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Research article

Product visibility in the South African citrus cold chain: Examining the efficacy of temperature loggers

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A R T I C L E I N F O

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A B S T R A C T

Product visibility is a challenge for many fruit cold chains. Most challenges arise because of technological constraints, which lead to the inability to predict whether fruit temperatures are still within the stipulated requirements. To ensure that the intricately linked cold chain for citrus fruit is well coordinated and offers the visibility of fruit temperature, technologies such as temperature data loggers are used to record and communicate temperature measurements. Concerns arise because temperature-monitoring loggers are not automated and therefore do not offer real-time temperature visibility. They require manual handling, which makes continuous access to temperature data impossible. Receiving real-time temperature data of citrus fruit during the different stages of the cold chain would enable exporters proactively to address issues linked to temperature as the citrus fruit moves along the supply chain. The aim of this study was to assess the potential value of using cellular loggers in contrast to conventional loggers to allow the real-time monitoring of citrus fruit in transit. At present, exporters cannot monitor the temperature conditions of their consignments during the critical phase of cold sterilisation at sea because conventional loggers do not provide visibility of temperature data. To determine the efficacy of cellular loggers, the researchers collected temperature data at the different stages of the cold chain. In addition, interviews were conducted with industry experts in the South African citrus cold chain to determine their experience with different loggers. These interviews identified that conventional (wired) loggers offer a low-cost option, but not real-time product visibility. Cellular loggers offer more real-time data than conventional loggers, but as they depend on cell-phone towers, they offer restricted real-time visibility, especially during the sea leg of the consignment. For this reason, the study recommends that the use of cellular temperature loggers be adopted during land-based stages of the citrus cold chain but not during the sea leg, despite exporters' concern about the limitations of conventional loggers.

1. Introduction

The cold chain is vital to prolong the shelf life of citrus fruit. It reduces physiological developments in the fruit, eliminates pests and diseases and influences market rates [1]. Like other industries, the South African citrus fruit industry uses the cold chain to comply with the prescribed phytosanitary temperature protocols for fruit-exporting countries. Fruit fly, for example, is a polyphagous pest of

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several South African export crops. Citrus fruit is one of the cultivated hosts of fruit fly. It is possible to control this pest by imposing phytosanitary regulations such as cold treatment. Phytosanitary regulations are imposed by the importing country, with the exporter having little capacity to challenge the decisions made on conformance [2]. However, phytosanitary regulations are ever-changing because of the global trade in fresh fruit. A lack of infrastructure, technology, product visibility and temperature maintenance hamper an effective response to these changes [2].

Recently, the European Union (EU), which accounted for 41% of South Africa's exports in 2021, imposed new regulations, stipulating that citrus fruit has to undergo cold-sterilisation treatment for up to 25 days at low temperatures. The changes in the regulations put further pressure on the South African citrus export chain, which is currently also dealing with challenges such as congested ports, a shortage of containers, non-conformance issues and a lack of product visibility due to the current devices used to monitor shipment temperatures. In addition, the low temperatures required for cold-sterilisation treatment increases the risk of chilling injury depending on the cultivar. As there is little product visibility during shipment, chilling injury is hard to detect.

Phytosanitary cold-sterilisation treatment requires the tracking of the temperature history of citrus fruit to estimate quality evolution throughout the cold chain. Pulp temperature is monitored during the forced-air cooling and shipment of fresh produce to determine whether effective cooling had taken place and the target temperature was maintained [3].

The pulp temperatures of fruit are difficult to measure for citrus that has been packed for shipment. Temperature loggers such USDA probes (so called because the US Department of Agriculture requires a minimum of three pulp sensors to measure the fruit core temperature in shipments to the USA) and loggers that measure air (ambient) temperature are only inserted after citrus fruit has been packed into cartons and stacked on pallets. This temperature data can only be retrieved at the end destination, making it impossible for exporters to monitor and track temperature deviations while the fruit is in transit.

A deviation in temperature that occurs once cold-sterilisation treatment has begun results in either the need for additional precooling processes, or the consignment being rejected upon arrival at the end destination or being diverted to another market [1].

Existing studies on the South African citrus cold chain have mainly focused on temperature breaks or abuse, or temperature variability and disruption. Defraeye et al. [4–6]; for example, explored the use of warm ambient loading as a possible phytosanitary measure. Warm ambient loading implies that fruit is loaded warm into reefer containers for cooling during the sea voyage. Conradie [7] identified temperature breaks in the initial stages of the cold chain for clementines and navel oranges to the USA. Goedhals-Gerber and Khumalo (2020) investigated temperature deviations in the navel orange export cold chain from the orchard to the port of destination in the and Khumalo et al. [1] examined factors pertaining to the non-conformance of in-transit citrus shipments with cold-chain specifications. However, very little research has been conducted on the use of cellular temperature loggers in the South African citrus cold chain.

Given the limitations of the loggers that are currently used to monitor temperature during the citrus cold chain, this study assessed the benefits of using cellular temperature loggers to provide visibility and facilitate corrective action while the fruit is in transit. The primary aim of temperature loggers is to establish the temperature history of citrus fruit across the different stages in the cold chain. The temperature history of citrus fruit is used for two primary reasons: first, importing countries can find out whether the fruit was exposed to the required temperature as stipulated in predefined protocols. This is an essential management control point. Second, the temperature history can evaluate whether the fruit was stored appropriately to preserve quality during transit. Therefore, to examine the efficacy of some technologies applied in the South African citrus cold chain to monitor and control the temperature of fruit while in transit, the following research questions guided this study: 1) Do temperature loggers provide product visibility in the South African citrus cold chain? 2) How effective are cellular loggers in the citrus cold chain to provide real-time temperature data and enable exporters to take corrective action?

For this study, product visibility refers to the ability to track the temperature of citrus fruit being exported in real-time through various stages of the cold chain. This study examined the efficacy of cellular temperature loggers through collecting temperature data from 20 refrigerated containers and interviewing industry experts and key role players in the cold chain to determine the advantages and disadvantages of using conventional and cellular loggers to monitor citrus fruit shipments. The interviews also addressed the key challenges that should be considered in the adoption of the different available technologies The study also examined the South African citrus cold chain and the different temperature-monitoring technologies used.

2. Literature review

2.1. The cold chain

The South African citrus industry estimated that 158.7 million cartons would be exported in 2021 [8,9]. Attaining the estimates (and more) represented a third consecutive season of record export volumes: 130 million cartons were exported in 2019, 146 million in 2020 and, eventually, 161.1 million in 2021 [8,9]. The increase in exports is driven largely by attractive investment returns, profit margins and citrus growers' reaction to the global demand for late mandarins and lemons. The increased export volumes highlight logistical inefficiencies, such as road transportation demand outstripping supply, insufficient cold-storage capacity and congestion at ports, which contribute to cold-chain bottlenecks. The inability to provide efficient cold-chain logistics leads to non-optimal fruit handling. As a result, that some stages become weak links in the supply chain, increasing the risk of losing quality and value and adding costs for exporters.

In the South African citrus industry, the cold chain is used to counteract the limitations of perishability over distances and time, and to put into effect phytosanitary cold-chain protocols during shipment. The senescence process in citrus fruit begins at the point of harvest. The cold chain is used to keep the fruit metabolically active for as long as possible and adds significantly to the enhanced marketing window of citrus, enabling storage for up to two months by reducing decay and potential loss of quality.

Significant logistical challenges exist in the South African citrus cold chain because export protocols require different temperature regimes. The Republic of China, for example, requires citrus to be shipped at −0.6 °C for 24 days, whereas citrus fruit exported to Japan requires temperature treatment of −0.6 °C for 12 days. Temperature variability can occur when the temperature rises above or below stipulated ranges in the cold chain during loading, transport or shipment, affecting quality.

