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Investigating temperature fluctuations in the wine and liquor maritime supply chain from South Africa to the United Kingdom: A case study

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ABSTRACT

This study explored temperature fluctuations in dry shipping containers transporting wine and liquor along maritime supply chains. It also examined how these variations affect product quality, and evaluated the effectiveness of thermal foil container liners in mitigating temperature changes. Temperature trials were conducted from the South African loading depot and concluded at the first distribution centre in the United Kingdom. Ambient temperature sensors were placed on cartons of wine and liquor inside the thermal container liner and between the thermal liner and the door of the container. Weather data was also collected during the trials. Temperature profiles showed large fluctuations in temperature inside containers because of day and night cycles while the containers were stacked at the departure and destination ports, posing challenges for supply chain management. Descriptive statistics were used to analyse the temperature profiles, whereas logit analysis was used to determine the impact of the thermal container liner on the temperatures to which the wine and liquor were exposed. Blind tastings were used to evaluate product quality after exposure to temperature fluctuations. Results showed that thermal liners significantly reduced temperature variability, which is critical for maintaining wine and liquor quality. Despite this, blind tastings confirmed that some products were negatively affected by temperature deviations. The study recommends the use of thermal foil liners for maritime transport of wine and liquor to minimise product damage and financial losses. This finding is particularly relevant for exporters aiming to preserve the quality of their wine and liquor throughout long-distance shipping routes.

1. Introduction

Bottled wine and liquor (W&L) products could be exposed to a variety of environmental conditions, including light, humidity, vibrations and temperature fluctuations during transport and storage before consumption. Although W&L products are especially sensitive to fluctuations in temperature, they are mostly exported in dry containers (Meyer, 2002). This is because of the higher cost of using refrigerated (reefer) containers, which can be up to three times the shipping cost of dry containers (Mac Cawley, 2014). The length and route of the trip may influence whether the W&L products are exposed to undesirable conditions, and for how long. This is especially important for shipping routes where the shipment crosses the equator. The position of the container on the vessel and its position and waiting time in the stack in port (Jarumaneeroj et al., 2023) also affect the conditions to which the W&L products are exposed (Mac Cawley, 2014). Therefore, there is interest in determining whether the temperature profile fluctuates along W&L maritime supply chains and what the impact of these temperature fluctuations would be on the quality of W&L products (W&L Exporter A, 2021b).

Much research has been done on the effects of environmental conditions on the physical, chemical and sensory attributes of W&L products (Betnga et al., 2021; Butzke et al., 2012; Crandles et al., 2016; Guadalupe and Ayestarán, 2008; Hirlam et al., 2019; Ough, 1985; Recamales et al. 2006; Scrimgeour et al., 2015). However, hardly any studies have been conducted to identify where and why temperature fluctuations occur in the W&L maritime supply chain and how severe they are (Mac Cawley, 2014; Marquez et al., 2012). This study addresses this gap in the research. It analyses the temperature profiles obtained from temperature trials inside dry containers to identify high-risk areas and challenges in maintaining ideal temperatures for W&L products during export. The research advocates for the use of thermal foil container liners for all W&L exports using maritime transport. These liners effectively mitigate undesired temperatures and fluctuations,

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providing a cost-effective and environmentally friendly alternative to reefer containers.

The rest of the paper is structured as follows: first, the background introduces the South African W&L industry and provides an overview of the W&L maritime supply chain. The literature review discusses the impact of temperature during transportation on W&L quality; the ideal temperature for the storage and transport of W&L products; and the measurement of temperature inside shipping containers in maritime supply chains. The next section describes the research design and methodology used to conduct the research, including the processes followed in data collection and the statistical techniques used for data analyses. The data analyses are then explained and the findings of the research identified. Finally, the conclusions to the study are summarised and recommendations provided.

2. Background to the study

2.1. South African W&L industry

Globally, wine exports reached a high in both volume and value in 2021. According to Arthur (2022), figures released by OIV, the International Organisation of Vine and Wine, show that exports increased by 4 % in volume to reach 111.6 million hectolitres in 2021, whereas value increased by 16 % to reach €34.3 billion. In 2022, South Africa was the eighth largest producer of wine globally, exporting 386.5 million litres worth R10 billion (equivalent to €0.58 billion). The United Kingdom (UK) is South Africa's largest export market, accounting for approximately a quarter of the sales by volume and value (SAWIS, 2022).

The South African W&L industry contributes significantly to the South African economy, government tax revenue and export earnings while providing employment to thousands of households. In 2019, the contribution to GDP was R55 billion (equivalent to €3.4 billion), accounting for 1.1 % of the national GDP, while the contribution to capital formation and utilisation was R98.1 billion (equivalent to €6 billion). This contributed R17.9 billion (equivalent to €1.1 billion) to tax, accounting for 1.4 % of tax received by the South African government. The industry supported 269 096 employees in the entire value chain (1.6 % of national and informal employment), of which 80 183 were farm and cellar employees (WOSA, 2022). Ensuring the quality of W&L products is also essential to maintaining South Africa's brand reputation as a W&L exporter.

2.2. W&L maritime supply chain

W&L products have fairly complex production processes and supply chains. These products are affected by surrounding environmental conditions such as exposure to light, humidity, vibrations and temperature from the moment they are bottled, which affects their quality and shelf life (Crandles et al., 2016). They are often produced at sites far from the consumption points and in opposite hemispheres. This involves long travel distances from hot to cold climates or vice versa, and crossing the equator during journeys that last several weeks (Butzke et al., 2012).

W&L products that are shipped internationally move through different phases during shipping as they are transported in containers by trucks, vessels and trains. Most internationally transported bottled W&L products are moved in dry containers as insulation blankets and refrigerated containers are considered to be too expensive – the shipping cost of a refrigerated container can be up to three times more than for a dry container (Mac Cawley, 2014; Meyer, 2002). Also, using a refrigerated container significantly increases the greenhouse gas emissions of the shipment (Hillebrand-GORI, 2022a).

For bottled W&L products, 12-metre (40-foot) shipping containers are used to load 22 pallets. Inflatable bags filled with air are positioned between the pallets to prevent them from moving and damaging the products. Since the mid-2000 s, there has been a significant shift from exporting wine in bottles to exporting wine in bulk, and over 40 % of global wine exports are now in bulk (Walther et al., 2018). Bulk wine is exported in 24 000-litre flexitanks, which have disposable plastic flexibags that fit inside 6-metre (20-foot) containers. Flexitanks are cheaper, more readily available and simpler to use than ISO liquid tank containers (Walther et al., 2018).

The first phase of the supply chain includes the movement of the container from the winery or distillery to where the container is loaded onto the vessel. The W&L products are loaded into the container at the winery or distillery, or at a consolidation point before being moved to the port of origin. The container is stacked at the departure port once it arrives, waiting to be loaded onto the vessel. The at-sea phase starts when the container is loaded onto the vessel and ends as soon as it is unloaded at the port of discharge. If there is a transhipment phase in the maritime supply chain, it starts when the container is unloaded from the vessel at the first port of discharge. Transhipment times can vary from a few days to weeks, but this depends on the route and the shipping company. During this time, the container waits in a yard, stacked with other units of shipment. Here, it is exposed to various elements and weather conditions until being picked up and loaded onto the vessel. The last phase is from the unloading of the container at the last port of discharge until the recipient or importer receives the products (Higgins et al., 2011; Hillebrand-GORI, 2023; Mac Cawley, 2014).

3. Literature review

3.1. The impact of temperature during transportation on W&L quality

As mentioned in the previous section, various factors can affect the quality of W&L products during transportation. Of these, temperature is the most significant (Marquez et al., 2012). High and low temperatures are not conducive to the storage and transportation of W&L products for long periods because most of these products are very temperature sensitive (Hillebrand-GORI, 2022b; Xie and Kissling, 2007). Most white wines are heat stabilised with bentonite fining to avoid the formation of a visible protein haze, and cold stabilised to prevent the formation of tartrate crystals. Even if there is no visible damage to the wine, exposure to high temperatures will change its aging characteristics (Butzke et al., 2012).

Du Toit and Piquet (2014) investigated the effects of different temperatures on the sensory composition of South African white wines by simulating typical temperature scenarios that the wine would be exposed to during a 46-day trip from South Africa to Europe. The wines that were exposed to elevated temperatures developed unwanted aromas and a yellow colour. Jung et al. (2021) simulated shipping conditions in a climate chamber for five wines, namely two white and two red still wines and one sparkling wine, to investigate the effect of transport temperature profiles on wine quality. Sixteen scenarios were simulated, ranging in duration from 25 to 42 days and in temperature from 15 °C and 40 °C. The temperature changes occurred gradually in a single step – no day-night cycles were simulated. The lighter, fruity wines were found to be more sensitive than the wines with a higher alcohol content or wooded aging.

The characteristics of W&L products directly depend on the temperature profile and time for which these products have been exposed to high temperatures; excessively high temperatures can lead to the quick deterioration of wine (Guadalupe and Ayestarán, 2008). The formation of ethyl carbamate (or urethane), for example, can accelerate exponentially at high temperatures. As ethyl carbamate has been classified as a Group 2A carcinogen, its concentration has to be minimised in wine (Butzke et al., 2012). Most liquor products typically take longer than wine to be affected by high temperatures; however, continued exposure to heat can lead to oxidation of some compounds such as oils and fats, resulting in rancidity (Wine Enthusiast, 2022).

