Final Report

Warming the frozen meat supply chain

Reducing energy consumption and emissions (-18°C to -12°C

Project Code
2024-1058

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1.0 Executive Summary

The current Codex Alimentarius *Code of Practice* recommends distribution of quick-frozen foods should maintain a temperature of -18°C but permits competent authorities to allow -12°C during transport with the product temperature reduced to -18°C as soon as possible. In practice, -18°C has become, for most, a rigid barrier.

In the financial years ending 30.6.2019 through to 30.6.2023, an average of 1,660,000 tonnes of red meat (beef, sheep, goat, including offal) were exported each year, of which 77% was frozen. Of the frozen product, 86% was muscle meat and 14% offal. It is assumed that very little frozen product is processed for the domestic market.

The major markets (accounting for over 50% of frozen exports) were China, USA, and Japan. Due to the proportion of frozen muscle meat exported compared to offal, the major markets for muscle meats are essentially the same in proportion to total frozen exports. The major importing countries for frozen offal differs, with South Korea, Indonesia, and Hong Kong accounting for 48% of exports.

Meat & Livestock Australia conducted a study to establish the practical shelf life of frozen beef and lamb, such as would be exported from Australia. This study demonstrated that if held at, or around, -18°C, frozen beef and lamb can be stored without significant sensory degradation for a period of over 36 months. The results at -12°C demonstrated no meaningful differences. No food safety hazards we detected.

This project aimed to:

- Explore the likelihood for permitted storage and transport temperatures for frozen meat to be increased
- Evaluate the energy, environmental and other benefits of permitting higher temperature storage and transportation of frozen meat
- Develop and understanding of the regulatory environment and propose the actions that would need to be taken to achieve change
- Prepare documents that could be used to promote acceptance of change in storage and transport temperatures for frozen meat

There are indications that the -18°C barrier could be broken and the frozen food supply chain allowed to operate at a warmer temperature. A report from the Centre for Sustainable Cooling (produced with International Institute of Refrigeration, and London South Bank University, among others), regarding warming the frozen food supply chain is the ‘Three Degrees of Change’ report (Allouche et al., 2023). The report suggests that frozen food temperatures could be changed from -18°C to -15°C to reduce carbon emissions of 17.1m tonnes per year and generate 5-7% savings across the entire food chain.

During the course of this project the innovation system has been developing; new actors have entered the system and coalitions of actors have formed. In particular, the ‘Moving to -15 Coalition’ has formed. This coalition of industry partners aims to change the frozen food storage and transportation temperature around the world, and is using the ‘Three Degrees of Change’ report as the basis.

Unilever’s Ice Cream business announced in May 2022 that they would be running two pilots to trial warmer ice cream freezer cabinet temperatures with the aim of reducing energy use and greenhouse gas emissions by approximately 25%. A pilot was conducted in Germany in 2022 and a second pilot will be conducted in Indonesia during 2024.

The Australian red meat industry could save $2.5m pa annum by changing the freezing temperature, with additional savings on storage and transportation costs. A reduction in carbon emissions of about 11% would result from warming the temperature of the entire supply chain to the importing country.

In Australia, the Australia New Zealand Food Standards Code requires food intended to be stored frozen, to be maintained frozen without specifying a temperature. Similar lack of prescription can be found in USA, Indonesia and Hong Kong.

An approach, through the Codex Alimentarius Commission, to update the *Code of Practice for the Processing and Handling of Quick Frozen Foods*, would provide an opportunity for education, exploration and consensus-building for a change to recommended supply chain temperatures for frozen foods. This approach may be required to achieve change in countries such as China, Japan, South Korea and Europe.

There is great opportunity to work with like-minded organisations (nationally and internationally, trade associations and single issue groups), emphasising the benefits in emission reductions to the world at little or no cost and no risk to consumers as the means to warming the frozen supply chain. The 'Moving to -15' coalition has a focus on collecting supply chain data, and industrial pilots before approaching governments to implement regulation. Other groups may also form with an interest in this work.

As part of this project, the following documents have been developed:

- A manuscript for a peer reviewed scientific journal documenting the excellent shelf life of Australian red meat at -12°C
- A fact sheet on the shelf life of red meat at -12°C
- A fact sheet on the energy and emission implications of freezing to -12°C
- A draft project description for revision of the Codex *Code of Practice for the Processing and Handling of Quick Frozen Foods*

A presentation was given to the Refrigerated Warehouse and Transport Association of Australia, who are supportive of change. A presentation will be made at the Dubai International Food Safety Conference in October 2024.

Recommendations for AMPC

- Consider the benefits of paying the open access fee when manuscript is accepted to allow AMPC and others to use the published paper to support the campaign.
- Consider whether shelf life data on frozen offal stored at -12°C is required.
- Consider collection of data on air and product temperature variability in supply chains and the (lack of) impact on product quality
- Find small supply chains (perhaps between a processor and a subsidiary operation; in Australia and in international container shipping) where temperature control at a higher temperature could be piloted. This activity might require the involvement of government/s. It is likely that other organisations such as AFGC, RWTA etc may be setting up similar pilots. Data collection needs to be standardised to support national and international regulatory and practice change
- Consider working with groups such as the Moving to -15C coalition
- Consider how to engage Codex Alimentarius Commission in revising the *Code of Practice for the Processing and Handling of Quick Frozen Foods*

2.0 Introduction

In 1964, the International Institute of Refrigeration (IIR) recommended a minimum temperature of -18°C for frozen food.[1] By 1966, the Codex Alimentarius Commission (CAC) was considering standards on frozen foods and recommended that the temperature of product should be maintained at -18°C (0°F) and that any rise in the temperature of product during transportation and unloading should be limited to very brief periods and never be warmer than -15°C.[2]

The current Codex Alimentarius *Code of Practice* recommends distribution of quick-frozen foods should maintain a temperature of -18°C but permits competent authorities to allow -12°C during transport with the product temperature reduced to -18°C as soon as possible.[3]

There are, however, indications that other temperatures can be acceptable. The IIR note that -10°C is a satisfactory temperature for meat storage.[4] Lawrie[5] reported that it is customary in Britain to store frozen meat at -10°C and notes research reporting that fats of beef and lamb are relatively resistant to such oxidation and may still be good after 18 months storage at -10°C. Research conducted in New Zealand in the 1980s stored lamb at -10°C with satisfactory results for 14-18 months, depending upon processing conditions.[6]

Meat & Livestock Australia conducted a study to establish the practical shelf life (PSL) of frozen beef and lamb, such as would be exported from Australia.[7] This study demonstrated that if held at, or around, -18°C, frozen beef and lamb can be stored without significant sensory degradation for a period of over 36 months. The results at -12°C demonstrated no meaningful differences. No food safety hazards we detected.

AMIC and AMPC conducted a consultation with industry members in March 2023. Interest was expressed in the possibilities for storage/transport of frozen meat at -12°C. Gaining agreement of relevant stakeholders was identified as the outcome of a potential project. The proposal arose from an ATMAC grant received by AMIC and the requirement of the grant to identify opportunities where market access outcomes could be improved by additional industry scientific R&D. AMIC and AMPC agreed to include this topic on a short list for development of this brief.

A consultation with AMIC members was held in October 2023. Members expressed an opinion that the time was right to pursue this project, and that beyond acceptance of the science, it would still need to be sold to trading partners. Other foods would also need to be considered, and other stakeholders such as the shipping and insurance industries, and importing countries that might have the temperature set by legislation.

This final report describes work conducted between January and August 2024, by:

- FIRST Management – market, supply chain temperature and trade barrier analysis, stakeholder and innovation system analysis, fact sheets and final report

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[1] Liebherr. The ideal freezer temperature. Why is -18°C the ideal freezer temperature? | Liebherr

[2] Joint FAO/WHO Program on Food Standards. Codex Alimentarius Commission. (1966) Report of the Second Session of the Joint ECE/Codex Alimentarius Group of Experts on Standardization of Quick (Deep) Frozen Foods. Annex I. Proposed Draft Provisional General Standard for Quick (deep) Frozen Foods at Step 3. ALINORM 66/25 October 1966. Microsoft Word - al66_25e.rtf (fao.org)

[3] Codex Alimentarius Commission. (2008). *Code of Practice for the Processing and Handling of Quick Frozen Foods*. FAO APPENDIX I (fao.org)

[4] Bøgh-Sørensen, L. (Ed.) (2006). *Recommendations for the Processing and Handling of Frozen Foods*. Paris: International Institute of Refrigeration.

[5] Lawrie, R. A., & Ledward, D. A. (2006). *Lawrie's meat science*. Abingdon: Woodhead Publishing.

[6] Winger, R. J. (1984). Storage life and eating-related quality of New-Zealand frozen lamb: A compendium of irrepressible longevity. In P. Zeuthen (Ed.), *Thermal processing and quality of foods* (pp. 541-543). London: Elsevier.

[7] James, C. et al. (2022) The shelf-life of Australian frozen red meat MLA Final Report V.MFS.0428 The shelf-life of Australian frozen red meat | Meat & Livestock Australia (mla.com.au)

- All Energy Pty Ltd – energy and carbon emissions analysis, and construction of spreadsheet
- Fairholm Scientific Ltd – writing the scientific manuscript, assistance with stakeholder interviews

The prospects for warming the frozen food supply chain have changed considerably since the project was first proposed during 2023, and the potential for change is rapidly evolving.

