Identifying temperature breaks in the export cold chain of navel oranges: A Western Cape case

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ABSTRACT

Research shows that significant volumes of food produced globally is wasted due to supply chain failures from farm to retail. In addition, the category of fruits, vegetables, roots and tubers has the highest loss and wastage rate of any food per annum. Temperature has the greatest influence on fresh-produce deterioration rates and potential market life. Temperature breaks that occur in the cold chain result in financial losses due to quality loss issues and deviation from export protocols as well as a loss in market opportunity. This article presents a case study on navel oranges exported from Citrusdal in the Western Cape, South Africa to the United States of America. The United States of America is a steri-market, which means citrus fruits shipped to their ports must be exported at sub-zero temperatures for phytosanitary purposes. The procedure is known as cold sterilisation treatment. The likelihood of temperature breaks occurring in a vital industry in the economy prompted further investigation. The article aims to highlight the importance of the cold chain, from the citrus farms to the port of destination, by discussing trial shipments conducted on navel oranges. The results showed that temperature spikes and temperature breaks do occur along the navel orange export cold chain from the orchards until the navels are loaded onto reefer vessels. The results also showed that no temperature breaks are experienced once the navels are loaded on-board the reefer vessels. The research benefits the South African fruit industry by identifying the need for continuous improvement of the cold chain, which would assist in minimising temperature breaks.

1. Introduction

It is estimated that approximately one third of the four billion tons of food produced globally per annum is wasted due to supply chain failures from farm to retail, as well as final consumption losses at restaurants or in homes (FAO, 2011). It is further estimated that close to 815 million people, or 11% of the world’s population, are undernourished (World Hunger Education Service, 2018). The category fruits, vegetables, roots and tubers has the highest loss and wastage rate of any food per annum, estimated at 40–50%, compared to 35% for fish, 30% for cereals, and 20% for oil seeds, meat and dairy (FAO, 2011). Two case studies conducted by the FAO (2015) provide examples of the high losses in the fresh produce category: (1) total post-harvest losses (from farm to consumption) was estimated at 61% along a domestic commercial tomato supply chain in Fiji, and (2) post-harvest losses of 45% along a domestic cassava value chain in Nigeria (FAO, 2015). Wang, Fu, Fruk, Chen, and Zhang (2018) refer to quality losses of between 25 and 30% in a honey peach export chain in China.

In developed countries food losses typically arise at the end-consumer stage due to poor temperature management during final display, end-consumer aesthetic standards, conservative sell-by dates, and household wastage. In developing countries food losses typically occur at the post-harvest stages due to a lack of appropriate logistics infrastructure and lack of knowledge regarding handling of perishables. This translates into the need for increased investments in infrastructure, cold chains, packaging and market facilities, combined with increased education and awareness around sanitary standards and cold chain management (FAO, 2015; Gustavsson, Cederberg, & Sonesson, 2011).

Hunter, Smith, Schipanski, Atwood, and Mortensen (2017) estimate a maximum required increase in agricultural production of 70% by 2050. Half of this requirement can be met by significantly reducing food losses, which will then also contribute to reducing the environmental burden on the planet as the current waste and losses of food throughout the supply chain have a significant sunk cost in terms of direct and indirect cost impacts of logistics activities. A key component of reducing food losses is optimising fresh produce logistics due to the inherent perishability of the goods transported (Montanari, 2008; Aung & Chang, 2014). This necessitates the use of temperature-controlled supply chains, or cold chains.

The South African fruit industry exports approximately 2.7 million...
tons of fresh produce annually to 87 countries on four continents, which places it among the top 10 fruit-exporting countries in the world (DAFF, 2015).

Previous research confirmed the presence of temperature breaks in fresh produce cold chains through the Port of Cape Town. An analysis of the export cold chain for grapes, plums, pears and apples showed that only approximately 10% of the containers studied in the 2011/12 and 2012/13 export seasons did not experience any temperature breaks (Goedhals-Gerber, Haasbroek, Freiboth, & Van Dyk, 2015). A study on grape, plum and pear fruit container exports between January and March 2014 indicated that only one-fifth of containers experienced no temperature breaks, while almost a quarter never cooled down to the target temperature (Goedhals-Gerber, Stander, & Van Dyk, 2017).

South Africa is the second largest exporter of oranges worldwide and accounts for a quarter of all oranges traded internationally. Oranges were also the top contributor to South Africa’s value of fruit exports in 2016, contributing one fifth of fruit export value (National Agricultural Marketing Council, 2017). The USA has been identified as a strategic growth market for citrus exports from South Africa. The purpose of this article is to discuss research on the incidence and causes of temperature breaks along South Africa’s citrus export cold chain from the Western Cape through the Port of Cape Town to the USA, in order to guide the industry’s export programme.

