on the temperature conditions observed during rail transportation is scarce. Perishable food can be transported in 3 types of train cars: insulated cars, ice-cooled cars, and mechanically refrigerated cars (International Institute of Refrigeration 1995). For insulated train cars, the only thermal equipment is the insulation, while ice-cooled train cars are cooled by ice contained in the bunkers at the ends of the car and are equipped with fans that circulate the air through the ice and the cargo. The 3rd type of train car is equipped with a refrigeration unit to maintain the temperature at a set value.

Because transportation by rail is time-consuming, it is at a disadvantage compared with all-road transport for transportation of perishable goods (Sommar and Woxenius 2007). However, there is substantial growth potential if the obstacles caused by sensitivity to time can be handled. Current developments that may result in increased rail transportation include high-speed trains reserved for freight for medium-sized loads, with maximum reduction of intermediate times (Fronda 2013), and the promotion and development of fast intermodal transport solutions (Inbound Logistics 2010; Sandberg Hanssen and Mathisen 2011).

Intermodal transportation. Intermodal transportation is the movement of food in a single loading unit (intermodal container) along a cold chain with 2 or more modes of transport (road, sea, or rail) (Sandberg Hanssen and Mathisen 2011). Many types of intermodal containers exist and they are found in a number of standardized sizes. Dry-freight containers of either 20 or 40 foot (6 or 12 m) standard length, with heights of 8 feet 6 inches (2.6 m) and 9 feet 6 inches (2.9 m) are the most common. Special sizes of dry-freight containers, such as 45-, 48-, and 53-foot containers (2%), and refrigerated containers ("reefers") for transportation of perishable goods (5%) are growing market segments in intermodal transportation (Rodrigue 2013).

Reefers are versatile, are able to carry around 20 to 25 tons of refrigerated cargo, can accommodate a wide range of temperature settings, and accordingly a wide range of temperature sensitive products. When transported by ship, reefers are connected to the ships power supply allowing the refrigeration unit to run. When transported by either rail or road, they are connected to an external power supply, such as a generator, in order to regulate and control the temperature inside of the shipping container. Up to 18 reefers can be powered up by a refrigerated block train (Sun Gate 2015). Reefers have gratings on the floor and proper clearance must be kept between the ceiling and the cargo to ensure sufficient air circulation. Cold air coming out of the refrigeration unit flows through the bottom part of the reefer and as it warms up it climbs toward the ceiling to flow back to the refrigeration unit, usually 0.5 °C to 3 °C warmer.

The refrigeration units being generally designed to maintain the temperature within a predetermined range, the shipment must generally be brought to the required temperature before being loaded into the reefers. During the past decade, however, a few studies were carried out to explore the potential of ambient loading into reefers, for cooling during long-haul sea transportation, as an alternative to forced-air precooling of produce before it is loaded into the reefer. Defraeye and others (2015b, 2016) explored the potential of this cold chain protocol for the ambient loading of citrus fruit, while Jedermann and others (2013, 2014b) explored it for the banana chain. Ambient loading reduces the time and cost required to handle and precool the pallets at precooling facilities. It can also reduce postharvest losses when applied immediately after palletization, since the cold chain starts earlier than when precooling occurs at the harbor, as transport to those facilities is often unrefrigerated. However, CFD simulations (Defraeye and others 2015b) showed that the fruit cooling rate with ambient loading into reefers is slower in comparison with forced-air precooling. Also, the cooling heterogeneity between different layers of boxes (in height) and between individual fruits in a single box is larger for ambient loading. Optimizing box design and box stacking on the pallet and reducing the airflow short circuits between the pallets were the main strategies proposed for future improvement of the ambient loading cold chain protocol.

A number of studies on developing energy efficiency in refrigerated devices were carried out by Lukasse and others (2007, 2009a, 2009b). These authors illustrated the potential of selectively managing the operation of refrigeration unit components to conserve energy, which would allow air temperature variations to occur without compromising the temperature of products and achieve lower operating costs in comparison with the conventional mode of operation. A collaboration between Wageningen Univ. and Research, Maersk Line, and Carrier Transicold resulted in the development and implementation of a special control software, Quest II, for use with perishable cargo, with the goal of helping improve refrigerated container shipping by reducing costs associated with onboard energy production and the associated greenhouse gas emissions (Carrier Corporation 2017). The main energy savers in Quest II are a balanced internal air circulation and a no part-load compressor operation. Quest II was tested on apples, kiwifruit, bananas, grapes, pineapples, iceberg lettuce, garlic, and chilled lamb meat, as well as other commodities (Carrier Corporation 2017).

Storage at the distribution center

After harvesting or processing, perishable food is generally transported to 1 or multiple distribution centers to be sorted and shipped to a retailer that is selected based on product demand and a predetermined management system. Given that the perishable food can be stored at the distribution center for multiple days (Derens and others 2006; Derens-Bertheau and others 2015), proper refrigeration is required. As will be discussed in the quality-driven distribution section, the distribution center is at the core of most cold chain management systems, as it offers flexibility to adjust the destination of the food to match its current state.

Studies indicate that proper refrigeration is achieved during storage at the distribution center. Derens and others (2006) reported that only 0.5% of measurements taken along the cold chain for meat products in France were above 6.0 °C during storage at the distribution center, in comparison with 31% during storage at retail and 66% during storage in domestic refrigerators. Studies measuring time–temperature profiles along the cold chain for meat products (Derens and others 2006; Derens-Bertheau and others 2015; Gogou and others 2015), fish (Morelli and Derens-Bertheau 2009), dairy products (Derens and others 2006), and vegetables (McKellar and others 2012, 2014) all reported that the average temperature during storage at the distribution center was below 4.0 °C. However, it is important to note that these studies were conducted in developed countries, specifically France, Greece, and Canada. Temperature conditions during storage at distribution centers along cold chains in developing countries, where the availability of refrigeration equipment is much more limited, may be significantly different.

