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RESEARCH ARTICLE

Temperature Control and Data Exchange in Food Supply Chains: Current Situation and the Applicability of a Digitalized System of Time–Temperature-Indicators to Optimize Temperature Monitoring in Different Cold Chains

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Abstract

The current situation of temperature monitoring in perishable food supply chains and the optimization of temperature control was studied by combining two approaches. First, a survey among German companies (production, processing, logistics, wholesale, retail) was conducted to analyze the current temperature monitoring and data management conditions as well as the use of novel monitoring systems, such as Time–Temperature-Indicators (TTIs). Second, the temperature conditions in three different supply chains (B2C for raw pork sausage, B2B for fish, B2C e-commerce for mixed products) were investigated to analyze the applicability of TTIs with an app-based read-out system to identify weak points and to optimize cold chain management under practical conditions. The results of the survey showed that mainly static conditions are tested along the supply chain. Thus, the actors rely mostly on visual inspection or best-before date labeling while TTIs are not widely used. Currently, temperature data are barely exchanged by stakeholders. In the B2C chain, mean temperatures on different pallet levels were comparable, also reflected by TTIs and the app-based read-out system, respectively. In the B2B chain, temperature interruptions during the unloading process were detected, revealing main challenges in perishable supply chains. Temperature monitoring by TTIs on a box level was possible by positioning the label close to the product. Results in the e-commerce sector showed heterogeneous conditions in different boxes depending on initial product temperatures and loading. TTIs and the app-based read-out system showed reliable results based on different temperature scenarios, when TTIs are positioned close to the most sensitive product.

Keywords Time-temperature-indicators · Temperature monitoring · Supply chain management · Logistic processes · App-based TTI read-out · Food e-commerce

Introduction

Temperature monitoring along food supply chains is of special importance for the traceability of goods, the optimization of logistic processes and to get accurate information about the real quality of products at the point of incoming and outgoing inspection. Several studies show that temperature abuses along transports of perishable food are crucial since they affect quality and safety of food [35, 52, 55, 60, 75]. Currently, temperature monitoring systems and data exchange in food supply chains are not optimized yet [24]. Even if legal temperature requirements for perishable products do exist [69], the full temperature history of the product is not available and the measurement of the ambient temperature can be misleading [43, 61]. Consequently, lots of products are wasted along the chain due to cold chain interruptions and misinterpretation of data [10, 26, 55]. There is a high need for temperature monitoring systems with close contact to the product, especially for multi-step supply chains with pre-cooling, transports, transshipment,

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and platform points as well as storage at the retailer and consumer [4]. Furthermore, appropriate measuring devices are required. As one possible solution, lots of progress has been made in the field of sensor technology. RFID and Wireless Sensor Networks (WSN) systems are temperature monitoring and data transfer tools showing a high potential through covering the complete transport [6, 11, 38, 61]. The application of IoT-based and blockchain technologies can support confidential data management and process control along distribution [1, 7, 9, 77]. The use of software-based systems for tracing and scanning of goods on a pallet and box level is also possible [43, 51] and can automatize monitoring processes by replacing paper-based documentation [31, 68]. Until now, these technologies are not widely spread in the food industry. Main reasons are varying and complex supply chain characteristics, high implementation costs, unknown requirements of the different actors and missing guidelines for the implementation and selection of suitable technologies as well as standardized data exchange systems [38]. Sensors are often applied only on the pallet level and do not track the history of each product within the last mile, which is the most sensitive part of the supply chain and constitutes half of its total costs [6, 39, 71].

Beside wireless sensor technologies, the use of Time–Temperature-Indicators (TTIs), which show the temperature history of a product by a color change, has also been discussed for more than 30 years [67]. At the moment, however, they are also not implemented in a wide range because of costs, legal issues and missing trust of stakeholders and consumers [21, 65]. Moreover, digitalized systems for read-out are still missing and currently performed either visually or by specific measurement devices. A promising and cost-effective way for the digital read-out of TTIs is the use of smartphones, which can optimize work flows, e.g. in logistics, due to the fast exchange of measured data [3]. TTI systems are also a promising tool for the e-commerce sector. The lack of temperature controlling in the last mile is particularly critical here, thus, retailers and parcel services hold the responsibility and must rely on each other concerning the compliance with temperature requirements [25, 50]. Online ordered perishable food products are usually delivered in passively cooled boxes with mixed products in different quantities and with various initial temperatures. Depending on the design of the box and the temperature of the different products, there is a risk for an increasing temperature of the fresh produce and thus, a decrease in freshness. Therefore, monitoring the temperature in the last mile is of high importance.

Currently, TTI solutions are moving more into the political and industrial discussion due to the emerging food waste problem [58, 63]. Therefore, several actors in the food supply chain are familiar with the technologies and their use is being reconsidered in order to reduce the amount of waste. For the successful and efficient implementation of new monitoring tools, capturing the status quo about existing and established temperature monitoring and data exchanging systems along the chains is mandatory. Thus, this study aimed at the investigation of the status quo of temperature monitoring in food supply chains. Therefore, a comprehensive survey among different companies was conducted to determine the status quo of temperature monitoring and data management conditions, applied monitoring solutions as well as the establishment of novel, digital monitoring systems and their requirements. Secondly, three selected supply chains were investigated in practical studies. The applicability of the OnVu™ using a novel app for the color read-out was tested as a temperature monitoring tool to identify weak points in the cold chains and to optimize cold chain management. The supply chains were a conventional B2C supply chain for raw-pork sausage, a B2B supply chain for fish and a B2C-e-commerce for mixed products. Focus was laid on different requirements for the TTI as a temperature monitoring tool in different supply chains, i.e., the reflection of temperature conditions on a pallet and single unit packaging level, the reliable indication of temperature conditions on the box level and the application in boxes with mixed products.

Methodology

Experimental Design

To investigate temperature control systems in cold food supply chains, two approaches were combined. In the first step, a comprehensive survey of German companies dealing with perishable food production, processing, logistics, wholesale, and retail was carried out to gather information regarding current temperature monitoring and data management conditions as well as the applied temperature monitoring systems, such as TTIs. In the second step, the applicability of the OnVu™ TTI combined with a novel, app-based read-out system and cloud-based data collection as a tool for the temperature monitoring and identification of weak points in the cold chain was tested under real chain conditions in different supply chains. Three separate pilot studies were conducted in the B2C, B2B and B2C e-commerce sector, characterized by different supply chain properties. The first study was conducted in a classical B2C supply chain of raw pork sausage. The aim was to test the general applicability of TTIs and the app for the reproducible reflection of temperature conditions on single unit packaging and pallet level as well as during storage. The second pilot study was conducted in a B2B supply chain of MA packed fish. The objective was the implementation of TTIs in combination with the app as a reliable indicator of temperature conditions also at the secondary packaging level. The third study was conducted in a B2C e-commerce supply chain. The aim was to investigate TTIs and the app as a tool during the last mile for delivery services as well as for end customers. Here, the focus was laid on the challenge if temperature conditions can be adequately reflected by TTIs in boxes with mixed products under the influence of different goods, loadings, and initial temperatures.