This research contributes to a gap in understanding cold chain management in developing economies, as identified by Ndraha, Hsiao, Vlajic, Yang, and Lin (2018). The research also adds to the growing global discourse on reducing food waste and losses (as discussed earlier).

2. Literature survey

2.1. South Africa’s citrus industry

As mentioned, the South African fruit industry is among the top 10 fruit-exporting countries in the world (DAFF, 2015). Citrus fruits contribute 60% of fruit export volumes, pome fruit (apples and pears) 22%, and grapes 14%, combined constituting 95% of South African fruit export volumes (Post Harvest Innovation Programme, 2012). The citrus industry yields revenue of over R2bn per annum, of which 92% constitutes exports, and employs more than 100,000 people. Of the total citrus export volumes, 70% is oranges, 16% grapefruit, 8% lemons and 6% mandarins. Navel oranges contribute about 20% of the citrus export market (Biznews, 2019; Ndou, 2012).

Steady growth in citrus volumes is evident over the past two decades (refer Fig. 1) (the sharp drop in 2016 was due to hot and dry conditions in the north of the country, which negatively affected fruit quality), with volumes increasing by about 60% between 2000 and the 2014 peak. Yet, there was almost eight-fold increase in the value of South Africa’s citrus from 2000 to 2017. Average export values (in South African Rand) increased significantly since 2008: lemons quadrupled in value, while oranges, grapefruit and soft citrus yielded about 2.5 times more per ton in 2017 compared to 2008 (Citrus Growers Association, 2018), partly attributable to the depreciation of the South African currency (the Rand depreciated by approximately 61% against the US dollar from 2008 to 2017 (Nedbank, 2019).

The geographical contribution of export markets are also shifting. Exports to the traditional markets of Western Europe and the UK declined from 60% of citrus exports in 2000 to 40% in 2017, with Asian markets growing from 16% in 2000 to almost 25% in 2017, Middle East from 12% in 2000 to approximately 20% in 2017, North America from 4% in 2000 to 7% in 2017, and Eastern European exports from 4% to 9% in 2017 (Citrus Growers Association, 2018).

Growth in South Africa’s export volumes of citrus necessitated diversification into new markets, both to address challenges in traditional markets and to leverage opportunities in growing economies. In terms of challenges, diversification reduces the risk of excess supply, which negatively impacts returns in export markets (Citrus Growers Association, 2018). In addition, continuous challenges with exports to Western Europe due to stringent export requirements relating to citrus black spot (a foliar disease) could impact growth to that region (USDA, 2018), compounded by resistance from especially Spanish exporters to continued growth in South African exports (Wasserman, 2019).

Despite current small volumes, the USA is regarded as one of the South African fruit industry’s strategic markets in terms of high export potential (Kapuya, Chinembiri, & Kalaba, 2014). Citrus export volumes from South Africa to the USA averaged around 50,000 tonnes per annum for the past 4 years, with navel contributions contributing approximately 50%–60% to export volumes (refer Fig. 2) (Citrus Growers Association, 2018).

Together with China, Japan, Korea and Thailand, the USA is designated as a so-called ‘special market’ for South African exports with strict phytosanitary requirements to prevent the importation of agricultural pests into these markets (DAFF, 2018). In these instances, the export cold chain therefore not only plays the significant role of ensuring delivery of high quality fresh produce to end customers, but must also ensure that temperatures are maintained at the prescribed levels to meet the phytosanitary requirements of each market to eliminate consignment rejection.

In the next sections, the cold chain and phytosanitary measures are defined, followed by a description of the phytosanitary requirements prescribed by the United States and a review of the navel orange supply chain.

2.2. The cold chain

The cold chain is a temperature-controlled supply chain that allows for national and trans-national trade in perishable products such as fresh fruit and vegetables (Rodrigue & Notteboom, 2017). Efficient temperature monitoring and management from the point of harvest to the point of final consumption is the critical post-harvest success factor, which inhibits fruit deterioration and confers optimal shelf life as it reduces the rate of respiratory maturation and prevents microbial decay (Arah, Amaglo, Kumah, & Ofori, 2015; Berry, Delele, Griessel, & Opara, 2015; Matare, 2012). The maintenance of external fruit quality is an

![Fig. 1. Volume and value of South African citrus (export, local and processed) Source: Citrus Growers Association, 2018.](image1)