Display at retail

On arrival at the retailer, perishable food is generally placed in a display cabinet or rotated between a display cabinet and a refrigerated storage room. A survey of 217 consumers in Slovenia indicated that the majority of them have confidence that perishable food is kept at the required temperature by retailers (Likar and Jevšnik 2006). Yet time–temperature measurements indicate that storage in display cabinets is generally not the most efficient step in the cold chain, as the temperature frequently rises above the desired limit. An explanation for the poor refrigeration reported during display at retail may be that some retailers are concerned more about the appeal of a product than about its preservation, for instance, overloading the front of display cabinets or placing the racks at the highest position (Villeneuve and others 2002a).

LeBlanc and others (1996) measured the temperature of fruits and vegetables in display cabinets in 28 retail stores in Canada and reported an average temperature of 8 °C, significantly above the recommended temperature of 4 °C. Similarly, Villeneuve and others (2002a) reported average temperatures of 8.6 °C or 10.8 °C for potatoes in display cabinets used by a Canadian retail chain, depending on whether the rack was placed at the lower or upper position, respectively. Likar and Jevšnik (2006) measured the temperature of 1688 perishable food products displayed by retailers in Slovenia. The temperature at the surface of the chilled food ranged from 2.0 °C to 16.0 °C. Derens and others (2006) monitored the temperature along the cold chain for yogurt and meat products in France. Approximately 31% of the measurements were above 6 °C. For 67 samples of smoked salmon in France, Morelli and Derens-Bertheau (2009) reported temperatures during display at retail from 1.4 °C to 9.8 °C, with an average of 5.6 °C. For the cold chain in Greece, Koutsoumanis and others (2010) reported an average temperature of milk in display cabinets of 4.9 °C, with more than 35% of the measurements above 6.0 °C. More recent studies, however, indicate better refrigeration during display at retail: McKellar and others (2012, 2014) reported average display temperatures of 4.1 °C and 3.5 °C for fresh-cut lettuce during the winter and summer, respectively. Derens-Bertheau and others (2015) reported an average temperature of 2.8 °C for 83 meat products during display at retail in France, with no difference observed between supermarkets and hypermarkets. Gogou and others (2015) reported an average temperature of 4.0 °C during display at retail of meat products in Greece. The lower temperatures during display at retail reported over the last few years may suggest recent improvements in retailers' practices or the implementation of more efficient refrigeration systems.

As stated above, studies have reported a wide range of perishable food temperatures during display at retail. These contrasting results may be explained by several factors, a significant one being the heterogeneity of the temperature according to the position inside the display cabinet. LeBlanc and others (1996) reported that the temperature of fruits and vegetables placed toward the front of a display cabinet was on average 0.8 °C higher than the temperature of those placed toward the back. Villeneuve and others (2002a) reported that the temperature of potatoes on the side of a display cabinet was 3.9 °C above the temperature of those near the center. Nunes and others (2009) measured the temperature in display cabinets of 3 retail stores. Those authors showed that the temperature was generally warmer at the top of the display cabinets and that the placement of the fruits and vegetables was frequently inefficient given their recommended temperature. Derens-Bertheau and others (2015) reported temperature differences up to 4.0 °C for 2 packages of meat products placed at different positions inside a display cabinet. The causes of temperature heterogeneity inside display cabinets include the penetration of ambient air, the proximity to the lighting system, the defrost cycle, and the heterogeneity of the airflow (Villeneuve and others 2003; Nunes and others 2009; Derens-Bertheau and others 2015). Additional factors explaining the wide range of temperatures during display at retail reported in the literature may include differences in the type, function, efficiency, set point temperature, turnover rate, and door opening rate of display cabinets.

Regarding the duration of display at retail, time–temperature measurements have shown highly product-specific results. Durations of display at retail as low as a few hours were reported for fresh-cut lettuce and milk (Koutsoumanis and others 2010; McKellar and others 2014), in contrast to nearly a month for sliced meat products (Gogou and others 2015). Furthermore, Derens-Bertheau and others (2015) reported an average duration of display at retail for ham products of 9 d in supermarkets in comparison with 3 d in hypermarkets, suggesting that the store size has an impact on the duration of display at retail as a result of differences in turnover rate.

Transportation and storage by consumers

All studies on cold chains for perishable food that have measured time–temperature profiles from the moment the product is bought by the consumer until it is consumed indicate insufficient refrigeration of the food. For transportation from the retailer to the consumer's home, Derens and others (2006) reported an average temperature of 7.8 °C for yogurt and meat products along the cold chain in France, with more than 85% of the products reaching a temperature above 6.0 °C. Morelli and Derens-Bertheau (2009) and Gogou and others (2015) reported average temperatures during transportation by consumers of 13.0 °C and 9.8 °C for smoked salmon and meat products, respectively. In their study on meat products along the cold chain in France, Derens-Bertheau and others (2015) observed a slightly lower average temperature during transportation by consumers, 6.5 °C, which was nevertheless above the recommended temperature. All the aforementioned studies reported an average duration of transportation by consumers of between 40 and 75 min.

Several studies have specifically investigated the temperature inside domestic refrigerators. Such studies conducted before 2006 were reviewed by James and others (2008). An average temperature inside domestic refrigerators in New Zealand of 4.9 °C was reported by O'Brien (1997), while the other 7 studies conducted in Europe or the United States and reviewed by James and others (2008) indicated that the average temperature inside domestic refrigerators was between 5.9 °C and 7.0 °C in those countries. Accordingly, surveys indicate that the majority of consumers do not verify that the temperature inside their refrigerator is below 4.0 °C (James and others 2008; Vegara and others 2014). Carrasco and others (2007) measured the temperature inside 30 domestic refrigerators in Spain and reported an average temperature of 6.6 °C. Hassan and others (2015) reported an average temperature of 8.0 °C inside 147 domestic refrigerators in Lebanon. Carrasco and others (2007) and Hassan and others (2015) both reported that the temperature inside domestic refrigerators is approximately 0.5 °C to 1.0 °C colder during the night, as explained by less frequent opening of the door. Janjić and others (2016) measured the temperature inside 100 domestic refrigerators in Serbia and reported an average temperature of 9.3 °C and a temperature above 4.0 °C in 92% of the refrigerators. The temperature was nearly 2.0 °C higher when it was measured inside the door of the refrigerator in comparison with the bottom shelf. Janjić and others (2016) also reported no significant differences between the temperature inside old (>10 y) and new (<5 y) domestic refrigerators.