Analysis of Temperature Monitoring and Data Management Conditions in Food Supply Chains — Design of the Survey

The survey was developed based on a comprehensive literature research, including scientific papers, regulations, legislations, and patent specifications. The questionnaire was created using the web-based application UmfrageOnline (enuvo GmbH, Pfäffikon SZ, Switzerland). German companies in the field of perishable food production, processing, logistics as well as wholesale and retail companies (including e-commerce) have been contacted by email including an individualized online link to the questionnaire. It consisted of 53 questions (50 mandatory questions, three questions with reply by choice in a text field), with 22 questions addressed to all participants and 31 questions addressed in dependence on the participant's answer or affiliation.

The survey was divided into four parts with the following content priorities:

1. Sector, related product categories and general information about the company
2. Transport, delivery, and cooling/refrigeration technologies
3. Temperature monitoring, control, and systems
4. Data collection and management

The first part included questions about the specific sector and product categories, which are produced, transported, or provided, as well as the size of the company and the commuting area. In the second part, transport processes, the frequency of delivered or received products, and applied cooling technologies were characterized. The third part evaluated challenges and weak points along the supply chain as well as temperature and quality control at the point of incoming and outgoing goods, its frequency and applied monitoring systems, such as contact thermometers, data loggers or smart technologies. The fourth part focused on the methods and technologies of product identification and traceability, data collection as well as a future conversion and application of digital systems. Ways of temperature data storage and exchange were identified. In total, 550 companies were approached based on online search and by using existing address lists of the participating academic institutions. The sample included in total 45 companies, who have answered the questionnaire, with $n = 35$ from the production/processing sector, $n = 16$ from the logistics sector, $n = 14$ wholesaler, $n = 11$ retailer, and $n = 6$ e-commerce (multiple answers were possible).

Investigation of different supply chains to analyze the application of the OnVu™ TTI with an app-based read-out system for the temperature monitoring

Charging of the OnVu™ TTI and Measuring by App and Colorimeter

For all pilot studies, the well-investigated OnVu™ TTI (Ciba Specialty Chemicals & Freshpoint, Basel, Switzerland, patent WO/2006/048412, Batch 21.06.2021, Color Batch 00552HN8) was used. The pigmented water ink in the center of the label is activated by a UV light charger (GLP 80/56 TTI, Bizerba, Germany) and automatically equipped with a protective UV-filter (LOT# 000018272) by thermal transfer print at ambient temperatures of 3–5 °C. The color of the label changes from blue to white dependent on time and temperature conditions [36]. The amount of UV light can be individually set with the duration of illumination in milliseconds (ms) to determine the initial color of the label and the length of the discoloration. Labels were attached to the packages at defined positions with two underlying layers of self-adhesive white paper to ensure a consistent background for color measurements. Each label included a printed QR code, enabling a serialized product attribution to measured TTI values after scanning.

The color measurement app used to read out the labels is described by Waldhans et al. [73]. It works for Android operating systems. While taking a picture of the TTI, color values of the blue dot in the center of the label and color values of the surrounding white points were automatically measured to calculate the TTI values including a white balancing to eliminate environmental influences. Color values were saved as CSV files on the smartphone. App measurements were conducted using two Android smartphones, Nokia 7.2 Dual-SIM Android™ 9.0 48 m pixels (Nokia Oyj, Espoo, Finland) and HUAWEI P30 lite Dual-SIM Android™ 9.0 48 m pixels (Huawei Technologies Co., Ltd, Shenzhen, China). Measurements apart from the laboratory were conducted free-handed, measurements in the laboratory in a darkroom with a fixed holder for the smartphones, each with a 2 × zoom in an appropriate distance horizontally to the TTI. A daylight lamp (1620Lm, 6500 K, Tageslichtlampen24.de, Kiel, Germany) was used for sufficient light conditions in both settings. Color measurements were in parallel conducted by colorimeter as reference using EyeOne i1 Basic Pro1 and the software KeyWizard v2.50 (X-rite; Gretag Macbeth, Regensdorf, Switzerland). In all pilot studies, samples/packaging units were stored after transport in the laboratory for further investigations in high-precision low temperature incubators (MIR 153, SANYO Electric Co., Ora-Gun, Gumma, Japan). Temperature was monitored by data loggers (Testo SE & Co. KGaA, Titisee-Neustadt, Germany).

Pilot Study in a B2C Raw-Pork Sausage Supply Chain

The first practical trial was conducted in a German supply chain for raw pork sausage to test the general applicability of the OnVu™ TTI and the measurement app for the reproducible reflection of temperature conditions on a product and pallet level. Two pallets, containing each 113 (pallet 1) and 262 (pallet 2) single unit packages of MA packed raw pork sausages (750 g per package, 5 sausages with each 150 g), were monitored. The temperature limit for the product was 4 °C. The study was performed during the summer season as this is the main season for the demand of raw pork sausages and a critical time for cold chains interruptions. TTI labels were charged (1500 ms) and fixed on each single unit packaging immediately after production. Single unit packages were packed in open cardboard boxes, each containing four packages. Eight cardboard boxes were arranged on each pallet layer, resulting in 3.5 pallet layers for pallet 1 (Fig. 1a) and eight layers for pallet 2. On pallet 1, data loggers (iButton DS1922L Thermochron Data Logger, Maxim Integrated, San Jose, CA, USA) were positioned at four different positions on the pallet (top and bottom layers) to monitor the temperature conditions during storage, commissioning and transport every 5 min. After storage and commissioning at the producer, the pallets were distributed to the factory sale in an actively cooled truck. Pallet 1 was unloaded and single packages were either stored in the cold storage room or in the display. Temperature conditions in the cold storage room were furthermore measured by the attached loggers, where packages in the cardboard boxes were redistributed. Temperature in the display was likewise measured by data loggers (Testo SE & Co. KGaA, Titisee-Neustadt, Germany) every 5 min. Pallet 2 was further transported to the laboratory, where packages were stored at four different constant temperature conditions (2, 4, 7, 10 °C). All TTIs were measured by app and colorimeter at the initial charging point ($t = 0$ h). TTIs on pallet 1 were in addition measured upon arrival at the factory sale ($t = 15$ h), after storage in the cold storage room and in the display ($t = 22$ h). TTIs on pallet 2 were in addition measured upon arrival at the laboratory ($t = 48$ h) and at defined investigations points dependent on the storage temperature.

Pilot Study in a B2B Fish Supply Chain

The applicability of the OnVu™ TTI and the measurement app at the box level as secondary packaging was investigated in a B2B fish supply chain in the second scenario. Three expanded polystyrene (EPS) boxes ($\lambda = 0.035$ W/mK [41], 395 × 295 × 190 mm,thickness: 15 mm at walls and bottom, 12 mm at lid), each containing two packages of MA packed gilthead seabream (*Sparus aurata*) with 2–3 fishes à 300–400 g per package (total weight per box 1.8–2.1 kg) were monitored. The field study was conducted during the winter season. TTIs were charged (500 ms) at a logistics platform. Each box was equipped with 19 TTI labels at different positions inside and outside the box as well as on the fish packages (Fig. 1b): Two labels on each outside, two labels on two insides each, two labels on the inside of the lid, four labels on the top of the upper packaging, and one label on the side of the upper packaging. As coolant, frozen gel cooling packs were positioned on the upper packaging. The polystyrene boxes were perforated at the bottom to enable draining of melt water. The boxes were equipped with temperature loggers (iButton DS1922L Thermochron Data Logger, Maxim Integrated, San Jose, CA, USA) at five different positions (long and short outside and inside, lid, upper side of the packaging) near the attached TTIs, monitoring