According to W&L experts, fluctuations in temperature have a much worse effect than a constant high or low temperature (Meyer, 2002; Robinson, 1995; Sims, 2004; Stevenson, 2005). Thermal cycling, where the temperature varies significantly between day and night, should especially be avoided (Hirlam et al., 2019). Temperature fluctuations can lead to irreversible changes in the chemical and sensory profiles of the W&L products, such as a reduction in SO_2 that results in browning and a decrease in fresh, fruity and floral aromas in white wines (Ough, 1985). They may also lead to the premature aging of wine because of the repeated expansion and contraction cycles that accompany temperature fluctuations (Betnga et al., 2021). Recamales et al. (2006) detected a decrease in phenols in wine that had been subjected to variable temperatures, leading to a discolouration of the wine because phenols affect the taste, feel and colour of wine.

Atmospheric conditions influence the temperatures inside cartons and bottles to a lesser degree. In a study by Butzke et al. (2012,) a difference of 2 °C to 4 °C was measured between the ambient temperature surrounding the wine bottle and the temperature of the wine inside the bottle. The wine is thus protected against brief fluctuations in ambient temperature as glass and liquid take longer to change temperature than air (Häge et al., 2016). However, the air inside a dry shipping container exposed to direct sunlight can become much hotter than the ambient temperature outside the container, similar to a car parked in the sun. Shipping containers are typically only packed to approximately half of their height owing to the weight of bottled wine, resulting in a large volume of air which, once warmed up, can take a long time to cool off again (Butzke et al., 2012).

According to Betnga et al. (2021) temperature fluctuations are more prevalent during the transport of wine over land than during the sea leg. Research by Marquez et al. (2012) supports these findings. Container storage in ports has been identified as a critical phase along the maritime supply chain that could affect the quality of wine owing to “diurnal fluctuations” (Mac Cawley, 2014). The diurnal range is the difference between the night-time and daytime temperature at any location along the supply chain. It is also described as the variance between the hottest and coolest temperature in a 24-hour period.

Wine that is stored and transported at temperatures of between 20 °C and 40 °C can thermally expand by up to 0.8 % of its volume, or 0.3 ml for each degree Celsius in extreme cases, for example in wines with high levels of residual sugar. The repeated expansion and contraction of a wine that is subjected to daily fluctuations can cause significant changes to the wine. Air is expelled from the bottle as the wine warms, which may feasibly result in cork movement. When the wine cools, air is drawn into the bottle, especially if the cork has been compromised. This “pump effect” increases the risk of oxidation of the wine, as well as a change in vapour pressure and carbon dioxide solubility (Boiling, 2021; Scrimgeour et al., 2015). If the cork has moved visibly, the bottle cannot be sold and has to be discarded. Screw caps are not affected in this way, as they have synthetic liners that allow a limited amount of air to escape (Swan, 2018).

Dry shipping containers can be fitted with a thermal container liner to provide some insulation and reduce the impact of temperature variations on the bottled wines and liquor during transportation. These foil liners can reflect up to 94 % of radiant heat and limit temperature increases to an average of 8 °C to 11 °C (Hillebrand-GORI, 2022a).

3.2. Ideal temperature for W&L storage and transport

The ideal temperature standard for W&L storage and transport varies from expert to expert. Robinson (1995) states that the optimal temperature at which to store wine is between 10 °C and 12 °C, but that no significant harm is done to the product between 15 °C and 20 °C. The more volatile compounds of wine may be boiled off at temperatures above 25 °C (Robinson, 1995). Sims (2004) suggests that most wines should be safe from harm between temperatures of 13 °C and 18 °C. Stevenson (2005) posits that the perfect temperature for the storage of wine is 11 °C, but that anything between 5 °C and 18 °C would suffice for most wines. According to Ough (1992), wine quality will be negatively affected in storage places where temperatures rise above 25 °C for longer periods and 40 °C for shorter periods. Temperatures higher that 40 °C will cause visual and sensory changes to wines in only a few days (Ough, 1985). Most liquor should be fine at room temperature (20–25 °C), but some experts prefer to keep liquor at 15 °C (Wine Enthusiast, 2022).

Table 1
Wine temperature storage guidelines.

Storage time	Heat exposure	Cold exposure
Long-term storage	10 °C–16 °C	10 °C–16 °C
1–4 weeks	24 °C or below	10 °C or below
Spikes of 30 mins or less	29 °C or below	0 °C or below
Never	30 °C or above	−5 °C or below

Source: Butzke (n.d.).

Table 1 summarises the Purdue University’s Wine Storage Guidelines (Butzke, n.d.).

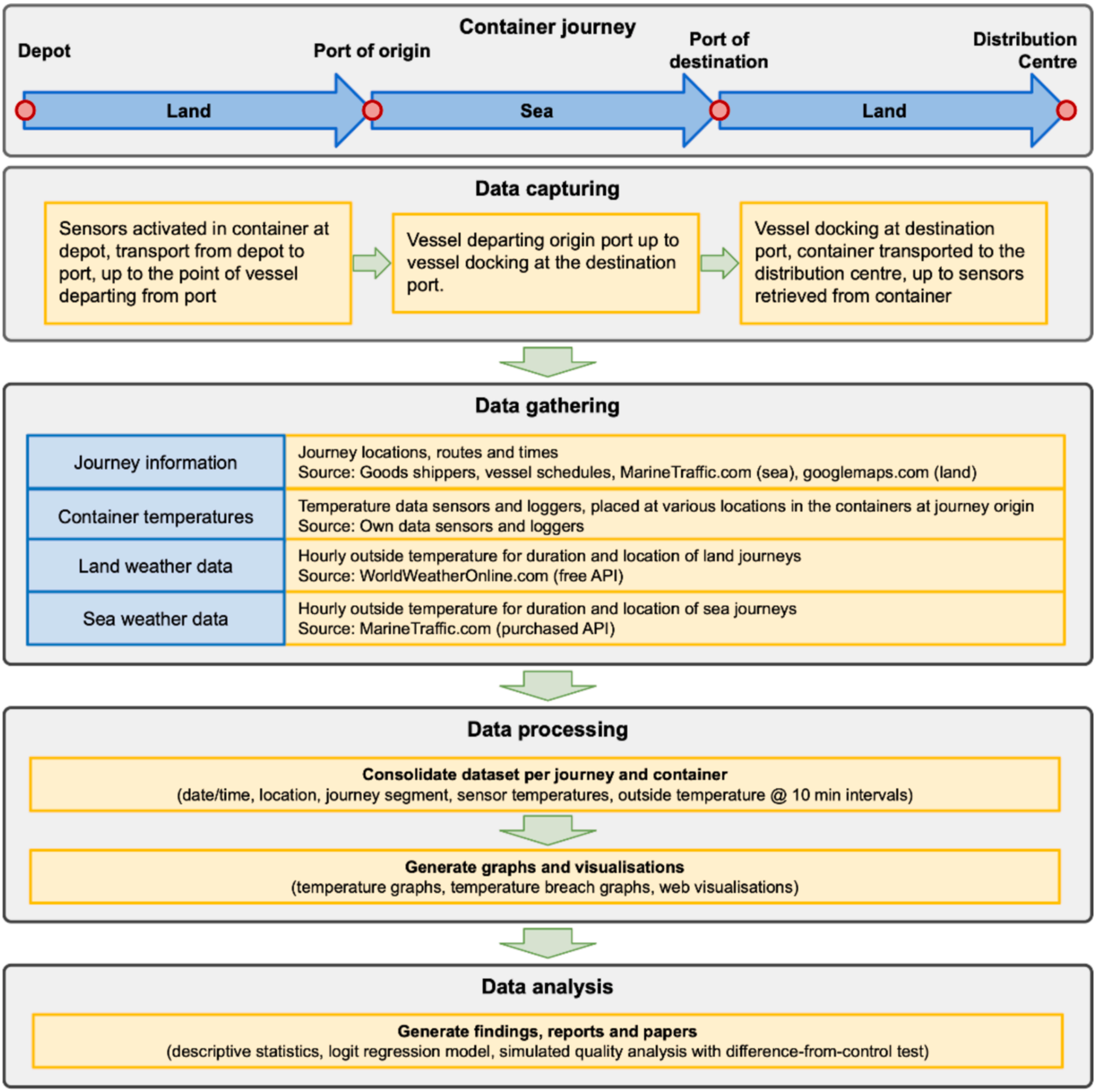
The Ontario Liquor Board requires that all wine shipments arriving in Canada between 15 November and 1 April via maritime transport must be in reefer containers with a set point between 5 °C and 10 °C and be stowed below deck. In addition, wine arriving between 15 June and 31 August and that sells for more than CA$30, must be transported in reefer containers. This does not apply to liquor with an alcohol content of over 30 %. However, all luxury products must always be transported in reefer containers – this includes cream liqueurs (Meyer, 2002).

3.3. Measuring temperature inside shipping containers in maritime supply chains

Marquez et al. (2012) conducted temperature trials for bottled wine shipped from Australia to the USA. Small ambient temperature recorders (similar in size to a watch battery) were placed in envelopes inside a few cartons with bottles of wine in standard dry shipping containers. Results showed that temperatures fluctuated much more during the Australian and USA land transport portions than during the sea voyage. Daily temperature fluctuations as well as the total number of hours that the temperature exceeded 25 °C and 40 °C were analysed, in response to the research by Ough (1992). The results were used to advise the Australian wine industry on shipping guidelines.

The Mac Cawley (2014) study included temperature trials for bottled wine shipped from a number of southern hemisphere wine-producing countries to the USA. Most of the data was for trials from Chile (65.4 %) and Australia (24.2 %) (reported by Marquez et al., 2012), whereas 2.5 % was from South Africa. The analyses focused on the data from Chile and Australia. Roughly 20 % of these shipments were fitted with thermal container liners. The analyses investigated the temperatures to which the wine had been exposed, the duration of exposure and the cumulative effect of the exposure on the chemical reactions in the wine. Changes in the sensory composition of the wine were evaluated through blind tastings. The effect of the thermal liners was also investigated. Recommendations included using thermal liners and avoiding routes with transhipments, if possible.