The studies conducted on time–temperature measurements along the cold chain that have considered storage of the perishable food inside domestic refrigerators are in agreement with those that have focused specifically on this last step in the cold chain. In France, Morelli and Derens-Bertheau (2009) and Derens-Bertheau and others (2015) reported an average temperature inside domestic refrigerators of 6.5 °C and 6.3 °C, respectively, and Derens and others (2006) reported that the temperature was above 6.0 °C inside approximately 65% of domestic refrigerators. In Greece, Koutsoumanis and others (2010) reported average temperatures inside domestic refrigerators of between 6.3 °C and 8.4 °C, depending on the position of the measurement, and Gogou and others (2015) reported an average temperature of 6.8 °C. Overall, the majority of studies points to an average temperature inside domestic refrigerators of between 6.0 °C and 7.0 °C, with the temperature being 1.0 °C to 2.0 °C higher inside the door.

The higher-than-recommended temperature inside most domestic refrigerators could be attributed to various factors, including insufficient consumer awareness about the importance of proper temperature for food quality and safety. Even though the critical impact of consumer practices on the proper preservation of perishable food is well established, surveys show that most consumers are unaware of their important role in the cold chain and place most of the responsibility for maintaining food quality and safety on the industry (Ovca and Jevšnik 2009). Additional factors explaining the high temperature inside domestic refrigerators include frequent opening of the door, overloading or inadequate placement of the food, and inappropriate temperature settings. The high temperatures observed inside domestic refrigerators indicate that substantial improvements to consumer practices are required to improve perishable food preservation and limit food safety risks.

Cold Chain Management Systems Based on Time–Temperature Measurement

Quality-driven distribution

First Expired, First Out (FEFO) management system at the distribution center. The pallets of food in a distribution center are generally shipped out based on a First In, First Out (FIFO) management system, where the rotation of pallets is based on the time that they have been stored in the distribution center. However, the FIFO management system is inefficient because the time spent at the distribution center represents only a small factor affecting the remaining shelf-life of food. A pallet of food that has just entered the distribution center can have a shorter remaining shelf-life than a pallet of the same product that has been stored in the distribution center for a long period if the newly arrived pallet was of lower quality after harvest, came from a more distant location, had a longer delay before precooling, or was subjected to temperature abuses during transportation. In this scenario, it would be more appropriate to ship the newly arrived pallet out of the distribution center first, and preferably to a closer destination, to avoid delivering a pallet of unacceptable quality to retail. This more appropriate strategy is applied in a FEFO management system, in which the inventory is rotated in a way to best match the time to retail and turnover rate of each available destination to the remaining shelf-life of the perishable food.

The application of a FEFO management system requires knowledge of the remaining shelf-life of the food. Visual inspection of the food to detect indicators of decay was shown to be an inaccurate method of estimating remaining shelf-life, as early decay indicators are generally invisible (Nunes and others 2014; Jedermann and others 2014a). As an example, Nunes and others (2014) reported, in an investigation of the cold chain for blackberries, that the remaining shelf-life of 57% of the food at a distribution center was not long enough to allow the food to be sent to the farthest destination, even though the food was considered to be of sufficient quality following the visual inspection. A more robust approach to estimate the remaining shelf-life of perishable food is based on the measurement of the temperature of the food along the cold chain and the application of quality and safety models to quantify the remaining shelf-life (Labuza and Taoukis 1990). Generic kinetic models to predict quality or remaining shelf-life from time–temperature history have been developed by Tijskens and Janna (1996) and Hertog and others (2014). Specific models describing quality or remaining shelf-life as a function of temperature and other environmental conditions have been developed for many perishable food products, including fresh-cut vegetables (Jacxsens and others 2002), bananas (Jedermann and others 2014b), shrimp (Dabadé and others 2015), pork and poultry (Bruckner and others 2013), yogurt (Mataragas and others 2011), and kiwifruits (Hertog and others 2016). Additional quality models have been developed for many additional food products as part of the European FRISBEE project and can be found in the project's online database (Gwanpua and others 2015).

The simulation of product flow along the cold chain shows the significant contribution of a FEFO management system to food waste reduction. Koutsoumanis and others (2002) simulated the implementation of a FEFO management system at a distribution center where sea bass could be sent to a close or a distant retailer. Monte Carlo simulation indicated that FEFO could decrease the percentage of sea bass with unacceptable quality at consumption from 7% to 0% at the local retailer and from 30% to 13% at the distant retailer in comparison with a traditional FIFO management system. In a similar study on meat products, Koutsoumanis and others (2005) reported a decrease in the percentage of food with unacceptable quality at consumption from 12.5% to 4.3% at the distant retailer, in addition to improved food safety. Dada and Thiesse (2008) simulated the quality of perishable food along a fictitious cold chain for different initial states of the product and different management systems and reported that FEFO could decrease the variability of food quality at retail by approximately half in comparison with a FIFO management system. Nunes and others (2014) investigated the blackberry cold chain and estimated that the percentage of food at risk of having an insufficient shelf-life at retail would be reduced from 57% to 1% by the implementation of a FEFO management system.

Global-scale FEFO management system. In a conventional FEFO management system, the distribution center represents the critical control point where the time–temperature data are read, processed, and used to adjust the cold chain in response to the quality of perishable food. In the presence of temperature abuses or differences in the initial state of the food, the corrective actions taken at 1 distribution center to match the food's remaining shelf-life with the available destinations are generally independent of the corrective actions taken at other distribution centers (Hertog and others 2014).