3.0 Project Objectives

The project objectives were to:

- Explore the likelihood for permitted storage and transport temperatures for frozen meat to be increased
- Evaluate the energy, environmental and other benefits of permitting higher temperature storage and transportation of frozen meat
- Develop and understanding of the regulatory environment and propose the actions that would need to be taken to achieve change
- Prepare documents that could be used to promote acceptance of change in storage and transport temperatures for frozen meat

4.0 Methodology

4.1 Export statistics

Statistical data on export of frozen meat from Australia was obtained from the Department of Agriculture Fisheries and Forestry, via the National Livestock Reporting Service (https://www.mla.com.au/prices-markets/statistics/).

4.2 Temperature control of frozen meat through the supply chain

Unlike chilled meat exports, little data have been collected on temperature control for frozen meat shipments. To provide data, time-temperature data files were obtained from an Australian exporter for the temperature inside an export shipping container. The data were collected by the Maersk ‘Captain Peter’ remote container management system (Captain Peter™ | Maersk).

4.3 Energy and emissions

A review of scientific publications and industry literature was made to determine the significance of frozen food transport to carbon emissions. Using thermodynamic calculations, detailed refrigeration calculators, physical property data, and published factors an estimate of potential benefits in terms of energy usage and carbon emissions were determined. An explanation of the background calculation methodology for each step is discussed in this report.

The potential flow of product from Australian processor to customer in an importing country market was considered including options that product would transit through a cold store in Australia prior to packing into a shipping container, and that that trans-shipment (transfer from one vessel to another) may occur during the journey to the importing country (Table 1).

A simple spreadsheet-based calculation tool was developed so that the effect of different conditions along the cold chain can be assessed.

Table 1: Product journey from processor to customer

Stage	Location	Action	Control
Processor	Australia	Packing / Freezing	Processor/Exporter
		Cold Store	
		Load onto pallets	
Cold store		Pack into container	
Shipper		Container in warehouse / on board	
	International Waters	Container on board	
	Foreign Country (Intermediate)	Trans-shipment	
	International Waters	Container on board	
	Importing Country	Unloaded	
Competent Authority		Inspection	Under control of importing country
Customer		Warehousing, shipping, marketplace	

Initial chill temperature.

The refrigeration work and emissions to chill to an initial temperature at the processor is calculated according to basic thermodynamics of sensible and latent heat. Assumptions and key data are as follows:

- Thermodynamic properties of round[8], full cut including lean and fat:
    - Moisture content 64.75 %
    - Freezing temperature 0 °C
    - Latent heat of fusion 216 kJ/kg. . This is the energy required to freeze 1.0 kg of primal at 0 °C
    - Specific heat capacity above freezing 3.39 kJ/kg.K. This is the energy required to be removed from 1 kg of unfrozen meat per degree change.
    - Specific heat capacity below freezing 2.18 kJ/kg.K. This is the energy required to be removed from 1 kg of frozen meat per degree change.
- Refrigerant 5 °C colder than the meat (this provides a driving force for the exchange of thermal energy).
- Starting temperature of 38.5 °C (assumed live temperature).
- Co-efficient of Performance (CoP) following trend of 3.744*EXP(0.0254*Temp)[9]. This trend shows that as temperatures drop, the CoP decreases; that is, the amount of energy required to reduce the temperature of meat increases as meat becomes colder.

[8] Used as a representative primal, taken from 2006 ASHRAE Handbook – Refrigeration (SI)
[9] As regressed from the data in *Energy Performance Assessment of R134a / LPG Blend as Replacement of R134a in Vapor Compression Refrigeration System*. Note that it is very difficult to estimate CoP over a wide temperature range as manufacturers do not report this data,

- Cost of power at the processor 20 c/kWh. Typical of demand and volume charge for median size processors >800 hpd on an 11 kV feed.
- Average of Scope 2 and 3 emissions from grid power for East Coast Australia 0.86 kg CO_2 / kWh grid power.

Freight – Active Movement "Closed System"

For this report it is assumed that transportation of red meat whilst in transit is in a "closed" system, that is, during shipping and trucking the doors of a refrigerated system are not opened hence thermal energy gain is predominantly due to the transfer of heat through walls, floors and roof surface areas. Energy consumption during transit can be very difficult to put a precise number on due to the large number of variables, unknowns and unpredictable factors that influence energy requirements and emissions production. The following factors influence energy consumption in refrigerated containers (also known as "reefers")

- Temperature set point
- Types of goods / thermal properties
- Insulation quality
- Container size and load efficiency
- Ambient conditions
- Efficiency of the refrigeration unit itself

A very useful cooling calculator was developed by Spanish refrigeration equipment manufacturer Intarcon, accessible at Cooling calculator (calcooling.com). Using this tool, the following parameters were used to simulate a 40' refrigerated shipping container

- Modular cold room 12.03 x 2.35 x 2.39 m internal dimensions with 100mm insulation
- Negative temperature refrigeration with varying set points (i.e. -25, -22, -18 °C etc)
- Ambient temperature 25 °C with 90% humidity
- Meat thermodynamic characteristics as above
- 250 kg / m^3 packing density hence approx. 17 tonnes payload per container
- 0% turnover
- 12 air renewals per day
- No openings
- No personnel thermal loads

The output of the calculator is the necessary cooling capacity to maintain temperature setpoint in kW, which is multiplied by the journey duration and divided by the tare mass of the container to result in kWh / t HSCW / hour.

The energy required to maintain temperature and the resulting emissions were calculated for a 40 foot container (Table 2). These calculated figures are consistent with anecdotal estimated that the saving of reducing from -18 to -15 °C would save 5-7% of energy and that maintaining a 40' refrigerated container at freezing temperatures consumes 3-4 kWh/hr .

Sample journeys were considered (Table 3) with different durations and distances When converting freight distances into a journey duration, cargo shipping was assumed to be a constant 14 knot or 26 km/hr speed.

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and independent studies that do calculate CoP above 0 °C do so for heat pumps. Same thermodynamic cycle and principle as refrigeration, but operating in reverse so not applicable.

Table 2: Estimated energy and emissions for a 40 foot container held at different temperatures

Temperature °C	Electrical energy load whilst in freight kWh / t HSCW / day	Emissions whilst in freight kg CO_2-e / t HSCW / day
-25	6.1	5.3
-22	5.8	5.0
-18	5.4	4.6
-15	5.1	4.4
-12	4.8	4.1

Table 3: Distance and duration of sample journeys[10].

Origin Port	Destination Port	Days in transit	Distance transit
Sydney	Dalian	14 days, 10 hrs	8,976
Brisbane	Philadelphia	28 days, 15 hrs	17,834
Melbourne	Dubai	19 days, 14 hrs	12,203

Freight – Warehousing and Storage "Open System"

There are points in the supply chain where frozen meat will be kept in a warehouse / storage system before and after transit e.g. aggregation of product pre-shipping and distribution of product after shipping.

Energy used and emissions generated were estimated using the Cooling Calculator for frozen product stored at different temperatures (Table 4) in an open condition where heat is exchanged primarily through door openings. The main thermal energy gains were assumed to be due to heat gain through insulated walls (~15%), thermal loss due to equipment, people, and lighting (~37%), and "air renewal" (opening of access doors, ventilation for air quality; 48%)[11].

Table 4: Estimated energy and emissions for a warehouse running at different temperatures

Temperature °C	Electrical energy load whilst in storage. kWh / t HSCW / day	Emissions whilst in storage. kg CO_2-e / t HSCW / day
-25	10.2	8.8
-22	9.9	8.5
-18	9.3	8.0
-15	8.9	7.7
-12	8.4	7.2

[10] Cargo Calculator | Sea Distance Calculator for Shipping (searates.com)
[11] CalCooling 2021 v3.8, Cooling calculator (calcooling.com), accessed 24th Jan 2024.

4.4 Stakeholders

A search was made of organisations that have an interest in frozen storage temperature control and their position on the proposition of increasing the storage temperature (of meat) from -18°C to -12°C. This was achieved from internet and news searches, personal contacts, and snowball sampling. Public documents relating to these organisations were assessed, and in some cases, representatives of these organisations were interviewed.

The salience and nature of stakeholder involvement in this issue was assessed (Mitchell et al., 1997) to determine who was really important in the system, and the change in characteristics required to change their role. Mitchell et al. classify stakeholders based on the attributes of power, legitimacy and urgency, and suggests a response based on their type (Table 5).

The legislation and regulations of major importers of Australian meat were reviewed to determine the nature of the trade barriers to warming the temperature of frozen meat. For the purposes of processing, Australian legislation and regulation was also assessed. Documents, in all cases, were accessed via the internet, and Google translations were prepared as required.

Table 5 Stakeholder typology (Mitchell et al. 1997)

Type	Attribute			Response
	Power	Legitimacy	Urgency	
Dormant	X			Because of their ability to acquire a second attribute, there is a need to be cognizant of such stakeholders. Which dormant stakeholders may become salient?
Discretionary		X		There is absolutely no pressure to engage in an active relationship, except to change the status and value of the stakeholder.
Demanding			X	Mosquitoes buzzing in the ears of managers. Irksome but not dangerous; bothersome but not warranting more than passing management attention, if any at all.
Dominant	X	X		Should have some formal mechanism in place that acknowledges the importance of their relationship with the proposition. Expect and receive much of the attention.
Dangerous	X		X	The actions of these stakeholders are outside the bounds of legitimacy but are dangerous, both to the stakeholder-manager relationship and to the individuals and entities involved.
Dependent		X	X	Power in this relationship is not reciprocal, its exercise is governed either through the advocacy or guardianship of other stakeholders, or through the guidance of internal management values. Need to find and exercise power.
Definitive	X	X	X	A clear and immediate mandate to attend to and give priority to that stakeholder's claim.

