Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations

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Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations

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Abstract

The management of food cold chains is receiving more and more attention, both in practice and in the scientific literature. In this paper, we review temperature abuse in food cold chains that operate in different countries, as well as cold chain solutions focused on food quality and safety. Our key findings are: 1) temperature management in chilled food products was the main focus of research, the most investigated food categories were meat, dairy, fish, fruit, and vegetable products; 2) most temperature abuse reported is in the cold chains of developed countries, whereas much less is known about the situation in developing countries; 3) recent technology applied in temperature monitoring provides a significant contribution to food cold chain, but, further investigation of its application is necessary to generate appropriate data; and 4) food waste may be reduced with a better temperature management in food cold chains. Additionally, we also investigated a new possibility for future research in food cold chains.

Keywords: temperature abuses, perishable products, food safety, food quality, food waste

1 Introduction

A cold chain is an uninterrupted-temperature controlled transport and storage system of refrigerated goods between upstream suppliers and consumers designed to maintain the quality and safety of food products (Montanari, 2008; Taoukis et al., 2016). Unexpected temperature changes or abuses in food cold chain can lead to compromised food safety and food quality that ultimately can result in loss of consumer confidence and increased levels of food waste. It has been reported that roughly one-third of global food production is wasted annually (Gustavsson et al., 2011). Food waste refers to an unacceptable level of quality of food or food discarded by retailers or consumers due to microbial rot, disease or insect damage. A high share of these losses is related to poor post-harvest handling, lack of proper facilities, and insufficient training for operators in the cold chain. In the last decade, cold chain problems have been investigated and reviewed (Koutsoumanis & Gougouli, 2015; Mercier et al., 2017; Montanari, 2008; Taoukis et al., 2016). These studies, however, have little discussion about the possible means of managing temperature abuse with consideration to recent technological advancements. To respond to this gap, this article gives an overview of recommendations, including temperature-monitoring technologies and systems.

2 Materials and methods

Literature reviews may be carried out to improve the understanding of the topic or to investigate new research opportunities. Following the methods of Cherrafi et al. (2016) with a minor modification, we performed content analysis on the reviewed papers to define the unit of analysis, classify the publication content, evaluate the content, and delimit the field. The journal databases used in this study were PubMed, Elsevier, Wiley Online, Emerald, Springer, and Taylor & Francis. In our search, we used the following key phrases: food cold chain management, temperature abuse in food cold chain, food cold chain monitoring tool, and a combination of keywords and phrases related to temperature abuse in food cold chain during transportation and storage. In the search, we selected topical books and book chapters, peer-reviewed papers, and reports published by the relevant professional organizations (e.g., FAO). In addition, we also checked the reference lists of papers and reports already retrieved to identify additional potentially relevant materials. We did not include unpublished articles or grey literature. Through a screening of relevant articles, eighty-six references were obtained from publisher databases (see Figure 1). In general, the distribution shows a rising number of studies related to cold chain since 2002, which indicates that issues of cold chain management have gradually received more and more attention recently.

With respect to publication scope, we categorized the obtained references into four themes: food science and technology, supply chain management, computer engineering, and others (e.g., legal requirement) (see Figure 2). These categories were made to simplify the data analysis. Most of the academic material was found in publications devoted to food science and technology and computer engineering. The majority of articles were published in “Food Control”, the “International Journal of Food Microbiology,” and “Trends in Food Science and Technology”. A smaller but growing number of outputs related to technical issues associated with temperature abuse were published that concern supply chain management.

3 Results and discussion

3.1 Refrigerated food categories in cold chains

In general, refrigerated food can be divided into four categories related to storage temperature: frozen at -18 °C or below, cold-chilled at 0 °C to 1 °C, medium-chilled at 5 °C, and exotic-chilled at 10 °C to 15 °C (Fernie & Sparks, 2004; Gustafsson et al., 2006). These levels of temperature were established to suit different type of food products. However, several food products were stored or distributed at another level of temperature to achieve their optimum temperature. For study purposes, therefore, we categorized the food products in Table 1 according to the temperature level used in the published studies.

In the literature reviewed for this study, typical food kept frozen were tilapia fish and ice cream (Likar & Jevšnik, 2006; Tingman et al., 2010). Cold-chilled foods included fresh cod loins, fish, meat, and ready-to-eat food (Koutsoumanis et al., 2010; Likar & Jevšnik, 2006; Lundén, Vanhanen, Myllymäki, et al., 2014; Martinsdóttir et al., 2010; Nunes et al., 2009; Pelletier et al., 2011). Medium-chilled foods included minced meat and processed fish, prepacked meat, ready-to-eat foods, cooked products, yoghurt, bakery products, butchered pork, dairy products, and salmon (Brown et al., 2016a, 2016b; Derens-Bertheau et al., 2015; Derens et al., 2006; Koseki & Isobe, 2005; Likar & Jevšnik, 2006; Lundén, Vanhanen, Kotilainen, et al., 2014; Mai et al., 2012; McKellar et al., 2012; Morelli et al., 2012; Nunes et al., 2009; Rediers et al., 2009; Zeng et al., 2014; Zubeldia et al., 2016). Exotic-chilled foods were vegetables (Nunes et al., 2009).

As shown in Table 1, chilled food (-1 °C to 8 °C) has been the focus of many studies, perhaps because this type of food product is generally sold in a short period and it sensitive to temperature. Little attention has been paid, however, to frozen food (-18 °C or below) and exotic chilled food (10 °C to 15 °C) in food cold chains. Additionally, it is obvious that meat, dairy, fish, fruit, and vegetable products have been the main subjects of research.