As part of the Intelligent Container project, a FEFO system in which inventory management decisions are decentralized from the distribution center and are taken considering the state of all available loads currently in transit was investigated. More specifically, containers equipped with a wireless sensor network to measure the environmental conditions affecting the quality of the food (such as its temperature) and a central processing unit to estimate the food's remaining shelf-life were developed (Dittmer and others 2012). When poor storage conditions occur and it is predicted that the quality of the food will be unacceptable at delivery, the container communicates with other containers to investigate whether destinations can be exchanged, with the objective of maximizing the total number of containers arriving at their destination on time and with sufficient quality. Simulations performed for the cold chain for bananas shipped from Costa Rica to different markets in Europe indicated that implementing such a global-scale FEFO system would provide a reduction of up to 22% in food waste as well as a reduction in CO_2 emissions, as a result of the smaller number of spoiled loads that would need to be replaced. Similar food waste reductions using the intelligent containers were also estimated by Lütjen and others (2012).

Management at retail

Knowledge by the retailers of the time–temperature history of the perishable food gives it an added value that can be used to improve the cold chain. A relevant approach at retail is the implementation of a dynamic shelf-life assessment (DSLA) system. In a DSLA system, the expiration date (or use-by, sell-by, or best-before date) of a food is adjusted considering its time–temperature history (Labuza and Taoukis 1990). A shelf-life that is representative of the food's true quality is thus established, reducing waste caused by conservative expiration dates. Tromp and others (2012) simulated waste along a cold chain for a meat product and reported that DSLA could reduce waste due to date-labeling by up to 80%. In addition to waste reduction, knowledge of the time–temperature history can also be used to identify perishable food that has been subjected to severe temperature abuses that may have compromised its safety. The product at risk can be removed by retailers, and there is thus an additional barrier against foodborne outbreaks resulting from cold chain failure.

An additional improvement at retail resulting from knowledge of the time–temperature history of a food is the implementation of a dynamic pricing system. Such a system is based on the assumption that a food product with a longer remaining shelf-life has greater value than a food product that has to be consumed quickly. This system can reduce food waste by providing an economic incentive to buy food with a short remaining shelf-life, which may otherwise be wasted when fresher products are continuously available (Afshar-Nadjafi 2016). Dynamic pricing is conceptually similar to discounts on food approaching its best-before date or to FEFO management, from the perspective that all these systems aim to remove food with the lowest remaining shelf-life from the inventory first. Wang and Li (2012) simulated the impact of dynamic pricing at retail and reported significant profit increases that were attributed in part to a lower rate of food waste, although that rate was not quantified. Those authors also showed that the accuracy of the predicted remaining shelf-life, the accuracy of the predicted consumer demand, and the frequency of price changes significantly affect the efficiency of dynamic pricing (Wang and Li 2012).

Feedback and feedforward cold chain improvements

Monitoring the temperature can improve the transparency of the cold chain through communication of the current state of the food. In turn, this greater transparency can be used to improve the cold chain, either through modifications of the cold chain to reduce the probability that an error will occur again (feedback improvement) or through mitigation of the impact that an identified error will have on the downstream stakeholders (feedforward improvement).

An example of feedback improvement is informing the farm or processing center if unacceptable quality of the perishable food is detected during transportation or storage at the distribution center. This information can then be used to adjust the harvesting or precooling conditions to improve the quality of future shipments (Jedermann and others 2014b; Haass and others 2015). An additional example would be constructing a sufficient database of time–temperature histories and then performing statistical analysis on it to identify the destinations where food temperature increases are the most frequent, and apply this new knowledge to improve the vehicle routing problem (Hsu and others 2007). With respect to feedforward improvements, if the quality of food is expected to be insufficient when it is delivered at retail because of cold chain failure, the retailer can order new shipments earlier and manage its inventory accordingly, creating a more responsive and flexible cold chain.

Discussion

What are the weaknesses in the cold chain?

Steps in the cold chain most susceptible to temperature abuses. Field studies show that the temperature along the cold chain frequently increases above the desired limit, creating food waste and endangering food safety. However, such temperature increases are not distributed evenly along the cold chain; some specific steps or operations are particularly susceptible to improper food preservation. In the review of published field studies, the following 4 key steps or operations representing the weak links in the cold chain in terms of temperature control were identified.