![Fig. 2. Citrus export volumes from South Africa to the USA Source: Citrus Growers Association, 2018.](image2)
important determinant of customer acceptance and therefore market price, while the maintenance of internal fruit quality is important for the repeated consumption of fresh citrus (Ladaniya, 2008; Torres, Pérez-Marin, De la Haba, & Sánchez, 2017). The objective of cold chain management is to maintain the integrity of the cold chain through adherence to globally agreed product-specific temperature ranges during storage and distribution activities. Integrity breaches – when the monitored temperature moves outside of the prescribed temperature ranges – can occur during transportation, transshipment or storage; continuous monitoring is thus imperative (Rodrige & Notteboom, 2017). Ndraha et al. (2018) and Badia-Melis, Mc Carthy, Ruiz-Garcia, Garcia-Hierro, and Villalba (2018) report on the frequent occurrences of cold chain integrity breaches across geographies and commodity types. The short shelf life of fresh fruit and vegetables, compounded by increasing trading distances, and the significant direct and indirect costs of food waste and losses, motivate ongoing research to improve cold chain integrity. The use of virtual cold chain methods to predict the temperature history and quality loss for each individual fruit throughout the cold chain, based on computational fluid dynamics and kinetic quality modelling, is being researched (Defraeye et al., 2016; Wu et al., 2018). This will provide data at a much higher spatial resolution, which will aid in inter alia packaging designs and cooling strategies. The ultimate aim is to engineer temperature traceability across the entire supply chain through a combination of wireless temperature-monitoring technologies to optimise cold chain integrity and minimise food waste (leveraging the Internet of Things) (Badia-Melis et al., 2018; Ndraha et al., 2018; Wang et al., 2018). Real-time information that enables preventative interventions is expected to improve food quality and safety, therefore, decreasing food losses and food waste, and improving the economic and environmental sustainability of the food supply chain (Ndraha et al., 2018).

The key cold chain elements for the South African citrus exports from the Port of Cape Town to the United States are sufficient cold store and conventional reefer capacity. The Citrus Growers Association estimates that the demand for cold store capacity in the Western Cape region is likely to increase by 6000 pallet spaces up to 2021. It is not foreseen that there will be capacity challenges during the citrus season as supply of out of season deciduous fruit capacity will exceed projected demands (Watts, 2019).

Navel oranges are exported from Cape Town on conventional reefer vessels. The share of conventional reeferers in the transport of refrigerated perishables decreased from 55% in 2000 to 18% in 2017 (the remainder is transported by reefer containers). Further reductions in sulphur emissions by the International Maritime Organisation will come into effect on January 1, 2020, which could lead to the scrapping of a number of old conventional reefer vessels. However, there has been virtually no new building activity since the turn of the century; in 2014 two ships were delivered, and in 2015 one, while 13 were scheduled for delivery in 2018 (Dynamar, 2018).

Reefer vessels are beneficial compared to reefer containers for citrus fruit exports. The vessels are self-contained with built-in cranes on the ship’s deck, making them independent of shore crane equipment. Breakbulk ship loading can continue in high winds, while container loading has to stop at a certain wind speed for safety reasons, especially important for exports through the Port of Cape Town owing to the high wind speeds experienced in the region. Importantly, individual operation of below-deck compartments in conventional vessels allows for spot checks to be done without compromising cold chain integrity, therefore, rendering cold sterilisation procedures more reliable (DAFF, 2010). Cold sterilisation treatment is the most common phytosanitary measure applied in perishable trade.

2.3. Phytosanitary measures

2.3.1. General description of phytosanitary measures

Phytosanitary measures refer to any legislation, regulation or official procedure having the purpose to prevent the introduction or spread of quarantine pests, or to limit the economic impact of regulated non-quarantine pests (FAO, 2017). Phytosanitary treatments are therefore used to disinfect agricultural commodities of quarantine pests, so that the commodities can be shipped out of quarantined areas. Phytosanitary treatments are measures done to the regulated article itself to lower the risk of the article carrying reproductively viable quarantine pests to levels that are acceptable. If live quarantine pests are found upon inspection, it is concluded that the treatment was not done, done sub-eficaciously, or the commodity was re-infested after treatment, and the consignment is rejected. These treatments comprise a group of measures whereby commodities are subjected to a process that kills, removes, or otherwise renders harmless quarantine pests that might be present (Hallman, 2017).

South Africa is home to a number of quarantine pests. Of specific reference to citrus are false codling moth (FCM), the Mediterranean fruit fly and the Natal fruit fly. Navel oranges are most prone to FCM attacks. For the cold chain under investigation this causes a high phytosanitary import threat as vast agriculture production areas in the south western states of the USA have similar climatic characteristics as South Africa (Goble, 2009). This means fruit has to be exported under quarantine measures to help combat these pests. The most common method used is cold sterilisation treatment.

Cold sterilisation treatments have been proven to eradicate larvae or eggs of pests when exposed to sub-zero temperatures (Ladaniya, 2008). Defraeye et al. (2016) report that the current standard dates from more than five decades ago, where a temperature of −0.55 °C for a duration of 21 days was shown to achieve 99.997% mortality at the 95% confidence level, so-called probit-9 mortality. (Recent research calls these low temperatures into question due to the high potential for chilling injury. This will be discussed later).