Walther et al. (2018) monitored the temperatures of bulk Chardonnay wine shipments, in 24 000-litre flexitanks placed inside standard dry 20-foot containers, from Australia to Germany. Trials were conducted during three different seasons. The containers were placed in three different locations on the vessel, namely on deck, below deck near the stern and below deck near the bow. In each container, a temperature probe was submerged 1 m into the wine and an ambient temperature recorder was attached to the inside of one of the container walls. Diurnal ambient temperatures inside the containers fluctuated from 9 °C to 47 °C in the Australian port during the summer months. In all the containers, the wine temperature exceeded 25 °C for at least 20 days, irrespective of the season or location of the container on the vessel, with the maximum wine temperature reaching 31 °C. Exposure of the wine to temperatures above 25 °C resulted in a decrease in SO_2 content, development of a yellow colour and a loss of freshness, among other symptoms.



Sensors activated in container at depot, transport from depot to port, up to the point of vessel departing from port

Vessel departing origin port up to vessel docking at the destination port.

Vessel docking at destination port, container transported to the distribution centre, up to sensors retrieved from container

Journey information	Journey locations, routes and times Source: Goods shippers, vessel schedules, MarineTraffic.com (sea), googlemaps.com (land)
Container temperatures	Temperature data sensors and loggers, placed at various locations in the containers at journey origin Source: Own data sensors and loggers
Land weather data	Hourly outside temperature for duration and location of land journeys Source: WorldWeatherOnline.com (free API)
Sea weather data	Hourly outside temperature for duration and location of sea journeys Source: MarineTraffic.com (purchased API)

Consolidate dataset per journey and container
(date/time, location, journey segment, sensor temperatures, outside temperature @ 10 min intervals)

Generate graphs and visualisations
(temperature graphs, temperature breach graphs, web visualisations)

Generate findings, reports and papers
(descriptive statistics, logit regression model, simulated quality analysis with difference-from-control test)

Fig. 1. Multiple sources of data and flow diagram of methodology used in the research.

Csavajda and Böröcz (2019) measured ambient temperature and relative humidity inside standard 40-foot high-cube dry shipping containers with automotive parts transported from Hungary by road, rail and ship to South Africa, India and China. In each container, an ambient temperature and humidity monitor was attached to the geometrical midpoint of the floor. The container destined for South Africa was shipped from Hungary in early summer (April) on the upper deck of the vessel and arrived in South Africa in July (winter). Ambient temperatures inside the container ranged between 9.19 °C and 27.23 °C, while the relative humidity varied from 29.98 % to 79.07 %. Diurnal ambient temperature and humidity cycles were pronounced on land, especially in the South African port. During the sea voyage, the relative humidity remained fairly constant, while the temperature increased gradually as the vessel approached the equator. The results were used to improve packaging materials to protect automotive parts against corrosion and other damage.

Garafulic and Mac Cawley (2024) expanded on the study by Mac Cawley (2014) by using the same dataset to determine the correlation between the internal container temperature and the external temperature, which is available from the global NCEP-NCAR database. They then developed a decision support model that can be used to compare different shipping routes based on total cost as well as a set of temperature risk indices, rather than just selecting the least-cost route.

None of the above studies conducted temperature trials for bottled wine shipments from South Africa to Europe to identify where and why temperature fluctuations occur in the W&L maritime supply chain and how severe they are. This study addresses that gap and investigates how effectively a thermal foil container liner can dampen the temperature fluctuations, rather than resorting to the use of reefer containers, which have higher costs and greenhouse gas emissions, to control temperature.

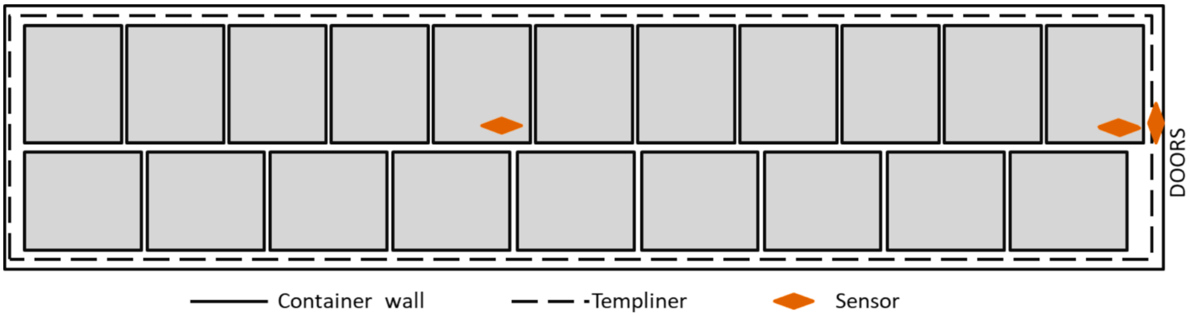


Fig. 2. Position of temperature sensors in monitored containers as viewed from the top.

4. Research design and methodology

4.1. Methodology

A deductive, mixed-methods approach, namely facilitation, was followed (Bryman et al., 2016:62) to gather primary and secondary qualitative data to support the quantitative data analysis. Primary quantitative data was gathered using Sensitech TempTale Ultra Fit sensors to record the ambient temperature inside containers. Each container was fitted with a thermal liner. The sensors were placed on cartons of W&L products inside the lined container and between the thermal liner and the door of the container. The temperature sensors were inserted at the loading depots in South Africa and followed the supply chain and its transit phases until being removed at the importer's distribution centre. Because of limitations caused by the Covid-19 pandemic, food safety concerns and financial implications, it was not possible to measure the W&L temperatures inside the bottles. This would have entailed inserting a temperature probe into a bottle, resulting in the loss of that bottle of wine or liquor. Therefore, only ambient temperatures were measured.

The temperature data was manually downloaded from the sensors by the University of Hull in the UK onto a cloud-based system called ColdStream® and then exported to Excel. Besides the primary temperature sensor data and shipping route schedules, secondary data was obtained from external sources (see Fig. 1). API refers to "Application Programming Interface". Fig. 1 also provides a flow diagram of the methodology used in the research.

Outside air temperature and vessel position data (longitude and latitude) for the sea journey of each shipment were purchased from MarineTraffic (MarineTraffic, 2021). Outdoor temperatures for landside container locations were retrieved from World Weather Online (2021). These temperature readings were taken during loading at the wine-loading depot prior to the products being transported to the port, during storage in the container stack at the port before loading onto the vessel, and between the destination port and customer distribution centre in the UK.

The primary quantitative data collection method used in this study has been established and proven through previous research in the wine industry. Descriptive statistics, including box-and-whisker plots, were used to analyse the distribution of ambient temperatures and the number and duration of temperature breaches along the supply chain. Box-and-whisker plots are useful for showing the spread of the data. A box is drawn from the first quartile (25th percentile) to the third quartile (75th percentile), which is called the interquartile range (IQR). The median (middle) value separates the two shades of the box. The first quartile (Q1) is connected to the minimum value Q1 − 1.5 × IQR by a whisker and the third quartile (Q3) is connected to the maximum value Q3 + 1.5 × IQR by a whisker. Any values below the minimum and above the maximum are considered outliers.

The logit regression model was used to examine the impact of the thermal container liner on the temperatures to which the W&L products were exposed. A new variable was generated to capture the temperature breaches as the raw sensor temperature distribution data was not in the right format for that purpose. The new variable was defined to capture the temperature breaches for the ambient temperature sensors for both regular and temperature-sensitive bottled W&L products, that is, every instance in which the temperature readings rose above the ideal temperature of 24.9 °C for over 30 min. Thus the raw sensor data was used to generate binary dependent variables for the ambient sensors associated with the regular and temperature-sensitive bottled W&L products, assuming dichotomous values (1 = if a temperature breach is recorded and 0 = if otherwise). This set of outcomes with only two possibilities provides a binary set (Strickland, 2017) and is the reason for choosing a binary logit model specification, as it is the most suitable for predicting categorical dependent variables.

According to Hilbe (2015), logit regression allows a binary variable (response variable), which takes on the values 0 or 1, to be modelled based on one or more other variables (predictors). The predictors can each be a binary variable (indicator variable [0,1]) or a continuous variable (real value). Hilbe (2015) notes that the logit regression is based on the Bernoulli distribution, a distribution of 1 s and 0 s. Thus, following Gould et al. (2010) and Hilbe (2015), the probability function from the Bernoulli distribution is

$$f(\pi_i; y_i) = \pi_i^{y_i}(1-\pi_i)^{1-y_i} \tag{1}$$

where π_i is the probability that $y_i = 1$ (1 shows a success or that the event of interest has occurred); $0 \le \pi_i \le 1$ and y_i only assume values of 1 or 0.

The likelihood function, which describes the relationship between the parameters (π_i and y_i) to be estimated, is then formulated. To allow for summation across all observations, the log on both sides of the likelihood function is taken, resulting in the Bernoulli log-likelihood function being given as

$$L(\pi; y) = \sum_{i=1}^{n} \left\{ y_i ln\left(\frac{\pi_i}{1-\pi_i}\right) + ln(1-\pi_i) \right\} \tag{2}$$

The predicted model of the logit model is based on the log of the odds ratio $\left(\frac{\pi_i}{1-\pi_i}\right)$ (the logit function) and the linear predictor $x_i b$ through the relationship $ln\left(\frac{\pi_i}{1-\pi_i}\right) = x_i b$.

