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Investigating the effect of cold store airlocks on the temperature control and protocol compliance during orange handling operations

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Author:
Leila L. Goedhals-Gerber[1]

Affiliation:
[1]Department of Industrial Engineering, Faculty of Engineering, Stellenbosch University, Stellenbosch, South Africa

Corresponding author:
Leila Goedhals-Gerber,
leila@sun.ac.za

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Background: Cold storage facilities must balance energy conservation with temperature compliance for perishable exports, yet comparative evidence on airlock design and refrigeration technology remains limited.

Objectives: This study compared cooling performance of two cold storage facilities with differing refrigeration technologies and airlock configurations during orange handling.

Method: iButtons® were placed in orange cartons across five pallets per facility during July–August, coinciding with peak Western Cape Valencia orange export season. CS1 used conventional refrigeration with non-temperature-controlled (NTC) airlocks; CS2 used advanced refrigeration with temperature-controlled (TC) airlocks. Data were recorded at 15-minute intervals and analysed using descriptive statistics, a chi-square test, and the Mann–Whitney U test. Cooling rate was defined as time elapsed until average pallet temperature first reached 5 °C.

Results: CS2 achieved superior control, with 85.92% of readings at or below 5 °C versus 57.46% for CS1. Mean temperatures were 2.98 °C (CS2) and 6.14 °C (CS1). CS2 reached 5 °C within approximately 1.5 hours of pallet arrival; CS1 required approximately 25 hours. Differences between facilities were highly significant ($p < 0.001$), with large effect sizes (Cohen's $d = 1.04$; rank-biserial $r = 0.73$).

Conclusion: TC airlock systems substantially improved protocol compliance over selective-cooling approaches. For citrus exports requiring sub-5 °C storage, TC airlocks are essential for maintaining export quality.

Contribution: Findings offer evidence-based guidance for cold chain operators and policymakers balancing energy efficiency with temperature control in South African agricultural export management.

Keywords: cold storage; cold chain; airlock loading bay; refrigerated storage; fresh fruit exports.

Introduction

The global trade in perishable agricultural products relies heavily on sophisticated cold chain systems to maintain product quality and extend shelf life during extended transportation periods. This is particularly critical for citrus fruits, which represent a significant portion of the international fresh produce trade. South Africa, as the world's second-largest fresh citrus exporter, contributes substantially to this trade, exporting 2.6 million tonnes in 2022 and generating over $3.3 billion in export revenue (Citrus Growers' Association 2025; Fresh Produce Exporters' Forum 2025).

The effectiveness of cold storage facilities in maintaining optimal temperatures throughout the handling and storage process is fundamental to preserving fruit quality and meeting international market standards. However, cold storage operations are energy intensive, creating pressure on facility operators to optimise energy use while maintaining temperature protocols.

Recent studies have highlighted the substantial environmental impact of cold storage operations within freshly produced supply chains. Du Plessis, Van Eeden and Goedhals-Gerber (2024) determined that cold storage contributes 8% of total carbon emissions in the citrus export chain from South Africa to international markets, representing 0.87 kg CO_2e per kg of oranges. Du

Plessis, Van Eeden and Goedhals-Gerber (2022) also quantified the energy requirements for cold storage operations at 7.62 kWh per pallet per day, equivalent to 7.52 kg CO_2e daily emissions per pallet.

These energy considerations have led some cold storage facilities to implement energy-saving measures that may compromise temperature control effectiveness. One common practice involves selectively cooling specific areas within the facility while leaving others, such as loading bays and transition areas, without active refrigeration.

This approach raises critical questions about the trade-off between energy conservation and temperature maintenance effectiveness.

Oranges were selected as the model fruit because they are the dominant Western Cape citrus export by volume, have a well-established 5 °C protocol storage temperature, and are commercially handled in large volumes by both participating facilities, allowing matched comparisons. Their relatively thick rind also makes them less susceptible to mechanical damage from instrumentation, so observed effects can be attributed to temperature rather than handling artefacts. Although the focus is on oranges, the airlock and refrigeration findings are expected to be broadly applicable to other citrus varieties that share the same protocol temperature.