Citrus Black Spot (CBS), a foliar disease caused by a fungal pathogen, is restricted by specific climatic parameters and has not been recorded in Mediterranean citrus producing climates such as the Western Cape and Northern Cape. These areas have been declared CBS free and may export to North America. Other citrus-producing areas in South Africa may not (DAFF, 2010; Stotter, 2009).

2.3.2. Steri-market protocol for exports to the Unites States

The cold sterilisation protocol as set out by the USA Animal Plant Health Inspection Service (APHIS) is as follows (PPECB, 2012; 2019a):

- Fruit is pre-cooled for a period of 72 h in a cold store at or close to the port. During the last 24 h the fruit must be at the protocol temperature of −0.55 °C. The recommended cold store delivery air should not be colder than −1.5 °C.
- Citrus must be shipped to the end destination at a temperature of −0.55 °C for a period of 22 days. The treatment will commence when all three sensors on-board the reefer vessel are reading 31 °F (−0.55 °C) or below.
- The carrying temperature delivered to the compartment (in practice the set point of the thermostat controller) in the reefer vessel must be −1.5 °C for the full duration of the voyage.
- If the temperature of any of the three sensors exceeds 0 °C, the treatment shall be extended. If the temperature of any of the three sensors exceeds 1.11 °C at any time, the treatment for a common (AB) or independent (A) deck will be nullified for that specific deck. However, if the rejected deck is, for example, the upper deck, 1A, 2AB, 3AB or 4AB, then the fruit in the decks below the upper deck will also be nullified. The treatment shall be extended 8 h for each temperature spike that is above 0 °C. If the temperature spike is longer than 8 h, add another 8 h.
Sixty-two (62) temperature probes are inserted into fruit per deck and if any of these probes record a temperature above 1.11 °C, cold sterilisation treatment is nullified and the fruit is rejected upon arrival in the USA.

This protocol seems to have yielded success. In 2016, 5.8% of total citrus cartons exported were rejected by the USA, in 2017 2.7% and in 2018 only 1%. In 2017, 40% of rejections was due to FCM (46% in 2016) and 25% due to fruit fly (27% in 2016) (DAFF, 2019).

There are however concerns that chilling injury or freeze damage to fruit may occur at this low temperature. This refers to a reduction in the external quality of the fruit due to physiological disorders such as flavedo (peel) disorder, which occurs from sunken lesions and discolouration due to permanent damage to plant cells, because of exposure to temperatures below critical thresholds (Mathaba, 2012).

The PPECB (2019b) cautions against pulp temperatures dropping below −1.38 °C, while the BMT Cargo Handbook (2012) states that oranges start to freeze at temperatures below −1 °C. Koegelenberg (2019) quotes a representative from the Citrus Growers Association who goes as far as to state that, generally, 4.5 °C would be a much more preferable storage and shipping temperature for citrus. This might not be so far-fetched. Defraeye et al. (2016) conducted an experiment with three containers and note that there was no survival of FCM larvae in two of their three air-flow configurations, despite the fact that the fruit spent fewer than 18 days at (positive) 2 °C or below (container set point at 1 °C). The authors concede that to demonstrate the probit-9 mortality referred to earlier, 94,587 test individuals (in this case, oranges) are required, whereas in their experiment only 442 larvae were available. They are, however, confident that their study provides a strong indication that a partial cold-sterilisation protocol could successfully reduce the risk to a negligible level or even, in practical terms, eliminate it. This is an important avenue for future research as adhering to the current strict protocols is very onerous and costly. There is also a concern that very strict protocols can function as a trade barrier for exporting countries (Singh, 2016). The research on a combination of wireless temperature-monitoring technologies mentioned earlier, will make an important contribution to better inform appropriate temperatures for cold sterilisation.

2.4. Review of the navel orange supply chain

One of the main aspects of the cold chain that has to be taken into consideration to guarantee good logistical management is the cooling of fresh produce straight after harvest. The cold chain is largely responsible for maintaining product quality. After cooling, the deterioration and quality loss associated with senescence of fruit occurs at a much lower rate. The highest level of quality of fruit is at the moment of harvest, while the highest monetary value is at the moment of sale (Blackburn & Scudder, 2009).