To determine π in terms of the linear predictor, xb, the logit function is solved for π, without subscripts, as

$$\pi = h(xb) = \frac{e^{xb}}{1+e^{xb}} = \frac{1}{1+e^{-xb}} \tag{3}$$

This particular function is commonly referred to as the logistic function or inverse logit function (Gould et al., 2010; Hilbe 2015).

Since the variable of interest is dichotomous, the logit regression model is used to forecast the probability that the response variable (ambient temperature) takes on a value of 1 given a specific set of predictor values (outside temperature and sensor position). For this model:

$Y_j = 1$ if ambient temperature rises above 24.9 °C; and
$Y_j = 0$ if ambient temperature does not rise above 24.9 °C.

4.2. Data collection

4.2.1. Instrumentation of W&L containers

The temperature was tracked from the loading depot in South Africa until the distribution centre in the UK. A team member from Stellenbosch University travelled to the relevant loading depots to insert the sensors. Sensors were inserted into five containers with bottled W&L products.

As the bottled W&L products were shipped in regular, non-refrigerated containers, each container was fitted with a thermal foil container liner (Templiner) to provide some insulation. Three ambient temperature sensors were placed in each container – on the 5th pallet in the middle of the container and on the pallet closest to the door, both inside the Templiner, and on the outside of the Templiner just inside the container door (Fig. 2). This allowed for a comparison of the variation in temperature inside and outside the Templiner. All 15 sensors were successfully retrieved from the five monitored containers.

South African wine exporters request that containers with wine be protected by other containers in the container stack in the port, but this is not guaranteed. They further request these containers to be stowed below deck away from the engine room, but containers with fruit are given preference (Meyer, 2002; W&L Exporter A, 2021b).

4.2.2. Sea route and land temperature data

MarineTraffic gathers vessel-tracking information through the international marine Automatic Identification System (AIS), which it then enhances by merging the AIS position data with data from other sources (e.g. weather information).

AIS takes a vessel's position and movements via the vessel's GPS system, or an internal sensor built into an AIS unit. That information is then collated along with programmable information from the AIS unit (e.g. Maritime Mobile Service Identity (MMSI) number, vessel name, destination, cargo type) and transmitted in the background at regular intervals. At the same time, AIS information is received from other vessels within its receiver range. Because of the significant safety benefits offered by AIS, this technology was made compulsory throughout the world in 2002 for all passenger ferries and vessels over 300 gross tonnes. Transmitted AIS data is also received by a network of terrestrial receiving stations along the coastline, or satellite receivers where vessels are out of range of terrestrial receivers (typically about 65 km (40 miles)).

MarineTraffic enhances the AIS data by adding selected weather data, including temperature and wind direction. This information is obtained from a nautical temperature forecasting and history service. The enhanced AIS data is provided as a service and made available on a subscription basis through the MarineTraffic.com website or through an API (Application Programming Interface) mechanism.

There is a significant difference in cost for obtaining API data received through the terrestrial AIS network and those received from the satellite AIS network, with the satellite data (SAT-AIS) being significantly more expensive. SAT-AIS technology is quite a recent development (after 2010). The network of satellites fitted with AIS receivers is relatively limited and some technology challenges still need to be addressed.

For this research, all the vessel and weather data required were available, except for limited gaps in the temperature data, which were filled by using interpolation techniques. The data was harnessed using an API, specifically the MarineTraffic API, which allows one to retrieve the precise historical position of vessels and related data over a period. It includes the vessel AIS identifier, MMSI number, position data (LAT, LON), navigation data (heading/course/speed), timestamp and weather data (temperature).

Weather data for land locations was retrieved from World Weather Online (2021). This included weather data for the wine-loading depots in South Africa, the container stacks at the Port of Cape Town and at the destination port, and the retailer's distribution centre in the UK.

Table 2
W&L shipment from South Africa to the UK.

Activity	Distance	Date	Location
Sensors inserted in MRSU and MSKU at depot		25 Feb 2021	Exporter loading depot, SA
MRSU and MSKU depart from depot for port	50 km	25 Feb 2021	Exporter loading depot, SA
Vessel departs from port of origin		9 Mar 2021	Cape Town, SA
Vessel arrived at destination port	11 427 km	25 Mar 2021	London Gateway, UK
MRSU and MSKU arrived at destination depot		26 Mar 2021	Interim depot, UK
MRSU delivered to customer distribution centre (DC)	660 km	1 Apr 2022	Wine importer DC, UK
MRSU unpacked at customer DC		2 Apr 2022	Wine importer DC, UK
MSKU delivered to and unpacked at customer DC		8 Apr 2022	Wine importer DC, UK

Table 3
Temperature categories for bottled W&L products.

Temperature range	Category
Temp < 25 °C	Ideal
25 °C ≤ Temp < 30 °C	Caution
30 °C ≤ Temp < 40 °C	Damaging
Temp ≥ 40 °C	Critical

5. Data analysis and results

The analyses performed for two of the five W&L containers shipped from South Africa to the UK are discussed in this paper as a representative example. Container MRSU carried W&L products that were considered to be particularly temperature sensitive, whereas container MSKU carried regular wine that was not considered to be particularly temperature sensitive. Both containers were fitted with thermal foil liners and shipped on the Santa Rosa container vessel. The locations of the containers on the vessel are unknown. Table 2 shows the shipping information for the two containers.

This section covers descriptive statistics of the W&L data used in this study, which form the basis for the quantitative (logit regression) and quality analyses that follow afterwards.

5.1. Analysis of temperature breaches

The analysis focused on temperature breaches. In this study, a temperature breach for W&L products is defined as every instance in which the temperature readings rise higher than the ideal temperature for over 30 min, as defined in Table 1. The categories in Table 3 were defined based on the impact of temperature on W&L products, as discussed in Sections 3.1 and 3.2.

For data-gathering and analysis purposes, the W&L supply chain steps were grouped into three stages, namely container stack, sea route and distribution centre.

The container stack stage starts with the loading of the container at the loading depot of W&L Exporter A. Temperature sensors are fitted during the loading process. Once the container doors have been closed, the container is transported to the port of export where it is placed into the container stack.

The sea route stage starts when the container is loaded onto the vessel and ends once the container has been offloaded at the destination port.

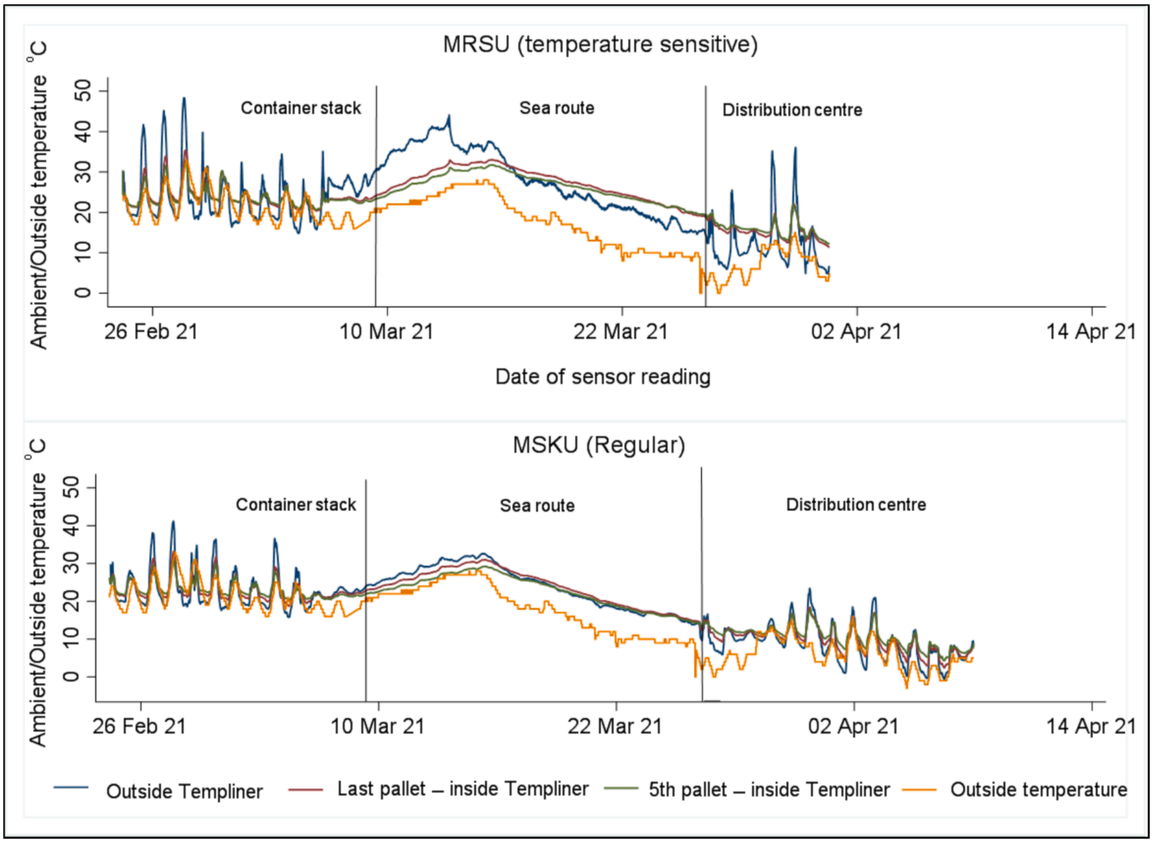


Fig. 3. Ambient temperature profiles from South Africa to the UK – temperature-sensitive and regular W&L.