- **Precooling**: The critical role of precooling has been established and is well illustrated by the significant reduction in remaining shelf-life caused by a small delay before precooling (Brosnan and Sun 2001; Pelletier and others 2011; Nunes and others 2014). Field studies reported significant heterogeneity of the temperature between pallets and between positions inside a pallet after precooling (Estrada-Flores and others 2002; Pelletier and others 2011; Nunes and others 2014). Uneven temperatures after precooling are explained by the difficulty of sufficiently decreasing the temperature at the center of the pallet while avoiding cold injuries to the food near the surface and by the inefficient adjustment of precooling time according to the characteristics of the load. Efficient precooling conditions need to be implemented to avoid the lasting effect that the remaining heat inside the food has on its preservation along the cold chain.
- **Ground operations during transportation**: Most studies reported efficient control of the temperature of food inside refrigerated trucks, but increases in temperature, sometimes to above 10 °C, during ground operations at the beginning and end of transportation were frequently reported (Raab and others 2008; McKellar and others 2014). Similarly, for air transportation, food temperature increases to above 10 °C have been reported within minutes of ground operations, and authors have suggested the need for onsite recooling units to quickly mitigate the impact on food quality and safety (Bollen and others 1998; Laurin and others 2003; Pelletier and others 2005; Villeneuve and others 2005). Field studies confirm the need to plan ground operations efficiently during land, air, or sea transportation to minimize the length of time that pallets are subjected to inappropriate ambient temperatures. Furthermore, to improve the transparency of the cold chain, ground operations appear to represent key steps where any delay should be transmitted to the stakeholders downstream in the cold chain so that corrective actions, such as the application of lower set temperatures, can be quickly applied to extend the shelf-life of the perishable food and evaluate any potential safety risk.
- **Display at retail**: A majority of studies reported high temperatures during display at retail, in some cases because of the importance given to a product's appeal at the expense of food quality and safety. An extreme example of a practice that is sometimes adopted at retail to improve food appeal, but that creates concerns for food quality and safety, is the display of strawberries in nonrefrigerated conditions to promote impulse purchases prompted by the aroma released by the strawberries at ambient temperature (Pelletier and others 2011). Nunes and others (2009) monitored temperature and food waste at 3 retail stores and reported that 55% of the stores' perishable food waste was caused by poor temperature control, including during display at retail. Recent field studies on fresh-cut lettuce and meat products reported more appropriate temperatures during display at retail (McKellar and others 2014; Derens-Bertheau and others 2015; Gogou and others 2015), a difference that may indicate an improvement in retailers' awareness of quality and safety issues. However, additional improvements may still be required, especially given that perishable food can remain on display at retail for several days.
- **Transportation and storage by consumers**: Many field studies show that the most significant temperature abuses occur during transportation and storage of perishable food by consumers, and authors have concluded that the consumer's end is the weakest link in many cold chains (Derens and others 2006; Gogou and others 2015). Inadequate preservation of food by consumers causes significant food waste. Brown and others (2014) estimated that decreasing the average temperature inside domestic refrigerators in the U.K. from 7 °C to 4 °C would save £162.9 million worth of perishable food annually. Temperature abuse in domestic

> refrigerators also poses significant safety risks, and it is estimated that up to half of foodborne illnesses that originate at home (which are more frequent than those that originate in commercial establishments, such as restaurants) are attributed to poor storage conditions and refrigerator management (Ryan and others 1996; Jackson and others 2007). Solutions proposed to improve the quality and safety of perishable food include educating consumers to improve their awareness of the deterioration in quality and risks to safety associated with high storage temperatures, installing thermometers inside domestic refrigerators, and encouraging the use of insulated bags during domestic transportation (Kennedy and others 2005; WRAP 2010).

The weak links in the cold chain in terms of temperature control are thus found at the start of the chain (during precooling, where the greatest food temperature change occurs), at the end (during display at retail and transportation and storage by consumers, where temperature control is out of the manufacturer's hands and awareness of the issues associated with temperature abuses may not be as strong), and during the logistics operations in which the food may be directly subjected to the environmental conditions (such as ground operations during transportation). All these steps or operations represent specific areas of the cold chain where improvements for better food preservation may be most relevant.

Temperature variability within a shipment. The variability in the temperature of foods at different locations within a shipment is significant and can be as high as approximately 10 °C (Raab and others 2008). Such a high level of heterogeneity significantly affects the remaining shelf-life of the food. As an example, the storage of blackberries at 2.8 °C for 1 h corresponds to a loss of 1.6 h of shelf-life, while the storage of blackberries at 15.6 °C for the same duration corresponds to a loss of 5.5 h of shelf-life, which is nearly 4 times higher (Nunes and others 2014). This heterogeneity of temperature makes the implementation of inventory management systems based on time–temperature measurement much more complicated. Because of this heterogeneity, multiple temperature sensors, or a combined measurement-modeling approach, are required for proper monitoring of the temperature distribution (Jedermann and others 2009; Mercier and others 2017). The inventory management system based on time–temperature measurement also needs to be implemented at the pallet, or even package, scale in order to account for this variability (Nunes and others 2014). The heterogeneity of temperature can be explained by, among other things, variability in harvest temperature and in time until precooling; nonuniform precooling; nonuniform temperature variation during ground operations; proximity to refrigeration units; door openings; and poor performance of containers causing a low rate of air circulation around some pallets and a low rate of air penetration inside the pallets (Pelletier 2010; Nunes and others 2014; Defraeye and others 2015b; Olatunji and others 2017). The operating conditions (such as the air circulation rate within a container), loading protocols (to obtain optimal gaps between the pallets, providing a proper balance between cooling rate and uniformity), package design (number, size, and position of vent areas), box stacking pattern on the pallet (to avoid bypass or air between packages), and container design (such as the proper design of floor gratings to improve bottom-air delivery systems) are different factors that can be modified to decrease the temperature heterogeneity within shipments (Smale 2004; Ferrua and Singh 2009d; Jedermann and others 2013; Defraeye and others 2015b, 2015c; O'Sullivan and others 2016).

Handling practices. Existing sets of practices may need to be revisited by major retailers and their suppliers in order to improve the preservation of perishable food along the cold chain. A closer look at how best handling and manufacturing practices for food items are implemented today would show that requirements are met mostly on a good-faith basis, as there is no reliable approach to trace the temperature history of a food all the way back to the field. For instance, a pallet of strawberries fresh from the field could spend anywhere from 30 min to more than 1 h in the field, mostly under the sun, before it is transported to a precooling facility nearby, a situation that would result in significant variations in the food's actual shelf-life. Products such as apples may stay in the field after harvest for a few days. Temperature-monitoring procedures are significantly better during the precooling process to balance the efficient use of facility resources and energy with the preservation of product quality. Nevertheless, because of limited facility resources, the precooling time may be reduced during productive harvest days to ensure that each pallet is precooled before the following day, resulting in an insufficient temperature decrease. After precooling, quality-control personnel evaluate randomly chosen packages in a pallet of perishable food before the pallet is loaded into refrigerated containers to be shipped to distribution centers, which are most commonly owned and operated by the retailer itself. In a typical transportation scenario, there are 3 stakeholders at this stage: the grower/packager, the transportation company, and the retailer. Given that each retailer has a different threshold for acceptable quality for a perishable item, the grower/packager keeps a log of the precooling process and performs its own quality control to ensure that no product is rejected at the distribution center. The transportation company wants to minimize its liability and thus has several loggers inside the container to monitor the temperature throughout the shipment. Finally, the retailer downloads these temperature logs and accepts or rejects pallets based on their history and on the retailer's own randomly conducted quality control at the distribution center.