The innovation system was analysed broadly as described by Jenson (2019) utilising the Sectoral Innovation System approach of Klein Woolthuis et al. (2005) and Klein Woolthuis (2010) and the Technological Innovation System approach of Hekkert et al. (2007). Multiple factor models, or frameworks, have been developed to explain innovation system performance within sectoral (Klein Woolthuis et al., 2005) and technological innovation systems (Hekkert et al., 2007), and these frameworks therefore have been used for diagnosis, and rectification, of any failure or weakness that may occur in the sectoral or technological innovation system. The elements of these innovation system failure frameworks (listed and defined in Table 6,Table 7) can be assessed and have been used in the study of the success or failure of technological innovation in industry sectors. The system elements may be thought of as prerequisite conditions and essential processes that occur in innovative industry sectors, and in successfully introduced technologies (Jenson, 2019).

Table 6: Sectoral innovation system elements and definitions (Jenson, 2019)

System element	Definition / Indication of being effective
Actors	Groups involved in the project have the competence to participate and capacity (resources) to do so.
Infrastructure	Items such as information and communication technology, power, scientific and applied knowledge and skills, facilities, Intellectual property protection, training, and education are sufficient.
Institutions	Availability of laws, finance, systems, culture, ‘rules of the game’ facilitate the innovation process.
Interaction	Good connections between actors - enough to bring the skills and views required, but not so close that no new approaches or ideas can be considered.
Market	The potential users can see the value in what is being proposed and can understand how implementing change will benefit them.

4.5 Drafting documents

Previous reports on shelf life (James et al. (2022) report prepared for MLA (V.MFS.0428)) and milestone reports for this project were used to draft a manuscript for submission to a scientific journal and fact sheets. A previous fact sheet used to explain the shelf life of beef and lamb at -18°C (Appendix 3).

Table 7: Technological innovation system elements and definitions (Jenson, 2019)

System element	Definition / Indication of being effective
Knowledge development	R&D and knowledge development; 'learning by searching' and 'learning by doing'; new knowledge of production, design, and markets.
Knowledge diffusion	Exchange of information, especially between R&D providers, government, competitors, and market that may be mediated through networks, supply chains, and standards.
Guidance of the search	Choices are made from various technological options for further investment, involving industry, government, and markets. Guiding actors to select options for investment through articulating visions, expectations, regulations, policy, or taking action.
Entrepreneurial activities	Turning the potential of know knowledge networks, and markets into concrete actions to generate, and take advantage of, new business opportunities. Investigation of new technologies and applications in an attempt to overcome the uncertainties that exist; social learning.
Market formation	Regulation and formation of market that will allow new, or developing, technologies to continue to be created and develop space through policies, standards or regulations that nurture demand for innovation; development of a market through capability to, and actual articulation of demand, price/performance requirement, or required reduction of uncertainties.
Acceptance / counteract resistance to change	Becoming part of an accepted paradigm or overthrowing it; development of advocacy groups for processes of change; social acceptance by relevant actors. Entry of new firms that resolve uncertainties about technologies and markets, and thus make the technology legitimate.
Resources mobilisation	Supply of resources, both financial and human capital, for innovation. The ability of the system to provide competence / human capital, financial capital and complementary products, service and network infrastructure.

5.0 Project Outcomes

5.1 International market for Australian frozen meat

In the financial years ending 30.6.2019 through to 30.6.2023, an average of 1,660,000 tonnes of red meat (beef, sheep, goat, including offal) were exported each year, of which 77% was frozen. Of the frozen product, 86% was muscle meat and 14% offal. It is assumed that very little frozen product is processed for the domestic market.

The major markets (accounting for over 50% of frozen exports) were China, USA, and Japan (Figure 1). Due to the proportion of frozen muscle meat exported compared to offal, the major markets for muscle meats are essentially the same in proportion to total frozen exports. The major importing countries for frozen offal differs, with South Korea, Indonesia, and Hong Kong accounting for 48% of exports (Figure 2).

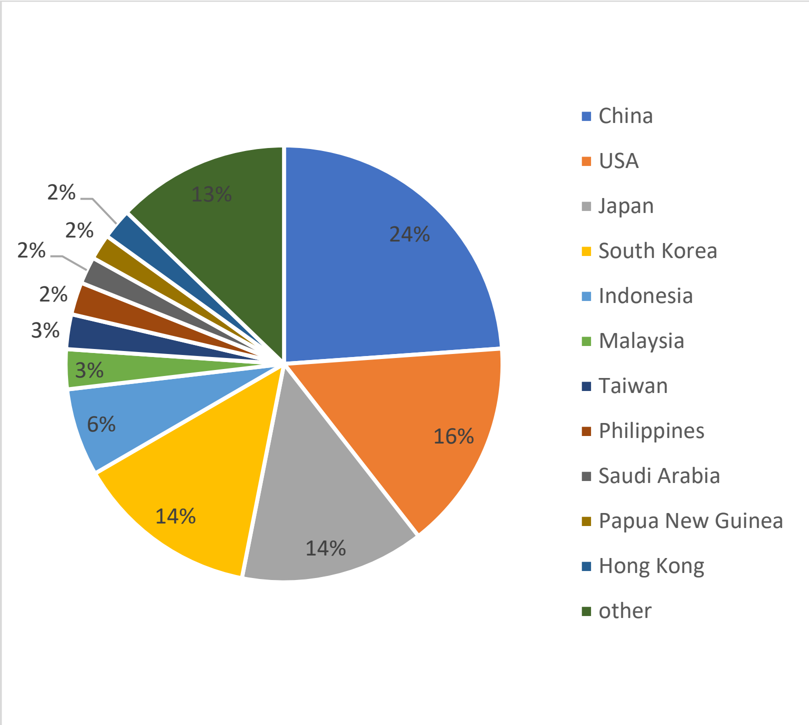


Figure 1 Countries importing Australian frozen red meat

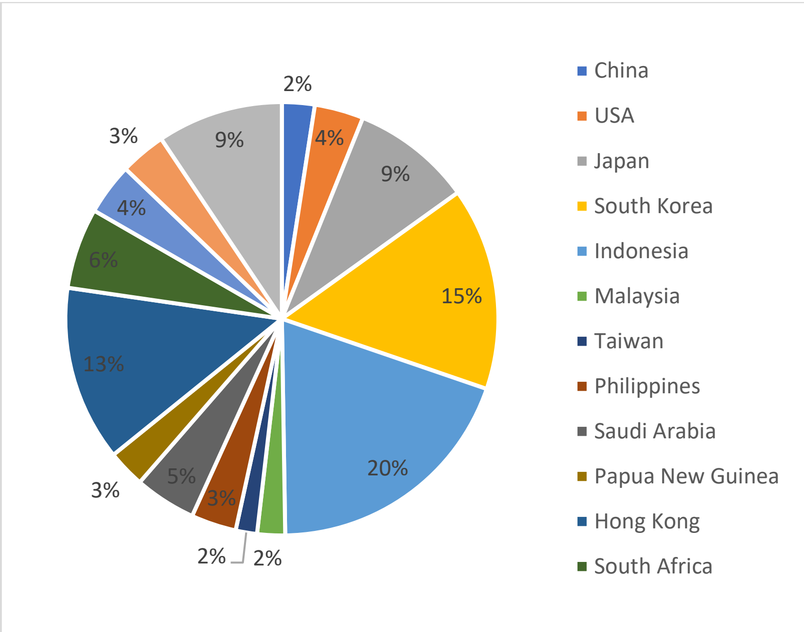


Figure 2 Countries importing Australian frozen red meat offal

When considering technical changes to market access conditions, it is important to consider how many countries may need to accept a change, in order to a) potentially, bring other countries along with them and b) avoid creating logistical complexity for exporters who may make a beneficial change, but at relatively high cost due to having to meet differing market expectations. Targeting the above mentioned countries (muscle and offal) would account for

75% of all frozen red meat exports. There may be benefit in addition of some smaller (or non-) markets, for strategic benefit (for example, a member states of the Gulf Cooperation Council and the European Union).

5.2 Temperature of frozen meat through the supply chain

Two time-temperature records were obtained for export meat shipments. Of interest is the choice of -25 °C as the shipping temperature for the product. It is not uncommon for product owners and the supply chain (see 5.4.1) to utilise set point temperatures well below the 'standard' -18 °C to ensure that product is not considered non-compliant by customers or importing countries at the time of inspection (see 5.5). The time-temperature records are for standard 20ft shipping containers, measuring air temperature rather than product temperature (**Figure *3*** and **Figure *4***). The data reported here can be considered to be artefacts of the system because they measure air temperature at specific points and times, and may be subject to algorithms affecting data collection and presentation.