Temperature variability can be attributed to factors such as inappropriate pre-cooling, loading or unloading processes, inefficiencies in container refrigeration resulting in insufficient airflow rates, and problematic on and off defrost cycles [10,11]. Significant temperature variation can lead to economic losses because of poor quality and failure to start phytosanitary protocols,

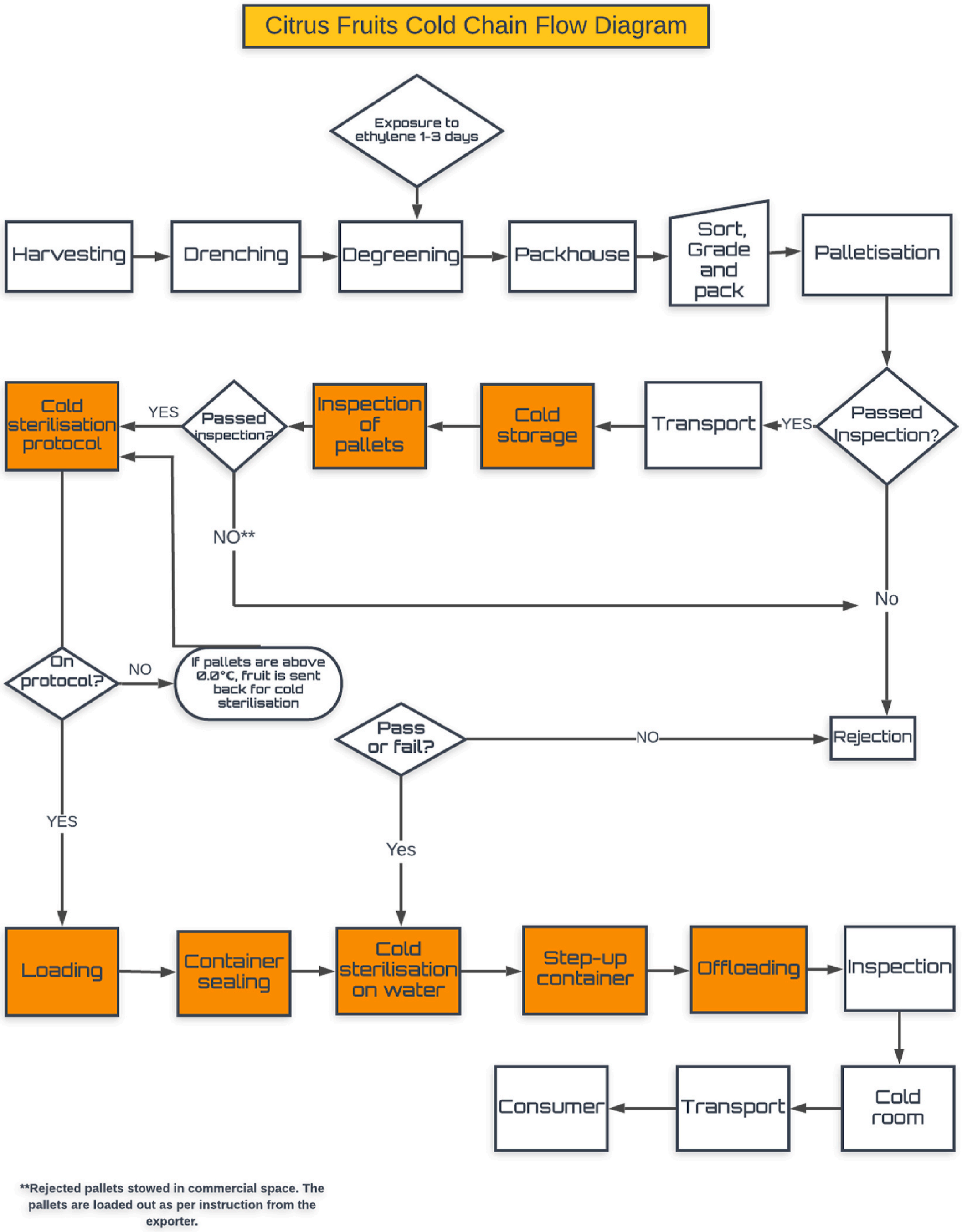


Fig. 1. A simplified flow diagram depicting the supply chain of South African citrus fruit from farm to consumer.
Source: Authors' own

resulting in penalties that increase the cost to exporters. In addition, any single temperature disturbance, irrespective of its duration or severity, can undermine the efficacy of the subsequent cold chain to deliver quality fruit to the end destination [12].

Ensuring that the cold chain of perishable products is maintained also requires purpose-designed packaging and an adequately designed cooling system with temperature-monitoring devices to measure changes in fruit pulp temperature and ambient temperature. It is important to note that pulp temperature is used to determine the cooling rates and the success of cold-sterilisation treatment. The flow diagram in Fig. 1 illustrates the cold chain for citrus fruit from South Africa to cold protocol markets and the processes that occur during the different cold-chain stages. The highlighted stages show the focus of this study, as these stages involve cold sterilisation and the use of temperature loggers.

Citrus fruit is harvested at peak maturity since it is classified as non-climacteric (i.e. it does not ripen further). Once the picking process is complete, the packhouse processes begin. These include different activities, ranging from drenching, degreening, fruit waxing and sorting to palletisation. After palletisation, officials from the Perishable Products Export Control Board (PPECB), South Africa's official perishable produce export certification control agency, conduct quality inspections. Pallet samples are chosen and if the cartons tested are found to be of acceptable quality and free from pests and diseases, the fruit is approved for exportation.

The next link in the citrus supply chain is the transportation of fruit pallets to the cold store and/or the port. Once at the cold store, packing, palletisation, inspection and certification by the PPECB takes place. Then the cold-sterilisation treatment procedure begins, following a three-stage process: pre-cooling, container loading and pulp stabilisation [13]. The PPECB begins cold-sterilisation treatment once temperature readings have been downloaded and sent by the shipping line (no later than 6 h) prior to the vessel's departure.

The measuring of pulp temperature is required to determine when to stop or continue applying pre-cooling and to evaluate the cooling of cargo during the sea leg of refrigerated containers [3]. The authors explored studies pertaining to the time-temperature monitoring of citrus and product visibility, along with studies in the fresh fruit industry, such as the use of a digital twin of citrus fruit to simulate the behaviour of citrus fruit [14]. Wu et al. [3] explored the use of a virtual cold-chain (VCC) method. The VCC method uses computational fluid dynamics (CFD) and kinetic quality to predict temperature history and quality loss for each individual fruit throughout the entire cold chain. Defraeye et al. [5,15] investigated the application of CFD solutions to help understand airflow patterns during pre-cooling. CFD has also been used to estimate the cooling performance of containers. Defraeye et al. [5] explored the use of ambient loading of citrus fruit into reefer containers for cooling during marine transport using CFD.

The existing field studies conducted in the South African citrus industry, as mentioned in section 1, were mostly conducted using traditional temperature loggers to measure temperature [7]; Goedhals-Gerber & Khumalo, 2020; [1]. Traditional temperature measurement and monitoring systems are the most popular and reliable methods used for controlling and documenting temperature conditions. Nico Vosloo explained that "the main temperature-monitoring instruments are wired loggers and wireless loggers, such as button loggers and strip charts" (personal communication, March 26, 2021). Other loggers, such as USB loggers (wired), radio frequency (RF) loggers (wired) and SigFox loggers (wireless) are also used. In this article, wired conventional loggers refer to temperature loggers that require the use of a cable or USB port to download temperature data. Wireless conventional loggers refer to data loggers that do not require manual manipulation to download data.

Cellular technologies have been introduced in the cold chain to monitor the temperature of citrus fruit. Because it is difficult to get temperature data from conventional loggers, the remote monitoring provided by cellular technologies could prove beneficial to exporters wanting to monitor the temperature of their cargo while it is in transit. Table 1 [1,3,4,7,14,15], presents a summary of empirical studies that were conducted in the citrus industry by different authors.

Table 1
Empirical studies undertaken in the citrus industry and technology used.

Product	Data type	Sensors	Methodology	Reference
Time-temperature monitoring of citrus and product visibility studies				
Citrus	Temperature profile	CFD	CFD calculations in refrigerated containers	Defraeye et al. [15]
Citrus	Air cooling flow patterns	CFD	CFD in containers	Defraeye et al. [4]
Fresh fruit	Temperature	CFD	Virtual cold chain method	Wu et al. [3]
Citrus	Sensor data	Simulations	Conducts the simulation of physical, physiological and microbiological behaviour of citrus fruits.	Shrivastava et al. [14]
Some existing field studies explored in South African citrus using traditional loggers				
Clementines and Valencias	Temperature	Data loggers (iButtons)	Quantitative: Statistical analysis of temperature and duration using historical data and trial shipment data	Conradie [7]
Navel oranges	Temperature	Data loggers (iButtons)	Quantitative: Statistical analysis of temperature and duration using historical data and trial shipment data	Goedhals-Gerber & Khumalo (2020)
Valencias and grapefruit	–	–	Systematic literature review	Khumalo et al. [1]

2.2. Survey of existing temperature measurement technologies

2.2.1. Conventional loggers

Conventional temperature loggers are predominantly used to monitor temperature during the different stages in the citrus cold chain. Most of the conventional loggers currently in use measure ambient temperature, but a few measure pulp temperature. Conventional loggers can be divided into wired and wireless loggers.

2.2.1.1. Wired conventional loggers. **Strip-chart monitors** are temperature recorders that generate a permanent strip-chart record of temperature data and conditions along the supply chain. Strip charts are typically operated at an accuracy of ±1.1 °C (±2.0 °F) and can measure temperature ranging from −29 °C to 38 °C [16]. Currently, strip charts can record information in digital format to be downloaded through a computer known as a virtual chart recorder. Strip-chart devices are not used for temperature recording of citrus exports under cold sterilisation because newer technologies are available.