3.2 Issues with time-temperature in cold chains

Preservation of quality and safety of fresh food products along the supply chain is closely related to the exposure of these products to the optimal temperature, humidity, and other conditions (Taoukis et al., 2016). In this paper, we focus on temperature abuse in the cold chain. We define temperature abuse as an unacceptable deviation from the optimal temperature or optimal temperature regime for a given food product for a certain period of time, taking into account ambient temperature and the type of activities food products are exposed to.

3.2.1 Cross-country comparison of refrigerated foods in cold chains

The identification of locations or stages in cold chains where temperature abuses occur is crucial for suitable intervention (c.f., Tromp et al., 2016). Most of the reviewed studies show that a temperature abuses occur at all stages in the cold chain, and are not confined to any particular type of food product (Table 2).

Temperature abuse has been reportedly occurred during transportation, retailer storage, and retailer display of food products. In the European countries, temperature abuse was reported in Iceland, Finland, Slovenia, Spain, and France. In Iceland, during transportation of fresh cod loin fillets, Martinsdóttir et al. (2010) observed that 35 % and 18 % of the time by air and sea transportation, respectively, the temperature was higher than recommended (0 ± 1 °C). Similarly, Mai et al. (2012) also reported that 17 % and 36.1 % of the total time required for two air freight deliveries of cod loin and haddock fillets, the temperature was higher than 5 °C.

In Finland, Lundén, Vanhanen, Myllymäki, et al. (2014) monitored the temperature of fish, meat, and ready-to-eat food in retail stores and found that about 50 % of the temperature of these products were out of their controlled temperature range (i.e., above 1 °C) for up to 24 hours. In addition, there was a significant deviation between the actual product temperature and the temperature indicated by the refrigeration equipment up to 6 °C. On another occasion, Lundén, Vanhanen, Kotilainen, et al. (2014) reported that a food business operator did not notice or react to temperature abuses, and 50.0 % and 46.2 % of the time, minced meat and processed fish temperatures were higher than 3 °C for more than 30 minutes.

In Slovenia, Likar and Jevšnik (2006) reported that temperatures in retail freezer cases fluctuated from 0 °C to 10.5 °C for pre-packaged frankfurters and pre-packaged poultry, 0 °C to 16 °C for butter, yoghurt, cottage cheese, and cream product, -23 °C to 10 °C for ice cream product, and 0 °C to 17 °C for eggs. They also found that temperature measured by fixed temperature devices and by the researcher was not necessarily the same. In addition, this study revealed that some of the food business operators had inadequate knowledge of cold chain integrity.

In Spain, Zubeldia et al. (2016) reported that temperature abuse in retail freezer cases cabinet was highly pronounced in the summertime, particular for products located on the top shelves. Due to abusive temperature, remaining shelf life was reduced by 40 %, 57 % and 25 % for smoked salmon, cooked chicken breast, and fresh cheese, respectively. These authors suggested revising the operational procedures adopted for the retail cold chain in Spain due to the finding that existing guidelines did not comply with the safety specifications for perishable food.

In France, Morelli et al. (2012) noted that the temperature of 70 % of the freezer cases in bakeries, a pork butcher, and dairy product in retailers exceeded 7 °C. The occurrence of temperature abuse was mainly associated with professional practices. Poor design of the refrigeration equipment was also contributed to temperature fluctuation. These authors suggested that the food producers or refrigerator users should only store food products as instructed by the equipment manufacturer. Derens et al. (2006) reported that the temperature during refrigerated transport to retailers was more stable, but that, 6.5 % and 79.7 % of the time, the temperature in retailer display cases and domestic vehicles, respectively, exceeded the recommended temperature. In the entire ham cold chain, Derens-Bertheau et al. (2015) discovered that 42 % of ham products were kept above 4 °C. In the pasteurized milk chain in Greece, Koutsoumanis et al. (2010) observed that the temperature fluctuated from 3.6 to 10.9 °C in trucks during transport and from 0 °C to 11.7 °C at the retailer.

In the United States, Pelletier et al. (2011) reported that the temperature was generally stable in the strawberry cold chain, fluctuating from 0.7 °C to 3.7 °C during precooling, cold storage, transport, and retail. Despite the small temperature fluctuations, the strawberries were found to have deteriorated in terms of moisture content while being transported to the retailer. In contrast, Nunes et al. (2009) reported a wide range of temperature fluctuation of produce in display cases: from -1.2 °C to 17.7 °C for berries and grapes, -0.7 °C to 19.2 °C for fresh-cut fruit and vegetables, 1.1 °C to 19.2 °C for salad bags, and -0.8 °C to 14.1 °C for cucumbers and peppers. Interestingly, Nunes et al. (2009) also revealed that some of the chill-sensitive fruits and vegetables were transported too cold, whereas heat-sensitive produce was transported too warm. As result, more than half of these products were wasted. Moreover, Zeng et al. (2014) reported that temperature fluctuation for bagged salads between -0.3 °C and 7.7 °C and between -1.1 to 9.7 °C while in transport and at the retailer, whereas the temperature should be maintained between 0.17 °C and 5 °C. A similar trend was observed by Brown et al. (2016b) who found that 52.78 %, 22.22 %, 9.75 %, and 15.28 % of the time during transport in spring, summer, fall, and winter season, respectively, exceeded 5 °C. On another occasion, 40 % and 58 % of the temperatures recorded in retail cases and retailer facilities were higher than 7.2 °C (Brown et al., 2016a).