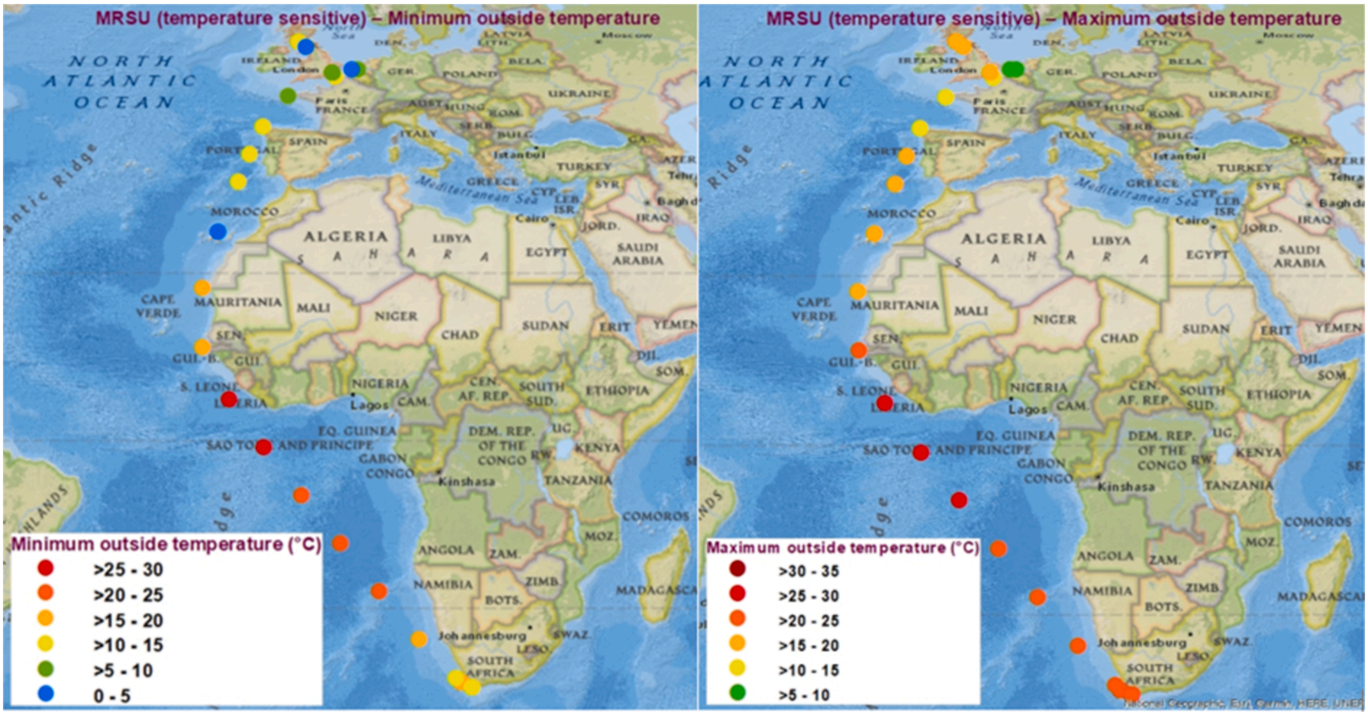


Fig. 4. Minimum and maximum outside temperature along the W&L maritime supply chain from South Africa to the UK for container MRSU. Data Source: MarineTraffic.com outside temperature data.

The distribution centre stage starts once the container is removed from the port of import and taken either to an intermediary depot or directly to the importer's distribution centre. This stage ends once the W&L products have been unloaded from the container and the sensors retrieved.

Fig. 3 depicts the ambient temperature profile inside the containers

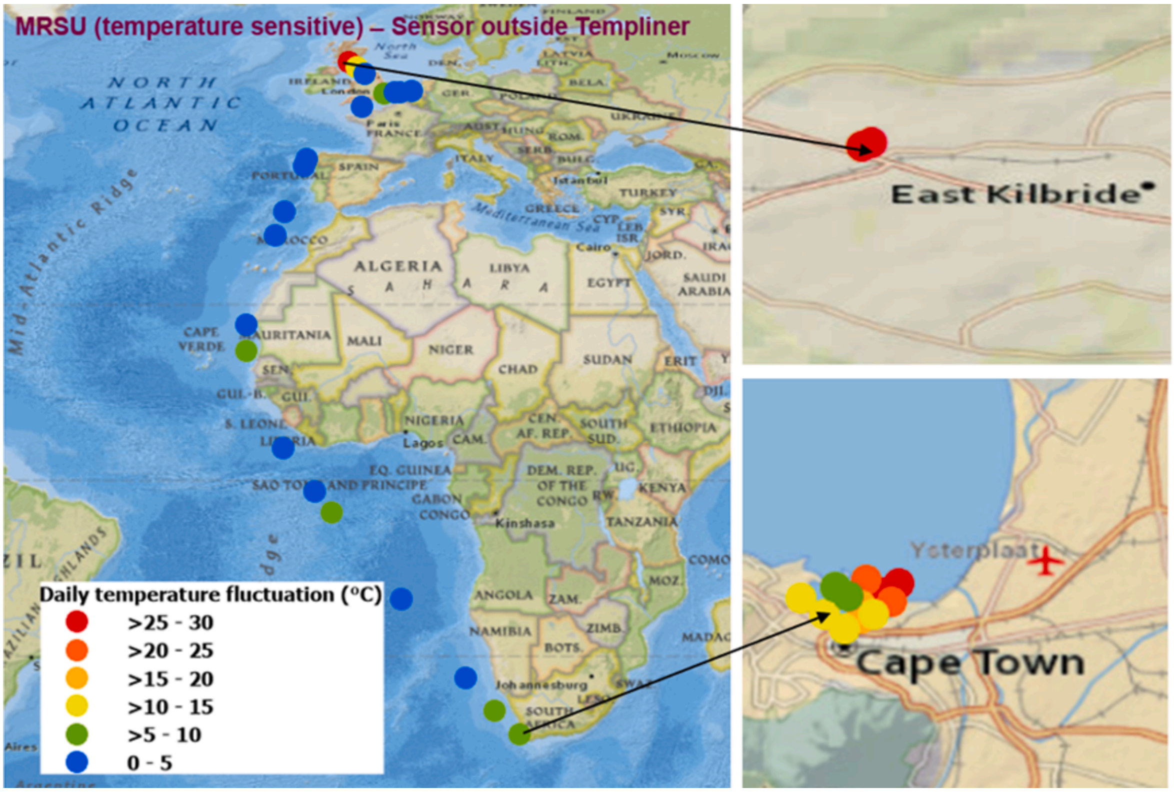


Fig. 5a. Daily temperature fluctuation along the W&L maritime supply chain from South Africa to the UK for sensor located outside the Templiner in container MRSU.

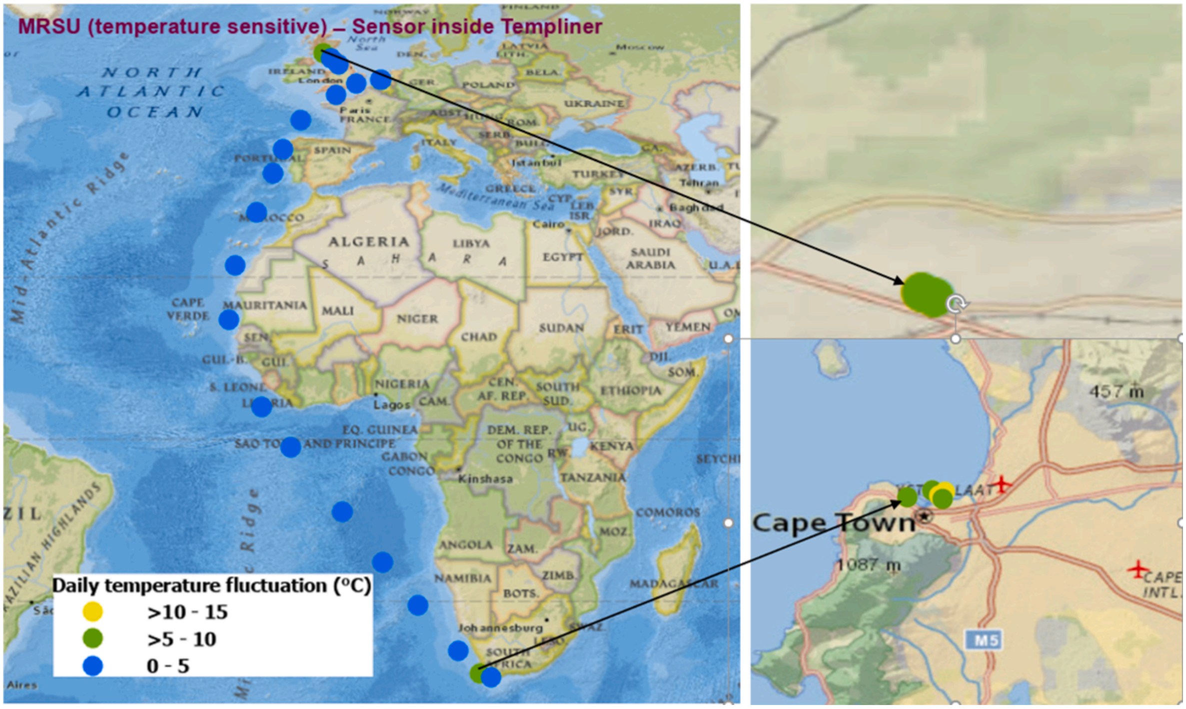


Fig. 5b. Daily temperature fluctuation along the W&L maritime supply chain from South Africa to the UK for sensor located inside the Templiner in container MSRU, closest to the door.

and the outside temperature (weather) at each stage of the supply chain from South Africa to the UK. Fig. 4 maps the minimum night-time and maximum daytime temperatures recorded at particular longitude and latitude points along the route for one of the trials, namely container MRSU (MarineTraffic, 2021).