To the author's knowledge, this is the first published controlled comparison of two operational South African citrus cold stores using contrasting refrigeration and airlock technologies under matched protocol conditions. The study therefore provides a quantitative basis for the energy-versus-compliance trade-off that has previously been discussed only qualitatively in the literature.

Formally, the following hypotheses were tested with respect to the impact of temperature-controlled (TC) versus non-temperature-controlled (NTC) airlocks on cooling performance:

H_0: There is no difference in the temperature distribution of orange cartons handled in cold stores employing TC airlocks compared with those employing NTC airlocks.

H_1: Cold stores employing TC airlocks maintain a significantly higher proportion of carton temperature readings at or below the 5 °C protocol threshold than cold stores employing NTC airlocks and exhibit lower mean and median temperatures during loading operations.

This study addresses this knowledge gap by comparing the cooling performance of two different cold storage facility designs: One employing advanced refrigeration technology with TC airlock systems and another using conventional cooling technology with NTC loading areas. The research examines the effectiveness of these different approaches in achieving and maintaining protocol temperatures for exported oranges, providing insights into the relationship between refrigeration technology investment and temperature control performance.

Theoretical framework

South African citrus industry

South Africa is the second largest exporter of fresh citrus globally, exporting 2.38 million tonnes in 2023/2024 (Citrus Growers' Association 2025), which accounted for 54% of the country's fresh fruit exports (Fresh Produce Exporters' Forum 2025). Fresh fruit represented approximately 35% of the country's agricultural exports, and the economic value generated from fresh fruit and vegetable exports in 2024 was estimated to exceed $4 billion (Fresh Produce Exporters' Forum 2025). Citrus is a perishable product that requires being handled, stored and transported at protocol temperature with the help of a cold chain to maximise shelf life and maintain its competitiveness in the global market (Arah et al. 2015; Berry et al. 2015; Goedhals-Gerber & Khumalo 2020; Khumalo et al. 2023a; Matare 2012).

Citrus export cold chain

The citrus supply chain starts in the orchard when the fruits are harvested upon reaching maturity. After harvesting, the fruits are drenched, degreened with ethylene at 18–25 °C (Citrus Academy 2022), graded, packed into cartons and palletised (Conradie, Goedhals-Gerber & Van Dyk 2022). Pallets are transported to a cold store near the port of export, where they undergo forced-air cooling (FAC) to reduce the fruit pulp temperature to the required protocol temperature. Once protocol temperature is reached, pallets are moved to the staging area for loading into reefer containers, transported to the port, loaded onto the vessel and shipped.

Figure 1 depicts a typical citrus cold chain, which starts at the cold store and should be maintained until the fruit reaches the shelf in the retail outlet. This study focusses on the FAC, staging and loading of fruit into reefer containers at the cold store, highlighted by the red block in Figure 1. To maintain the cold chain during loading, an airlock may be used.

Cold storage refrigeration systems and energy efficiency

Cold storage facilities for perishable products operate on fundamental principles of heat transfer and thermodynamic cycles to maintain product quality while managing energy consumption. The effectiveness of refrigeration systems

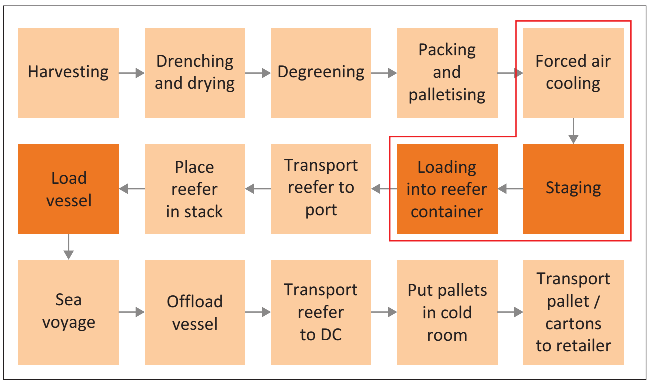


FIGURE 1: A typical citrus export cold chain.

depends on system design, airflow management and thermal load distribution (Fikiin & Markov 2014). Energy costs typically represent 60% – 70% of total operational expenses in refrigerated storage operations, and loading and staging areas represent critical points where temperature control can be compromised (Johansson & Marmy 2019).