New regulations may provide the necessary driver for the improvement of some of these industry practices. In April 2016, the U.S. Food and Drug Administration (FDA) issued a rule establishing requirements for shippers, loaders, carriers, and receivers to use sanitary transportation practices and ensure the safety of the food. In this rule, the FDA thoroughly describes the necessary safety requirements. For example, the FDA includes additional requirements with respect to previous regulations regarding the design, condition, and sanitation of the vehicles or specific procedures to ensure that the food is consistently preserved at the desired temperature. To comply with the FDA's recent rule, some industry practices will require better, more consistent, and possibly higher-resolution record-keeping when it comes to satisfying the temperature requirements for each different perishable product. As an example, Figure 6 provides a summary of the existing handling practices for a popular perishable food product, strawberries.

What are the hurdles delaying the implementation of management systems based on time–temperature measurement?

Management systems based on time–temperature measurement for perishable food have been developed, and there is strong evidence that they improve the efficiency of the cold chain, decrease food waste, and improve food safety. Technological hurdles, namely, cost-efficient wireless temperature sensors and convenient hardware for communication of the results and analysis of the data,

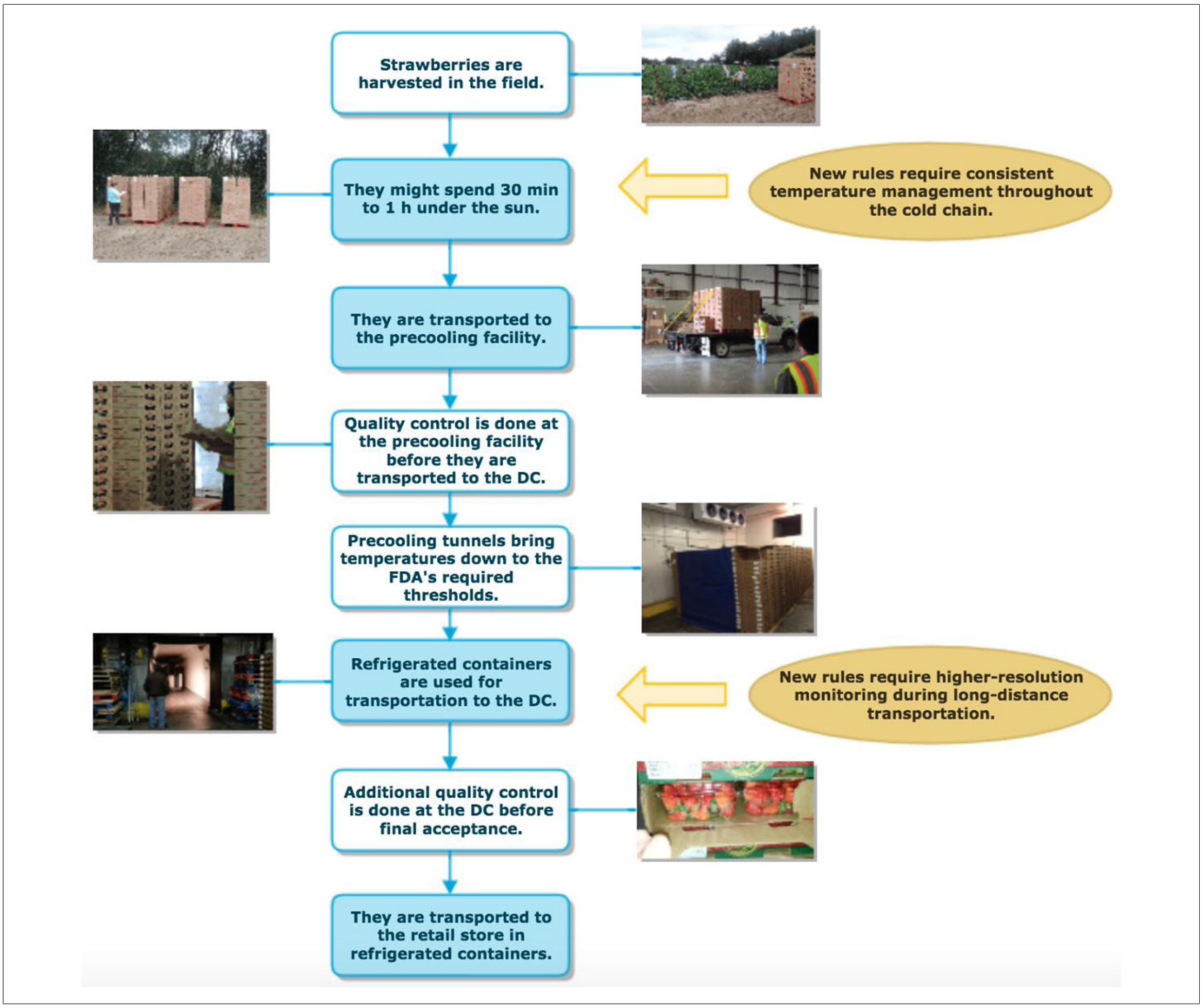

Figure 6–Steps, identified by colored boxes, in the cold chain where good practices may need to be improved to comply with the new United States Food and Drug Administration (FDA) rules. DC, distribution center.

have become significantly smaller over the last decade, and test trials have confirmed the technical feasibility of time–temperature measurement systems (Raab and others 2011; Grunow and Piramuthu 2013; Mack and others 2014). Yet, the commercial application of management systems based on time–temperature measurement has been very limited thus far, in large part because of remaining cooperation and instrumentation issues, and the inaccuracy of shelf-life estimates from temperature measurements (Raab and others 2011; Jedermann and others 2014a).