Button loggers are coin-sized electronic devices that act as temperature sensors and electronic memory [17]. The devices are enclosed in a 16 mm thick stainless steel casing designed to withstand harsh environments. They can measure temperatures from −30 °C to 85 °C in 0.5 °C increments and are accurate to ±1 °C [17]. Data is stored in three ways, namely as temperature loggings, histogram bins and threshold alarms. The button devices require a host system (e.g. a laptop), a reader to extract information from the button, as well as software to interface button devices with computers and produce the desired information in the desired format [17].

USB data loggers connect to the USB port of typically a Windows PC for programming and data retrieval, but other platforms may be supported depending on the specific product. These loggers require the use of software to retrieve data. USB loggers can measure temperature, relative humidity and voltage. Their selectable parameters include the logging rate, measurement units and threshold alarms. Depending on the model, USB data loggers can record up to 4000 measurement values. The battery life potentially lasts up to 500 days. USB data loggers can measure temperatures from −35 °C to 80 °C, with ±0.3 °C accuracy. They can store up to over 10 000 temperature readings and log temperature at a minimum of 10-s and a maximum of 12-h intervals [18].

USDA probes are the official temperature-monitoring probes used to monitor temperature in shipments where the importing country requires cold-sterilisation treatments [19]. USDA probes are PT100 sensors that have an outer sheath diameter of 6.4 mm or less. They are fitted into the container at the container port and can be calibrated for a refrigerated container [19]. USDA probes provide high accuracy and have also become standard for markets other than the USA that require on-board sensors.

Each sensor is equipped with a flexible piercing probe and a cable with a maximum length of 15 m that allows the device to be inserted inside a fruit within a carton. These probes typically record product temperature readings that range between −40 °C and 60 °C and are downloaded manually from the container at the destination port. However, for more advanced reefer containers, internal product temperature readings recorded by USDA probes are transmitted to a central computer on board the ship for instant real-time monitoring. These probes are placed into the fruit during the loading of fruit pallets into a container in order to monitor the fruit during the entire voyage.

2.2.1.2. Wireless conventional loggers. **Radio frequency (RF) loggers** are small, credit-card-sized devices that can measure various environmental conditions automatically [20]. They use radio frequency and depend on an RF transceiver. The RF transceiver connects to the data logger through a port and then transmits what the data logger receives to a corresponding receiver connected to a computer. These loggers can measure temperatures ranging from −40 °C to 60 °C or −30 °C–70 °C. RF loggers differ from radio frequency identification (RFID) technology (see section 2.2.2) in that they rely on a transceiver to share data. RFID is a product identification tool that automatically identifies static or moving objects and exchanges the digital information.

SigFox data loggers use SigFox communication technology, which uses a Low-Power-Wide-Area (LPWA) network. SigFox technology uses wireless networks to connect to lower-power energy objects such as sensors and devices, and reports data back to the COMET Cloud interface. COMET Cloud is an Internet storage system designed for recording measured values from selected COMET measuring instruments. From the COMET Cloud, users can view and download data and receive alarm notifications. SigFox sensors can monitor temperature, humidity and atmospheric pressure [21]. The loggers have a temperature measurement range of −30 °C–60 °C, with an accuracy of ±0.4 °C and transmission intervals from 10 min to 24 h.

2.2.1.3. Conventional loggers: overview. The technologies surveyed form part of the temperature loggers currently available to monitor temperature throughout the different stages of the South African citrus cold chain. Most of the conventional loggers are battery-powered, which allows for the storage of temperature data for extended periods and at a low cost. At present, the USDA probes are the official temperature loggers used to measure data during shipment, as stipulated by the USDA. The other loggers are predominantly used by exporters and the different cold-chain role players to monitor temperature in case a deviation occurs. However, the weakness of conventional loggers (except the on-board internal temperature recorders in advanced reefer containers) lies in their inability to offer real-time temperature data that would allow for corrective action and traceability. The features, advantages, disadvantages and applications of these loggers are summarised in Table 2 [16,20,22].

2.2.2. Wireless sensing technology

To counteract the limitations of traditional measuring methods, alternative technologies and methods have been developed to record temperatures in the cold chain, for example Bluetooth temperature sensors, radio frequency identification (RFID) and wireless sensor networks (WSNs) [12].

Table 2
Conventional data loggers used in cold chains: features, advantages, disadvantages and applications.

Logger type	Features	Advantages	Disadvantages	Applications	Illustration
Wired conventional loggers					
Strip-chart monitors	• Bi-metallic coil • Single or multi-channel styles • Fitted with a pointer/stylus • Tamperproof security seal	• Some are battery-powered • Easy activation • Produce a hard copy • Easy to operate • Reusable	• Need to be calibrated • Offer no real-time temperature • Data on the strip chart is not easily shared • Hard copies must be filed • Require regular checks and calibration • Require the use of correct pens and charts	• Shipping industry • Road transportation	
Button loggers	• Metal sheath case	• Battery-powered • Low cost • Reusable	• Need to be calibrated • May fail because of exposure to cold temperatures	• Shipping industry • Road transportation • Cold storage	
USB loggers	• Flashing indication • Built-in real-time clock • Polycarbonate casing • On-board software	• Battery-powered • Easily programmable • Low cost	• Require configuration • Easy loss of battery capacity	• Road transportation • Shipping industry	
USDA-approved probes	• Metal sheath • Long probe length	• High calibration • Sufficient memory to store temperature data from loading port until port of discharge	• Require a longer time to achieve the correct temperature of the product being measured • Necessary to ensure penetration of the probe into the product for accurate temperature reading • High cost	• In cold chains to cold-sterilisation protocol markets • Cold chain of vaccines	
Wireless conventional loggers					
RF loggers	• Embedded with a transceiver	• Easy installation • Low cost • Able to collect data from distant places	• Some RF loggers do not provide temperature alerts • Require checking before and after installation to ensure that they work as required • Signal depends on frequency and antenna	• Road transportation • Warehousing	
SigFox loggers	• Lightweight • Integrated modem • Wireless setting	• Battery-powered • Integrated conversion tables • Ease of set-up	• Frequencies can vary according to national regulations, making them susceptible to interference, which can vary from country to country	• Cold chain • Shipping industry	

Sources: RS Components, [22]; Sensitech, [16]; Blulog [20].

Wireless sensing technology allows for real-time temperature monitoring, as temperature data can be accessed via the Internet if a continuous connection can be maintained [23]. The different wireless sensing technologies are briefly discussed below.

2.2.2.1. Bluetooth technologies. Bluetooth is a wireless protocol developed for short-range communication between different Bluetooth-enabled devices in wireless personal area networks [24]. It is mainly designed to maximise ad hoc network functionality. **Bluetooth temperature loggers**, also known as Bluetooth beacons, which function on Bluetooth low-energy (BLE) technology, use BLE tags. The signal sent out by these small devices is picked up by other Bluetooth devices and shows the distance between the tag and the reader.

Bluetooth loggers offer a wireless data extraction point upon completion of a trip by using a wireless gateway hotspot such as a smartphone [25]. However, the receiver needs to be specifically calibrated to pick up the signal of these loggers. The gateway hotspot receives the sensor readings and uploads them to a cloud using data plans. It also adds a location tag to the data that is shared using Global Positioning Systems (GPS) or cellular triangulation to verify the location at the point where the data was captured.

The advantages of Bluetooth temperature sensors include their reliability in broadcasting data because of their adaptive frequency method. However, captured temperature data is transferred wirelessly to Bluetooth-enabled devices only when the shipment reaches its intended destination, which provides no real-time information.

2.2.2.2. Radio frequency identification. **Radio frequency identification** (RFID) is a technology that transfers data from an electronic tag called an RFID label. It allows for the visibility of products through the different cold-chain stages and provides wireless identification of products by detecting electromagnetic signals [26]. RFID systems comprise a tag, a reader and a sensor. Radio signals are emitted from a reader to activate the tag and allow the data to be received. Through the reader, communication is established between the tag and the transceiver [26]. The RFID tag detects the activation signal off the reader. The reader decrypts the data that was encrypted in the integrated circuit of the tag and transfers it for processing. The tag can be positioned on the consignment to record and communicate the location and physical parameters, such as the relative humidity and temperature of products, to a database. Over the years, several solutions for implementing temperature-managed systems using RFID tags have been reported [27]. These include a smart cold-chain system that uses semi-passive tags, 1G-RFID systems and 2G-RFID-systems [27].

RFID technology has shown significant advantages, among others, the ability of the RFID tag to withstand harsh conditions such as sub-zero temperatures. RFID has the potential to allow corrective action through automatic identification, as the tags do not require manual scanning and provide data remotely and continuously [26]. Limitations include the structure of the RFID system according to its various components, such as the technology being limited to a single sensor [26]. As discussed in section 2.1.2, RFID technology differs from RF loggers as it is a product identification tool, whereas RF loggers are wireless conventional temperature loggers that use radio frequencies.