Airlock systems in cold storage operations

Airlock systems serve as thermal barriers between refrigerated storage areas and ambient conditions, designed to minimise heat infiltration during loading and unloading (Maiorino, Petruzziello & Aprea 2021). Temperature-controlled (TC) airlock systems maintain active refrigeration throughout loading operations, providing consistent thermal protection (Wang 2000). In contrast, non-temperature-controlled (NTC) systems rely on passive thermal protection through insulation and air curtains, depending on residual cold air from adjacent refrigerated areas (Wang et al. 2025). Fikiin and Markov (2014) demonstrated that properly designed airlock systems can reduce refrigeration energy consumption by 15% – 25% while maintaining temperature protocols. The energy trade-offs between active airlock cooling and increased refrigeration loads from compromised temperature control require careful evaluation in facility design decisions.

Temperature control in citrus cold storage

Citrus fruits require precise temperature management to maintain quality attributes and extend shelf life during storage and transportation (Khumalo et al. 2023a). The optimal storage temperature for most citrus varieties is maintained below 5 °C to minimise respiration rates, reduce moisture loss and inhibit microbial decay (Goedhals-Gerber & Khumalo 2020). Temperature fluctuations above this threshold can accelerate physiological processes leading to quality deterioration, including loss of firmness, colour degradation and increased susceptibility to pathogenic decay.

Energy considerations in cold storage operations

Cold storage operations are inherently energy-intensive. Du Plessis et al. (2022) quantified energy requirements for cold storage operations at 7.62 kWh per pallet per day (7.52 kg CO_2e daily emissions per pallet). Within the broader citrus export supply chain, cold storage contributes approximately 8% of total carbon emissions, representing 0.87 kg CO_2e per kilogram of oranges (Du Plessis et al. 2024). Energy conservation strategies such as selective area cooling may compromise temperature control in critical areas; the trade-off between energy conservation and temperature protocol compliance represents a key operational challenge requiring evidence-based guidance.

Research methods and design

Temperature trials were conducted with oranges in two cold stores in the vicinity of Cape Town during the winter months of July and August. July and August were selected because they coincide with the peak Western Cape Valencia orange export season, when both facilities are operating under representative commercial throughput.

Conducting trials in winter also provides the most rigorous comparison of the two airlock designs, because the smaller temperature gradient between ambient and protocol temperature is the condition under which an NTC airlock is most likely to perform acceptably; observing significant differences under winter conditions, therefore, represents a conservative test. Both facilities specialise in the cold storage of fruit exported from South Africa. Cold store 2 is a facility with TC airlock offloading and loading bays, while CS1 is equipped with NTC airlock loading bays whose loading bays rely on cold air released from the FAC tunnels.

Invasive methods are required to measure fruit pulp temperature, resulting in the loss of fruit, while ambient temperatures can be recorded in non-invasive ways. Therefore, only ambient temperatures were recorded by placing iButtons® inside the cartons between the oranges. Although fruit pulp temperature is the most direct indicator of physiological state, invasive pulp probing damages the fruit and renders it unsalable, which was not acceptable to the participating commercial facilities. Ambient temperature recorded between fruit inside a closed carton has been shown to track pulp temperature closely once FAC has been completed (typically within ~0.5 °C to 1 °C), and is the standard measurement used in commercial cold chain monitoring (Goedhals-Gerber & Khumalo 2020; Khumalo et al. 2023a). The ambient temperature approach is therefore acknowledged as a limitation for the very early cool-down phase but is not expected to bias the between-facility comparison because the same instrumentation and placement protocol was applied identically to both cold stores. An iButton® is a small, coin-sized electronic temperature sensor that records and stores temperature readings, with a precision of ± 0.5 °C from −10 °C to 65 °C (Analogue Devices 2026; Khumalo et al. 2023b).