The implementation of management systems based on time–temperature measurement requires a holistic approach in which the actions of each stakeholder in response to a temperature deviation are coordinated to create a responsive and flexible cold chain and extract the full potential of the measurements. Given that cold chains are complex networks involving several actors that are rarely under the same ownership, management systems based on time–temperature measurement create several interorganizational challenges. One challenge stems from the uneven costs and rewards of these management systems for the various stakeholders in the cold chain. The reduction of food waste and the greater uniformity of food quality may be particularly beneficial to retailers. Indeed, the blame for low-quality food is generally assigned to the place where the food decay is observed, which is frequently at retail, even if the cause of the quality loss was temperature abuse during upstream operations (Nunes and others 2014). Yet the major costs associated with the implementation of management systems based on time–temperature measurement would be assumed by manufacturers and suppliers. Another challenge is the creation of harmonized and synchronized information-sharing channels throughout the cold chain, a potentially difficult task, especially for stakeholders that are not under the same ownership. As stated by Jedermann and others (2014a), "stakeholders, such as farmers, suppliers and distributers, are usually reluctant to enable free data exchange of temperature recordings for a particular shipping lane, out of fear that they could be used against them in filing claims or other types of disputes." Interorganizational challenges are frequently regarded as some of the most important challenges that must be overcome for the widespread implementation of management systems based on time–temperature measurement, and such challenges may require a culture shift so that greater transparency in the cold chain is regarded as an opportunity not to find fault, but to demonstrate that good practices are being followed.

The proper instrumentation of a shipment to measure the temperature of the food along the cold chain poses several challenges, as no guidelines have been established to help with implementing a strategy that minimizes measurement costs while meeting measurement resolution and accuracy requirements. Simulation, experimental, and field studies showed that the boxes inside a pallet can have significantly different temperatures and, therefore, that the temperature inside each of them should be known in order to have an optimal management system based on time–temperature measurement (Margeirsson and others 2012; Nunes and others 2014). However, cost considerations generally limit the number of temperature measurements to a few boxes per shipment, meaning that an estimation strategy, based on a mathematical model, is needed to approximate the temperature inside the boxes where no measurements are taken (Jedermann and others 2009, 2011; Nunes and others 2014; Mercier and others 2017). How many sensors to use per shipment, which boxes inside a pallet should have their temperature measured, whether the temperature should be measured at the surface or at the core of the food, and which modeling approach (physics-based or data-based) should be used to complement the measurements are critical decisions that must be made when implementing an instrumentation strategy. Currently, these decisions generally need to be based on intuition or simple heuristics, as they have not been the focus of sufficient research.

Finally, even though it has been the topic of intensive research for many years, the estimation of a food's remaining shelf-life from time–temperature measurements still faces several challenges. Each food product is affected to a different extent by inappropriate temperature, a fact that complicates the estimation of remaining shelf-life, as each food product needs a specific decay model. In addition, shelf-life can depend on more than 1 quality attribute (a given quality attribute may not always be the limiting one) and on more than just temperature. As a result, remaining shelf-life can be estimated only within a given confidence interval. This confidence interval is hard to estimate, because it depends on the initial state of the food after harvest, which can vary significantly depending on harvest conditions, date and location, mechanical injuries, and inherent biological variations (Gwanpua and others 2013). The measurement of simple postharvest quality indicators, such as color, and the prediction of the storability of each batch from the behavior of subsamples stored at high temperature have been proposed as methods to quantify the initial state of a food (Schouten and others 2002; East 2011). Knowledge about the accuracy of predictions of remaining shelf-life is required to estimate the efficiency of management systems based on time–temperature measurement and to forecast their contribution to better food quality and safety.

What should be the focus of future research on the cold chain?

In light of the weaknesses in the cold chain, the remaining knowledge gaps about the cold chain, and the challenges related to the implementation of management systems based on time–temperature measurement, the following 3 specific subjects have been identified in this review as being critical to investigate in future research on the cold chain.

- **Efficient precooling**: Precooling, as the 1st operation in most cold chains, is where the greatest change in food temperature occurs. Insufficient precooling puts significant pressure on the remainder of the cold chain for the delivery of food with sufficient quality. Yet, the operating conditions applied during precooling are frequently selected by a trial-and-error process, which, given the difficulty of monitoring the temperature and quality of food at the center of a pallet, leaves the food in an uncertain state. For the design and operation of efficient precooling processes, an attractive approach is the modeling of momentum, heat, and mass transfer mechanisms. Precooling is frequently performed by forcing the circulation of cold air around the food. The rate at which the food temperature decreases can be described using 1 of 3 approaches: macroporous, zonal, and CFD-based. In the macroporous approach, the food, the packaging, and the gas phase properties are averaged, generally at the pallet scale, and a simplified constitutive equation, such as Darcy's, or the Darcy–Forchheimer, law, is used to describe the average air velocity (Verboven and others 2006). In the zonal approach, the domain, for instance the pallet, is divided into zones at the macroscale. In every zone, each phase is assumed to have uniform properties. Heat and mass transfer within a zone is described using ordinary differential equations derived from heat and mass balances, and the exchange of energy and mass between the zones is estimated from a sum of resistances (Tanner and others 2002a, 2002b). In the CFD approach, no averaging at the macroscopic scale is performed, and the air velocity around the food is described using a Navier–Stokes equation (Ferrua and Singh 2009a; Defraeye and others 2014; Han and others 2015; Berry and others 2016; O'Sullivan and others 2016). The CFD approach is the most complete and provides the most accurate estimates of temperature and airflow, especially for complex packaging and low package-to-product-size ratios (Verboven and others 2006; Ferrua and Singh 2009a; Dehghannya and others 2011, 2012). However, the implementation of the CFD approach is frequently limited to a single-box or single-pallet scenario, as fine grids and computationally intensive numerical schemes are required. Possible opportunities for the efficient large-scale modeling of precooling processes could arise from the coupled modeling of momentum, heat, and mass transfer using the lattice Boltzmann method. In that method, the constitutive equations are solved using an explicit time-stepping scheme, facilitating the parallelization of the algorithm and the description of airflow with complex geometries (He and others 2009; Ho and others 2013; Grucelski and Pozorski 2015; Perumal and Dass 2015). Modeling a complete precooling process for different numbers of pallets, products, and operating conditions, for instance, using a lattice Boltzmann approach, would provide a dynamic and detailed description of the food's state and offer a relevant decision-support tool for efficient precooling. In addition, the model can be combined with a quantitative heterogeneity index, in order to identify package designs and tunnel operating conditions that promote uniform precooling (Ferrua and Singh 2009d; Olatunji and others 2017).
- **Accurate forecasts of the impacts of management systems based on time–temperature measurement**: Accurate forecasts of the capital and operating costs, reduction in food waste, and improvement in food safety resulting from management systems based on time–temperature measurement are required by the industry to justify the investments needed to implement such systems. Estimates of the food waste reduction resulting from management systems based on