2.2.2.3. Wireless sensor networks. **Wireless sensor networks** (WSNs) comprise RF transceivers, sensors and micro-controllers and use a base station that acts as an interface between users and the network. WSNs comprise innumerable wireless sensor nodes, which are devices fitted with a processor, a radio interface and analogue-to-digital converter sensors, memory and a power supply [28]. These nodes communicate among themselves using radio signals. Instrumented with a variety of sensors, such as temperature, humidity, vibration, pressure and volatile compound detection, they allow monitoring of different environments. They can also respond to queries sent from a control site to perform specific instructions or provide sensing samples [29].

The primary advantages of WSNs is that they allow different network topologies and multi-hop communication, the wireless transmission of data and continuous information flow, which are needed to provide real-time data. The disadvantages of WSNs include their high cost compared to RFID technology and their inability to withstand harsh environmental conditions.

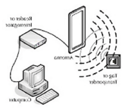
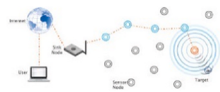
2.2.2.4. Wireless sensing technology: overview. The wireless technologies surveyed in this section form part of the sensor technologies available to monitor traceability and visibility across the cold chain. These technologies allow for the monitoring of the temperature of products in transit and have been successfully applied to diverse industries such as healthcare and agri-food [12,30]. Table 3 [12,31], summarises the features, advantages, disadvantages and applications of wireless sensing technology in the cold chain.

2.2.3. Cellular temperature loggers

Due to the high adoption costs of technologies and stipulated regulations (e.g. having to use USDA probes as the official temperature monitors during shipment), the South African citrus industry uses traditional data loggers such as USDA probes and independent monitoring units. These cold-chain monitoring systems cannot provide real-time information as the loggers are not automated; thus, they require manual inspection and input [32]. As a result, it is not possible to provide assurances that the cold chain has been maintained en route to the export destination, which means the shelf life or product quality of the citrus fruit cannot be predicted. To counteract these inefficiencies, cellular temperature-logger technology has been introduced.

Cellular temperature-logger technology is a wireless technology that uses cell towers to act as a gateway for data transfer. The Global System for Mobile (GSM) communication network connection is used by the temperature sensors to upload data. The GSM mobile digital network is popular among cell phone users. The device, the base station subsystem (BSS), the network-switching subsystem (NSS), and the operation and support system are the four distinct components that make up the GSM network (OSS). The subscriber identity module (SIM) card gives the network information that identifies the device and allows it to connect to the network via hardware. The BSS controls traffic in this area between the device and the NSS [33].

Table 3
Wireless sensing technology used in cold chains: features, advantages, disadvantages and applications.

Technology type	Features	Advantages	Disadvantages	Applications	Illustration
Bluetooth	• Equipped with Bluetooth low-energy (BLE) technology	• Battery-powered • Low cost • Easy configuration via near-field communication (NFC)	• Lack of real-time visibility	• Shipping industry • Trucking industry	
Radio frequency identification (RFID)	• Each tag has unique identification • Higher reading range than bar codes • Integrated memory	• Long battery life • Wireless transmission of data	• Shorter reading range compared to wireless sensor networks	• Transportation industry • Shipping industry	
Wireless sensor networks (WSNs)	• Integrated memory • Multiple sensors per node	• Real-time information • High reading range	• High cost • Not as suitable for harsh conditions	• Shipping industry • Food industry	

Sources [12,31].

The base transceiver station and the base station controller are the base station's two constituent parts. The base transceiver station houses the communication hardware for mobile devices, primarily radio transmitters, receivers, and antennas.

A home location registry and a mobile-switching centre are two of the NSS's components. These components carry out a variety of tasks, including call routing, SMS delivery, SIM card authorisation and keeping of caller account data, as well as SMS delivery and short message service (SMS). Cellular recorders can be utilised outside of their nation of origin because GSM network operators have roaming arrangements with foreign operators. As a result, the NSS can monitor the whereabouts of devices. Through radio frequency channelling, the cell-phone tower (mobile mast) reacts to the signal and delivers the data. The cell phone tower serves as an intermediary station, converting the incoming radio signal into data and sending it to a server [33].

A cellular logger records temperature and relative humidity data obtained from built-in sensors. The data logger continuously records temperature in the internal memory and periodically emails the recorded data over GPRS (General Packet Radio Service). If temperature and relative humidity limits are exceeded, an SMS is sent via a GPRS data connection. This type of logger is a portable solution for remote temperature monitoring. The sensors can be programmed to download temperature data every 60 min.

Cellular loggers require software set-up on an online platform (a web-based portal), i.e., exporters must input the details of their shipments that are being monitored by sensors onto the portal. The cellular temperature loggers measure ambient air temperature and can be placed directly into fruit cartons stacked on pallets or somewhere in the reefer container to provide information that shows temperature along the cold chain. The exporter can remotely activate the cellular loggers before starting the cold-sterilisation process for the shipment until the port of destination or via a geofence system.

While reefer containers are in transit, data is downloaded whenever temperature sensors pass through transhipment hubs (i.e., when network reception is available) and sent to the end-user (the exporter or shipping line), who can monitor the temperature and make informed decisions about the shipment. Cellular temperature loggers either use 2nd generation (2G), 3rd generation (3G), 4th generation (4G) or 5th generation (5G) cellular network coverage.

The primary advantages of 2G technologies are the low power-usage requirements and very large transmission ranges. However, these benefits come at the cost of low bandwidth. The 3G network provides data transfer speeds ranging from 128 kbps to 3 Mbps. The higher speeds allow 3G connections with tablets and any other portable device that could benefit from a faster and higher-quality Internet connection. 3G also provides users with better security through user authentication capabilities when communicating with other wireless devices [34]. It also boasts better power control methods for both uplink and downlink, with the network using a target signal-to-interference ratio to adjust its output power. It also improves spectrum utilisation through shared channels in the radio interface, making it more effective than 2G networks [34].

4G networks are currently the most advanced technology used by most mobile network service providers and offer a download speed of approximately 14 Mbps, five times faster than 3G. 4G also allows for improved latency times. The next generation, 5G, allows for further improved speed and lower latency, which makes it possible to connect multiple devices to the Internet. However, 5G uses higher-frequency radio waves that cover a shorter distance, requiring more transmitter masts, so cellular temperature loggers might not come in range of the 5G network for data transmission.

2.2.3.1. Cellular temperature-logging technologies: overview. Cellular temperature loggers are relatively new to the South African citrus industry. They allow for visibility of citrus fruit throughout the different stages of the cold chain. Most of the cellular temperature loggers are battery-powered, thus allowing for the storage of temperature data for extended periods. Table 4 summarises the features, advantages, disadvantages and applications of cellular loggers.

2.3. Gap in the literature and contribution of the study

The literature in section 2.1 outlined various studies in the citrus fruit industry and other fresh-fruit industries that explored time-temperature monitoring. In addition, field studies that had been conducted in the citrus industry were explored. These studies used either a qualitative, quantitative or a mixed-method approach. [14]; for example, used a quantitative approach to explore the use of a

Table 4
Cellular temperature loggers used in cold chain*s: a*dvantages, disadvantages and applications.

Technology type	Features	Advantages	Disadvantages	Applications	Illustration
Cellular loggers	• Use GSM/GPRS connectivity • One-touch activation	• Immediate access to data • System alert if corrective action is needed • Provide location updates • No infrastructure needed • Low cost	• Data only uploaded once GSM network is available • Loggers do not consistently record temperature at the set regular intervals	• Transportation industry • Shipping industry	

Source: Authors' own

Table 5
Summary of the ability of loggers to provide visibility in the cold chain.