Figs. 5(a) and (b) show the daily temperature fluctuations geographically along the supply chain from South Africa to the UK for the sensor located outside and inside the Templiner, respectively, on

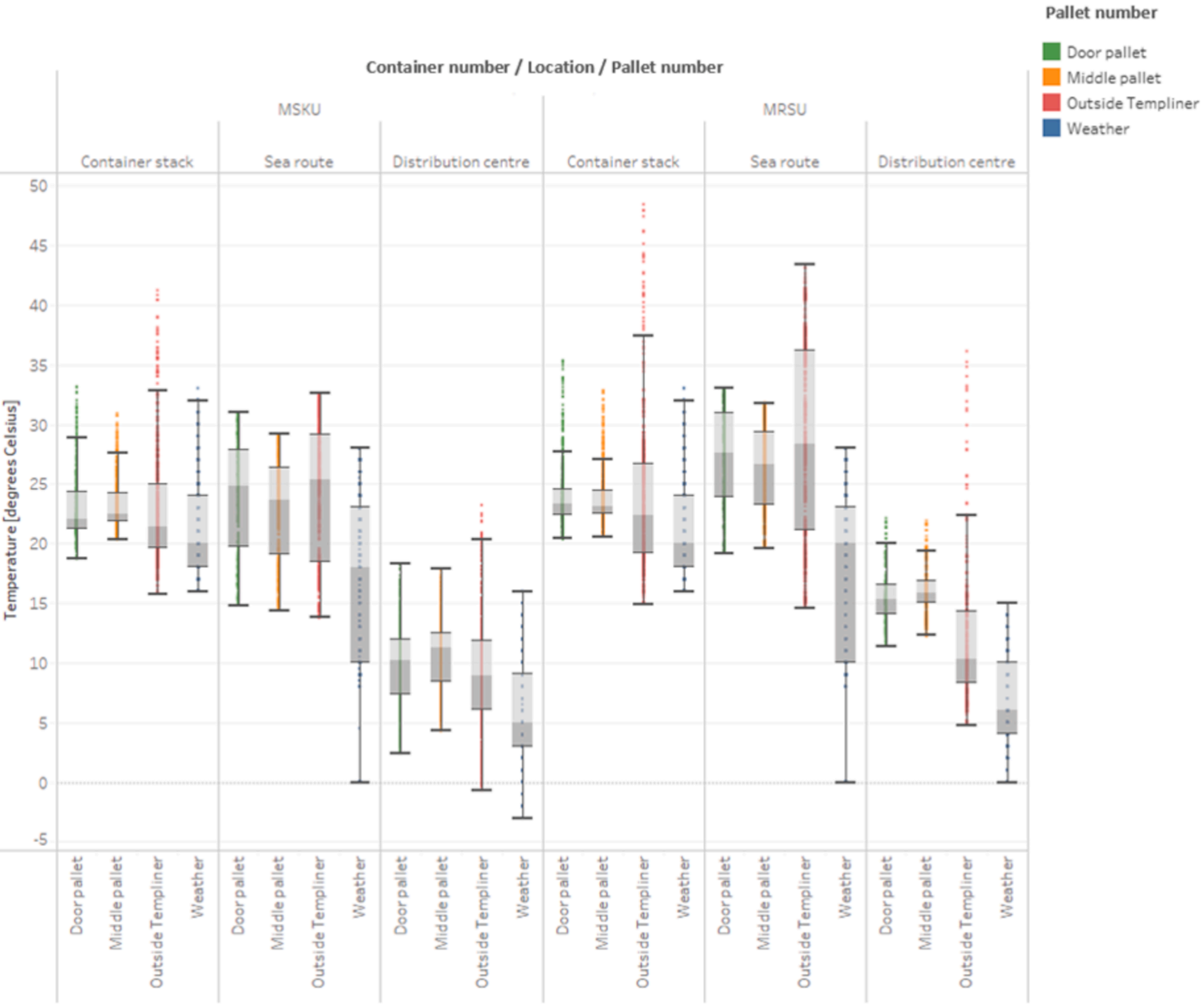


Fig. 6. Ambient temperature distributions per sensor and stage in the W&L maritime supply chain.

container MRSU.

From Figs. 4 and 5, it is clear that the Templiner plays an important role in keeping the temperatures to which the W&L products are exposed within the desired limits. In Fig. 3, the temperature profile of the sensor on the outside of the Templiner shows much more volatility than that of the sensors inside the Templiner, with spikes of extremely high and low temperatures. The temperature fluctuations outside the Templiner were especially more pronounced on land at the origin (container stack stage) and destination (distribution centre stage) compared to the sea route, as shown in Fig. 5a. Although both containers were on the same vessel, the location of the container in the stack and on the vessel may have contributed to the differences in temperature readings. Information pertaining to these positions was not available.

5.1.1. *Ambient temperature distribution along the maritime supply chain*

Fig. 6 displays the distributions of the ambient temperatures recorded by the sensors inside and outside the Templiner and the weather data for the various stages of the maritime supply chain for both containers.

For container MSKU, the median values of the two sensors inside the Templiner do not exceed 25 °C, but the upper quartile values are in the caution range during the sea route stage. The maximum values are in the caution and damaging ranges during the container stack and sea route stages, respectively. For container MSRU, the median values of the two sensors inside the Templiner are in the caution range and the upper quartile values are on the lower border of the damaging range during the sea route stage. The maximum values are in the caution and damaging ranges during the container stack and sea route stages, respectively. However, during the container stack stage, all the sensors recorded a significant number of outliers beyond the maximum values. These values went well into the damaging range, as shown in Fig. 6.

The range of the sensor data outside the Templiner is larger than for the sensors inside the Templiner. The weather data and the outliers reach much higher temperatures, showing that the temperatures recorded inside the container are more extreme than those outside the container. This implies that the Templiner reduces the range of temperatures that the wine is exposed to.

5.1.2. *Determining the number and duration of ambient temperature breaches*

Fig. 7 presents the number of temperature breaches recorded both inside and outside the Templiner for the different stages of the maritime supply chain. It is apparent that there are fewer breaches inside the Templiner and that these breachers are less severe than those outside the

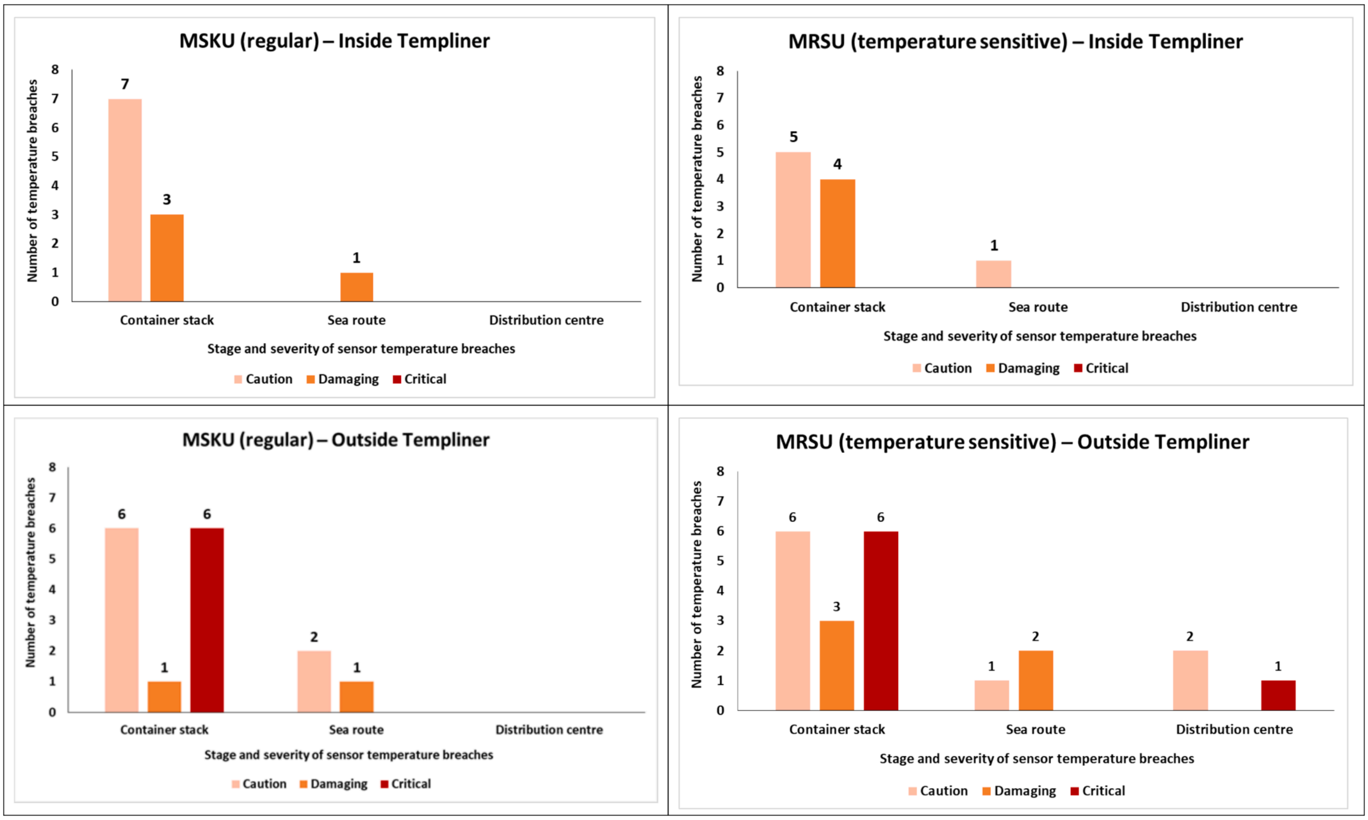


Fig. 7. Number of ambient temperature breaches inside and outside Templiner per supply chain stage.