In Canada, McKellar et al. (2012) found that temperature was well-controlled in the entire cold chain for ready-to-eat baby leaf lettuce; however, Rediers et al. (2009) observed that temperatures were allowed to increase up to 16 °C, with an average of 2 °C during transportation to the processor’s storage facility in the fresh-cut endive cold chain.

In Japan, the temperature of refrigerated iceberg lettuce was found to fluctuate in the range of 3 °C to 15 °C during transport (Koseki & Isobe, 2005). Observation of frozen tilapia fish fillets in China showed that the ambient temperature fluctuated between -18.6 °C and 16.8 °C after 6 hours of transport, but, the sample temperature only increased slightly to -17 °C (Tingman et al., 2010). On the other hand, these authors found that the shelf life of products stored with temperature fluctuation in range of 2.0 °C had two months' shorter shelf life than products with a temperature fluctuation of less than 0.5 °C.

A broken cold chain in produce (fruits and vegetables) product was also reported in South Africa. In two different studies, it was found that 81 and 41.5 % of the product temperature rose above 2 °C for longer than 90 minutes within fruit reefer containers at the port terminal (L.L. Goedhals-Gerber et al., 2017; Leila L. Goedhals-Gerber et al., 2015).

The current review revealed that most temperature abuse has been reported is in the cold chains of developed countries. Much less is known of the situation in developing countries as has already been pointed out by Mercier et al. (2017). This situation may be caused by low awareness of the quality and safety risks associated with poor temperature control in food cold chains in developing countries.

3.2.2 Sensitive links in food cold chain

It has been demonstrated that temperature fluctuations can be easily encountered in the entire cold chain. Temperature control problems during the storage of refrigerated food at the retailer typically occur due to lack of compliance with the temperature specifications for refrigerated food (Lundén, Vanhanen, Kotilainen, et al., 2014; Lundén, Vanhanen, Myllymäki, et al., 2014), poor design of the cold storage facilities (Morelli et al., 2012), and uneven temperature distribution for all kinds of food on the shelves (Zubeldia et al., 2016).

During transport, Moureh et al. (2002) found that temperature deviations were associated with the positions of products and packages in the container. The top corner was the most sensitive areas because they had larger surfaces for temperature exchanges with the surroundings. In particular, the situation is worsened for refrigerated food when the cold chain is broken during loading and unloading of the cargo or freight (Estrada-Flores & Eddy, 2006).

3.2.3 Food waste and temperature control

Food waste typically results from damage to food products, food loss, and deterioration of product quality or food safety features. The scale of the problem is overwhelming: approximately one-third of perishable products finish as waste (Gustavsson et al., 2011). Among other reasons, mismanagement of temperature control or other settings (e.g., of humidity or gasses) in any point in the cold chain contributes to food waste (Parfitt et al., 2010; Vlajic, 2015; Vlajic et al., 2016). The potential for food waste rises with an increase in the length of the supply chain, e.g., with the internationalization of the food supply chain. An important aspect of this is that temperature abuse in a certain time period or the violation of any other important parameter at only in one place in the supply chain triggers deterioration, which is sometimes discovered too late, at the retailer or at homes of the end customers. Although mismanagement may happen at one point of the chain, food waste occurs at the end of the chain, in retail stores or households. The situation is additionally complicated by the different management practices and resources available to large and small retail companies (Vlajic, 2015).

In principle, food waste could be minimized by optimizing the temperature for low-temperature food products. Brown et al. (2014) proved that lowering refrigerator temperatures from 7 °C to 4 °C can extend storage life and reduce food waste. They estimated that this approach could save food amounting to GBP 283.8 million, with an energy impact reduced to GBP 80.9 million in the United Kingdom alone. Time-temperature management can potentially be managed by an effective logistic system integrated with the Internet of Things (IoT) technology to minimize food waste. While an effective logistic system could make autonomous decisions regarding the condition of its transported goods (Flämig, 2016; Jedermann et al., 2014; Lütjen et al., 2013), IoT technology could bridge the communication gap between the objects used in the logistic chain (Alaba et al., 2017; Atzori et al., 2010). In short, temperature management control may help to reduce the food waste in food supply chains.

3.3 Challenges concerning time-temperature management in food cold chains

Table 3 summarizes the available resources, challenges, and possible solutions pertaining to time-temperature management problems in food cold chains. Four key areas are addressed bellow: time-temperature monitoring and measurement technology, user-friendly software for shelf-life modeling, time-temperature monitoring and measurement systems, and legal requirements.

3.3.1 Real-time temperature monitoring technology in food cold chains

Monitoring, tracking, and measuring food temperature enable information about past and real-time temperature abuse to be monitored by supply chain members in order that corrective actions be made in timely fashion. To date, wireless temperature-monitoring technologies, notably Radio Frequency Identification (RFID) tags and Wireless Sensor Networks (WSN), and Time-Temperature Integrators (TTIs) are probably the most widely employed systems used to measure, record, and monitor the product temperatures in food cold chain (Koutsoumanis & Gougouli, 2015; Kumari et al., 2015).

The utilization of RFID and WSN to monitor and measure the temperature of perishable food products has been demonstrated recently (Hafliðason et al., 2012; Kumari et al., 2015; J. Wang et al., 2015; X. Wang et al., 2017; Xiao et al., 2016). Nowadays, the evolve of these tools has been favored because they can record data more accurately and more convenient, and are available at lower cost. However, several drawbacks of this tool has been noted, for example, the time required to load large amounts data, the reading range, and limitation on the real-time delivery of data and sensing capability still limit the utility of such monitoring systems (Ahmed et al., 2015; Becker et al., 2009; Fescioglu-Unver et al., 2015; Ruiz-Garcia & Lunadei, 2011).