Fig. 3 depicts the steps of a generic cold chain of navel oranges to the USA market under cold sterilisation protocols, which takes approximately 50–52 days. The chain starts at the farm. Citrus fruits are harvested once they reach peak maturity, which is determined through a maturity index. Fruit has to meet minimum regulatory standards for juice, sugar to acid ratio and peel colour before harvesting. The proposed use of fruits in the market helps distinguish parameters for fruit quality. The harvesting of oranges takes place once fruit trees and oranges are determined to be dry to avoid the occurrence of rind injury due to rupturing of oil glands, which is also known as oil spotting or oleocellosis. The greatest risk of oleocellosis occurring is in the early morning as dew from low early morning temperatures settles on trees.

Navel oranges are then transported to an open area for drenching, where they are left to dry in an open (unshaded) area for 24 h. Citrus fruits commonly go through a drenching process for reasons such as the removal of field heat to prevent moisture loss from the rind, lowering the chances of oleocellosis occurring, disease control and to allow degreening processes to be efficiently carried out (Muller, 2006). Once the fruit are dry, they are transported to the pack house where they first undergo the process of degreening, before following the necessary pack house processes.

Degreening is a method used to accelerate colour change in fruit with a ripening hormone called ethylene (Arpaia, 2015). Navel oranges are non-climacteric and do not change colour once harvested. Hence, degreening is required to achieve the orange colour required by consumers. Degreening is limited to three days and citrus fruits are degreened under temperatures ranging from 20 to 25 °C. Once navel oranges are taken out of the degreening chamber, they are moved to the pack house where they are placed into the pack line segment until all processes have been completed. Next, the navel oranges are transported to cold store facilities at the Port of Cape Town through road transportation.

The cold chain of navel oranges begins at the cold store. The cooling process occurs in two stages. The first stage involves citrus fruit pallets being offloaded and placed into a cold room for pre-cooling, to remove heat, which may have accumulated on the fruit during transportation. The methods used to pre-cool citrus are Forced Air-Cooling (FAC) and Room Cooling (RC), with FAC being the only method used for cold sterilisation treatment. FAC, also known as pressure cooling, involves fruits being placed in cooling chambers where extractor fans are used to create a pressure differential across pallets (at a temperature of approximately −1 °C, as oranges and grapefruits have an optimum temperature of −0.55 °C). FAC is achieved by exposing fruit to higher pressure on one side of the pallet, which forces the cool air through pallets and cartons, where it picks up heat, greatly increasing the rate of heat transfer. FAC plays a vital role in cooling down fruit to target temperature within a short period.

The second stage of the cooling process occurs after fruit have been inspected for quality. Palletised fruit are placed into cold chambers for the cold disinfection treatment to begin. Fruits are placed under FAC for a minimum of 72 h to reach a target temperature of −0.55 °C or below prior to loading. During the last 24 h, the pulp temperature is forced down to the optimum temperature of −0.55 °C. In the case of navel oranges shipped under cold sterilisation, fruit needs to be sufficiently pre-cooled to be able to maintain the required sub-zero temperatures. Navel oranges are transported to their end destination through specialised reefer vessels. Once inspectors have cleared the vessel, pallets are loaded using cranes. Once the loading process is complete, the conventional vessel doors are closed and the cold sterilisation procedure begins. The cold sterilisation protocol prescribes a mandatory exposure of −0.55 °C for 22 days on-board a vessel. After the mandatory 22 days, the delivery air temperature is increased to 0.5 °C as long as the vessel has not reached the port. The consignment is offloaded upon arrival and is sent for inspection. Upon passing inspection, the fruit is sent to a cold store to maintain cooling before distribution to the final market.

Each step of the cold chain has an impact on the final quality of navel oranges and temperature abuses that exceed the temperature levels may occur at any point leading to the raise in phytosanitary safety concerns (Mercier, Villeneuve, Mondor, & Uysal, 2017). Despite the measures put in place to ensure proficient export processes, losses still occur due to temperature breaks. This article seeks to fill the information gap on whether temperature breaks occur along the export cold chain and what the possible causes of temperature breaks are.

3. Materials and methods

The main objective of the study was to identify whether there are temperature breaks in the different phases of the navel orange export cold chain from the Citrusdal region, in the Western Cape, South Africa to Philadelphia in the USA. Data was collected in the Citrusdal region at Farm X and Pack house Z. The main objective was achieved by analysing the temperatures collected through temperature trials along the
different stages of the cold chain. Temperature trials refer to gathering of pulp temperature data through the insertion of temperature monitors inside the pulp of the citrus fruit and ambient temperature by measuring the temperature inside cartons stacked on pallets. Temperature monitors known as iButtons® were used to record both pulp and ambient temperature. An iButton® is a coin-sized electronic device that acts as a temperature sensor with an electronic memory to record temperature readings. To record temperature data as close to product temperature as possible, iButtons® were used to record both pulp and ambient temperature. An iButton® was inserted into the pulp of the fruit and for ambient temperature, iButtons® were placed amidst fruit cartons stacked on pallets. iButtons® capture temperatures at pre-set intervals; for this research pulp and ambient temperatures were captured every 30 min for the duration of the export cold chain.