Logger type	Can the logger identify problems?	Does the logger allow for corrective action?	Does the logger reduce costs for the exporter?	Is the logger easy to retrieve from export market destinations?	When can data be downloaded?
Wired conventional loggers					
Strip-chart monitors	No, loggers do not offer real-time data	Only upon arrival at destination	No	Not easy to retrieve by exporters The sheets of paper can easily get lost	Data downloadable once logger has been retrieved at destination
Button loggers	No, loggers do not offer real-time data	Only upon arrival at destination	No	Not easy to retrieve, especially in high-risk markets such as China because exporters/shipping lines are not responsible for a consignment once it has been accepted by USDA officials	Data downloadable once logger has been retrieved at destination
USB loggers	Not able to identify problems until end of shipment	Only upon arrival at destination	No	Not easy to retrieve, especially in high-risk markets, thus can get lost with pallets	Data easy to retrieve once logger has been retrieved at the end of a shipment
USDA-approved probes	Yes, allow shipping lines to identify temperature problems	Allow for corrective action, especially in advanced containers with a central computer for instant real-time monitoring	Could reduce cost because shipping lines communicate with exporters	Easy to retrieve; however, temperature data remains the property of shipping lines	Can be downloaded while on board through a central computer system connected to the container
Wireless conventional loggers					
RF loggers	No, loggers do not offer real-time data	Do not allow for corrective action until consignment arrives at the end destination	No cost reduction	Not easy to retrieve from high-value markets such as China.	Data downloadable once logger has been retrieved
SigFox loggers	Yes, allow for identification of problems	Allow for corrective action, on condition that there is a range of coverage	Costs are reduced if data is transmitted and allows for corrective action	Not easy to retrieve from high-value markets such as China.	Data can be downloaded while product is en route
Wireless sensing technologies					
Bluetooth technologies	No, loggers do not offer real-time data	Only upon arrival at destination	No	No	Data downloadable once loggers have been retrieved at destination
Radio frequency Identification (RFID)	Yes, allow for identification of problems	Allow for corrective action	Costs are reduced if data is transmitted and allows for corrective action	Retrieval of tags depends on the country of import	Data can be downloaded while product is en route
Wireless sensor networks (WSNs)	Yes, allow for identification of problems	Allow for corrective action	Costs are reduced if data is transmitted and allows for corrective action	Retrieval of nodes depends on the country of import	Data can be downloaded while product is en route
Cellular technologies					
Cellular loggers	Yes, provide real-time data	Allow for corrective action, on condition that there is network coverage	Yes, if data is uploaded timely via GSM network	Not easy to retrieve from high-value markets such as China	Data can be downloaded while product is en route

Source: Authors' own

citrus digital twin to overcome problems associated with fruit quality, product visibility and low temperatures prescribed due to phytosanitary regulations. The aim of the digital twin technology is to get real-time coupling with sensor data to monitor food quality and marketability. The digital twin simulates the physical, physiological and microbiological behaviour of citrus fruits shipped at sub-zero temperatures and reveals that half of the shipments lie outside the ideal trade-off range to maintain quality [5]. used a quantitative approach to explore the use of ambient loading of citrus fruit into reefer containers for cooling during marine transport through computational fluid dynamics (CFD). Similarly [4,15], used a quantitative approach to investigate the application of CFD solutions to help understand airflow patterns during pre-cooling.

Regarding field studies in which temperature loggers were used, [7]; for instance, focused on the initial stages of the citrus cold chain to the USA using statistical analysis to investigate the main problem areas in the supply chain that cause temperature breaks. The study used conventional temperature loggers for the collection of data. Goedhals-Gerber and Khumalo (2020) also employed statistical analysis to investigate temperature deviations from the cold-sterilisation protocol in the navel orange export cold chain from orchard to sea route. The study also used conventional temperature loggers for the collection of data [1]. reviewed the cold-treatment engagement process necessary for the success of shipments to meet phytosanitary requirements. The study found that during the container-packing phase, the export regulatory body requires that, for cold-treatment markets such as the USA, China, South Korea and others, the container be fitted with at least two air temperature sensors (delivery and return air) and pulp temperature loggers (USDA) in at least three specified locations.

This study is unique to the citrus industry because it explores the use and assesses the benefits of conventional and cellular loggers. It explores how cellular loggers can increase product visibility in order to ensure that the fruit adheres to phytosanitary requirements. To the authors' best knowledge, a study on the use of cellular loggers in the citrus industry for fruit under cold-sterilisation treatment has not yet been conducted. Therefore, this study offers knowledge on whether the use of cellular loggers would help to provide visibility. Increased visibility in part of the cold chain through temperature-monitoring devices would offer the opportunity to manage the risk of quality loss and improve logistical performance. Cold-chain visibility aims to manage complexities such as geographical distance, resilience to unforeseen risks, scale complexity and product complexity [35].

Table 5 summarises the ability of the different loggers to provide visibility in the cold chain.

3. Materials and methods

3.1. Interviews

Interviews were conducted to gain the perspective of industry role players on which temperature loggers are most suitable for the South African citrus cold chain and, based on their experience, on the perceived advantages and disadvantages of the respective temperature loggers. In this study, industry experts were defined as persons who had a minimum of 10 years' experience in and knowledge of the citrus cold chain. Industry experts working in different sectors and different provinces of South Africa were interviewed. Interview questions were sent to 18 experts and responses were received from 10. The 18 industry experts were selected from a pool of contacts with whom the researchers had previously worked with in conducting other research studies. The selected number of interviewees was supported by Creswell's recommendation of attaining data saturation with 5–25 participants [36,37].

Homogenous purposive sampling enabled the researchers to focus on a specific group in which the members have similar traits. The sample of the 10 interviewed participants comprised different role players in the citrus cold chain: exporters, shipping lines, academics, consultants and regulatory body officials. They were all familiar with the use of temperature loggers in this cold chain. The role players selected had also experienced issues relating to the lack of product visibility and the use of real-time temperature-monitoring loggers, such as cellular loggers.

Consent forms, which needed to be signed, were sent to participants before the interviews were conducted. The questions were structured in such a way that the interviewees' responses helped to answer the research questions. After obtaining the participants' permission, the interviews were audio-recorded and transcribed verbatim. The 10 role players were each given a unique identification. Each role player was grouped into a specific category: fruit exporters, government regulatory bodies, shipping lines, key citrus role players (e.g. researchers and academics) and technology experts (e.g. consultants), as shown in Table 6.

With the aid of the semi-structured interview guide compiled by the researchers, the challenges of using temperature loggers for cold-chain management were explored. For this study, challenges were defined as factors that participants considered a hindrance that prevent the temperature loggers currently in use in the South African citrus cold chain from performing expected cold-chain management outcomes, such as providing product visibility.

The interview guide comprised 20 questions, which were grouped into four subdomains: "reliability", "visibility", "cold chain management" and "ease of use".

- The reliability subdomain consisted of questions such as: *How do temperature loggers improve the flow of information across the cold chain? Do temperature loggers provide a competitive advantage for export companies? How reliable are the temperature loggers used in recording data*?
- The visibility subdomain contained questions such as: *At which point of the cold chain can temperature data be downloaded or extracted? Do temperature loggers provide visibility in the cold chain*?
- In the cold-chain management subdomain, participants' knowledge of cold-chain management issues, such as different temperature ranges in the cold chain, were assessed. Questions included: *How is temperature monitored? What are the different stipulated temperatures in the different stages of the cold chain?*

Table 6
Summary of the interviewee categories and the number of participants.

Data collection phase	Interviewee categories	Number of participants per category	Sampling
Semi-structured interviews	Fruit exporters	3	Purposive
	Government regulatory bodies	1	Purposive
	Shipping lines	1	Purposive
	Key citrus industry role players	4	Purposive
	Technology experts	1	Purposive

- The ease of use subdomain consisted of questions such as: *In which positions are temperature loggers placed in citrus pallets? How easy is it to insert these loggers into fruit or cartons?*

3.2. Collection of temperature data

To determine the potential benefit of cellular temperature loggers at the different stages of the cold chain, the loggers were placed in containers at cold stores at the Port of Durban. As the Far East countries are a key Asian market growth region for South African citrus exports, the focus was on citrus fruit pallets exported to the Republic of China and South Korea.

Cold-chain monitoring with the cellular temperature loggers spanned from the storage of the fruit in the ambient storage area in the cold store, to pre-cooling, container loading and pulp stabilisation, until arrival at the port of destination. The time to complete the container-loading process (from the time the refrigeration doors were opened until the container doors were sealed) was recorded. While containers were in transit at the container-stacking area at the port and at sea, data was downloaded hourly whenever the cellular loggers passed through a cell-phone tower network at a transhipment hub.

Cellular temperature loggers from three different manufacturing companies were used, with two types measuring ambient temperature and one type measuring pulp temperature. The loggers were Sensitech TempTale® GEO Eagle trackers, trackers from MOST technologies and Emerson GO Real-Time Flex trackers. The results were grouped together because all the loggers yielded similar findings.

The cellular loggers were placed among fruit in palletised cartons (on the top and middle cartons) in 20 refrigerated containers: 10 in grapefruit and 10 in oranges. The containers were loaded during June and August 2019.

4. Results and discussion

The interview questions were structured in such a way that the interviewees' responses helped to answer the research questions in section 1 (discussed in sections 5 and 5.2) and to determine the importance of temperature loggers in the cold chain (discussed in section 5.3). Section 5.1 answers whether temperature loggers provide product visibility in the South African citrus cold chain. Section 5.2 deals with the effectiveness of cellular loggers in the citrus cold chain to provide real-time temperature data that would enable exporters to take corrective action as temperature breaks occur. Since the study aimed to help exporters to redress problems associated with product visibility, the results from the interviews conducted with key role players are discussed in section 5.3.