time–temperature measurement have been made in the literature for different food products (Koutsoumanis and others 2002, 2005; Dada and Thiesse 2008; Dittmer and others 2012; Lütjen and others 2012; Tromp and others 2012; Nunes and others 2014). However, these estimates were obtained considering simple cold chains (generally 1 distribution system and a few retailers) with a constant temperature at each step and are therefore not very robust. More realistic estimates of the economic, social, and environmental contributions of management systems based on time–temperature measurement may now be possible as a result of the European FRISBEE project, during which hundreds of time–temperature histories of perishable food along the cold chain have been measured and compiled in an online database, in combination with geospatial systems detailing cold chain networks at national scales (Gwanpua and others 2015; LeBlanc and others 2015; Sciortino and others 2016). Efforts should be made to merge the recent knowledge of time–temperature conditions along current commercial cold chains with detailed geospatial descriptions of cold chain networks for accurate economic, social, and environmental forecasts. Robust forecasts of the improvements obtained by management systems based on time–temperature measurement, in addition to an increasing awareness of the food security dangers related to food waste in the context of a growing world population, may provide the required combination of social and economic drivers that will stimulate the widespread implementation of these systems.

- **The cold chain in developing countries**: Field studies monitoring the temperature of perishable food along the cold chain have been conducted in developed countries, notably in France, Greece, the U.S., and Canada, but equivalent studies in developing countries are scarce. It is well known that the cold chain in developing countries is very different and is limited by the high capital and operating costs of refrigeration equipment and, in some cases, by the absence of reliable sources of electricity (FAO 2004; International Inst. of Refrigeration 2009). In China, it is estimated that only 15% of perishable food products are transported in refrigerated trucks, in comparison with 90% in developed countries (USDA 2008). In India, positive developments have been observed over the last few years as economic and political drivers have stimulated the improvement of refrigerated infrastructure and distribution systems, but a fully refrigerated supply chain from farm to fork is still in its infancy (Dharni and Sharma 2015; Saurav and Potti 2016). Yet, it is in developing countries that food refrigeration may be most important, given their faster population growth rates and already severe food security problems (International Inst. of Refrigeration 2009; United Nations 2015). It is estimated that if the same level of refrigeration used in developed countries were to be applied in developing countries, more than 200 million tons of perishable food per year, approximately 14% of those countries' consumption, would be saved (International Institute of Refrigeration 2009). Detailed knowledge of the state of the cold chain in many developing countries remains unavailable, and the most pressing issues to be addressed for better food safety and quality are unclear. Future research should aim to provide a clear assessment of the state of the cold chain in developing countries, and the knowledge that is acquired should be applied to raising awareness of the quality and safety risks associated with poor temperature control and to supporting the development of equally efficient and sustainable cold chains around the world.

Conclusion

The cold chain is a necessary component of our society's system for delivering food to consumers, and the sustainability of the cold chain is an unavoidable topic given the current landscape of food insecurity and a growing world population. In this work, the state of the cold chain was reviewed in terms of its efficiency in maintaining food at the proper temperature. Weaknesses in the cold chain where identified and included heterogeneous precooling, ground operations during transportation, display at retail, storage in domestic refrigerators, the variability of temperature within shipments, and industry handling practices. Challenges for the commercial implementation of management systems based on time–temperature measurement were highlighted, and relevant prospective research were proposed, notably the development of large-scale models to support the design and operation of efficient precooling units, the establishment of accurate forecasts of the costs and benefits (from both economic and food safety and quality standpoints) resulting from management systems based on time–temperature measurement, and a detailed investigation of the state-of-the-cold-chain in developing countries.

The cold chain is an extensive and complex topic, and a single article cannot provide a complete overview of all its related aspects. Therefore, subjects such as the global harmonization of laws, regulations, and manufacturing practices, the cost, efficiency, and reliability of wireless temperature measurement hardware, the role of packaging in food preservation, and the environmental impact of the cold chain were not covered or were only briefly mentioned. Nevertheless, these aspects remain central to the successful implementation of any management system based on time–temperature measurement.

Many authors have identified collaboration between industrial stakeholders in the cold chain as one of the main challenges that need to be overcome for the successful implementation of management systems based on time–temperature measurement. However, the need for collaboration within the scientific community should not be underestimated. The investigation of the cold chain is a highly diversified and multidisciplinary topic that requires input from electrical engineers for developing hardware, food engineers for investigating the impact of food processing, food scientists for performing shelf-life assessments, microbiologists for studying the bacterial, viral, and mold spoilage of food, environmental engineers for determining greenhouse gas emissions and carrying out life cycle analyses, public health professionals for analyzing food safety risks and the impacts of foodborne outbreaks, economists for quantifying the costs and benefits of new management systems, and marketing and management specialists for bringing new management systems from a theoretical concept to commercial implementation, to name just a few. It is only through open channels of communication between research institutions, free information sharing, and true partnerships that quick and long-term improvements for a sustainable cold chain can be achieved.

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