Another limiting factor is the attenuation of the signal caused by food products containing a significant amount of water (Benelli & Pozzebo, 2013), as a result of which temperature sensors become less sensitive and cloud connections can be disrupted.

Time-Temperature Integrators (TTIs) can also visualize the time-temperature history in food cold chains (Arias-Mendez et al., 2014). Depending on the working principle involved, TTIs can be classified as biological, chemical, or physical systems (Ellouze & Augustin, 2010; Koutsoumanis & Gougouli, 2015; Wu et al., 2015). TTIs have been evaluated for several refrigerated food products such as fish and fishery products (Giannakourou et al., 2005), ground beef (Kim et al., 2012), meat products (Ellouze & Augustin, 2010), and produce (Giannakourou & Taoukis, 2003; Kim et al., 2016). Although TTIs are widely used, they tend underestimate the remaining shelf life. Bobelyn et al. (2006) shed some light on this subject when they reported that the TTI response was not always in line with food quality changes.

3.3.2 User-friendly software for shelf-life modeling

Obtaining the time-temperature information along the food cold chain enables the estimation of product shelf-life. Generally, kinetic model of temperature dependence has been employed to estimate the growth or inactivation of microorganism. A number tools have been developed to allow estimation of the shelf-life of various food product. The developed software can be used even by people who have limited knowledge about food science, which makes it user-friendly. Among others, software applications of this kind include Cold Chain Predictor; Seafood Spoilage Predictor; and ComBase (Dalgaard et al., 2002; Dolan et al., 2015; Gogou et al., 2015).

The use of shelf-life estimation software has proven help to the development of the food industry, however, modeling the shelf-life of different products by taking into account not only spoilage but also pathogens is very challenging, and a key factor in food safety. Besides, shelf-life modeling may not be effective if there is a time-temperature history effect due to temperature fluctuations (Shimoni & Labuza, 2001). That affects the growth of spoilage or pathogenic bacteria. Additionally, there are limited data on the effects of fluctuations in other factors (e.g., water activity, oxygen level, carbon dioxide level) on growth if the temperature is controlled.

3.3.3 Development of real-time temperature monitoring systems

A real-time temperature monitoring system can be defined as one having the ability to check, measure, and report the actual temperature at any time. Effective temperature monitoring will help the food business operators in making decisions, taking corrective action, and evaluating of their operation. Recently, Shih & Wang (2016) proposed a cold chain system based on Internet of Things (IoT) architecture. IoT would allow the real-time collection of temperature data at each point in the food cold chain. In their trial, the real-time temperature data was monitored, measured, and collected by RFID tags, with improved potential for managing time-temperature, increasing annual sales, and reducing energy consumption.

A novel real-time temperature monitoring system based on a smart logistic unit (SLU) has also been demonstrated in a food supply chain. Besides temperature, this system also considered the other important factors affecting the quality of food, such as changing in total volatile organic compounds (VOCs). This system was equipped with a GPS (Global Positioning System) module and a 3G connection (third generation of wireless mobile telecommunications technology), and connected to a web-cloud. That was used in order to allow data centralization, real-time observations, and online access by authorized stakeholders. In an experimental test using strawberry supply chain, Scalia et al. (2015) and Sciortino et al. (2016) proved that this technology can monitor the time-temperature and estimate the shelf life of the product effectively by recording changes in VOCs.

A robust temperature-monitoring system has been developed within the framework of the European FRISBEE project recently (Gwanpua et al., 2015). In order to improve the efficiency and sustainability of the system, this tool was used to simultaneously evaluate the quality of low-temperature food products, energy use, and the global warming impact of food cold chain. This was also a web-based platform that enabled data collection from the whole supply chain and more precise estimation of the remaining shelf life of a specific food product. It was also equipped with a stand-alone software, Cold Chain Predictor (CCP), enabled the prediction of the effective temperature and shelf life of a specific food product by using various scenarios in Monte Carlo simulation (Gogou et al., 2015). The simulations used a numerical approach to generate a probability distribution based on hypothetical scenarios in terms of reported time-temperature values throughout the cold chain. An experimental test on cold chain for apples, spinach, and ice cream showed that this tool can be used to assess the impact of temperature fluctuations and logistics management options in a refrigerated system. In a real situation, this tool was evaluated by Derens-Bertheau et al. (2015) for chilled food in France by collecting time and temperature information from production to consumption. This investigation revealed that transport between purchase and household refrigerator were the most sensitive link with respect to temperature abuse. On another occasion, Gogou et al. (2015) used this tool to evaluate the cold chain performance of local meat producers and retailers in Greece and France, they also found that the consumer refrigerator is the weakest link. These authors were able to estimate the effective temperature during the entire cold chain and thereby estimate the remaining shelf life of ready-to-eat meat products. This technological advancement may contribute to improving cold chain integrity; however, the value this technology's output is determined by user participation and data transparency in the food cold chain.