4.1. Do temperature loggers provide product visibility in the citrus cold chain?

Altogether, 90% of the participants stated that conventional loggers used in the citrus cold chain do not provide product visibility while the shipment is en route to its final destination. Conventional temperature loggers lack real-time tracking, except on-board internal temperature recorders in advanced reefer containers. However, the temperature data recorded by these on-board temperature loggers is accessed by the shipping line only, not by the exporter. The exporter therefore still does not have any real-time product visibility despite the advanced technology used in these reefers. Only 10% of the participants stated that conventional loggers are capable of providing product visibility as it would depend on the type of logger used, such as SigFox loggers.

Participants stated that product visibility provided by cellular temperature loggers comprised maps and temperature alerts, which enabled tracking of the current location of citrus shipments. However, cellular loggers provide greater product visibility during land-based processes, such as road transportation, than during the sea leg of the shipment because there is cell-phone reception during the land-based stages. This real-time data makes it possible for exporters to take corrective action to correct breaks in the cold chain during these stages. The limited real-time updates of cellular loggers can also be attributed to their shorter battery life compared to conventional loggers.

4.2. The efficacy of cellular loggers

Typically, the citrus cold chain to cold-sterilisation markets has to be maintained within the stipulated sub-zero temperature range. Fig. 2 shows the temperature graph of two cellular loggers from the ambient storage area until the unloading of fruit at the final destination. Cellular logger A measured ambient temperature and cellular logger B measured pulp temperature. The graph illustrates temperature ranges during the different stages of the cold chain. In the ambient storage area, the temperature is above the stipulated range, which is acceptable for citrus as the cold chain starts at the pre-cooling stage. During pre-cooling, both temperature readings

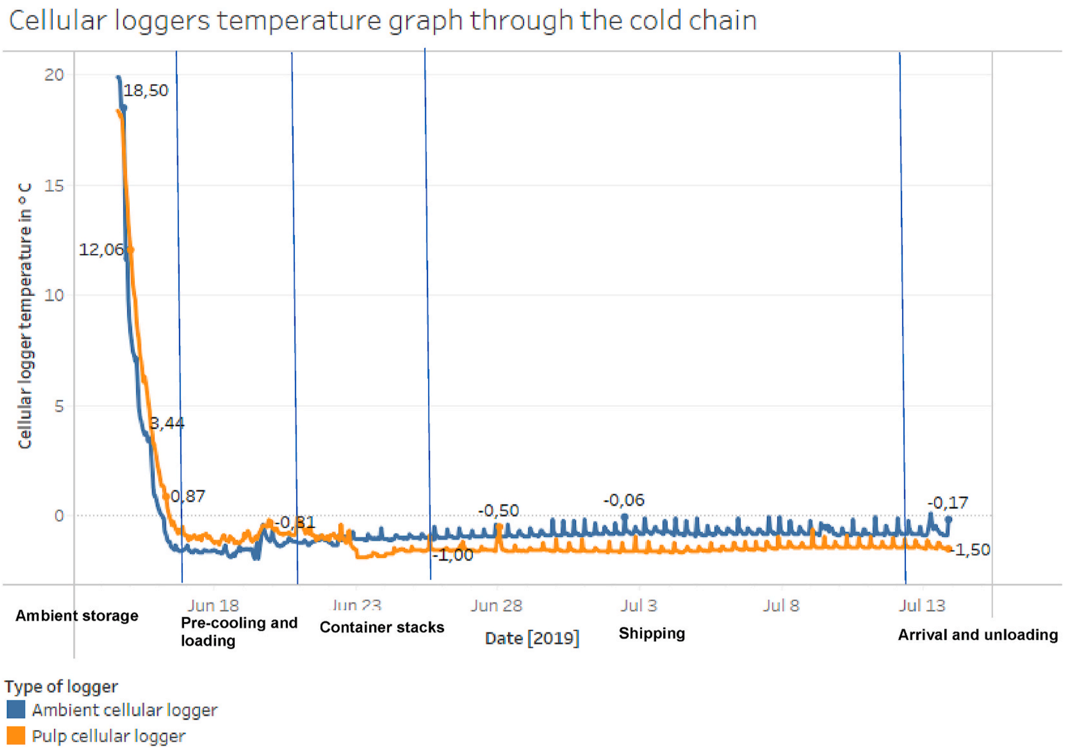


Fig. 2. Time-temperature graph of cellular loggers from port of origin to end destination, with the blue line depicting ambient temperature and the orange line pulp temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors' own

depict a decrease and during the last day of loading, the temperatures are within the protocol. The temperature ranges logged by the cellular loggers depict a well-maintained cold chain, with slight temperature variability in air temperature due to defrosting cycles, but still well within the stipulated temperature tolerance. Sections 5 and 5.2.2 further discuss the advantages and disadvantages associated with cellular loggers.

4.2.1. Advantages of using cellular loggers in the citrus cold chain

Efficient pre-cooling conditions need to be maintained to preserve the quality of citrus fruit exports and meet prescribed temperature requirements. At pre-cooling, the cold chain is started and fruit pulp temperatures can effectively be reduced using a step-down approach. The delivery air temperature is set to a certain target temperature and is decreased once the fruit approaches that temperature. Then the delivery air temperature is reduced again until the target temperature of −0.6 °C is achieved. The results showed that during pre-cooling, cellular temperature loggers provided real-time visibility, which allowed for the monitoring of the cold-sterilisation chamber for a uniform decrease in temperature. In a step-down procedure, for example, the delivery air temperature is first decreased to 15 °C after fruit is placed in the pre-cooling chamber. The temperature loggers were then monitored for uniformity in temperature before the temperature was decreased further, as depicted in Fig. 3. The figure shows the temperatures recorded in the pre-cooling chamber by cellular loggers compared to conventional loggers.

The temperature decreased when the fruit was placed in the pre-cooling chamber from the ambient storage area. Once the pallets were placed in the cold-sterilisation chamber, the figure shows a step-down reduction in temperature, from 3.33 °C to 0.94 °C. During the last day of cold sterilisation, the temperature decreased to −1.33 °C. The conventional loggers also showed a decrease in the fruit temperature. The temperature was 7.17 °C while the fruit was in ambient storage and decreased to −1.13 °C in the pre-cooling chamber.

Cellular temperature loggers enabled the researchers and exporters to check, in real time, whether cold treatment was occurring within the prescribed range during this stage. If temperatures had been below or above the threshold temperature, prompt corrective action could have been taken based on the real-time feedback received from the loggers.

During probing temperature loggers into fruit, cellular temperature loggers proved to be easier to insert into pallets and fruit cartons than conventional loggers. The loggers can be attached to pallets with double-sided tape or inserted into a carton among the fruit and activated at that stage through a start and stop button.

Some loggers can measure pulp temperature. A long-length probe that is attached to the logger makes it easy to insert it into the pulp of the fruit. The insertion of cellular loggers into fruit pallets required minimal equipment, such as a box cutter, for insertion into

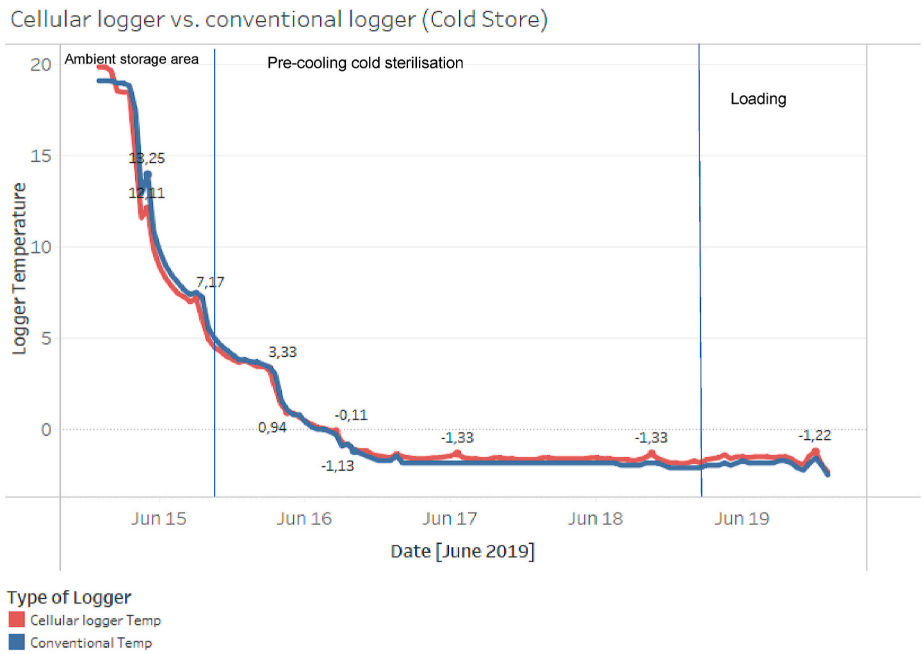


Fig. 3. A step-down approach in temperature shown by cellular loggers (red) and conventional loggers (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors' own

fruit that had already been palletised, or no equipment for insertion before the fruit was palletised. Conventional loggers were not as easy to insert into pallets and fruit. To measure pulp temperature using button loggers, for example, an incision had to be made into the fruit to insert the button. For easier retrieval, buttons were tied to a string so that they could easily be pulled from the fruit or pallets during container loading or upon arrival at the destination.