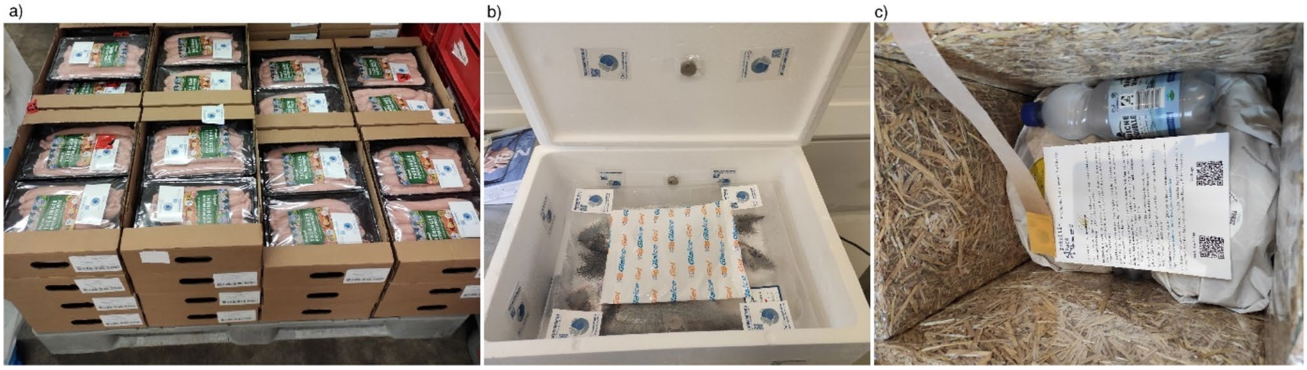

Fig. 1 **a** Packages of raw pork sausages with TTIs and temperature loggers on pallet 1, **b** Fish box with TTIs and temperature loggers at different positions, **c** Customer box with positioned TTI strap, inlay, packed products and coolant

the temperature during transport and storage every 5 min. Prepared boxes were positioned on a pallet with other perishable goods at different points (bottom, middle and top layer). Boxes were distributed from the logistics platform to the wholesale market in an actively cooled transporter within 24 h. An onward transport of the boxes to the laboratory at the University of Bonn was performed at ambient temperature conditions, simulating real temperature fluctuations occurring during customer transports. Boxes were then stored for 4 h at 4 °C and afterwards for 20 h at 2 °C to simulate storage conditions at the customer, i.e., catering and gastronomy. Color measurements by app and colorimeter were conducted at defined inspection points in the chain: at the initial charging point ($t=0$ h), at the factory sale ($t=20$ h), after arrival at the laboratory ($t=23$ h), after storage at 4 °C ($t=27$ h) and after storage at 2 °C ($t=48$ h).

Pilot Study in a B2C e-Commerce Supply Chain

The third supply chain is a B2C e-commerce for perishable and non-perishable food products with the aim to test TTI and app for the temperature monitoring in mixed boxes during the last mile. Sixty-four boxes with mixed perishable and non-perishable products were delivered from an e-commerce retailer to the customer in passively cooled boxes within 24 h of transport. The cardboard boxes used for transport (400 × 330 × 280 mm) were isolated with inserts made of pressed straw ($\lambda=0.041$ W/mK, thickness: 35 mm at walls, bottom and lid) wrapped with polyethylene foil. The volume of the box's interior is 18 l. As coolant, plastic bottles (0.5 l) with frozen water were used according to the company's specification. The field test was conducted in winter as this is the main season for orders. TTI labels were activated (450 ms) in the cooling room at the online retailer. One TTI label per box was fixed on a strap, the second TTI label was fixed on an inlay. The strap could be pulled out from the outside of the box to read-out the label without opening. 58 boxes for customers and 6 test boxes for the University of Bonn were packed with ordered goods, coolants and filling material according to the packing scheme of the company. Every box contained vacuum packed galeeny breast (ca. 600–700 g) as a reference product with a temperature limit of max 4 °C. When packing, strap and inlay were positioned in the center of the box close to the reference product, with no direct contact to the coolant (Fig. 1c). Ten customer boxes and six test boxes were equipped with temperature loggers (iButton DS1922L Thermochron Data Logger, Maxim Integrated, San Jose, CA, USA) fixed on the inlay, two test boxes were in addition equipped with data loggers outside to monitor the temperature every 5 min. Customer and test boxes were shipped in a transporter under ambient temperature conditions. Test boxes were stored at the laboratory for another 28 h. Boxes were stored at three different temperature scenarios (two boxes each): a constant scenario (28 h at 20 °C), a dynamic winter scenario according to a part of the AFNOR Standard 48 d (11 h at 5 °C, 9 h at 9 °C, 2 h at − 2 °C, 6 h at 5 °C) and a dynamic summer scenario according to a part of the AFNOR Standard 48 b (4 h at 25 °C, 4 h at 32 °C, 3 h at 25 °C, 9 h at 20 °C, 8 h at 25 °C). TTI color values were measured by app and colorimeter at three investigation points: all TTIs immediately after charging (0 h), test boxes at the arrival in the laboratory (20 h) and after storage at the different scenarios (48 h). The app was also made available to customers via QR Code. Customers were equipped with a guide to download, install and use the app. The customer was instructed to take proper pictures of the TTI by app immediately after opening the box under sufficient light conditions without shadows or surrounding borders. Color values measured by customers were automatically saved in a cloud database when taking the pictures.

Data analysis

Square values of the color values measured by app and colorimeter were calculated to describe the discoloration of the TTI and to compare results for app and colorimeter measurements. For app measurements, the medians of the gathered single R, G and B values for the blue dot (Rb; Gb; Bb) and the white color point (Rw; Gw; Bw) were calculated. Color values were corrected by white balancing color data for the blue dot, and then expressed as square values SV_{RcGcBc} as described by Waldhans et al. [73].

$$R_c = \left(255 - R_w\right) + R_b; G_c = \left(255 - G_w\right) + G_b; B_c = \left(255 - B_w\right) + B_b \tag{1}$$

where Rc; Gc; Bc: corrected color values by white balance; 255: absolute white; Rw; Gw; Bw: raw values for the white color points, Rb; Gb; Bb: raw values for the blue dot.

The square value SV_{RcGcBc} was then calculated with the corrected RGB color values.

$$SV_{R_cG_cB_c} = \sqrt{R_c^2 + G_c^2 + B_c^2} \tag{2}$$

The square value SV_{LAB} based on the measurements by colorimeter was calculated according to Kreyenschmidt et al. [36].

$$SV_{LAB} = \sqrt{L^2 + a^2 + b^2} \tag{3}$$

where SV: square value; L: lightness/luminance; a: red and green component; b: yellow and blue component of the color.

Calculations and figures concerning the survey were performed using Microsoft Excel 365 (Redmond, Washington, USA). Further calculations and figures were made using the program software OriginPro 8.0G (OriginLab Corp., Northampton, MA, USA).