3.3.4 Legal requirements for food cold chain management

The food business owner (FBO) takes primary responsibility for ensuring that the food product is fit for use. Specifically, FBOs in the cold chain have direct control over the correct storage and handling of their product in the food cold chain. To govern time-temperature in this chain, a growing number of specific compliance requirements and industry best-practice guidances for establishing an effective cold chain have been established. Recently, the Australian Food and Grocery Council (AFGC) issued a cold chain guideline for the distribution of food product from producer to consumer in Australia (AFGC, 2017). In this guideline, the AFGC thoroughly described the necessary safety and quality requirements to minimize food illness and reduce food waste. Similarly, the US FDA also issued a rule governing the food cold chain in the United States (US FDA, 2017). This rule requires food businesses to comply with specific requirements for vehicles, transportation equipment, and transportation operations in order to preserve the safety and quality of food. In the United Kingdom, a guidance on time-temperature control was issued by the Food Safety Authority in (FSA, 2007). This guidance specifies the permitted degree of flexibility within the temperature control requirements. In the European countries, time-temperature management in the food chain is controlled by the Regulation No. 852/2004 (EC, 2004). To benefit all parties and facilitate the international food trade, the recommendations on temperature management were elaborated in the general principles of food hygiene issued by the Codex Alimentarius Commission (CAC, 2003). Despite the existence of these legal requirements, effective temperature management in practice remains difficult. The lack of harmonization of legal requirements results in a lack of application in the food industry. Additionally, monitoring and measurement cost to satisfy the time-temperature requirements remains a challenge. Only limited guidelines have been established with regard to operational cost (Mercier et al., 2017). It is also worth considering the issues of social environmental impact, and food cold chain sustainability in the process of issuing regulations.

3.4 Possible solutions and future research opportunities

While better management of cold chains can improve food quality and food safety, any temperature abuse can contribute to the deterioration of food quality and safety and ultimately result in food waste. A number of findings have emerged from the present review.

First, a high rate of occurrence temperature abuse in the food cold chain indicates that food business operators have a limited knowledge of temperature control. In addition, because most of the studies are from developed countries, it may generally be expected that temperature abuse or fluctuation is common in developing countries.

Second, continuous temperature tracking and monitoring along the supply chain are important and a combination of wireless temperature-monitoring technologies can be a useful tool for cold chain management. Integration with a novel technology, such as SLU- and web-GIS-based applications is necessary to provide accessible online information for stakeholders. Furthermore, the temperature data thus made available can be used to predict and interpret the food quality degradation, which enables timely corrective action to be taken. Technical obstacles need to be resolved, though, and we propose the following directions for future studies:

First, tracked temperature information must be centralized and shared with cold chain partners. At the moment there is a large gap in the literature concerning means to achieve this. To promote user participation and data transparency in the food cold chain, Big Data and blockchain technology should be considered. While Big Data technology will allow data centralization and Big Data exchanges (Lakshmil & Vijayakumar, 2012; Ouaddah et al., 2017; Shih & Wang, 2016; Tian, 2017), blockchain technology will facilitate more secure and transparent information transfer, both fast-response and cost-efficient, and can be integrated into existing infrastructure (Hackius & Petersen, 2017; Nakasumi, 2017; Petersen & Jansson, 2017). Pre-defined criteria (for example, the temperature level of a particular food product) could be executed beyond a pre-defined threshold for a certain place and times, thorough a so-called "smart contract" (Bahga & Madisetti, 2016; Christidis & Devetsikiotis, 2016). A selection of smart contracts can be included in the blockchain platform to facilitate secure communication between the users and machines. Recently, the applicability of the Big Data and blockchain connected by IoT technology have sparked interest, especially in supply chain networks and retail management (Abeyratne & Monfared, 2016; Accorsi et al., 2017; Polim et al., 2017). However, these technologies need further support and improvement, especially with regard to issues of technical realization, infrastructural configuration, computation, scalability, preventing of privacy and data leakage and selfish mining, and an inadequate legal framework in practice (Atzori et al., 2010; Mendez et al., 2017; Mendling et al., 2017; Zheng et al., 2016).

Second, limited guidelines governing food cold chains have been established with consideration of energy use, economic risk, social impact, environmental issues, and sustainability. The establishment of guidelines by relevant regulatory authorities could help to bridge this gap, at both the national and international level. This step will also allow the implementation of the recent developed technologies and established systems for time-temperature monitoring in food cold chain.

Third, there is a need for integrated research considering carbon dioxide emission, food waste, energy use, temperature management, and management of cold food distribution systems. We urge that more research be devoted to the development of mathematical tools for quantifying the quality and safety of refrigerated food, energy usage and global warming impact, and extent of food waste, as well as evaluating the efficiency and sustainability of cold chains.

Figure 3 depicts inter-related concepts of temperature-controlled cold chain logistics. Cold chain management is a multidisciplinary area, which implies multiple organizational, technological, and managerial challenges in food supply chains. These challenges increase when cold chain management extends from a focus on one company to the entire chain. With real-time information, decisions about optimal handling or stock control can be better informed, which should prevent food waste, and thus achieve cold chain management with low economic losses and low environmental impact. In sum, further research in this area should be conducted with respect to food safety and quality, food loss and waste, and data transparency in the cold chain.

4 Conclusions

A cold chain is the uninterrupted temperature controlled transport and storage system of refrigerated goods between upstream suppliers and consumers to maintain the quality and safety of food products. While reviewing the studies on temperature abuse along the food cold chain, it is obvious that time-temperature management remain difficult. The main issue was a high rate of occurrence temperature abuse in the food cold chain caused by many factors, such as the practices of the food cold chain operators, poor design of refrigeration equipment, and the positions of products and packages in the storage container. The optimization of available resources to manage the time-temperature along this chain remain a challenge. Therefore, the establishment of guidelines by relevant regulatory authorities with consideration of energy use, economic risk, social impact, environmental issues, and sustainability are recommended to achieve the food cold chain integrity. Additionally, it is also worth considering the implementation of Big Data and blockchain technology in the process of issuing regulations.