The iButtons® were inserted before the fruit went into the FAC tunnels and were removed just before the pallets were loaded into the reefer containers.

The Coldstream software was used to calibrate the iButtons® to record the temperature every 15 min. A 15-min sampling interval is consistent with previous citrus cold chain monitoring studies (Conradie et al. 2022; Goedhals-Gerber & Khumalo 2020; Khumalo et al. 2023a) and is the standard interval used by commercial Coldstream loggers. It is sufficient to capture the loading-event temperature excursions of interest, which typically last from several minutes to several hours, while keeping logger memory and battery use within practical limits for multi-day trials. A pilot test at finer (5 min) resolution did not change the proportion of readings classified as above 5 °C and is therefore not reported separately. The iButtons® were spread over five pallets for each trial, with 39 iButtons® used in CS1 and 37 iButtons® used in CS2 in total. The iButtons® were inserted into open-top cartons containing oranges, which had to be kept at a temperature of below 5 °C, between the oranges in different layers of the pallets, with their locations recorded for identification.

Nine iButtons® in pallet 3 of CS1 and one iButton® in pallet 1 of CS1 malfunctioned, reducing the usable CS1 sample to 29 loggers (10 892 readings) versus 37 loggers (10 471 readings) in CS2. The total number of readings is therefore very similar between facilities, and statistical power for the nonparametric tests used here is not materially affected. To control for the residual difference in N, between-facility comparisons were performed on proportions of readings (e.g. percentage of readings ≤5 °C) rather than on absolute counts. As an additional sensitivity check, the analysis was re-run after randomly down-sampling CS2 to match the number of CS1 loggers; the conclusions were unchanged.

Descriptive and nonparametric statistical analyses were used to compare the two datasets. The data were cross-tabulated to determine the number of temperature readings above 5 °C and below or equal to 5 °C for each trial, and percentages were used to allow comparison, given the slightly different sample sizes. The cross-tabulation analysis was supplemented with a maximum likelihood chi-square test to determine whether the frequency of temperature readings above and below or equal to 5 °C differs between CS1 and CS2.

Because the temperature data are recorded over time and decrease as cooling progresses, they cannot reasonably be assumed to be normally distributed, so the nonparametric Mann–Whitney U test was used as the equivalent of the two-sample t test (Keller & Warrack 2000). The Mann–Whitney U test was preferred over the Kolmogorov–Smirnov (K-S) two-sample test because the research hypothesis concerns a difference in central tendency (i.e. whether one facility runs systematically warmer than the other), rather than differences in distributional shape per se. Mann–Whitney U is the more powerful test for stochastic-dominance-type alternatives such as that posed by H_1, and is also the standard nonparametric counterpart of the t test reported in cold chain studies, allowing direct comparison with prior literature. In addition to the significance tests, two effect-size statistics were computed: Cohen's *d*, calculated from the means and pooled standard deviation, and the rank-biserial correlation derived from the Mann–Whitney U statistic, which is appropriate for nonparametric two-sample comparisons.

Ethical considerations

Ethical clearance to conduct this study was obtained from the Departmental Ethics Screening Committee of Stellenbosch University, which assessed the research as low ethical risk. Access was granted to collect non-identifiable temperature data that were not linked to any individual or personal account.

Results

Data from 29 iButtons® in CS1 and all 37 iButtons® in CS2 were successfully retrieved, yielding 10 892 and 10 471 valid temperature readings, respectively (see 'Research methods and design' section for the data-loss handling protocol).

Figure 2 shows the average and the 20th and 80th percentile temperature profiles for CS1 and CS2. The X-axis has been re-labelled to show elapsed time in hours since the start of the trial, rather than the count of 15-min intervals, to make cooling rates directly comparable between the two facilities. The CS1 trial is longer than the CS2 trial because the fruit had to remain in the cold store waiting for the reefer container – this reflects operational dwell time rather than a difference in cooling capacity, and the proportional metrics in Table 2 are not biased by this difference. The weather was very similar in July and August, with maximum temperatures of 16 °C – 18 °C and is therefore not considered to have an impact on the results.