The chart containing all the data (top left) has data extracted and presented in charts showing a shorter period of time, for the initial adjustment of temperature of the container and other perturbations during the journey. In both cases, there was a period of adjustment until the return air temperature achieved the required set-point. Presumably, this was due to product being loaded at above the container set point. Once the return air temperature achieved the set point, perturbations in return air temperature did not last more than a day.

The product temperature is unknown, but may be deduced from the difference between the supply and return air temperatures (chart in bottom right corner of each figure). The temperature differences were most frequently 1-3 °C in the case where product was loaded above the set point, and 1-2 °C in the case where product was loaded close to the set point. One can deduce that product temperature would be stable and between the temperature of supply and return air.

A study was conducted of temperature control through the entire supply chain in 2006 (McPhail and Tume, 2006), with temperature loggers placed within cartons of manufacturing beef in a 20 ft container that was set for a 30 minute defrost cycle every 12.3 hours. Meat surface (carton liner) temperatures were noted to vary in different parts of the container, with the highest temperatures recorded near the container door (Figure 5) and fluctuations in temperature were much greater than noted in the contemporary data. Temperature rise was significant in the container when off-power, even for a few hours (Figure 6). The authors determined the effect of temperature abuse, equivalent to the worst that might be experienced when pallets of cartoned beef are exposed to ambient temperatures when refrigerated containers are off-power, on the organoleptic properties of manufacturing beef. They warmed frozen product to -5 °C in the centre of the carton on two occasions 4 weeks apart, then stored the product at -20 °C for another 4 weeks before analysis. The temperature abuse treatment did not appear to have any effect anti-oxidants (α-tocopherol and β-carotene), had similar percentages of polyunsaturated fatty acids and on cooking, generated similar levels of an oxidation product, hexanal in the head space. Peroxide values and TBARS contents were not significantly different. It therefore seems unlikely that there would be any rancidity or associated quality problems with meat treated in this way.