Templiner.

Fig. 8 shows a distribution of the number and duration of temperature breaches inside the Templiner. All the temperature breaches that occurred while the containers were in the stack in the port were shorter than 12 h, probably because of the cooler night-time temperatures. The temperature breaches recorded during the sea route lasted longer than 12 h; however, only a single breach was recorded in each container.

5.2. *Impact of Templiner*

Inferential statistics were employed to determine whether the Templiner makes a significant difference to the temperatures to which the W&L products were exposed. A logit model was used for the analysis. First, the impact of the weather on the ambient temperatures inside the container was investigated. Then the sensor on the last pallet near the door (inside the Templiner) was compared to the sensor on the outside of the Templiner. The sensor on the last pallet near the door (inside the Templiner) was also compared to the sensor on the 5th pallet, i.e. the one in the middle of the container, to determine whether there was a significant difference in temperature along the length of the container.

The estimates in Table 4 for both containers (regular and temperature-sensitive products) show that there is a high likelihood that the outside temperature profile (weather) will positively affect (i.e. increase) the ambient temperature that the L&W products are exposed to inside the containers (see Fig. 1). There is a high probability that the ambient temperatures recorded will fall outside the ideal range (that is, fall within one or more of the high exposure ranges, namely caution, damaging or extreme) because of the rising temperature outside the container. However, the magnitude of exposure was higher for container MSKU carrying regular wine (0.385) than for container MRSU carrying temperature-sensitive W&L products (0.224).

Compared to the sensor on the 5th pallet inside the Templiner, both the sensor outside the Templiner and the one immediately inside the Templiner (fitted on the last pallet) are more likely to record readings in one or more of the high exposure ranges. However, the impact as measured by the coefficients will be higher for the sensor outside the Templiner. This is true for both containers, although the effect is higher in the regular container than in the temperature-sensitive one. For the two sensors inside the Templiner, there is a high likelihood that the ambient temperature profiles will be within the ideal range (relative to the temperature profile of the sensor outside the Templiner). As before, the impact will be greater in the regular container than the temperature-sensitive container, but for both, the magnitude will be more for the sensor on the 5th pallet (in the middle of the container).

5.3. *Quality analysis*

Since the winemakers are based in South Africa and the W&L products shipped to the UK had to be compared to identical unshipped products, the quality analysis was performed in South Africa. Unfortunately, it was not possible to send a couple of bottles of each product back from the UK to South Africa by air freight for the quality analysis. It was therefore decided to simulate the shipping conditions that the products had been exposed to, as has been done in other studies (Jung et al., 2014; Crandles et al., 2016).

Six samples were selected from the same bottled W&L products that had not yet been shipped by W&L Exporter A. These samples were cycled in a LabTech oven between room temperature (17 °C to 23 °C) and 52 °C for two weeks to simulate the worst-case conditions that the products had been exposed to during export. The six samples were selected across four W&L product categories that had been shipped in the five containers monitored in this study. The first sample was taken from a temperature-sensitive product category, whereas samples 2 and 3 were obtained from two regular product categories. The remaining three samples (samples 4, 5 and 6) related to a single product category that was considered to be particularly sensitive to temperature variations.

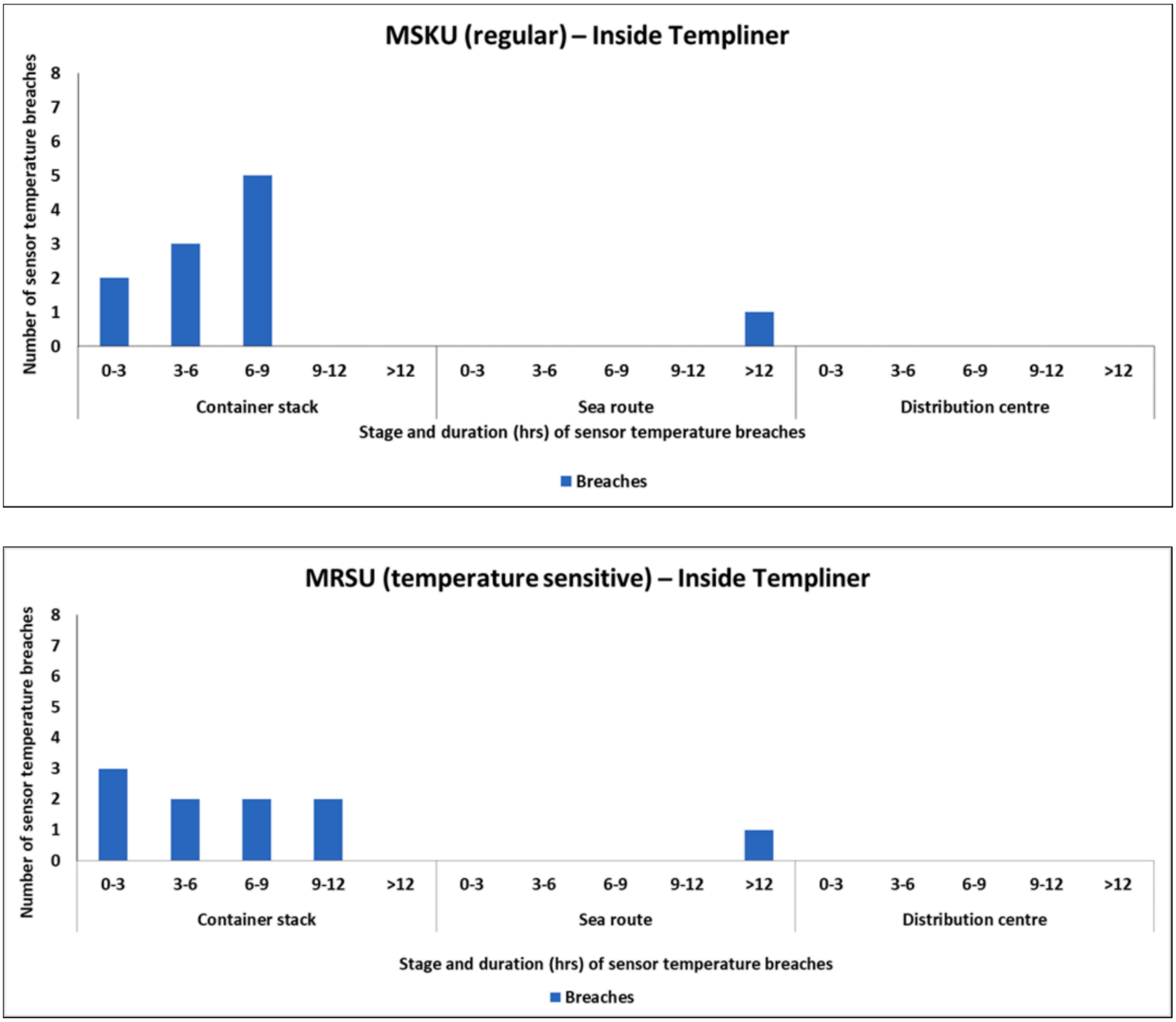


Fig. 8. Duration of temperature breaches inside the Templiner.

Each sample was divided into two portions: one was kept as a control as a baseline and the other was cycled in the oven, as described above. To identify whether differences between the control and the treated samples existed and whether the differences were acceptable, Difference-from-Control (DFC) tests were performed. In terms of acceptability, no significant differences between the scores from the control and treated samples would show that the treated samples did not deviate from the baseline.

From each sample, 30 ml was served in 250 ml Vitria tasting glasses to a panel of 12 tasters from the quality control department of W&L Exporter A. To eliminate bias and serving-order effects, samples were served randomly with three-digit blinding codes. Tastings were conducted on electronic ballots in white, odourless tasting booths where air conditioning and lighting were controlled. Twelve responses were collected for each test, using the measurement scale depicted in Fig. 9.

The results for samples 1 and 2 depicted in Fig. 10(a) and (b) show a significant difference between the control and treated samples in each case. The difference may be because of the chemical reduction of this product, aging, maturation and high levels of oxidisation. For sample 1, taste profiles were described as “reductive, aged, matured and oxidising”. For sample 2, tasters noted “less fresh, oxidised, flavour loss, less fresh fruit, more dusty”.

The results for samples 3 and 4 in Fig. 11(a) and (b) show no significant differences between the control and the treated samples.

The results for samples 5 and 6 in Fig. 12(a) and (b) show a measurable difference between the control and the treated samples. However, the difference is within the acceptable range.

Samples 1 and 2 had been made from white grapes and were therefore easily affected by high temperatures, as explained in Section 2.3. The other samples had been made from red grapes or had been distilled. In a previous study, the impact of high temperatures on red wines could not be detected by a tasting panel (Mac Cawley, 2014). The reason for this could be the large amount of phenolic antioxidants present in ageable red wines, which protects them against heat damage (Butzke et al., 2012). Liquor products are also less prone to heat damage, as explained in Section 2.3.

6. Conclusions and recommendations

Analysis of the temperature profiles identified high-risk areas along the maritime supply chains of W&L products, with temperature breaches identified in containers used to ship bottled W&L products. Depending on the stages and the position of the sensors, different categories of breaches and differences in the duration of these breaches were

Table 4
Logit model of ambient temperature by weather and sensor position.