Results and Discussion

Analysis of Temperature Monitoring and Data Management Conditions in Food Supply Chains — Results of the Survey

Most of the survey participants are dealing in the sector of production, transportation, and trading of perishable goods, i.e., dairy and meat products. The distribution between micro, small, middle and large-scale enterprises is balanced, with 20–29% of each companies, providing a good representation of the corporate landscape dealing with supply chains of food products. 96% of the companies are based in Germany and more than 70% are mainly operating in Germany and neighboring countries. For transport, trucks with active cooling are used by most of the participants from the logistics sector (75%, $n = 12$) and production/processing/trade sector (72%, $n = 31$). As cooling techniques, mainly mechanical cooling units (71%) and insulating boxes/containers (38%) are used, assuming that it depends on the sector and the product category. The frequency of goods delivery and reception is in most cases several times a day, with 66% and 52%, respectively. The main challenges and weak points of the cold chain are revealed as temperature fluctuations in transport vehicles (60%), loading processes (58%) and storage in private refrigerators (42%). Temperature and quality control methods of incoming and outgoing goods are shown in Fig. 2a. Incoming goods are mainly controlled by visual inspection (64%), the best-before/use-by date, measurement of the product surface temperature (each 60%) as well as the temperature recorder of the delivery vehicle and the labeling (each 53%). The control of outgoing goods is primarily conducted by ambient temperature measurement (67%), visual inspection (64%) and control of the best-before/use-by date (51%). Thus, often only a visual inspection or the control of static conditions is carried out. Other inspections, e.g., detailed sensory inspection, are often time consuming. More than 60% of respondents indicated that every delivery of incoming or outgoing goods is checked. However, it can be assumed that controls are randomized. This current state underlines the added value of TTIs as a measuring instrument at the individual product level. The results are partly similar to the results of Raab et al. [60], which also revealed that product and ambient temperature and control of the best-before date are one of the most frequently used methods in incoming inspection in pork and poultry chains. As temperature monitoring systems, non-contact thermometers (69%), electronic data loggers (62%), and contact thermometers (49%) are mainly applied at different steps along the chain (Fig. 2b). The use of data loggers during transport and storage is also shown by Raab et al. [60] and is predicted to rise due the possibilities of integrating monitored data into cloud technologies [29]. TTIs are only used by one company (2%). In addition, the use of wireless technologies with integrated temperature sensors, e.g., RFID, is negligible, and Smart Active Labels are not used at all by the participants. Furthermore, 87% pointed out not to plan replacing existing systems with new technologies, indicating that companies rely primarily on classical methods to carry out only the obligatory temperature controls. Most of the companies (87%) are generally using paper documentation (delivery notes) for product identification and traceability. The manual capture

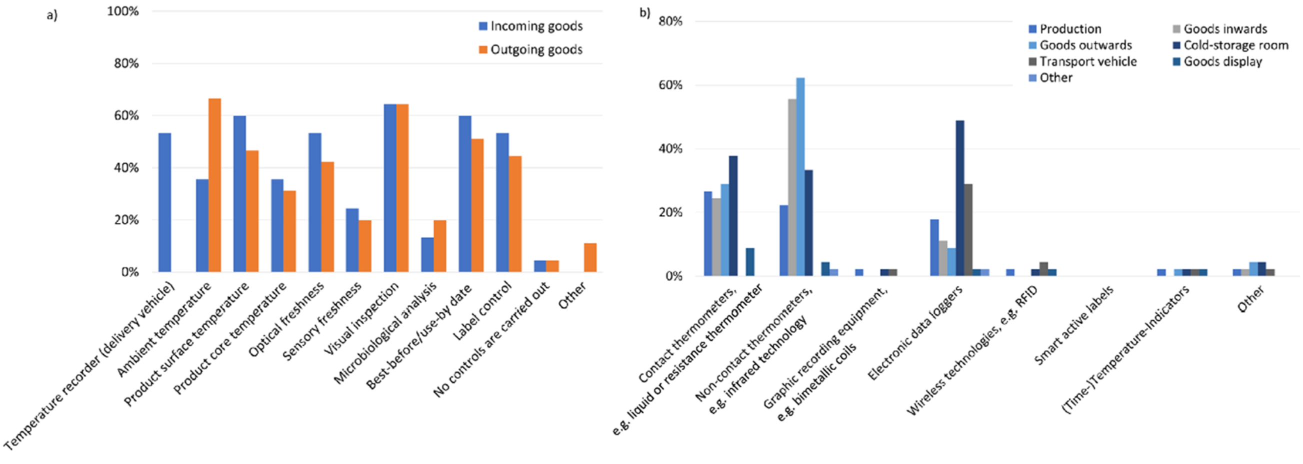

Fig. 2 **a** Type of temperature conditions, quality parameter or other inspection that are controlled at the point of incoming and outgoing of perishable products, **b** Usage of different temperature monitoring systems at different steps of the supply chain ($n = 45$, multiple mentioning was possible)

of printed product data and 1D barcodes are used by 31% and 29%, respectively. 2D/3D-Codes or RFID technologies are hardly or never used (0–7%). A low use of sensor technologies in the meat supply chain was also shown by Ersoy et al. [18]. Our survey revealed that temperature data is recorded either only digitally by 4%, only in written form by 24% or both digitally and in written form by 64%. 40% of the participants using partly or completely written documentation plan to switch their temperature monitoring to digital documentation. The main reasons are saving of time and simplifying data storage (each 94%), shown in Fig. 3a. Focus is also laid on simplification of processes, as data access and retrieval, collection and reporting as well as data sharing and traceability (69–75%). However, other participants (40%) are satisfied with the current system of written documentation. Stakeholder awareness is therefore needed to demonstrate the facilitation for controls through digital systems. Currently, digital temperature data in the companies are mainly stored on in-house/on-premise servers (33%), whereas cloud systems are negligible used or participants did not answer. Ersoy et al. [18] showed partly different results, revealing that in meat supply chains in Turkey, data mining and cloud computing are used for information sharing. 32% of the participants exchange temperature monitoring data with stakeholders by written transfer, 40% only on request or reclamation and only 2–9% use digital tracking or transmission at the point of incoming goods as well as share data in a cloud (Fig. 3b), which reveals overall low transparency along the chain.

The results showed that developments in data exchange have not substantially progressed in the last decade, which becomes clear by the fact that Raab et al. [60] already showed a data exchange of less than 50% between actors in pork and poultry chains and paper documentation as the most applied form of temperature inspection. The sharing of supply chain data is not only revealed both as highly valuable but also of highly sensitive concern [59]. This is also shown by the fact that some questions were not replied in this study. However, the results indicated that stakeholders are generally willing to share temperature and other information, also shown by the studies of Hsiao and Huang [30] and Minnens et al. [48]. Moreover, there is a change compared to previous decades, as the current developments in digitization play a decisive role in driving forward the data collection and exchange, complemented by the availability of a large amount of data [34]. The digitization brings with it new challenges, such as varying IT application systems and IT structures amongst stakeholders [18, 47]. Furthermore, especially small and medium-sized enterprises (SME) are still skeptical concerning the benefits for their organizational structure, also because resources and financial opportunities are rare [17, 33, 56, 62]. Based on the survey results, it can be assumed that stakeholders only implement the obligatory legal requirements on temperature monitoring and an investment in digital systems is not seen as an added value. This is supported by the fact that mainly classical temperature monitoring methods are used, even though there are many developments in the field of TTIs and other innovative technologies. However, the upcoming digital data exchange solutions could provide also new possibilities for the implementation of TTI systems, enabling data