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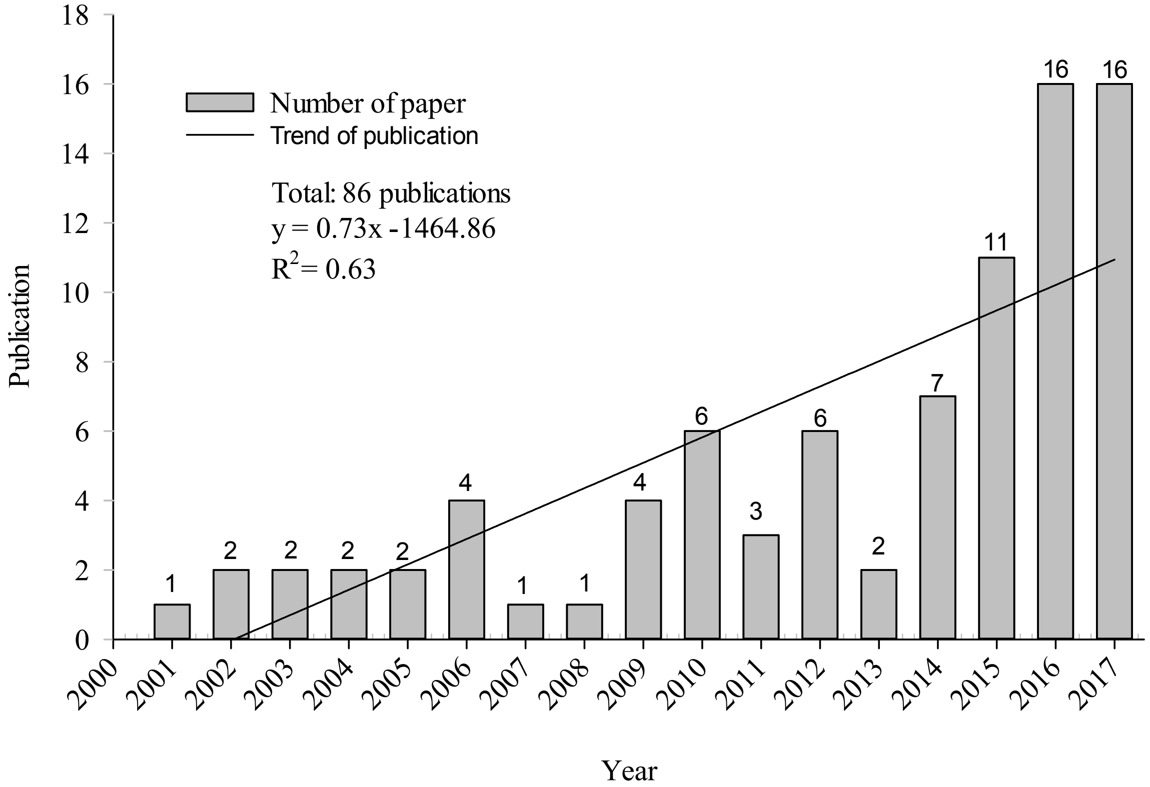

Figure 1. Distribution of publications per year across the period studied.

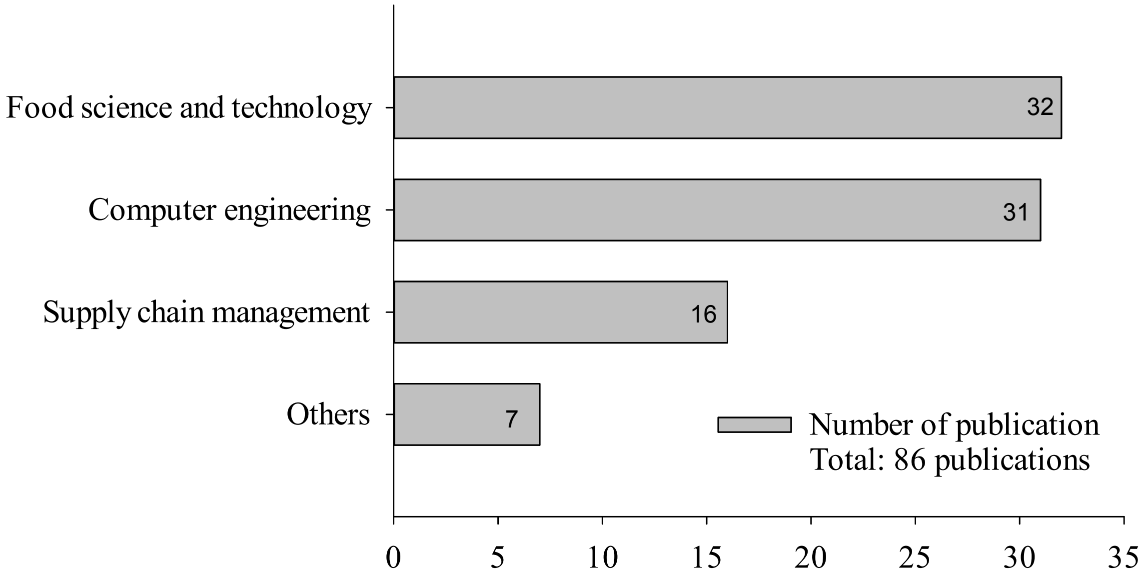

Figure 2. Distribution of references in publication field in paper review.