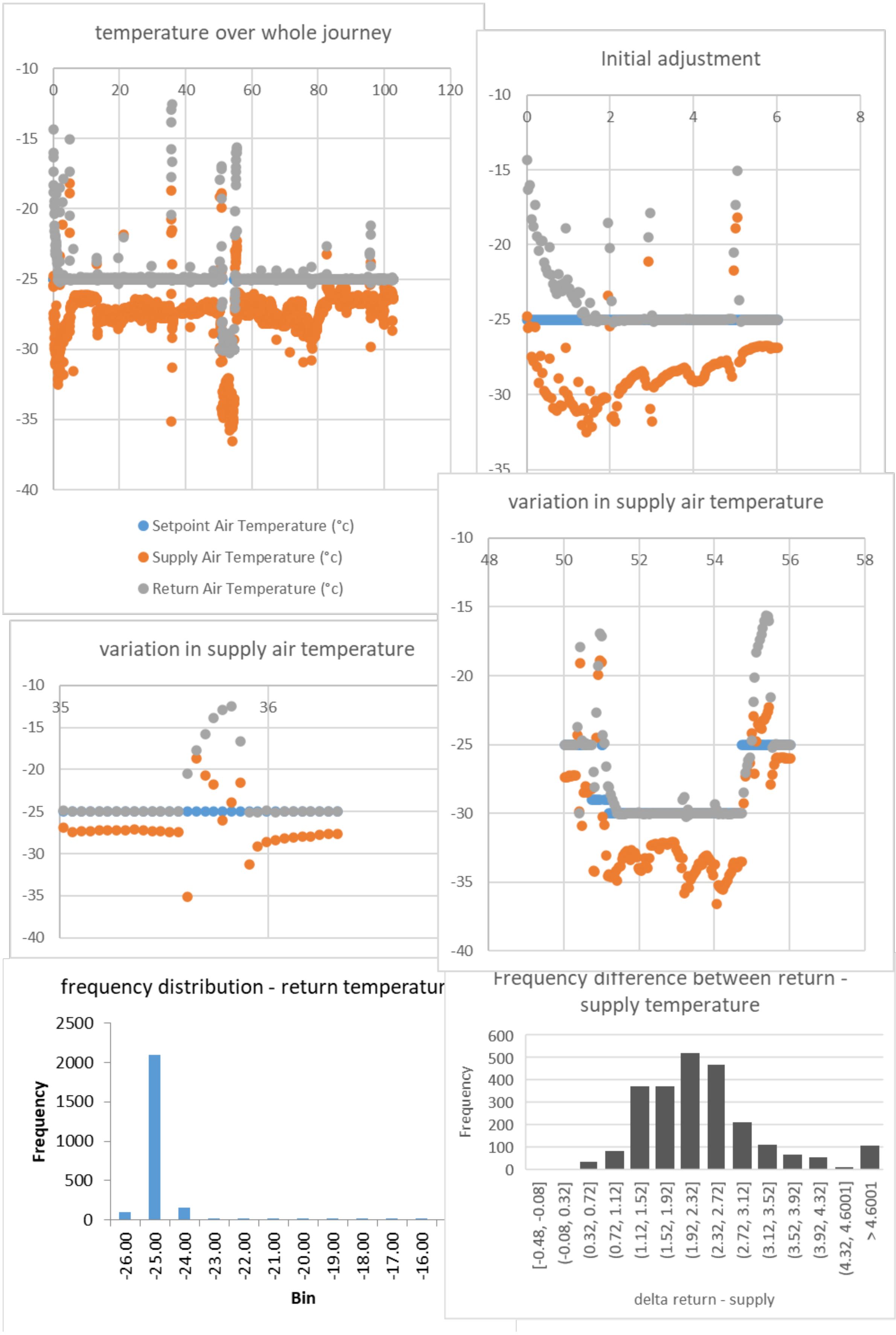


Figure 3 Frozen meat temperature control in shipping container 1

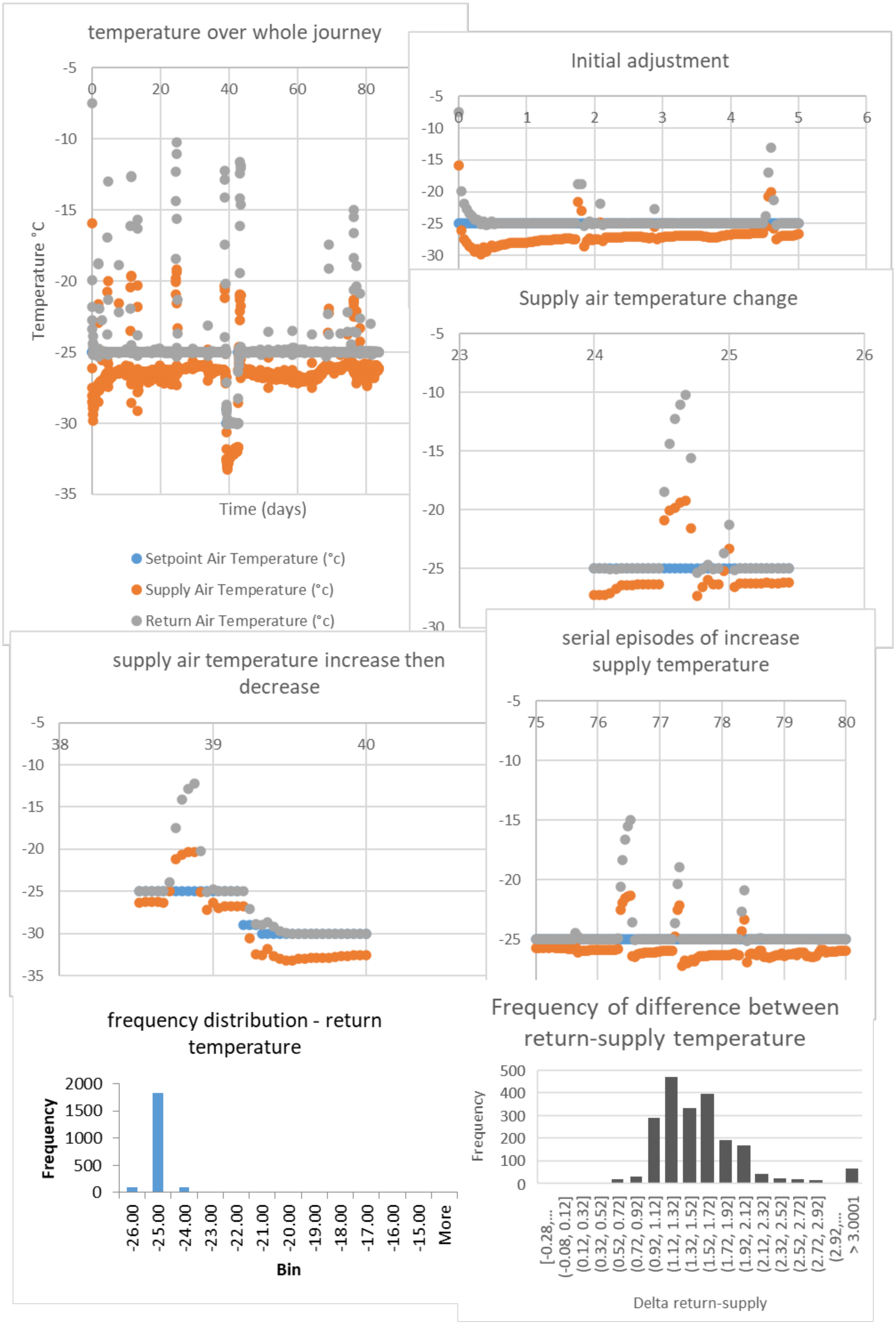


Figure 4 Frozen meat temperature control in shipping container 2

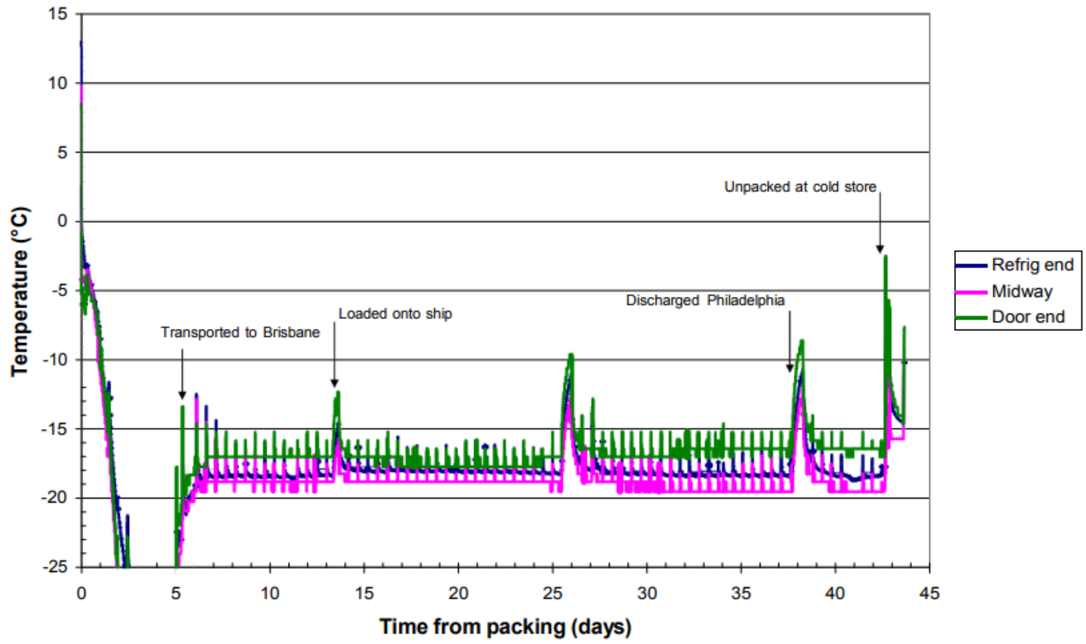


Figure 5 Meat surface temperatures in a 20ft container through its journey (McPhail and Tume, 2006)

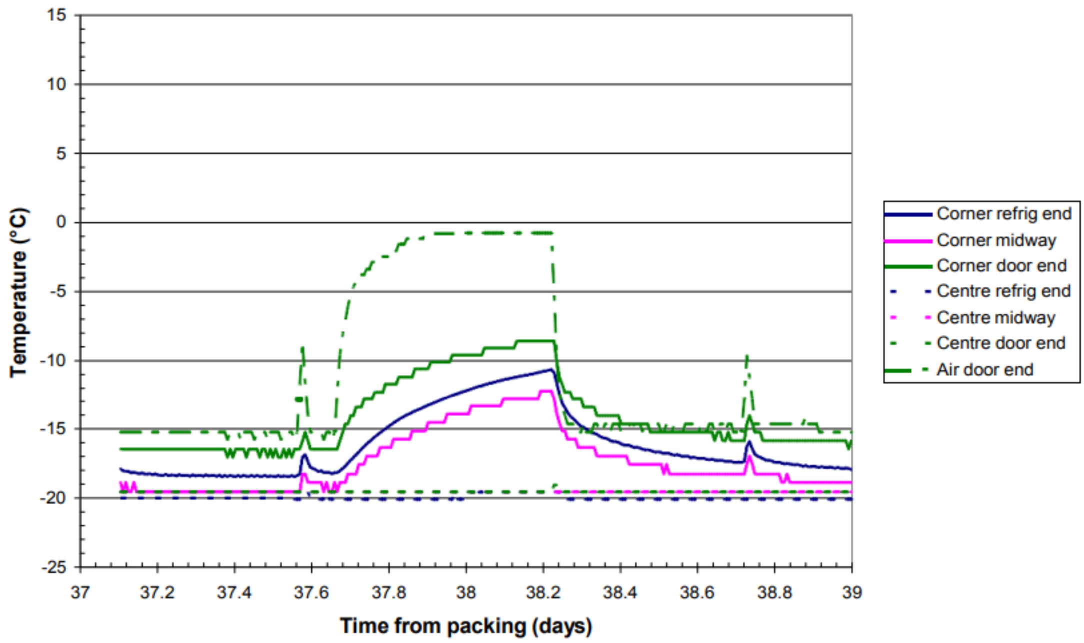


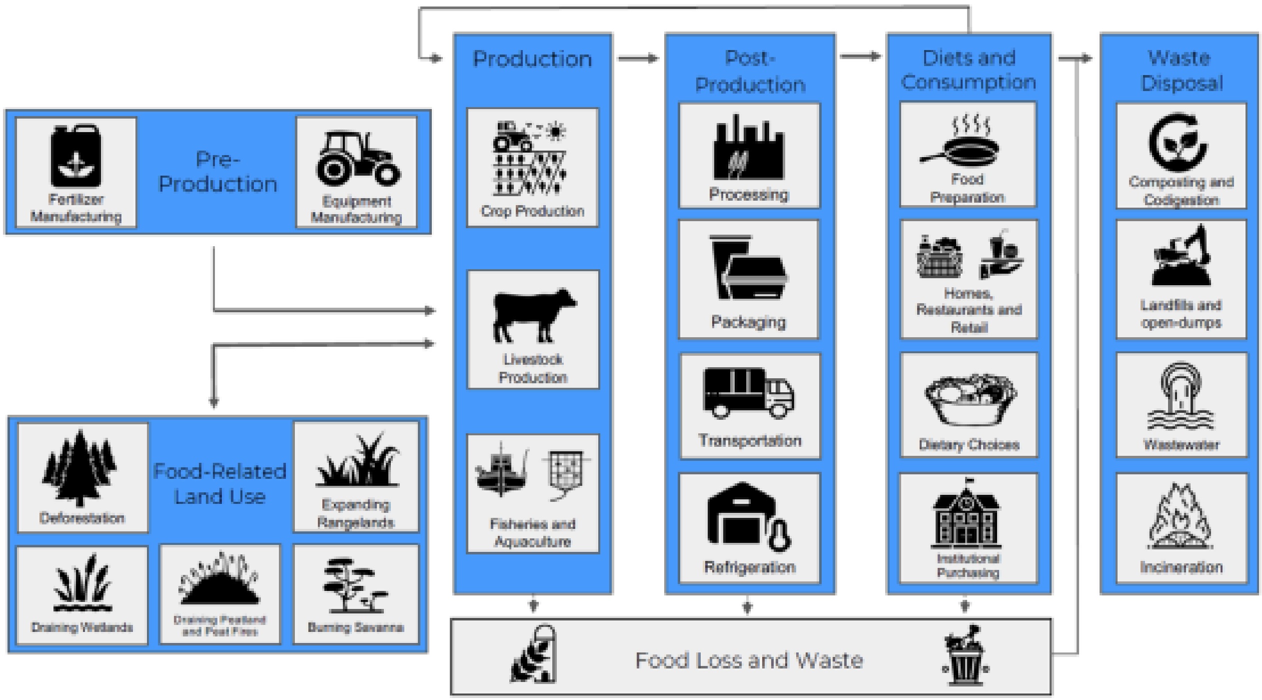
Figure 6 Meat surface temperatures during time off power (McPhail and Tume, 2006)

5.3 Energy and emissions

5.3.1 Contribution of frozen food to carbon emissions

Carbon emissions are rapidly becoming the common international currency for expressing energy usage and also environmental impact. Within the "food system" (Figure 7) (Rosenzweig et al., 2021) frozen foods are found at the post production stage, both in refrigerated storage and transport. A negative consequence of poor control of transportation and refrigerated storage Is food loss and waste.

The food system contributes more than 30% of the greenhouse gases emitted by human activities globally and food sector cold chain is responsible for almost 2% of global anthropogenic greenhouse gas emissions. Over 10% of the world's total energy consumption is used to create food products that are never consumed, and roughly 8% of anthropogenic greenhouse gas emissions result from producing, shipping, storing, and processing food that is lost or wasted (reviewed by (Sandalow et al., 2021).



GHG emissions sources in the food system. Reproduced from The Noun Project. CC BY 3.0.
From top-left to bottom-right: Fertilizer by Syaiful Amri,Tractor by Olivier, Forest by Nesdon Booth, Wetland by Iconathon, Moss by Laymik, Thick Grass by Hamish, Savanna by Hamish, Farming by ProSymbols, Cow by Alexandr Lavreniuk, Boat by Amethyst Studio, Aquaculutre by Angelo Troiano, Grains Silo by Ben Davis, GMO by Stephanie Wauters, Food Conatiner by dDara, Tranport by Prianka, Temperature by Andrejs Kirma, Cooking by Erik Arndt, Grocery by Iconixar, Fast Food by Kristina Margaryan, School Building by Siipkan Collective, Waste by Priyanka, Compostable by Luca Reghellin, Excavator on Landfill by Peter van Drie, Waste water by Mavadee, Incineration by Eucalyp.