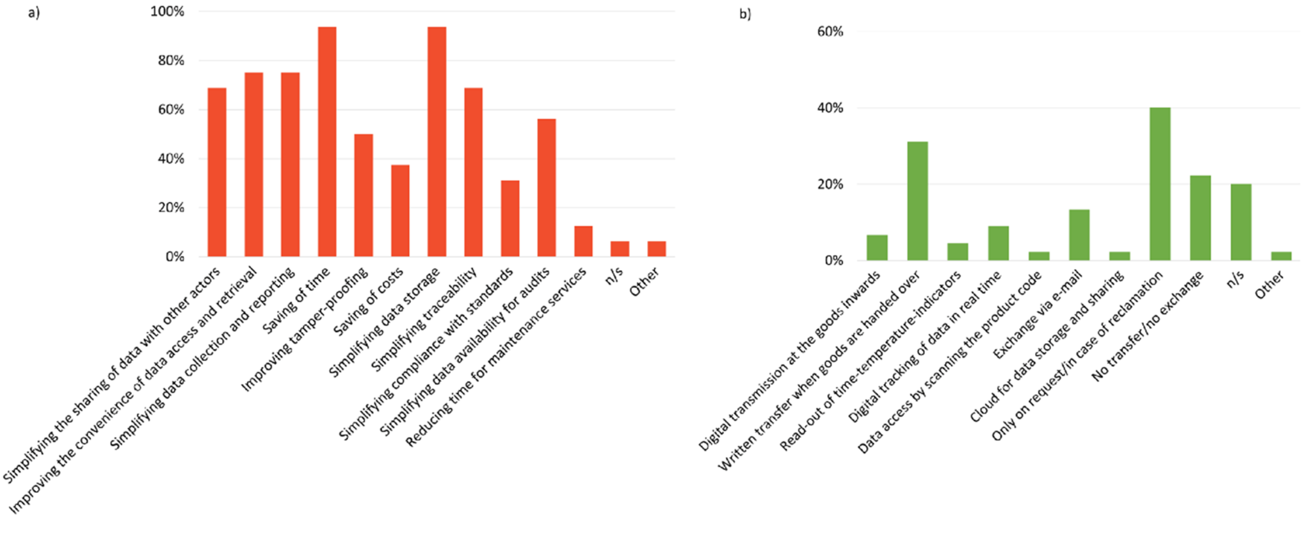

Fig. 3 **a** Reasons for switching to digital recording of temperature data ($n = 16$), **b** Methods of temperature data exchange with associated supply chain actors along the chain ($n = 45$) (Multiple mentioning was possible)

transmission and therefore eliminating disadvantages compared to more expensive RFID systems [78].

Application of the OnVu™ TTI and an App-Based Read-Out System for the Temperature Monitoring in Different Supply Chains

Pilot Study in a B2C Pork Meat Supply Chain

Temperature conditions during transport of pallet 1 and storage of samples in the factory sale are shown in Fig. 4. The mean temperatures on different pallet levels during commissioning and transport time were between 4.3 ± 0.9 °C (Bottom pallet layer 2) and 5.0 ± 0.6 °C (Bottom pallet layer 1). In the cold storage room and the sales display, mean temperatures of 4.2 °C ± 0.7 and 4.5 °C ± 0.6, respectively, were measured, revealing that temperatures during transport and storage were generally stable. Variances of up to 6.3 °C between pallet levels during transport and slight fluctuations during storage were caused by the exposure to cooling units and doors, as also shown by Raab et al. [60]. Mean temperatures were slightly above the threshold temperature (4 °C) which might be caused by the high ambient temperatures in summer. However, the variances were minor in contrast to other studies revealing temperature fluctuations of up to 19 °C during transport and at the retailer [22, 54, 74]. Despite high temperature differences on pallet levels during commissioning and storage, temperature conditions compensated each other (Fig. 4). TTI measurements by app (Nokia) after transport also revealed similar results on pallet levels from SV_{RcGcBc} 240.2 ± 14.28 to 243.32 ± 16.84 (Fig. 5) with comparable results for measurements by Huawei (data not shown), revealing that the app can reliably reflect the temperature conditions. Reference measurements by colorimeter confirmed the low variances during transport (SV_{LAB} 58.1 ± 0.39 to 58.5 ± 0.46, Fig. 5). The range of standard deviations for app measurements was comparable to colorimeter measurements, as already shown by Kreyenschmidt

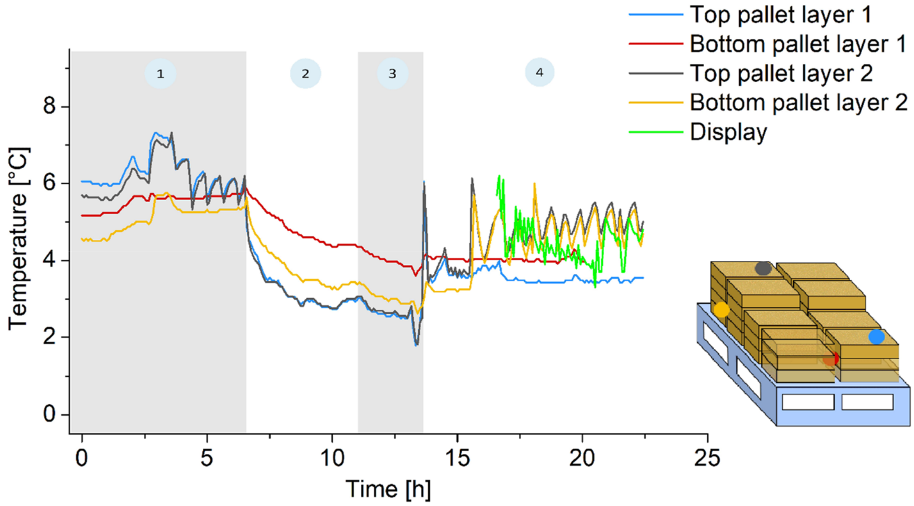

Fig. 4 Temperature conditions on pallet 1 during transport to factory sale and storage 1. Storage and commissioning at the production, 2. Transport, 3. Arrival and stay in the truck, 4. Storage at the factory sale's cold storage room and sales display

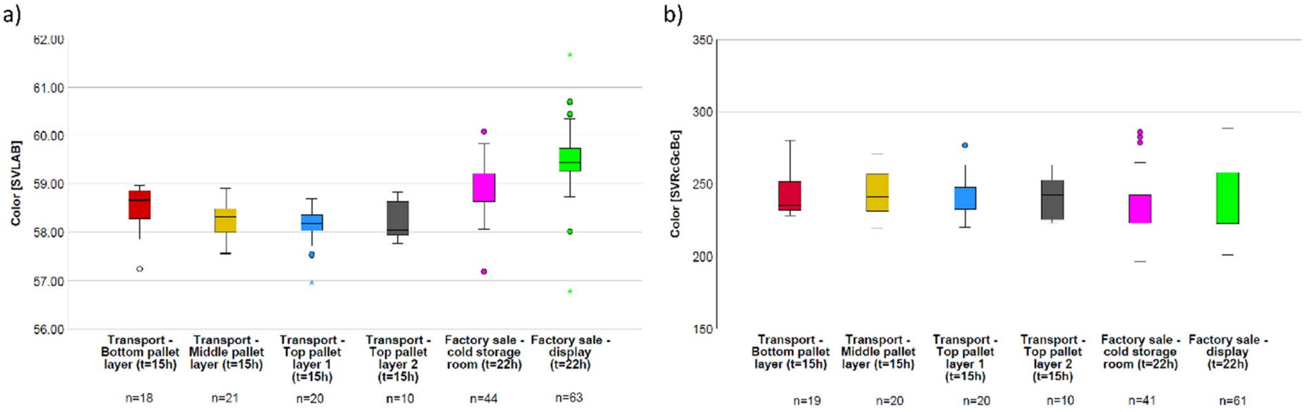

Fig. 5 Boxplots showing the color of TTIs at different positions on the pallet after transport and after storage at different areas the factory sale, measured by **a** colorimeter and **b** app. Dots reflect mild outliers. Stars reflect extreme outliers

et al. [36], which revealed a high reproducibility also achieved by the app. The stable temperature conditions during storage in the factory sale further revealed no remarkable or even lower discoloration of TTIs measured by app, whereas measurements by colorimeter showed a slightly increased discoloration (Fig. 5). This might be caused by a lower color sensitivity of the smartphone and the influence of environmental conditions as light exposure or shadows in the sales room.