Upon arrival at CS2, the oranges were offloaded into a TC airlock receiving area, which is reflected in the lower initial temperature in Figure 2. The fruit was cooled down much faster in CS2 and then maintained at its ideal temperature of below 5 °C. In CS1, the average temperature hovered slightly above 5 °C for an extended period before finally dropping below 5 °C. Defining cooling time as the elapsed time from the start of the trial until the average pallet temperature first reached the 5 °C protocol threshold, CS2 reached protocol within approximately 1.5 h of arrival, whereas the CS1 average only crossed 5 °C after roughly 25 h and remained marginal for an extended period thereafter. This represents an order-of-magnitude difference in cooling rate between the two facilities.

Discussion

Descriptive statistical analysis

The descriptive statistics for the two cold stores are reported in Table 1 and the box-and-whisker plot in Figure 3. CS2 has a lower value than CS1 for all the parameters.

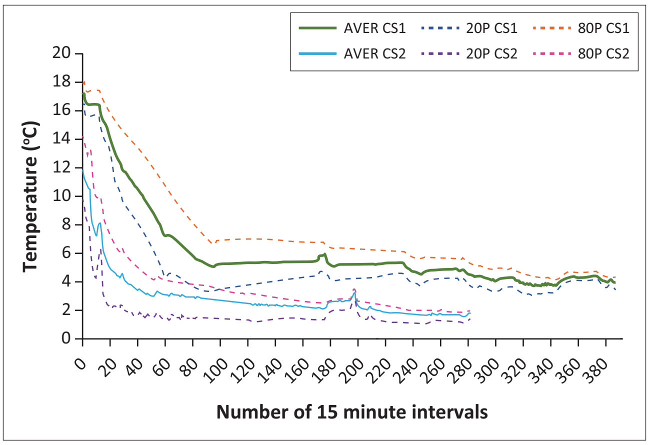
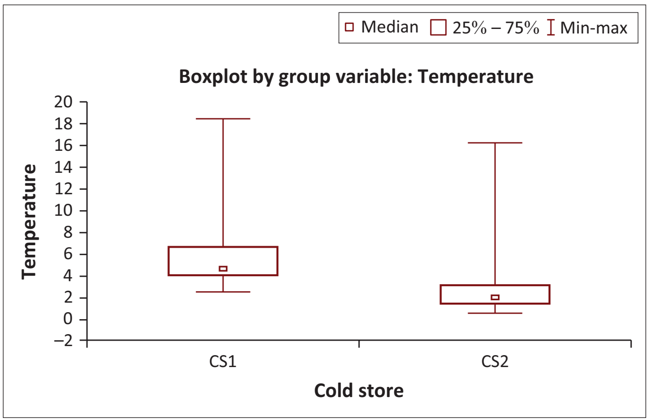


FIGURE 2: Temperature profiles for cold store 1 and cold store 2.

TABLE 1: Descriptive statistics for Cold store 1 and Cold store 2.

Cold store	N	Mean	Median	Min	Max	Lower Q	Upper Q
CS1	10 892	6.141	4.694	2.563	18.449	4.094	6.689
CS2	10 471	2.976	2.057	0.606	16.240	1.488	3.175

Note: Standard deviation: CS1 = 3.449 and CS2 = 2.524.
CS1, cold store 1; CS2, cold store 2; Min, minimum; Max, maximum.



CS1, cold store 1; CS2, cold store 2; Min-max, minimum to maximum.

FIGURE 3: Box-and-whisker plot for cold store 1 and cold store 2.

In Figure 3, the CS1 distribution exhibits a substantially higher upper whisker (18.4 °C vs. 16.2 °C in CS2), a higher median (4.69 °C vs. 2.06 °C), and an interquartile range that lies almost entirely above the interquartile range (IQR) of CS2.