Figure 7: The Food System (Rosenzweig et al., 2021)

To assess the impact of refrigeration setpoint temperature changes on supply chain energy consumption and emissions production, analysis was conducted on the energy intensity and emissions of processing and transport/warehousing. It is outside of the scope of this project to determine a Life Cycle Assessment, however the following section provides emissions information to be able to contextualise emissions associated with the red meat cold chain. Hence presented below are high level estimates of Scope 1 (direct emissions), Scope 2 (indirect emissions from power consumption) and Scope 3 (other indirect emissions) excluding biogenic, embodied, and non-fossil emissions in the producer and feedlot stage. Embedded or embodied carbon emissions, refer to the greenhouse gas emissions generated during the production and transportation of goods, from the extraction of raw materials to the manufacturing process and final delivery to the consumer.

5.3.2 Processor

Using the methodology and assumptions laid out in section 4.3, the processor results for temperatures of -25, -22, -18, -15, and -12 °C demonstrate the increased costs associated with freezing to lower temperatures and the savings that may be made, in energy (cost) and emissions by freezing to a warmer temperature (Table 8, Figure 8).

Preliminary conversations with processor stakeholders have suggested that if freezing to a higher temperature, refrigeration plant would be run the same as currently, with the setpoint temperature being achieved quicker. Note that without exploring unique power tariffs, this will mean that the assumed cost saving of 20 c/kWh will be significantly reduced as the overall kWh/t to cool is reduced at a higher temperature, but the kW instantaneous demand will stay the same, incurring the same demand charge from the electricity retailer.

It can be seen that there is a slight non-linearity in reduction, in that for each initial degree warmer above -25 °C, a higher proportionate saving in refrigeration work, emissions, and cost is made. As the freezing temperature progresses towards 0 °C, this saving per degree benefit decreases. This is due to the non-linear trend of refrigeration cycle CoP vs temperature. This relationship holds true up until the threshold of 0 °C, where the energy saving experiences a step increase due to the elimination of sensible heat below zero, and latent heat at zero i.e. the saving per degree above 0 °C is considerably higher per degree above freezing.

Table 8: Cost and Emissions associated with initial chilling of meat

T °C	Refrigeration Work [kWh / t HSCW]	Emissions [kg CO2-e / t HSCW]	Cost to Chill [$ / t HSCW]	Cost Saving by Raising Temp from -25°C [$ / t HSCW]
-25	56.1	48.5	$11.2	-
-22	51.2	44.2	$10.2	$1.0
-18	45.2	39.0	$9.0	$2.2
-15	41.2	35.6	$8.2	$3.0
-12	37.5	32.4	$7.5	$3.7

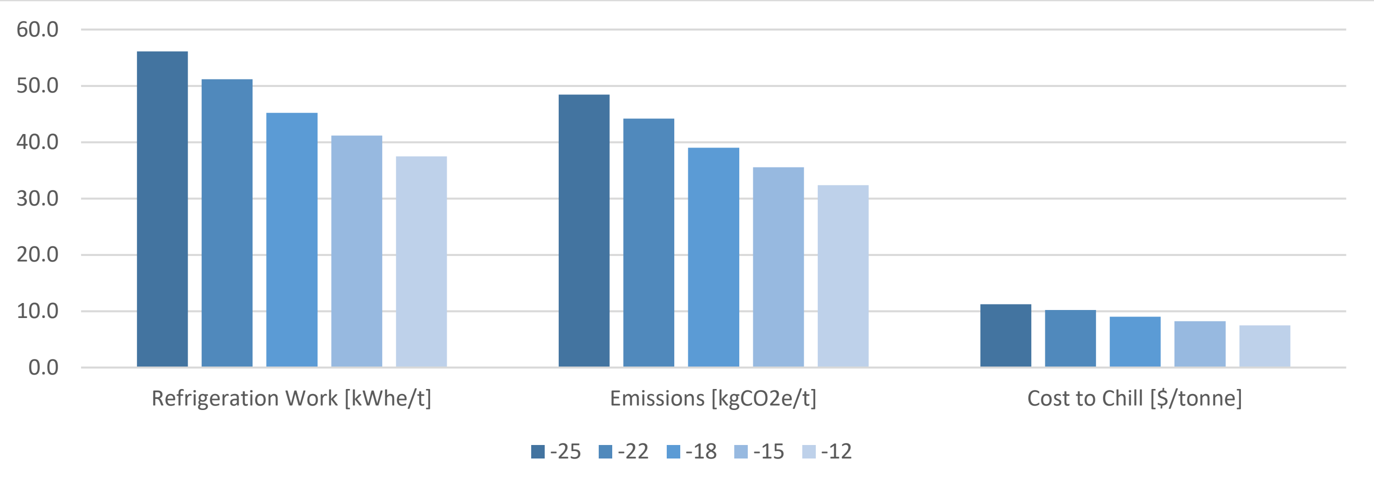


Figure 8: Cost and Emissions associated with initial chilling of meat

Consideration of how the above emissions intensity relate to other processor emissions requires consideration of the main sources of Scope 2 emissions within the processor boundary[12]. The following emissions considerations excludes Scope 1 emissions from burning fuel, biogenic emissions, embodied emissions, and non-fossil Scope 3 emissions:

- Scope 2 emissions from consumption of grid electricity
    - Reported in the 2022 sector-wide *Environmental Performance Review* to be 32.0% of total energy use, or 305.33 kWh/t HSCW
    - Using the East Coast average of 0.86 kg CO_2-e / kWh, this equates to an average Scope 2 GHG emissions intensity of 263.6 kg CO_2-e / t HSCW

Total Scope 2 emissions at the processing stage of the supply chain are 263.6 kg CO_2-e / t HSCW, therefore it can be seen that even by manipulating freezing temperatures from the current -25°C setpoint all the way down to -12, the resultant saving in processor emissions would be 6.1%, and insignificant relative to the total supply chain.

5.3.3 Transport & Storage

Using the transport and storage assumptions (section 4.3) for representative freight routes (Table 3), estimates of the emissions associated with storage (time of 14 days is assumed) (Table 9) and transport (refrigeration emissions only) (Table 10) were made and these estimates combined (Figure 9).

Table 9: Emissions associated with 14day cold storage

Temperature °C	14 Day Storage Emissions kg CO_2-e / t HSCW
-25	123.2
-22	119
-18	112
-15	107.8
-12	100.8

Table 10: Emissions associated with container storage during transport

Journey	Distance transit	Freight Emissions [kg CO2-e / t HSCW]
Sydney – Dalian	8,976	66.8
Brisbane – Philadelphia	17,834	132.7
Melbourne – Dubai	12,203	90.8

[12] In the proceeding analysis, data from processors collected during MLA and AMPC projects is used. Typical size is 1000 head processed per day, operating 250-300 days per annum with rendering and cold store on site.

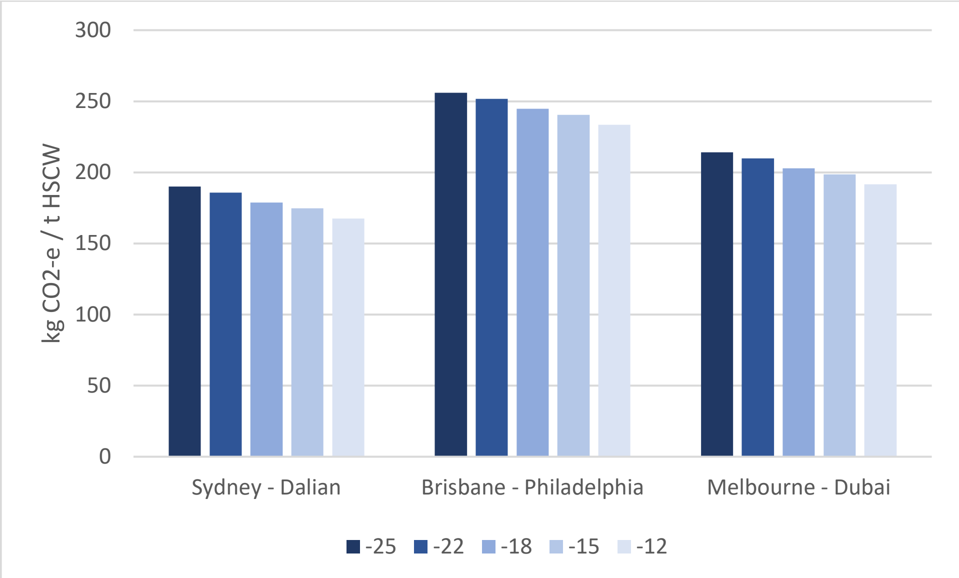


Figure 9: Emissions associated with cold storage and freight for sample journeys

It can be observed (Figure 2) that making incremental changes to storage temperature does not produce a major change in cold freight and storage emissions. The primary factors influencing cold freight and storage energy consumption and emissions production per tonne HSCW are

1. Days in storage / Days in freight
2. Number of door openings when in cold store
3. Number of air renewals when in freight
4. Packing density and efficiency

5.3.4 Energy calculation tool

A simple spreadsheet-based calculation tool was developed so that the effect of different conditions along the cold chain can be assessed (Appendix 1). Inputs to the calculator are

- Temperature of product chill at the processor and maintained throughout the cold chain
- Days in an “open” storage system (cold store) while awaiting freight
- Distance or time in a “closed” storage system (refrigerated container) while being freighted

The outputs are then total emissions and cost along the cold chain, inclusive of the energy and emissions to chill the product, maintain in storage and during freight; and exclusive of the cost of transport / storage or emissions from freight. The intent of the calculator is to enable “What If?” analyses, where processors can quantify the energy, cost, and emissions benefits of varying cold chain temperature set points to inform decision making.