The study divided temperature trials into two phases, firstly, from the orchard to the cold store (before the fruit consignment was accepted for pre-cooling) and secondly, from the cold store until the port of destination. The first phase was analysed for temperature spikes while temperature breaks were analysed during the second phase. For the purpose of data analysis, in order to determine what qualifies as a temperature spike or temperature break for the USA steri-market, definitions had to be developed. For the first phase of the supply chain, a temperature spike is defined “as any occurrence when temperature rises along the export cold chain.” The temperature has to rise by 2 °C or more for the rise to be significant and influence the fruit quality (Goedhals-Gerber et al., 2017). For the second phase of the supply chain, a temperature break is defined as “a temperature deviation above 0 °C or below −1.5 °C.” The latter definition takes into account steri-market protocol requirements. Steri-market protocols stipulate that pulp temperature may vary between −0.55 °C and 0 °C, but if temperatures exceed 0 °C, it is considered a steri-break and the cold treatment is extended so that temperature is decreased to −0.55 °C. If the temperature exceeds 1.11 °C, cold sterilisation treatment is nullified (PPECB, 2012). The fruit is considered as being at risk of chilling injury anytime the temperature is equal to, or drops below, the citrus chilling injury threshold of −1.5 °C.

In the orchard, drenching and degreening stages, iButtons® were randomly placed into fruit bins. From the pack house to the port of destination, iButtons® were inserted into fruit (pulp temperature) and placed inside cartons (ambient temperature), stacked on pallets. Each pallet is stacked with seven layers of cartons. Three cartons are placed lengthwise on the long side of the pallet, with another three next to them; four cartons are then placed crosswise to complete the first stacking layer. The iButtons® were placed in the first (bottom), fourth (middle) and seventh (top) layers of the pallets. For the purpose of this research, four temperature trials were conducted. The temperature trials used 280 iButtons® of which 216 measured pulp temperature and 64 measured ambient temperature. However, USDA officials only reused the iButtons® to download the temperature data for two of the four temperature trials. Therefore, the results are based on the data collected for two temperature trials, namely for navel oranges shipped on the Santa Lucia and Regal Bay vessels. For both temperature trials, 56 iButtons® were inserted to measure pulp temperature and 14 iButtons® were placed to measure ambient temperature. Both temperature trials took place during May and June 2017.

To supplement the trials, historic temperature data was used to analyse the deep-sea leg of the export cold chain in more detail, as the deep-sea leg forms part of the cold sterilisation treatment protocols. The historic data was received from exporting companies that monitor the fruit temperature from the cold store to the final port of destination. For confidentiality, these datasets are referred to as Cold Chain 1 and 2 in the article.

Cold Chain 1 belongs to an export organisation that provides cold chain management services. The data analysed is from May 2014. Temperature data supplied by Cold Chain 1 was received per deck and per day from one vessel transporting navel oranges to the United States of America. The data was analysed from when the decks and compartments on the reefer vessel were closed, and cold treatment commenced until the port of destination. Fruit pulp temperature was measured by at least three probes per deck or combined deck.

Cold Chain 2 belongs to an export company that supplies fresh fruit to global markets. The data that was sourced from Cold Chain 2 was collected at approximately the same time of year during the 2016 and 2017 export seasons as the data of this particular research, i.e. during May and June. The data analysed is from the deep-sea leg of the export cold chain phase. For Cold Chain 1 and 2, a temperature break for cold sterilisation protocols was identified when the temperature deviated above 0 °C or below −1.5 °C and a temperature break for cold sterilisation protocols was identified when the temperature exceeded 1.11 °C, as stipulated by the PPECB regulations.

4. Results

The results of the two temperature trials are first discussed, followed by the results of the historic data analysis.

Fig. 3. Depiction of the export cold chain.
4.1. Temperature trial 1: Santa Lucia vessel

Fig. 4 shows the time series of the average pulp and ambient temperatures of navel oranges from the orchard until the cold store, before pre-cooling commenced.