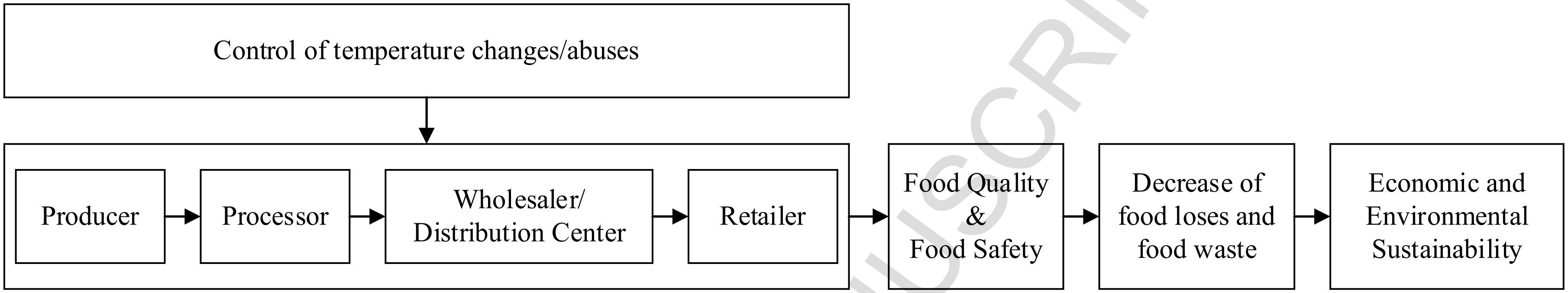

Figure 3. A framework for creating sustainable supply chain by enhancing cold chain logistics.

Table 1. Overview of reviewed publications on temperature ranges and food product categories in the food cold chain.

Author	Temperature range					Food product category					
	Frozen	Cold chill	Medium chill[1]		Exotic chill	Meat[2]	Dairy[3]	Fish	Fruit and or vegetable	Egg	RTE[4]
	≃ -18 °C	≃ 0 to 1 °C	≃ 5 °C	≃ 8 °C	≃ 10 to 15 °C						
Mai et al. (2012)			√					√			
Martinsdóttir et al. (2010)		√						√			
Lunden et al. (2014a)		√				√		√			√
Lunden et al. (2014b)			√			√		√			
Likar & Jevšnik (2006)	√	√	√	√		√	√			√	√
Zubeldia et al. (2016)			√	√		√	√	√	√		
Morelli et al. (2012)				√		√	√				√
Derens et al. (2006)			√			√	√				√
Derens-Bertheau et al. (2015)			√			√					
Koutsoumanis et al. (2010)		√					√				
Pelletier & Brecht (2011)		√							√		
Nunes et al. (2009)		√	√	√	√				√		
Zeng et al. (2014)			√						√		
Brown et al. (2016b)			√						√		
Brown et al. (2016a)				√					√		
McKellar et al. (2012)				√							√
Rediers et al. (2009)			√						√		
Koseki & Isobe (2005)				√					√		
Tingman et al. (2010)	√							√			

[1] Medium chilled food product generally stored at ≃ 5 °C, however, some of them stored at temperature up to 8 °C

[2] Meat and meat products, including poultry

[3] Dairy products and analogues

[4] RTE = Ready to eat food product, including bakeries product

Table 2. Time-temperature abuse identified along the food cold chain.

Country	Food chain	Number of samples	Product	TR[1]	Temperature abuse	Reference
Iceland	Air freight and sea transportation	232 boxes	Cod loins and haddock fillet	5 °C	17.0 % and 36.1 % of the total time in two air freight transportations had temperatures higher than 5 °C	(Mai et al., 2012)
	Air transportation and sea transportation	NA[2]	Cod loins	0 ± 1 °C	35 % and 18 % of the total time in air and sea transportation were under temperature losses	(Martinsdóttir et al., 2010)
Finland	Retailer	84 samples	Fish, meat, ready to eat food	1 °C	50 % of the temperature was higher than 1 °C for 249 to 781 minutes	(Lunden et al., 2014a)
	Retailer	NA	Minced meat and processed fish	3 °C	46.2 % ~ 50.0 % of the temperature was higher than 3 °C for more than 30 minutes	(Lunden et al., 2014b)
Spain	Retailer	11 supermarkets (101 and 99 food samples in winter and summer time, respectively)	Fresh meat, meat preparations, and vegetables	4 °C	38.5 % ~ 100 % of the temperature at the top shelves was higher than 4 °C at summer time	(Zubeldia et al., 2016)
			Meat products, fishery products	5 °C	50.0 % ~ 87.5 % of the temperature at the bottom shelves was higher than 5 °C at summer time	
			Mixed product	6 °C	76.0 % of the temperature at the top shelves was higher than 6 °C at summer time	
			Dairy products	8 °C	56.0 % of the temperature at the top shelves was higher than 8 °C at summer time	
France	Retailer	99 samples	Bakeries, pork butcher, dairy	7 °C	70 % of the temperature was higher than 7 °C	(Morelli et al., 2012)