While both facilities exhibit isolated extreme readings, the volume of high readings in CS1 (above the 5 °C threshold) is approximately three times that of CS2, indicating sustained periods of temperature instability rather than isolated excursions. Cross-referencing the operational logs with the temperature traces shows that the warm episodes in CS1 coincide with: (1) airlock door openings during pallet ingress and egress, (2) periods when fruit was held in the staging area awaiting reefer container loading and (3) the gap between forced-air cooling completion and dispatch – events during which the NTC loading area in CS1 has no active cooling and depends entirely on residual cold air from the FAC tunnels.

The data were cross-tabulated to determine the number and percentage of temperature readings above 5 °C and below or equal to 5 °C in each cold store. The results are displayed in Table 2.

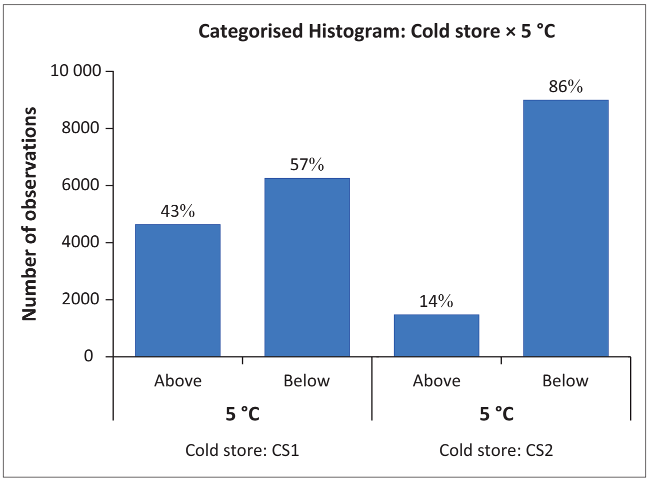
Nonparametric analysis

In Table 2, CS2 has a much larger percentage of data points below or equal to 5 °C than CS1. A maximum likelihood chi-square test was performed to determine whether the frequency of temperature readings above and below or equal to 5 °C differs between CS1 and CS2. The test was significant at the 99% confidence level (Chi-square [$df = 1$] = 2203.09, $p < 0.01$), as illustrated in Figure 4.

The Mann–Whitney U test was used to determine whether there is a significant difference between the temperature

TABLE 2: Contingency table of temperature readings above 5 °C and below or equal to 5 °C in each cold store.

Cold store	> 5 °C		< 5 °C		Row totals
	n	%	n	%	
CS1	4634	42.54	6258	57.46	10 892
CS2	1474	14.08	8997	85.92	10 471
Totals	**6108**	**-**	**15 255**	**-**	**21 363**



Note: Chi-square ($df = 1$) = 2203.09; $p < 0.01$.
CS1, cold store 1; CS2, cold store 2.

FIGURE 4: Histogram of the percentage data points above and below 5 °C for cold store 1 and cold store 2.

distributions of the two independent cold stores. With Rank Sums of 157 924 390 (CS1) and 70 275 176 (CS2), $U = 15\,449\,020$, $Z = 92.27$ and $p < 0.001$. The Z value that corresponds to a 99% level is approximately 2.58.

Since $Z = 92.27$ and $p < 0.001$, the results are highly significant, and there is overwhelming evidence to reject the null hypothesis in favour of the alternative hypothesis, namely that there is a difference between the central tendencies of the two samples.

To contextualise the practical significance of the difference, two effect-size statistics were computed. Cohen's d, calculated from the means and pooled standard deviation in Table 1, was 1.04, which exceeds the conventional threshold for a large effect ($d \geq 0.8$). The rank-biserial correlation derived from the Mann–Whitney U statistic was $r = 0.73$, also indicating a large effect. Together with the chi-square result, these effect sizes confirm that the difference between CS1 and CS2 is not only statistically significant, which is expected given the very large sample sizes, but also practically meaningful at a magnitude that is highly relevant for fruit quality outcomes.