Fig. 4 shows the practicality of inserting cellular temperature loggers into fruit cartons. The loggers were placed inside the cartons marked for quality control inspections.

Cellular temperature loggers also made it possible to identify loading delays and to determine the likely cause of the delay. Fig. 5

Fig. 4. Cartons where cellular loggers were inserted.
Source: Authors' own

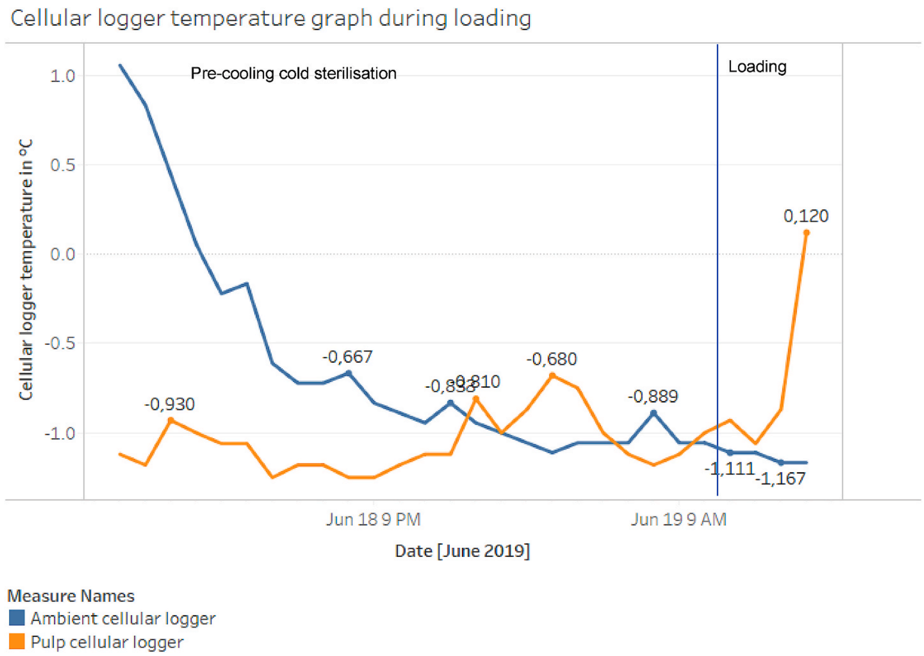


Fig. 5. Time-series graph of cellular loggers during loading of a container by an exporter, with cellular logger A (blue) denoting air temperature and cellular logger B (orange) denoting pulp temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors' own

shows the time-series graph of loggers during the loading stage. The figure depicts two cellular loggers (cellular logger A measuring ambient temperature and cellular logger B measuring pulp temperature) that were used during the loading of a container by an exporter. The researchers recorded the loading process, which took approximately 40 min. During loading, cellular logger B recorded an increase in temperature, which may have been because of pallets being staged on the loading dock before being loaded into the reefer container. Cellular logger B showed a temperature of 0.120 °C. Cellular logger A depicted a decrease in temperature from −1.111 °C to −1.167 °C after the pallets were loaded, the reefer container doors were closed and the reefer container was activated.

Another advantage of cellular loggers observed during the period of data collection was the remote and independent provision of data. Cellular-based temperature loggers could provide data remotely and independently of human intervention, without having to be retrieved from pallets or reefer containers. In contrast, the conventional loggers used by exporters for temperature monitoring had to be physically retrieved to download the data. It is often a challenge to retrieve these loggers at the final destination and they are sometimes discarded along with the pallets, so the data would be lost.

Cellular temperature loggers are equipped with a long-life battery. However, the battery life depends on the rate of sensor readings and GSM uploads. The cellular temperature loggers used to collect data for this study lasted 60 days on average. Through the mobile interface, the researchers could receive notification of how much battery life was left. However, conventional loggers such as button loggers and USB loggers have a longer battery life. On average, the batteries of these loggers lasted 90 days, which is 30 days longer than the batteries of cellular loggers.

Downloads of data recorded by cellular temperature loggers during different stages of the cold chain proved to depend on the presence of cell-phone towers and signal strength. The signal is lost during the sea leg of the shipping phase; therefore, data is stored in the internal memory of the loggers and transmitted once containers are at a transhipment hub and network coverage permits connectivity. Conventional loggers store data in an internal memory, which requires no signal.

Last, the lower cost of cellular temperature loggers and data ownership are also advantages. Once connectivity is established and the data has been transmitted, cellular loggers offer the advantage of definite data availability to exporters and researchers. In this study, this data visibility made it possible to take corrective action as the exporter could communicate with the shipping line to either reduce the delivery air temperature or apply cold blasting when the temperatures were not within the required range. In contrast, one complication of using the on-board USDA probes and button loggers (conventional loggers) is that there is limited data access for the cargo owner (in real time or after the fact), so temperature deviations cannot be corrected while the cargo is in transit. Also, the data belongs to the shipping lines.

The cost of acquiring and operating cellular temperature loggers compared to conventional loggers was considered. USDA probes, the standard required loggers for cold-sterilisation markets, are expensive, ranging from $250 to $300 per unit. According to observations made online, the adoption and implementation costs for cellular temperature loggers range between $40 and $120 per unit.

Table 7 summarises the advantages of cellular loggers and conventional loggers (USDA probes and button loggers) at different stages of the citrus cold chain.

Table 7
Advantages of cellular loggers compared to conventional loggers at different stages of the citrus cold chain.

Cold-chain stage	Cellular loggers	Conventional loggers (USDA probes and button loggers)
Pre-cooling	• Provide real-time temperature visibility • Allow for the checking of temperature and humidity levels	• High precision of temperature recording by button loggers
Loading	• Provide information on whether loading has been delayed or not • Provide a time stamp of how long the loading process took	• High precision of temperature recording through USDA probes
Container stacking	• Provide real-time temperature visibility • Provide a time stamp of how long the reefer container was on stacks	• High precision of temperature recording through USDA probes
Container shipping	• Provide information on the location of the shipment • The desired number of temperature loggers can be fitted in different positions in pallets	• USDA probes are connected to the reefer container, allowing for accurate recording of temperature data
Arrival of container	• Provide location and time stamp of the shipment • Allow exporters to locate the containers' arrival in the country of import	• USDA probes are connected to the reefer container, allowing for accessible temperature data that is downloaded upon arrival to check whether temperature has been within protocol
Container unloading	• Allow for real-time visibility of temperature values during unloading at the country of import	• High precision of temperature recording through USDA probes even during the unloading process

4.2.2. Disadvantages of using cellular loggers in the citrus cold chain

All the cellular loggers from the three different manufacturers showed a disadvantage to be the lack of continuous data availability. Whenever there was no cell-phone network available, data was not transmitted, meaning real-time monitoring was not possible and corrective action could not have been taken if needed. In addition, there was a need for initial set-up, which is unnecessary for conventional loggers. The tracking of the shipped consignment via cellular loggers occurred through a web-based control panel, which required to be set up before use.

The placement of the cellular loggers in the container also proved to be a factor because that affected cell-phone signal reception and thus the ability of the loggers to download data. Pallets containing the temperature loggers inserted by exporters were loaded randomly into the container. To measure relative humidity, for instance, where recommended levels generally fall between 85% and 95%, data loggers would have had to be positioned near the container drains that release excess water that might accumulate in the reefer container or at the door end of a 12-m container [38]. It should be noted that, in most cases, high humidity develops automatically in a reefer container.

Cellular temperature loggers showed temperature-recording failures once placed inside the fruit pallets. Some loggers showed the start location of the shipment (the Port of Durban) and did not update the location after that. This hindered the ability of the loggers to provide real-time temperature. In addition, four of the 18 cellular loggers used during data collection for this study showed a variation when the temperature was recorded. The loggers were set to record data hourly but some of them recorded data after every 10 min, followed by a two-to 3-h lapse before the temperature was recorded again. Three of the loggers stopped recording data after the first day. This might have been because of software or battery malfunction.

Table 8 summarises the disadvantages of cellular loggers compared to conventional loggers (USDA probes and button loggers) at different stages of the citrus cold chain. It is important to note that mostly USDA loggers (from loading until arrival at market) were used. However, in the pre-cooling section, iButtons were used and retrieved during the loading process.