Variables	MSKU (regular)		MRSU (temperature sensitive)	
	(Templiner) Prob. of Temp ≥ 25 °C	(5th pallet) Prob. of Temp ≥ 25 °C	(Templiner) Prob. of Temp ≥ 25 °C	(5th pallet) Prob. of Temp ≥ 25 °C
Vessel level data				
Outside temperature	0.385***	0.385***	0.224***	0.224***
	(0.00740)	(0.00740)	(0.00406)	(0.00406)
Position of sensor				
Last pallet	0.498***	−0.275***	0.230***	−0.158***
	(0.0614)	(0.0594)	(0.0501)	(0.0499)
Outside Templiner	0.773***		0.388***	
	(0.0610)		(0.0495)	
5th pallet		−0.773***		−0.388***
		(0.0610)		(0.0495)
Constant	−9.155***	−8.382***	−4.737***	−4.349***
	(0.171)	(0.158)	(0.0882)	(0.0850)
Observations	18,160	18,160	15,045	15,045
Pseudo R^2	0.4723	0.4723	0.2765	0.2765

Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

detected. The study found that the largest number of temperature breaches and the most severe ones occurred while the containers were stacked at the port of origin: temperature breaches in the caution and damaging categories were recorded inside the thermal container liner, and breaches in the critical category on the outside of the thermal container liner. This can be attributed to the fact that container walls heat up dramatically if stacked in direct sunlight for a period. There were no temperature breaches at the port of destination, owing to the containers arriving in April in the UK when the daytime temperatures are cool. Diurnal fluctuations could cause quality defects, as confirmed by the quality analyses.

A logit analysis confirmed that temperature breaches are more likely to occur on the outside of the thermal container liner than on the inside. It is, therefore, recommended that a thermal foil container liner should always be used when exporting W&L products by means of maritime supply chains.

The results from the quality analysis particularly interested W&L Exporter A, who had sent these shipments to the UK, and are likely to result in further analysis and potential changes in their shipping procedures and policies.

It would be beneficial to do more trials with sensors that transmit temperature and location data in real time to the Cloud, especially while the container is on land. Such devices are more expensive than the ones used in this study, but will enable a more detailed analysis of the causes of temperature breaches. These devices would also enable the exporter to monitor the shipment and detect extreme temperature fluctuations before the products are loaded onto the vessel at the port of origin. If extreme temperature fluctuations are detected on land, the exporter could opt to collect the container and divert the shipment to the local market if it passes a quality inspection. This would save the cost of shipping inferior quality products to the overseas market and protect the exporter's brand reputation.

The current research identified the port segments of the supply chain to be of particular interest. This is where the largest number of temperature fluctuations and the most severe temperature fluctuations occur, presumably because of the number of movements (truck to stack, stack to vessel, etc.) and the duration of exposure to the elements. Ports include ports of origin, destination ports and transhipment ports. A recommended area for further research is to collaborate with port operators to do more detailed analysis of the handling operations at the container terminal to identify weaknesses and opportunities for improvement. The impact of the location of the container in the stack at the terminal and the impact of the location of the container on the vessel could also be investigated. One exporter who participated in the study showed a keen interest in the results and has already taken steps to do further analysis and adjust some shipping practices based on the findings.

CRediT authorship contribution statement

Leila Louise Goedhals-Gerber: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Esbeth van Dyk:** Writing – original draft, Methodology, Investigation, Formal analysis. **Roland Yawo Getor:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis. **Barrie Louw:** Writing – review & editing, Validation, Project administration, Formal analysis.

Fig. 9. Measurement scale. Source: W&L Exporter A, 2021a.

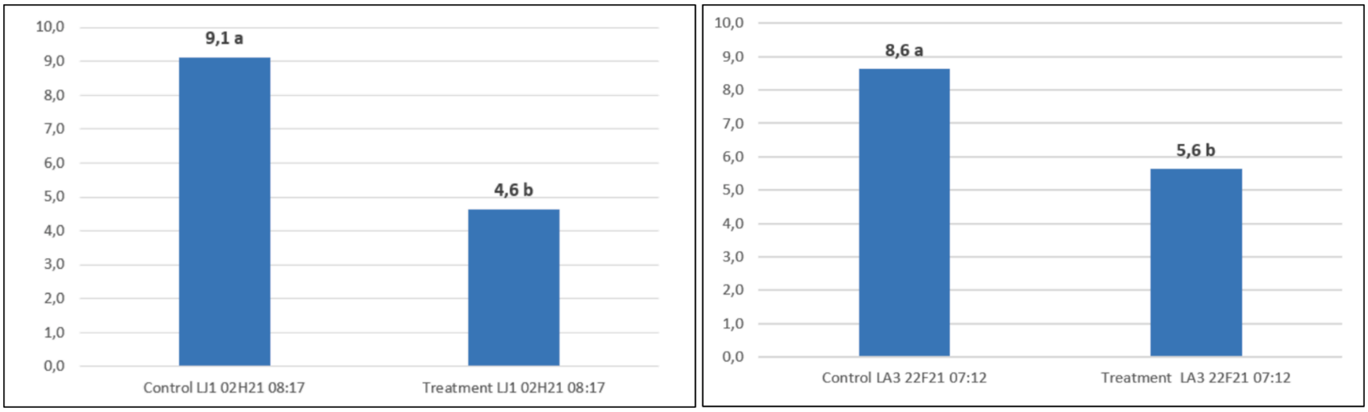


Fig. 10. (a): Sample 1 – temperature-sensitive product. (b): Sample 2 – regular product. Source: W&L Exporter A, 2021a.

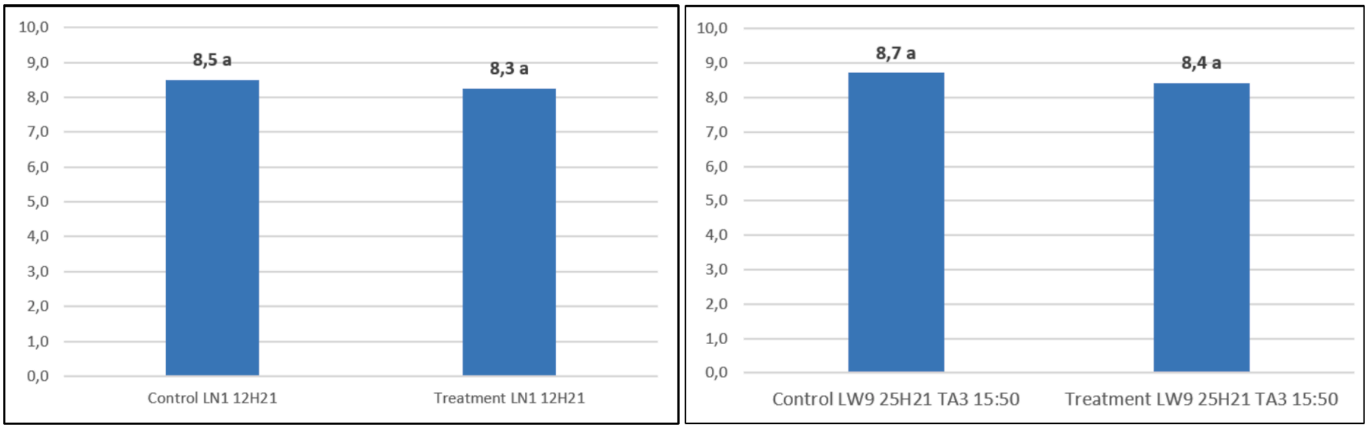


Fig. 11. (a): Sample 3 – regular product. (b): Sample 4 – temperature-sensitive product. Source: W&L Exporter A, 2021a.

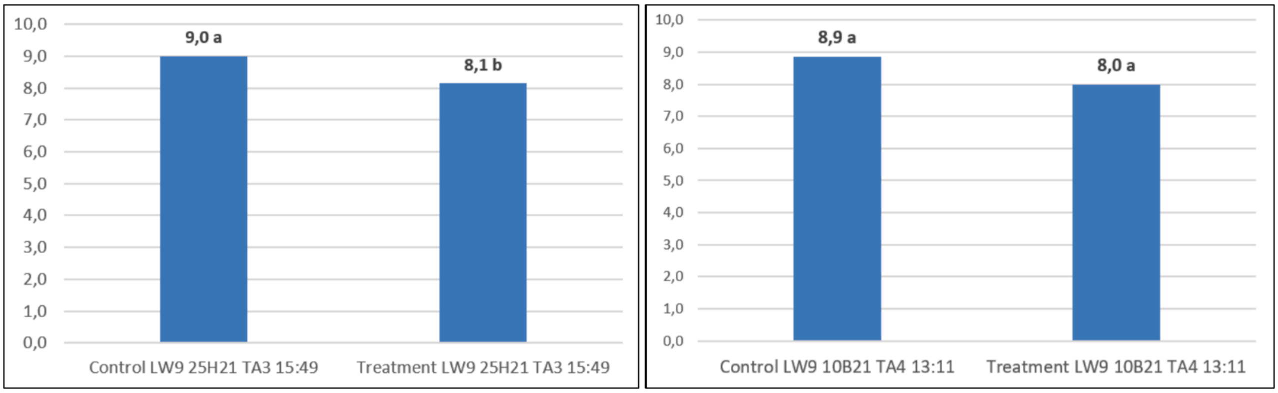


Fig. 12. (a): Sample 5 – temperature-sensitive product. (b): Sample 6 – temperature-sensitive product. Source: W&L Exporter A, 2021a.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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