Conclusion

This comparative study demonstrates significant differences in cooling performance between cold storage facilities employing different refrigeration technologies and airlock systems. The investigation of two cold storage facilities handling export oranges reveals that advanced cooling technology with TC airlock systems substantially outperforms conventional systems with NTC loading areas.

CS2 maintained 85.92% of temperature readings at or below the critical 5 °C threshold, compared to only 57.46% for CS1, with a mean temperature difference of 3.16 °C between facilities. Statistical analysis using the chi-square and Mann–Whitney U tests confirmed highly significant differences ($p < 0.001$) between the temperature distributions of the two facilities, with large effect sizes (Cohen's d = 1.04; rank-biserial r = 0.73). The faster cooling rates observed in CS2, particularly evident in the initial cooling phase, indicate that TC airlock systems effectively prevent temperature rises during fruit handling and loading operations.

These findings should be interpreted within the energy–compliance trade-off that motivates NTC airlock designs.

The 15% – 25% energy savings reported by Fikiin and Markov (2014) for selectively cooled airlock systems can be substantial: At 7.62 kWh per pallet per day (Du Plessis et al. 2022), a facility handling 1000 pallets per day might save in the order of 1500 kWh – 2000 kWh daily. However, the present results show that 42.5% of readings in CS1 exceeded the 5 °C protocol, putting fruit value at risk. Given that arrival rejections, claim deductions and reduced shelf life can easily exceed the value of the energy saved, the apparent NTC energy advantage is likely to be partially or wholly offset by quality losses in commercial operation. A formal cost–benefit analysis incorporating fruit value, rejection rates and current South African energy tariffs is identified as an important next step.

Although the study recommends investment in advanced TC airlock systems, the author recognises that a full retrofit may not be financially viable for small-scale operators. Several intermediate measures can narrow the compliance gap at a fraction of the cost: (1) installation of high-speed roll-up doors and air curtains at the loading bay to reduce heat infiltration during pallet movement, (2) scheduling loading operations to coincide with the coldest part of the day, (3) shortening pallet dwell times in the staging area through better synchronisation with reefer container availability, and (4) routine commissioning of existing FAC tunnels to ensure that residual cold air supplied to the loading bay is maximised. These measures preserve much of the energy advantage of NTC systems while substantially reducing the worst temperature excursions observed in this study.

Although the present study did not measure fruit quality directly, the temperature differences observed are well within the range that has been linked to measurable quality losses in citrus. Sustained excursions above 5 °C in the early cold chain have been associated in the literature (Goedhals-Gerber & Khumalo 2020; Khumalo et al. 2023a) with accelerated weight loss, increased decay incidence and elevated rates of market rejection on arrival in European ports. The 3.16 °C mean difference and the threefold difference in time spent above protocol observed here are therefore likely to translate into commercially significant differences in shelf life and arrival quality. Direct measurement of fruit quality outcomes in a follow-up study is recommended to quantify this link.

These findings have important implications for cold storage facility design and operation in the context of energy efficiency versus temperature control effectiveness. The superior performance of the advanced facility indicates that investment in comprehensive refrigeration technology, including TC airlock systems, is justified for maintaining export quality standards. Future research should investigate the long-term economic implications of comprehensive refrigeration system investment versus energy-saving operational practices, including analysis of fruit quality retention, shelf-life extension and market acceptance rates.

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Competing interest

The author declares that no financial or personal relationships inappropriately influenced the writing of this article.

CRediT authorship contribution

Leila L. Goedhals-Gerber: Conceptualisation, Formal analysis, Investigation, Methodology, Project administration, Software, Resources, Validation, Visualisation, Writing – original draft. The author confirms that this work is entirely their own, has reviewed the article, approved the final version for submission and publication and takes full responsibility for the integrity of its findings.

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Data availability

The data that support the findings of this study are not openly available and are available from the corresponding author, Leila L. Goedhals-Gerber, upon reasonable request.

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