Even if the cold chain in this study was generally well-maintained, slight fluctuations during transport and storage as described above implied the potential weak points in the chain during transport and loading processes caused by the position of the cooling unit, the airflow and varying initial product temperatures [16, 47, 55], which need an accurate monitoring. To evaluate if app measurements of TTIs could also reflect temperature abuses at weak points, they were in addition tested at different temperature scenarios in the laboratory. Differences in TTI color values at varying temperatures measured by app and colorimeter are exemplary shown for 4 °C and 10 °C in Fig. 6. The enhanced TTI discoloration at the higher storage temperature of 10 °C could reliably be reflected by app measurements, showing remarkably higher values at each time point than at 4 °C. Results were confirmed by colorimeter measurements. SDs were likewise low for both measuring methods. The application of TTIs as a valuable tool for temperature monitoring and detection of temperature abuses in perishable supply chains is well-known for years [67, 70], and TTI app measurements now offer a promising new tool for the detection of weak points along the chain. The simple procedure of the app measurement shows the general high feasibility of this method and further simplifies the easy-to-use response of a TTI based on its color [20]. Furthermore, reliable and objective app measurements overcome the existing hurdles concerning applicability of TTI use in practice [66]. Especially for the inspection of incoming goods and temperature controls several times a day, app measurements represent an alternative to existing, less reliable controls, such as the visual inspection or truck temperatures. The use of data concerning detected weak points combined with digitalized traceability systems of the stakeholders can optimize the cold chain management in the long term. In further combination with shelf life models for the product, temperature monitoring with TTIs can be extended by the calculation of a dynamic shelf life based on actual temperature data [3, 12]. This enables not only a helpful tool for all stakeholders including the consumer but also offers discounting strategies to reduce food waste and improve sustainability along the chain [8, 28, 58].

Temperature Monitoring in a B2B fish Supply Chain

Temperature conditions during transport and storage in the B2B chain are shown in Fig. 7 exemplary for box 1. Temperatures at the outside of the boxes increased at the warehouse for 5 h with a maximum value of 10.4 °C and a mean temperature of 6.9 °C ± 3.6, suggesting that the boxes were temporarily stored unchilled, e.g., at a walk-through room or loading area. Loading and unloading areas are critical points for temperature abuses, also shown by the survey results as well as by Raab et al. [60] and McKellar et al. [46]. Martinsdottir et al. [44] and Lundén et al. [42] showed strong temperatures abuses in fish supply chains at arrival points, too. The unchilled storage also caused temperatures above the threshold of 2 °C inside the box, however, temperatures were significantly lower compared to the box outside with a maximum value of 7.1 °C and a mean temperature of 4.8 °C ± 1.9. It was shown that the temperatures at box outsides did not reflect the real conditions inside the box, as they had been too strongly influenced by temperature interruptions and high fluctuations. Consequently, also TTIs

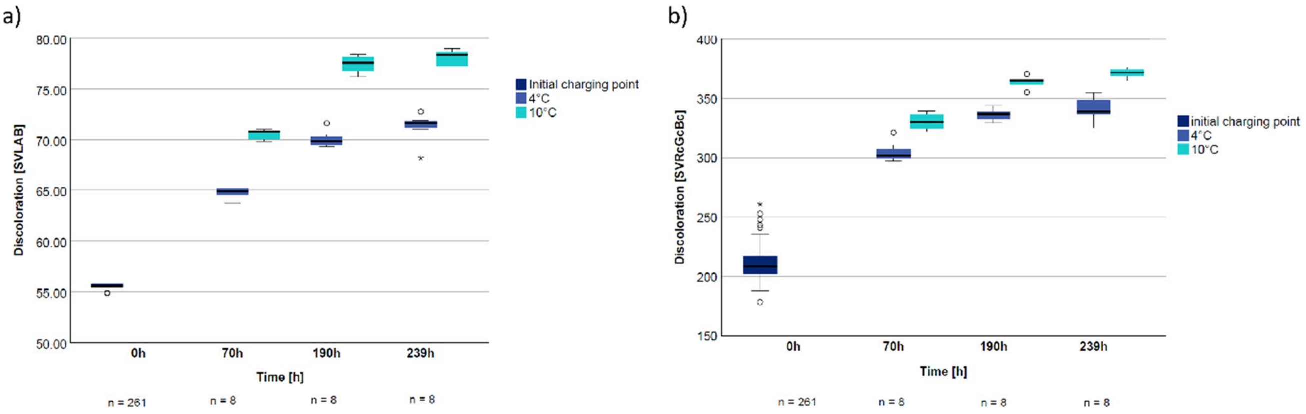

Fig. 6 Boxplots showing the TTI color at the initial charging point and discoloration of TTIs during storage at 4 °C and 10 °C at the laboratory at selected time points, measured by **a** colorimeter and **b** app. Dots reflect mild outliers. Stars reflect extreme outliers

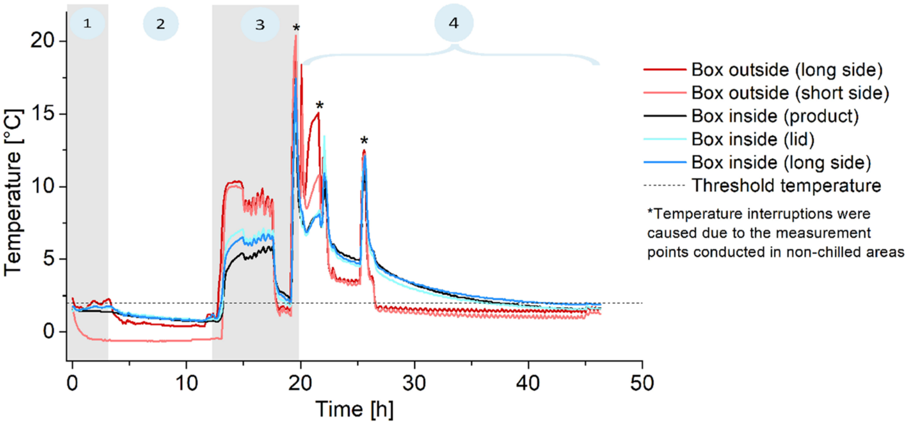

Fig. 7 Temperature conditions outside and inside of box 1 during transport and storage. 1. Commissioning 2. Transport, 3. Arrival and storage at the warehouse, 4. Transport, storage and measurements at the laboratory