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[1] Temperature requirement

[2] Not available/not applicable

Country	Food chain	Number of samples	Product	TR[1]	Temperature abuse	Reference
	Transportation, warehousing, distribution platform, display cases, domestic transport, domestic storage	314 samples	Prepacked meat, ready to eat or to cook product and yogurt	4 – 6 °C	13.6 % of the temperature in the entire cold chain was higher than recommended	(Derens et al., 2006)
	The end of production, refrigerated transport, logistic platform, cold room in the store, refrigerated display cabinet, transport after purchase and domestic refrigeration	83 samples	Sliced ham	4 °C	42 % of the total time in the entire cold chain had temperatures higher than 4 °C	(Derens-Bertheau et al., 2015)
	Transportation and retail cabinet	83 trucks, 60 retail cabinets	Pasteurized milk	0 °C	Transportation: 3.6 °C ~ 10.9 °C Retail storage: 0 °C ~ 11.7 °C	(Koutsoumanis et al., 2010)
Slovenia	Retailer	17 retailers and 217 consumers	Prepackaged frankfurters and pre-packaged poultry	0 - 4 °C	Retail display: 0 °C ~ 10.5 °C	(Likar & Jevsnik, 2006)
			Butter, yogurt, cottage cheese, cream	2 - 6 °C	Retail display: 0 °C ~ 16 °C	
			Ice cream	-18 °C	Retail display: -23 °C ~ 10 °C	
			Eggs	15 °C	Retail display: 0 °C ~ 17 °C	
United States	Precooling, cold storage, transportation, and retail	5 pallets	Strawberries	0 °C	Entire cold chain: 0.7 °C ~ 3.7 °C	(Pelletier & Brecht, 2011)
	Retailer	3 retailers (27	Fruits and	0 °C	Retail display: -1.2 °C ~ 19.2 °C	(Nunes et al.,

Country	Food chain	Number of samples	Product	TR[1]	Temperature abuse	Reference
		refrigerated blocks)	vegetables			2009)
	Transportation, retailer storage, and retailer display cases	9 supermarkets and 16 transport routes	Bagged salad	≤ 5 °C	Transportation: -0.3 °C ~ 7.7 °C Retail storage: 0.6 ~ 15.4 °C Retail display: -1.1 ~ 9.7 °C	(Zeng et al., 2014)
	Transportation	16 shipments with 6 pallets	Bagged leafy green	-0.17 – 5 °C	Transportation: 9.75 % ~ 52.78 % higher than 5 °C and 0 % ~ 56.41 % lower than -0.17 °C	(Brown et al., 2016b)
	Retailer	9 retailer storages and 9 retailer displays	Bagged salad	-0.17 – 7.2 °C	Retail display: 40 % higher than 7.2 °C and 17 % lower than 0.17 °C Retail storage: 58 % higher than 7.2 °C and 0 % lower than 0.17 °C	(Brown et al., 2016a)
Canada	Processor storage, transportation to a distribution center, distribution center storage, transportation to retail, and retail storage	3 stores (9 cases)	Ready-to-eat baby leaf lettuce	5 - 6 °C	The temperature was well-controlled under the permissible temperature	(McKellar et al., 2012)
	Producer, processor, and distributor	3 transportation routes from farmer to restaurant and 3 restaurant storages	Fresh-cut endive	4 °C	Transportation from the producer to the processor increased up to 16 °C and from the distributor to the restaurants: increased up to 4 °C	(Rediers et al., 2009)
Japan	Transportation	1 route from the farm to the retail store	Iceberg lettuce	5-7 °C	Transportation: 3 °C ~ 15 °C	(Koseki & Isobe, 2005)
China	Transportation	1 transportation route	Tilapia fish	-18 ± 2 °C	Transportation: -18.6 °C ~ 16.8 °C after 6 hours (ambient temperature), product temperature only increased slightly to -17 °C	(Tingman et al., 2010)
South Africa	Container storage at port terminal	121 containers	Fruits and vegetables	2 °C	81 % of the temperature breaks in fruit reefer containers longer than	(Goedhals-Gerber et al.,

Country	Food chain	Number of samples	Product	TR[1]	Temperature abuse	Reference
					90 minutes	2017)
	Container storage at port terminal	319 containers	Fruits and vegetables	2 °C	41.5 % of the temperature breaks in fruit reefer containers longer than 90 minutes	(Goedhals-Gerber et al., 2015)

Table 3. Recommendations for managing time-temperature abuse in the food cold chain.

Context	Available resource
Legal requirement	Legal requirement at national level: time-temperature monitoring control in the United States (US FDA, 2017), Australia (AFGC, 2017), the United Kingdom (FSA, 2007), the European countries (EC, 2004)
	Legal requirement at international level: Codex recommendation on time-temperature control (CAC, 2003)
Time-temperature monitoring and measurement technology	Wireless time-temperature monitoring, notably RFID[3] (Kumari et al., 2015) and WSN[4] (Wang et al., 2015; Xiao et al., 2016)
	Time-Temperature Integrator (Ellouze & Augustin, 2010; Giannakourou et al., 2005; Kim et al., 2012; Koutsoumanis & Gougouli, 2015; Giannakourou & Taoukis, 2003; Kim et al., 2016)
User-friendly software for shelf-life modeling	Cold Chain Predictor (Gogou et al., 2015), Seafood Spoilage Predictor (Dalgaard et al., 2002), and ComBase (Gwanpua et al., 2014; Zubeldia et al., 2016)
Time-temperature monitoring and measurement system	FRISBEE[5] (Derens-Bertheau et al., 2015; Gogou et al., 2015; Gwanpua et al., 2014) and SLU[6] (Shih & Wang, 2016; Scalia et al., 2015; Sciortino et al., 2016)

[3] Radio Frequency Identification

[4] Wireless Sensor Networks

[5] Food Refrigeration Innovations for Safety, consumers' Benefit, Environmental impact and Energy optimization along the cold chain in Europe

[6] Smart Logistic Unit