5.3 Why are temperature loggers important in the cold chain?

According to all fruit exporters, temperature loggers are most useful when dealing with claims. In the event of a break in cold-sterilisation treatment, claims are submitted to the relevant parties responsible for the consignment during the different stages of the citrus cold chain. The temperature data recorded by temperature loggers is used to support claims submitted by exporters against shipping lines or other parties and to determine what went wrong during the shipment. In addition, for exporters, the data recovered from temperature loggers is also used to make informed decisions about the reliability of shipping lines, thus improving the exporters' cold chain. Exporters also use temperature loggers to conduct research and run temperature trials. This enables exporters to identify ways of improving their cold chain.

All interviewed exporters and regulatory body officials stated that temperature loggers are also used as a requirement by the country of import. When citrus fruit exporters export citrus to the EU market, for example, the TempTale® GEO, which is a cellular logger, is used. The cellular temperature logger enhances visibility, which is essential to ensure the integrity of the cold-sterilisation protocols when exporting to the EU.

The shipping line respondents noted that they use temperature loggers as a risk-mitigation measure. Temperature loggers are used during the sea leg to monitor whether the citrus fruit is still being cooled to the required cold-sterilisation temperatures. In the event of

Table 8
Disadvantages of cellular loggers compared to conventional loggers (USDA probes and button loggers) in different stages of the citrus cold chain.

Cold-chain stage	Cellular loggers	Conventional loggers (USDA probes and button loggers)
Pre-cooling	• Require initial set-up through a web-based portal • Might encounter signal problems while in the pre-cooling chamber	• Temperature devices need to be calibrated before use
Loading	• Some loggers are not inserted into the pulp of fruit, which could cause them being shifted from the placed position during loading	• No real-time temperature visibility • Inserted at the end of the loading process, leading to the unpacking or repacking of pallets if temperature is over the threshold
Container stacking	• Might encounter network problems while the container is on stacks, therefore not able to transmit data	• No real-time temperature visibility
Container shipping	• Temperature information of loggers is accessed by exporters instead of shipping lines, which inhibits shipping lines from taking corrective action if the temperature goes off protocol and the exporter cannot alert them to the problem	• Logger positions are stipulated by the country of import and cannot be changed • Temperature information of loggers is accessed by shipping lines at the end of the trip, which means exporters have no access to real-time temperature data
Arrival of container	• Transmission of temperature data depends on the availability of network connectivity at the port of destination	• Data is downloaded by and remains the property of the shipping line • If one of the three USDA probes is found to have been above the protocol temperature, the shipment is rejected at the port of destination
Container unloading	• Transmission of temperature data depends on the availability of network connectivity at the port of destination	• If one of the three USDA probes is found to have been above protocol temperature, the shipment is rejected at the port of destination

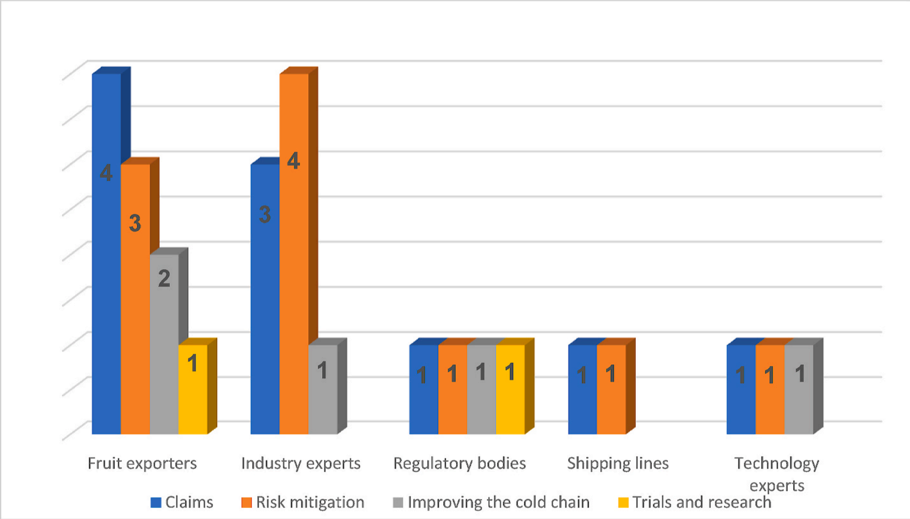


Fig. 6. Interviewees' views of the reasons for using temperature loggers in the South African citrus cold chain.
Source: Authors' own

a temperature break, which would be recorded by the temperature loggers, corrective action such as cold blasting or lowering of the delivery air temperature can be taken. Industry experts also considered risk mitigation as one of the main reasons for using temperature loggers.

Industry experts, regulatory bodies and technology experts all regarded temperature loggers as useful in improving the cold chain. Fig. 6 illustrates the different reasons identified by the participants why temperature loggers are important in the cold chain.

5. Conclusion

The study provided an overview of temperature loggers used in the South African citrus cold chain. It also assessed the benefits of using cellular temperature loggers to provide real-time visibility for temperature data and allow for corrective action if needed. The study is unique to the citrus industry because it explores the use of conventional loggers and cellular loggers and assesses their respective benefits. It explores how cellular loggers can increase product visibility in order to comply with phytosanitary requirements.

The temperature data recorded by the different loggers is largely used by exporters to support any claims against shipping lines or other parties if a break in the cold chain results in financial loss. However, if no problems occurred with the citrus shipment, then the fruit-exporting companies do not review the data recorded on the devices. The second most important reason identified by interviewees for using these devices is risk mitigation, which links directly to claims. Exporters and key role players also utilised temperature loggers to improve the export cold chain.

Other advantages of temperature loggers that were identified by the interviewees include the ability of temperature loggers to monitor different inputs such as temperature, voltage, pressure and humidity. The ability of the temperature loggers to record the additional inputs helps to maintain the optimum temperature levels to prolong fruit quality.

The limitations of temperature loggers, as identified by interviewees, pertain to the cost of the loggers and their battery life. Cellular temperature loggers, for example, are equipped with batteries that last between 30 and 60 days, whereas the batteries of conventional temperature loggers can last for 90 days or more, depending on the logger. Using cellular loggers would therefore require a lot more planning by exporters to ensure their optimal functioning during the duration of the cold chain, given their relatively short battery life.

By placing cellular temperature loggers and conventional loggers in fruit and monitoring them during the different stages of the cold chain, the study determined that cellular temperature loggers provide benefits such as real-time visibility, easy insertion and retrieval, and lower implementation costs. However, as observed during this study, real-time monitoring of the shipment by cellular loggers could be hindered by the loss of connectivity because of weak cell-phone signal strength from within the container, or no signal at all during the sea leg of the voyage, which hinders data downloads.

The research concluded that most of the temperature loggers available in the citrus cold chain do not allow real-time product visibility. However, cellular loggers offer real-time temperature visibility during land-based processes rather than during the sea leg as they are then within range of cell-phone towers and can transmit data. For this reason, the study recommends that the use of cellular temperature loggers not be adopted during the sea leg, despite exporters' concern about the limitations of conventional loggers.

Cellular temperature loggers could effectively be adopted to supply information during the land-based stages of the supply chain, such as transportation from the packhouse, pre-cooling and container loading. This would enable exporters to continuously monitor the temperature conditions of fruit before the consignments are handed over to the shipping line. In addition, most cold stores used for the pre-cooling of fruit that requires cold-sterilisation treatment are near the Port of Durban, where there is access to cell-phone towers. This would allow the real-time transmission of data by cellular loggers to exporters. These findings are important for implementing interventions to improve temperature monitoring in the cold chain.

Increased visibility along the citrus cold chain through the use of real-time temperature-monitoring devices would offer the opportunity to manage the risk of quality loss and improve logistical performance. Failure to monitor citrus fruit in real time may lead to failure to meet phytosanitary regulations. Given that the persistent changes imposed by import countries require constant changes and upgrades in technology, cellular loggers could assist exporters to ensure compliance.

It should be noted that, to the best of the authors' knowledge, no study has been conducted to determine the benefits of cellular temperature loggers in the citrus cold chain prior to this one. Therefore, it is recommended that a similar study be conducted that would assess the benefits of cellular loggers during the initial stages of the cold chain, such as harvesting, degreening, the packhouse processes and transportation. This would enable exporters to monitor the temperature of fruit in real time during these stages and take corrective action where necessary to ensure citrus exports of better quality.

Declarations

Author contribution statement

Gculisile Khumalo: Conceived and designed experiments; performed the experiments; analysed and interpreted the data; wrote the paper.

Prof Leila Goedhals-Gerber: Conceived and designed experiments; analysed and interpreted the data and wrote the paper

Prof Paul Cronje: Contributed reagents, materials, analysis tools and data and conceived and designed experiments.

Dr Tarl Berry: Contributed reagents, materials, analysis tools and data and conceived and designed experiments.

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Data availability statement

The data that has been used is confidential.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2022.e12732.

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