attached outside resulted in a significantly higher discoloration. Even though they are easier to attach and handle [32], the box outsides were not further considered as a reliable placement of TTIs. Temperatures inside the boxes at different positions are in a similar range during the entire storage time, revealing 3.1 °C ± 2.4 (product) to 3.3 °C ± 2.5 (long side) in box 1 and similar results for the other boxes. Lid and long inner side were slightly more sensitive to temperature interruptions and fluctuations than the product, showing higher increases at the time points regarded (Fig. 7). Giannakourou et al. [22] showed comparable results for temperature conditions in boxes with gilthead seabream, indicating that the warmest point was the top of the box and coldest temperatures were in the center near the product and ice coolants. Results for the discoloration of TTIs by colorimeter measurement showed similar behavior for the different positions inside the box, revealing the highest discoloration at the lid position in box 1 (Fig. 8). Comparable results were shown for box 2 and 3. App measurements showed partly differing tendencies with no visible trend regarding the positions, mainly caused by environmental light influences on the app measurements, also shown by the high SDs (Fig. 8). However, the study shows that it is generally possible to monitor the temperature conditions inside the box via TTI also at the general box level instead of the product level. The results of Giannakourou et al. [22] showed similar observations when comparing TTI responses with temperature data during the ice-cooled transport of gilthead seabream. To avoid inaccuracies at lid and inner side, the application of a TTI inlay close to the product should be considered to monitor product temperature as accurate as possible. Moreover, this would also facilitate the measurement process, since the study revealed that the read-out on the inside of the box is challenging.

Knowledge about the temperature conditions along the B2B chain, and the digital read out by app, whose data can also be stored and shared online, can help to detect temperature abuses before goods are reaching the consumers and to

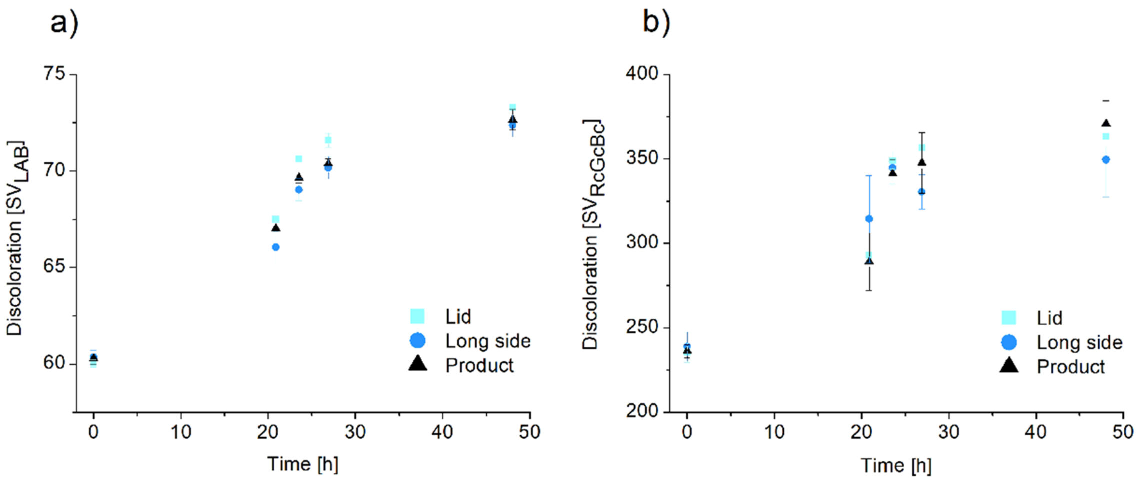

Fig. 8 Discoloration of the TTI at different positions (Lid: $n=2$, Long side: $n=4$, Product: $n=5$) inside box 1 during transport and storage, measured by **a** colorimeter and **b** app

optimize logistic processes. The integration of the QR code into the OnVu™ label for a direct serialized data transfer on product or box level is a valuable and cost-effective addition for the seafood sector [2, 64]. A link with other traceability platforms providing additional supply chain information such as described by Oliveira et al. [57] can offer an added value. However, it must be considered that exchanging sensitive data along B2B chains is dependent on multiple factors, such as the interaction and power of actors, the willingness to share data and the uncertainty of product quality [30, 37]. Efforts at persuasion are needed at different stages to successfully implement a temperature monitoring system.

Temperature Monitoring in a B2C-e-Commerce Supply Chain

Temperature conditions in customer and tests boxes during transport are shown in Fig. 9. Firstly, it must be mentioned that only five of ten temperature loggers dispatched with the customer boxes were returned. A return of less than 50% of the loggers by customers was also shown in the studies of Derens-Bertheau et al. [14] and Gogou et al. [23]. A more comprehensive data monitoring at the customer level in the future would be more revealing. Mean temperatures during transport ranged from 2.0 °C ± 1.3 (test box 1) to 4.6 °C ± 1.1 (test box 4) within the boxes. Thus, the cold chain in all boxes was generally well-maintained, showing a consistent decrease in temperature and no interruptions. However, the temperatures decreased variously and the threshold temperature of 4 °C was reached in a range of 0.5 to 11.9 h, leading to temperatures at the point of delivery from 1.0 to 3.4 °C. Temperature differences were caused by various packaging units, product loadings and initial product temperatures, demonstrating the need for an adequate temperature monitoring in mixed boxes as well as a proper cooling of the goods before delivery. TTIs on inlays could well

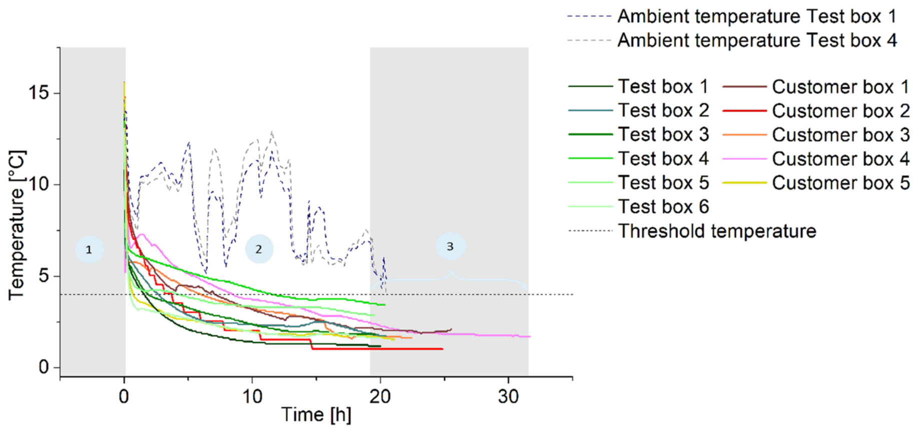

Fig. 9 Temperature conditions within the customer's and test boxes during transport. 1. Packing of the boxes, 2. Transport, 3. Arrival times/Opening of the boxes