Fig. 4 shows that a temperature spike was observed at the start of the chain. This is due to heat absorbed by the fruit after they have been left to dry from the drenching process. The highest pulp and ambient temperatures recorded during drenching were 23.09 °C and 20 °C respectively. The lowest pulp and ambient temperatures recorded were 15.54 °C and 14.53 °C respectively. The average pulp temperature increased gradually from 18.3 °C to a maximum of 22.7 °C, whilst the average ambient temperature increased from 15.7 °C to 18.3 °C. The rise in temperature is attributed to weather conditions on the day of harvest (the outside temperature was above 22 °C). The temperature rose gradually as the fruit was placed into the degreening chamber (but remained within the acceptable degreening range of 21 °C–25 °C, with the highest pulp and ambient temperatures recorded at 22 °C and 24.32 °C and the lowest pulp and ambient temperature recorded were 20.02 °C and 21.4 °C). The temperatures stayed relatively stable throughout the pack house processes. Fruit was transported to the cold store at the Port of Cape Town on 19 May. The transportation phase shows a continuous increase in temperature. The maximum pulp and ambient temperatures recorded were 22 °C and 25.06 °C respectively, with the average pulp temperature rising to 21.40 °C and the average ambient temperature rising to 20.2 °C. The lowest pulp temperature recorded during the transportation phase was 15.03 °C and the lowest ambient temperature recorded was 15.30 °C. The temperature eventually started decreasing once fruit pallets were placed into the cold store.

Fig. 5 identifies the incidents of temperature breaks during the second phase of the export cold chain, namely from the cold store to the port of arrival.

4.2. Temperature trial 2: Regal Bay vessel

Fig. 6 depicts the time series of the average pulp and ambient temperatures of navel oranges from the orchard until the cold store, before pre-cooling commenced. It shows a few pulp and ambient temperature anomalies.

For the Regal Bay temperature trial, export cold chain processes were not followed precisely. For instance, fruit was transported directly to the pack house instead of being left to dry outside in an unshaded area after drenching, which explains the decrease in pulp temperature soon after harvest. The average ambient temperature depicts a rapid decrease to 13.26 °C and the average pulp temperature decreased to 14.15 °C. A gradual temperature rise is depicted during the degreening
Fig. 5. Average ambient and pulp temperatures for phase 2 of the Santa Lucia trial (in °C).

Fig. 6. Average pulp and ambient temperature of phase 1 of the Regal Bay trial (in °C).
Fig. 7. Average pulp and ambient temperature of phase 2 of the Regal Bay trial (in °C).

Fig. 8. Average pulp temperature for navel oranges in 2014 for three decks.
stage, with the maximum pulp temperature recorded at 24.93 °C and the maximum ambient temperature recorded at 25.0 °C. The lowest pulp and ambient temperatures recorded during degreening were 21.07 °C and 21.4 °C respectively. No temperature spikes were identified as the temperature is kept within an acceptable degreening range (21 °C–25 °C). The average ambient and pulp temperature of the fruit shows a spike in temperature during transportation to the cold store at the Port of Cape Town. The highest pulp temperature recorded during transportation to the cold store was 22 °C and the highest ambient temperature recorded was 24.6 °C. The lowest pulp temperature recorded during transportation to the cold store was 19.1 °C and the lowest ambient temperature recorded was 21 °C.

Fig. 7 shows the second phase of the export cold chain on the Regal Bay vessel. It depicts the average pulp and ambient temperatures for cartons staged on pallets as they move through the cold store until the port of destination.

Fig. 7 shows that prior to the sail date, temperatures increased to outside the acceptable range. The maximum pulp temperature rose to 8.17 °C and the maximum ambient temperature rose to 10.23 °C. The average ambient temperature recorded in the pallets carrying the navel oranges reached an alarming 8.83 °C. The temperature break was recorded prior to the commencement of the cold sterilisation protocols in the reefer vessel. The average pulp temperature rose to 5.19 °C. The temperature breaks in both ambient and pulp temperatures lasted for approximately 9 h before the temperatures returned to below 0 °C. On the reefer sail date (02 July), temperatures were within cold sterilisation protocols, which varied from below –0.55 °C–0 °C, with the highest pulp temperature recorded at –0.2 °C and the highest ambient temperature recorded at –0.1 °C. Both the lowest pulp and ambient temperatures recorded during the sea leg were –0.6 °C and remained at –0.6 °C until arrival at the port of destination.

4.3. Historic data: Cold chain 1

Fig. 8 indicates the average pulp temperatures of fruit on different decks of a vessel used in 2014 (shown as V1, V2 and V3). The decks are individually operated, thus enabling a comparison in the temperatures supplied and an analysis on whether all consignments loaded onto the different decks of the vessel were able to meet cold sterilisation protocols. The graph shows that for the majority of the sea leg journey, temperature is kept below the threshold temperature until cold sterilisation protocols are completed. However, a temperature break did occur in V2. The temperature exceeded the steri-breath temperature of 0 °C, but not the threshold temperature of 1.11 °C. The temperature breaks are indicated on the graph on 19–20 June (the rise indicated on 16 July is due to the fruit arriving in port and the offloading process commencing). The rise in temperature above 0 °C in V2 means that Cold Chain 1’s fruit consignment would need to be cooled down to –0.55 °C for at least three days to meet steri-protocols. It is evident in Fig. 8 that this occurred.