5.4 Stakeholders

During the course of this project the innovation system has been developing; new actors have entered the system and coalitions of actors have formed. In particular, the ‘Moving to -15 Coalition’ has formed. This assessment of stakeholders will describe the Coalition as a single actor, and only describe their members where additional material is relevant.

5.4.1 Companies

Unilever

Unilever's Ice Cream business announced in May 2022 that they would be running two pilots to trial warmer ice cream freezer cabinet temperatures with the aim of reducing energy use and greenhouse gas emissions by approximately 25%. A pilot was conducted in Germany in 2022 and a second pilot will be conducted in Indonesia during 2024. In November 2023, Unilever announced that it was making its portfolio of 12 patent applications on reformulation of ice cream to achieve good quality at -12 °C available to other ice cream companies through a free, non-exclusive licence. The motivation for this action was stated to be reduction of emissions across the industry. Unilever has had a similar experience in the past, when, in the early 2000s, Unilever made changes to refrigerants used in its own freezers and influenced industry-wide change, in conjunction with like-minded users of freezers, environmental groups and technician training organisations. It has been suggested that Unilever's program to increase freezer temperatures will likely take 10 to 15 years to roll out because the company will face resistance from countries such as Denmark, South Africa, and Chile, where regulations mandate lower freezer temperatures.

Nomad Foods

Nomad Foods many frozen food brands including Birds Eye, Findus, and Igloo. In June 2024, they announced the results of trials for storage of several products above -18°C. Nine savoury frozen products are included in the study; poultry, coated fish, natural fish, vegetables, plant-based foods and pizza. Four temperatures (ranging from -18°C up to -9°C) and eight key areas including food safety, sensory, texture, rancidity, drip loss, nutrition, energy use and packaging impact were tested. Results after eighteen months showed no significant change to the products at -15°C versus -18°C, unless those products had passed their Best Before Date, where a drop in Vitamin C for some vegetable products could then be seen. No results were reported for -9°C or -12°C. They have suggested that storing frozen food at -15°C, instead of the industry standard -18°C, could reduce freezer energy consumption by more than 10% without any noticeable impact on product safety, texture, taste or nutrition of the frozen food products. They also acknowledge that additional gains may be made because -18 °C is seen by many as a 'hard maximum' so store products (e.g., warehouses) below -20 °C 'to be sure'. So far, the response they have received to the public statements they have made have been positive but UK regulators emphasise that one company cannot make this change alone, and more data needs to be available with more widespread acceptance. Some European countries (e.g. Belgium) are likely to be difficult, whereas much of Europe is flexible. Nomad does seem to be intent on making change and has been talking to industry associations, the Consumer Goods Forum (international consortium of largest manufacturers and retailers), and whitegoods manufacturers. It is likely that some collaboration with the "Three Degrees" consortium (see below) will be announced in the near future.

DP World

DP World, a global logistics firm based in Dubai, and a funder of the *Three Degrees* report which was launched at the DP World pavilion at COP 28. (see below). DP World has been foundational to the 'Moving to -15°C' coalition (https://www.dpworld.com/sustainability/jointhemovetominus15).

Australian export processor

Frozen product generally moves quickly out of the country, but some offal items may take a couple of weeks to move because it takes time to fill a container. Generally, products are sold "CIF" (including cost, insurance and freight) which means that the seller is responsible for costs until unloading commences in the importing country. However, risk for the product transfers once the product is onboard ship at the port of loading. This means that the exporter is concerned about the cost of shipping, but is not financially responsible for losses due to refrigeration problems onboard.

The seller is responsible for the temperature of shipments, and it is routine (for many exporters) to use a setpoint well below -18 °C (for example, -22°C or even -25°C) to ensure that product is at -18° C or lower when inspected at the point of entry in some importing countries (e.g., China) as containers may be off power for 1-2 days between unloading and inspection.

The cold chain participants often question temperatures and whether they can be changed, but need a lead from institutions (for example, government regulations, International Institute of Refrigeration, recommendations given in the MLA publication *Shelf life of Australian red meat*) before a change would be implemented.

Insurer

An insurer was consulted who indicated that few claims relating to temperature abuse were received because if problems occur, they are dealt with commercially rather than making a claim on insurance. Insurers are not standard setters on technical matters, but will be guided by normal industry practices, and the expertise of the supply chain and validated parameters.

Container operator

News of the idea of warming the supply chain is not widely known in the container sector. There are 4 major container builders. Not surprisingly, efficiency is a critical outcome and each have their own refrigeration engineering and software for control of temperature.

If product were shipped at a higher temperature then no change to the method of construction or operation of the container would be required.

Operation of containers at a higher temperature would make less demand on diesel-fuelled generators and less wear and tear on refrigeration equipment. It is difficult to calculate the size of the reduction in energy usage because of the variables in construction, engineering, and operating algorithms between and within container operators.

5.4.2 Academia

University of Birmingham, Centre for Sustainable Cooling

The Centre for Sustainable Cooling (CSC) is taking a systems approach to delivering sustainable and resilient cooling and cold chain for all. It therefore, engages in essential non-technological aspects such as, finance, business models, policy and behavioural challenges. They are also developing the evidence, frameworks, tools and strategies to help prioritise and increase the level of investment and government support into the development of sustainable and resilient cold-chain as critical infrastructure.

The CSC is a partner in the EU-funded ENOUGH project which aims to achieve a carbon neutral food industry (harvest to consumption) by reducing EU emissions by 50% by 2050.

A major output from the CSC (produced with International Institute of Refrigeration, and London South Bank University, among others), regarding warming the frozen food supply chain is the ‘Three Degrees of Change’ report (Allouche et al., 2023). The report suggests that frozen food temperatures could be changed from -18°C to -15°C to reduce carbon emissions of 17.1m tonnes per year and generate 5-7% savings across the entire food chain.

The ‘Three Degrees’ report was presented at the meetings and exhibitions held around COP 28 (see below).

London Southbank University

Prof Judith Evans was very involved in producing the Three Degrees report which was funded by DP World and presented at COP 28. A longer report, containing more data and analysis, may become available in the future. There does seem to be a lack of specific commodity data for the development of the idea of warming the supply chain. More work needs to be performed to understand what may happen in supply chains if, for example, -15 °C product is passed on in the supply chain to a business operating at -18 °C - who will incur additional energy and emission costs, and the effects on product quality of temperature changes are unknown. For some products, nutrition (e.g., vitamins), may be more affected than others. Data is required to be able to better model the impacts of making a change. There is a strong motivation in the academic community to support development of cold chains and development in Africa and India (frozen and chilled) where warming the frozen supply chain, may enable products to be stored frozen (and exported) which are not possible now. Three Degrees to -15 °C is a non-alarming, safe proposition which is a stepping stone to whatever is acceptable for a commodity and the ability of the supply chain to manage.

5.4.3 Non-government organisations

Moving to -15 Coalition

In March 2024 the *Moving to -15 Coalition* (M-15C) was formed at a global container shipping conference, and appointed a chair with experience in international frozen transport logistics[13] and a director with experience in multinational firm public relations. It's foundational member is DP World and building on the Three Degrees report.

The coalition claims (The Move To Minus 15°C | Cold Chain Sustainability) to be a 'coalition of industry partners to change the temperature that frozen food is stored and transported at around the world.' During 2024 it is planned to become a legal entity.

One initial task has been the building of membership through the supply chain (Figure 10). The coalition is heavily biased to supply chain logistics, with few food producers/manufacturers, and only one (very recent) UK-based retailer.