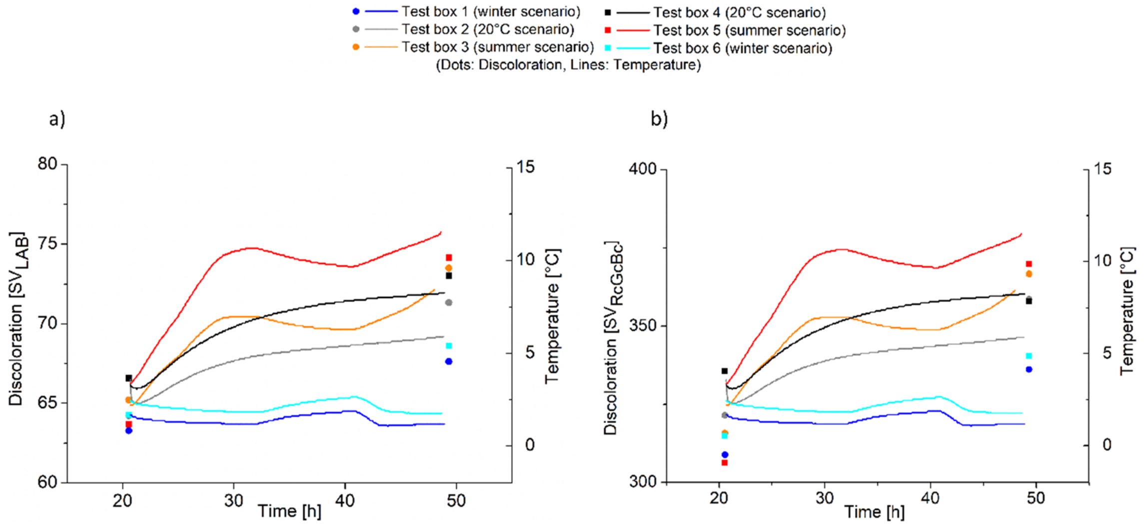

Fig. 10 Discoloration of the TTI positioned on the flyer and temperature conditions inside the Test boxes during storage at different temperature scenarios ($n = 2$ each), measured by **a** colorimeter and **b** app

reflect temperature conditions in the boxes, as color values mainly showed the same trend: Test box 4 showed the highest discoloration after 20 h with SV_{RcGcBc} 335.52 measured by app and SV_{LAB} 66.58 measured by colorimeter (Fig. 10). The lowest mean temperature of test box 1 is reflected by lower measured color values of SV_{RcGcBc} 306.35 and SV_{LAB} 63.29, respectively. Discoloration trends measured by app were highly comparable regarding both smartphone measurements. TTIs positioned on the strap could not exactly reflect the trend of varying mean temperatures. It must be considered that a slipping out of position during transport may have occurred and that temperature loggers were positioned closer to the inlays, resulting in more reliable results for the inlays.

TTIs on the inlays could also well reflect the temperature conditions within the mixed boxes during storage at the different temperature scenarios in the laboratory, showing results of SV_{RcGcBc} 358.60–357.92 for 20 °C scenario, 336.10–340.44 for winter scenario and 366.69–369.85 for summer scenario by app measurement (Fig. 10). Colorimeter measurements confirmed the trend. Varying temperatures in boxes stored at the same scenarios are caused by the temperature variations already existing in the boxes as described above. It can be concluded that the TTI is able to reflect temperature conditions inside the box when influenced by varying ambient temperatures, also at the coldest area near the reference product.

Concerning the TTI measurements at the customer level, six data sets could be evaluated. Measured TTIs were not in the same boxes as the received temperature data of the customers. The low response rates were presumably caused by the low availability of Android phones and errors during measurement attempts of the users inexperienced with the handling of the app. Successful app measurements were in a high range of SV_{RcGcBc} 289.31–383.31. High variations may be caused by the non-consistent measurement performances of the users, different light conditions during photographing and potentially older, low-resolution camera systems. In addition, the TTIs were probably not immediately measured after opening the box or were exposed to ambient temperatures. The uncertainties in the measurement conditions lead to the conclusion that the results of the customers can not be adequately evaluated.

Although the cold chain during transport of passively cooled boxes was well-maintained in this study, other studies in e-commerce revealed high variations of product temperatures in a range of 2.8 to 25.4 °C for perishable goods at the point of home delivery [13], and up to − 11 °C for a frozen meat delivery [39]. Passively cooled boxes enable a more flexible delivery and a decrease in transport costs [29], however, it may happen that deliveries are not directly received by the customer [53], enhancing the need for an adequate temperature monitoring. Our results showed that TTIs are able to reflect different temperature conditions also in boxes with mixed products and that the position close to the most sensitive product is useful to ensure that threshold temperatures are maintained. It is a promising tool for the temperature monitoring in e-commerce, offering a wide range of mixed perishable and non-perishable products [19]. Mixed boxes are also challenging in the B2B sector, thus, findings of this study can be transferred well. In the future, recommendations for temperature monitoring by TTI systems could be integrated in the guideline DIN 10543:2022–02 for regulating food e-commerce [15]. TTI systems can overcome concerns about e-commerce shopping of fresh produce due to the lack of information about visual freshness and product quality [5, 25, 76], and can furthermore fulfill the demand for enhanced sustainability [27]. The study of Lorentzen et al. [40] also showed that TTIs can be a beneficial tool for the consumer to evaluate the product quality after delivery. The QR code can be further used to integrate product information about origin of meat products and breeding circumstances, and thus to enhance consumers trust [39]. The use of a smartphone app for the temperature check might meet with approval, as e-commerce customers show high affinity towards smartphones for online purchases [49].

All pilot studies showed that TTIs are a valuable tool to reflect temperature conditions along different supply chains, which also turned out to be extremely necessary, as both survey and pilot studies had shown that typical weak points along the cold chain are still of high concern. TTIs combined with digital data sharing and exchange solutions thus can synchronize supply chain stakeholders and eliminate the uncertainty about temperature conditions [45, 72]. In the B2C sector, TTI data could be furthermore linked to shelf life models for selected products which — especially with the increasing potential of artificial intelligences — can be a useful decision-making tool for companies and an incentive to expand digital processes. In the B2B supply chain, an efficient monitoring of typical weak points during transport and storage as well as the optimization of logistic processes is possible, especially for highly sensitive supply chains such as fish and seafood. The e-commerce sector represents a novel and challenging situation for a correct temperature monitoring, but an app-based TTI system offers a significant added value compared to a more expensive and complex deposit system, as customers can easily discard the label. The main challenge of a successful implementation in the different sectors, however, is the lacking willingness of stakeholders to implement an innovative temperature monitoring system, as the financial investment and the benefit for companies is not completely comprehensible yet. The inclusion of TTI systems in legal regulations as a strategy to reduce food waste, costs and to increase sustainable processes could advance the application in the future. The digitization of the TTI system can be supportive, as it can facilitate the application in practice.

General Conclusion

In this study, the status quo of temperature monitoring and data exchange in perishable food supply chains was analyzed and the applicability of TTIs and an app-based readout system was tested to identify weak points and to optimize cold chain management. The survey has shown that mainly static product inspection is conducted and TTIs are still not widely used for temperature monitoring and that efficient data exchange amongst stakeholders is still challenging. However, the developments in digitization and the increasing willingness of stakeholders to exchange data offer promising possibilities for the introduction of TTI systems. TTIs measured by app were able to reflect temperature conditions in the three selected supply chains, revealing weak points and temperature abuses in the chain properly. The app-based system can contribute to an easier temperature monitoring and an efficient data exchange for the optimization of processes in the future and reduce the amount of food waste. Especially the application in e-commerce offers a valuable approach as there is no temperature monitoring yet in passive cooled mixed boxes.

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Data Availability The datasets generated and analysed during the current study may be available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors have no competing interests to declare that are relevant to the content of this article.

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