Only one of the decks utilised during the historic export season experienced a cold sterilisation protocol breach. Cold chain 1 depicts a fairly well managed export cold chain with a decrease in temperature and a few spikes along the sea leg.

4.4. Historic data: Cold chain 2

Fig. 9 illustrates the average temperatures of fruit on two vessels used by Cold Chain 2 for the 2016 and 2017 seasons (AVG V1 depicts the year 2016 and AVG V2 depicts the year 2017). The comparison was made between vessels that sailed at approximately the same time of year, but during different years. An analysis for the different years was undertaken to assess whether temperature breaks had occurred over the different export seasons for Cold Chain 2. The graph shows that the temperatures of the two vessels are within steri-protocols, further proving the efficiency of Cold Chain 2’s export cold chain.

5. Discussion

The Santa Lucia vessel (temperature trial 1) identified that temperature spikes were more prone during the drenching phase of the export cold chain. The temperature spikes started a few hours after the navel oranges were drenched and left to dry in an open area. These spikes continued until outside temperatures had dropped (below 22 °C). The temperature spikes were not depicted after the fruit was removed from the drench area and sent to the pack line segment of the cold chain. Temperature spikes were also identified during the transportation phase of the navel oranges to the cold store in the Port of Cape Town. After the navel oranges had been placed in cold storage, temperature breaks were most evident during the inspection and loading stages. During inspection, samples of fruit pallets are placed in an unrefrigerated area. However, prior to inspection, the fruit pallets are placed into a cold room with a set point of 4 °C. The fruit has to maintain the temperature induced in the cold room while undergoing inspection. However, it was evident that both ambient and pulp temperature of fruit rise during inspection. The loading stage also experienced temperature breaks. The loading phase for the Santa Lucia vessel trial showed that the temperature of navel oranges exceeded 0 °C for periods longer than 2 h on a number of occasions.

The Regal Bay vessel trial also indicated that temperature spikes were prone during the transportation phase from the pack house to the Port of Cape Town. Both pulp and ambient temperature showed an increase during transportation of fruit to the cold store. The inspection and loading phase also depicted temperature breaks. During the loading of the vessel, temperature breaks lasted for over 9 h. For both reefer vessels, no temperature breaks occurred once cold sterilisation treatment protocols had commenced, i.e. the temperature was kept below 0 °C, which proves the efficiency of the export cold chain during the sea leg.

It is important to note that in addition to the temperature monitoring devices inserted for the temperature trials, cold sterilisation protocols are validated on special probes inserted into the fruit by the PPECB. Sixty-two (62) temperature probes are inserted into fruit per deck and if any of these probes record a temperature above 1.11 °C, cold sterilisation treatment is nullified and the fruit is rejected upon arrival in the USA. During the two trial shipments conducted, there were no temperature breaks recorded by the PPECB, confirming the efficiency of the cold chain once cold sterilisation treatment protocols commence on the reefer vessels.

In addition, the historic temperature data analysed proved that cold sterilisation protocols are mostly kept within the stipulated temperature ranges. Cold Chain 1 depicted a steri-breach (but not break) in one vessel.

It is clear that there are very few temperature breaks in the cold store and deep-sea leg phases and relatively few temperature spikes are depicted in the beginning stages of the export cold chain. The export cold chain of navel oranges shipped to the US may owe its success largely to the fact that a consignment is rejected if cold sterilisation protocols are not adhered to, which in turn translates into a loss of projected revenue.

6. Conclusion

The citrus industry contributes substantially to the South African economy through the exportation of fresh navel oranges and other citrus fruits. The study aimed to identify whether temperature spikes and breaks occur in the navel orange export cold chain. From the data analysis it is clear that temperature spikes occurred during the drenching, transportation, inspection and loading segments. The spikes are thought to occur during those phases because of the exposure to different weather elements (the fruit had temperature spikes when the daily temperature was above 22 °C), delays during transportation, congestion at the port and delays during inspection.
The results derived from data analysis prove that there is room for improvement in terms of optimal management of the export cold chain. Recommendations made that can assist in the improvement of the cold chain include leaving fruit to dry under a shaded area after drenching and the inspection area to be set at the same temperature as pack houses (18 °C–25 °C) to avoid a steep rise in temperature while fruit pallets await inspection.

Although the study addressed a range of issues relating to temperature spikes and breaks, more research can still be undertaken on the topic. A similar research study could be conducted by focusing on a larger variety of citrus cultivars. This research showed that the deep-sea leg is efficient, so it would be interesting to focus on the first phase of the export cold chain, i.e. temperature data from the orchard until the cold store. The study could also be expanded to include citrus cultivars produced in other regions that are exported to steri-markets.

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References