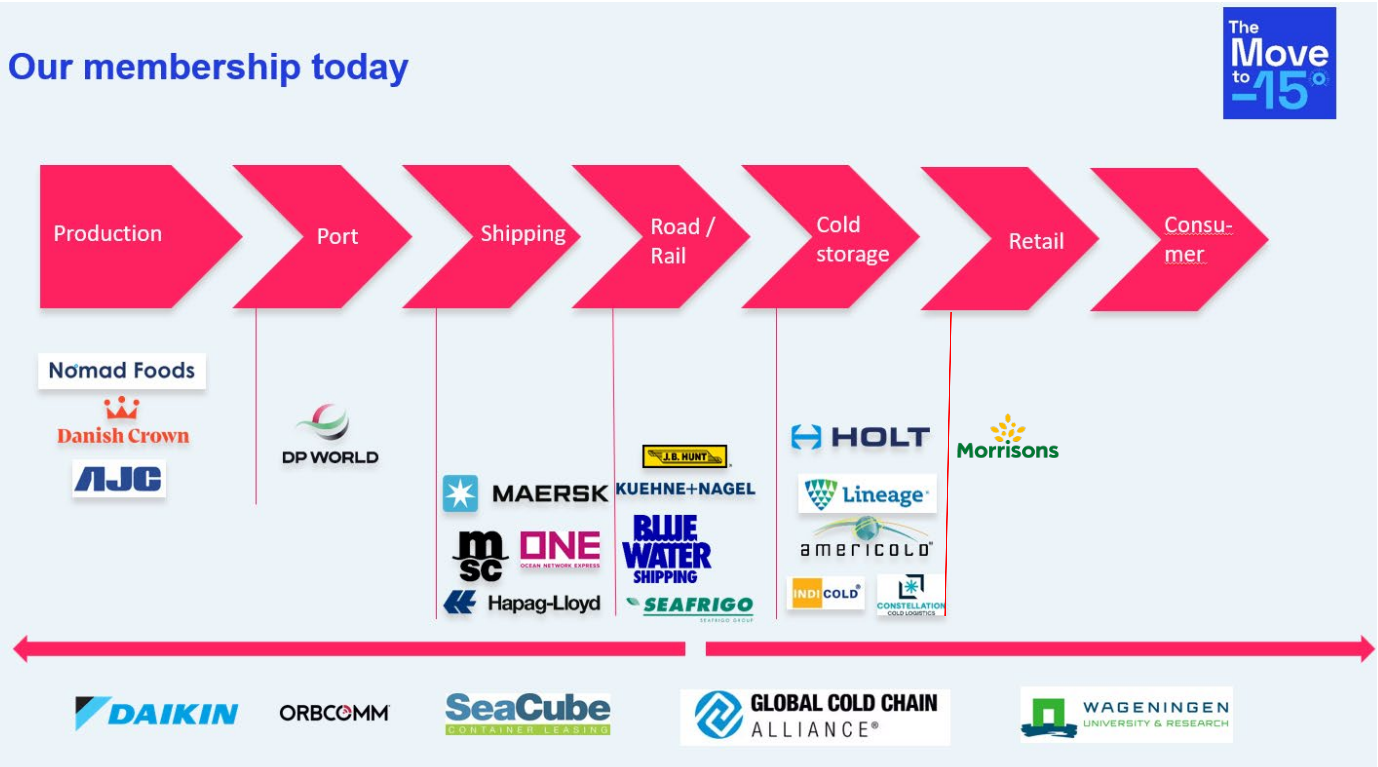


Figure 10: Supply chain membership of the Moving to -15 Coalition (August 2024)

A key activity for the coalition is understanding regulations that may prove to be a barrier to raising the temperature of the supply chain. Another is member-run pilots. It is not clear what these pilots may be. The shelf life work

[13] 'Move to -15' gains support and moves up the shipping agenda - The Loadstar

conducted by Nomad Foods (prior to joining) might be considered a pilot; it is notable that Nomad Foods only discuss the shelf life at -15°C, despite conducting studies at other temperature also. Collecting baseline data on the temperatures currently encountered in the supply chain is clearly useful data that can easily be collected by supply chains. Another type of pilot may be modification to supply chain temperatures; Morrisons has announced that they have increased the storage temperature of product in 10 retail stores.[14]

An advocacy plan is still to be developed and does not appear to be an explicit aspect of the key milestones/activities (prior to March 2025).

The M-15C appears to consider -15°C as the end point of cold chain reform.

International Institute of Refrigeration

The International Institute of Refrigeration (IIR) is an independent intergovernmental organisation, committed to promoting science-based knowledge about refrigeration and associated technologies. There a 59 member countries including Australia, though Australia has not been an active (fee-paying) member since 2011 so has no membership rights. IIR has specialised groups on areas such as food science and engineering, and storage and transport. They were involved in the *Three Degrees* report, are key participants in ENOUGH, and in 2024 will hold the 8th IIR Conference on Sustainability and the Cold Chain (June 2024 in Tokyo). IIR see themselves as honest brokers and providers of information for member countries, and do not intend to advocate for changes in temperature. They want to provide white papers and scientifically-based information to national governments, which is what they were able to do with the Three Degrees report at COP28. They are in a position to interact with governments and influence through provision of information. IIR will have a new Director General later this year, and intends to be more active in promoting the influence of the organisation in the international arena.

Australian Food Cold Chain Council

The Australian Food Cold Chain Council (AFCCC) is a not-for-profit group of cold chain industry leaders committed to reducing food wastage and improving innovation, compliance, and food safety for the Australian community. Their representative believes that not much attention is given, in Australia, to compliance with frozen temperature recommendations. He was not surprised that higher temperatures were suitable for many foods. One potential benefit for frozen transport being conducted at a higher temperature, is that it may reduce the energy requirements sufficiently, to make it possible for electric vehicles to undertake delivery of frozen goods. Current refrigeration equipment would not need to be modified to deliver a higher temperature, just adjustment to control software (setpoint). The AFCCC is very interested in cold chain and emissions and will hold a conference on the subject later this year.

Refrigerated Warehouse & Transport Association of Australia

The RWTA is very interested in the idea of warming the cold chain for frozen products because they see this as a very simple way of reducing costs and having lower carbon emissions. Labour and energy are their biggest issues. Their temperature controls are requirements of their customers, and domestically, they see retailers (large supermarkets) as the standards setters. The topic was a cornerstone of their 2024 conference 'On thin ice: negotiating Australia's cold chain viability (Appendix 6.2)

Global Cold Chain Alliance

The GCCA is an industry/trade association of businesses that provide temperature controlled warehouses and transport. They also have members involved in construction of warehouses. While US-based they also have offices in the EU, South America, and Africa.

[14] Morrisons becomes the first UK retailer to take action with the "Move to -15°C" Coalition and commits to raise freezer temperatures in drive to net zero (morrisons-corporate.com)

In the USA, there are no prescriptive regulation, but the -18 °C (0 °F) has been 'standard' since the 1940s. In the EU, the requirements (legally) are also about whether the food is considered a 'quick frozen food' which is a vague description.

The GCCA were supporters of the 'Three degree' report and were at COP28. There needs to be coordination and building of a coalition. DP World made the 'three degrees' sound more definite and end goal, whereas other see it as a stepping stone to flexible temperatures according to the needs of the product. Retailers have not been involved, and it was suggested that they have the power over retail supply chain behaviour.

American Frozen Food Institute

The AFFI represents US-based frozen food industry, including growers (e.g., vegetables), processors and transport. They have been heavily involved in frozen food safety (e.g., Listeria in frozen vegetables) and advocacy within the USA. They are considering how to position themselves as an organization on the issue of warming the frozen supply chain.

Australian Food and Grocery Council

The AFGC represents food and grocery suppliers and a currently considering how they can engage in the issue of warming the frozen supply chain for the benefit of members and sustainability.

5.4.4 Governmental organisations

Codex Alimentarius Commission

There is currently no committee within Codex that is obviously responsible for frozen foods. Previously, there was a Joint ECE [United Nations Economic Commission for Europe] / Codex Alimentarius groups of experts on standardization: Quick Frozen Foods (GEQFF) but the last meeting was held in 1980 when the group concluded that it had completed its current work and agreed to adjourn *sine die* (without any date for future meetings). It has now been abolished. The current Codex Alimentarius *Code of Practice for the processing and handling of quick frozen foods* (CAC/RCP 8-1976) recommends distribution of quick-frozen foods should maintain a temperature of -18°C but permits competent authorities to allow -12°C during transport with the product temperature reduced to -18°C as soon as possible. Any revision of this Code of Practice would probably rest with the Codex Committee on Food Hygiene.

Framework Convention on Climate Change - Conference of the Parties

The most recent Conference of the Parties (COP28) was held in Dubai in December 2023. In addition to the meetings of the Parties to the Convention there are associated meetings and conferences. It is difficult to understand, from documents alone, how all the pieces of the meeting puzzle may come together, especially since the situation is dynamic (ideas raised at one meeting may only become accepted at a later meeting, policies decisions take time to implement, decisions require funding to implement, and the actions of Parties are not clear).

COP28 had a focus on food systems, both from the effect of global warming on agricultural production (and sustainability development goals) and the contribution that improvements in food systems could make to reducing emissions.

The UAE Declaration on Sustainable Agriculture, Resilient Food Systems and Climate Action[15] made at COP28 may facilitate further consideration of warming the frozen meat supply chain. This declaration was signed by 159 countries. Amongst other things it emphasises shifting from higher greenhouse gas emitting practices to more sustainable production and consumption including reducing food loss and waste. The declaration includes a

[15] https://www.cop28.com/en/food-and-agriculture

commitment to increased investment in science and innovation and strengthening the multilateral trade system. However, it fails to refer to phase out of fossil fuels and scale up to renewables.

The presentation of the 'Three Degrees' report, probably had little or no impact on national delegations (parties) to the COP but it seems to be the intention of groups such as IIR and the Moving to -15 coalition to continue to engage with policy makers.

5.4.5 Stakeholder analysis

These stakeholders in frozen food storage and transport are classified according to their salience, and suggested implications for achieving change according to the Mitchell et al. typology (Table 11).

Table 1 Stakeholder salience and management according to Mitchell et al. typology

Stakeholder	Type	Relevant response
Unilever Moving to -15 Coalition	Definitive	These stakeholders will take the actions necessary to achieve their own objectives, which may (Nomad) align with some industry objectives. DP World consortium's objectives will be broad.
Codex Alimentarius Commission COP National governments IIR	Dominant	These stakeholders need to be engaged to act because their agreement is necessary to ensure widespread change
Universities AFCCC RWTA AFGC AFFI	Dependent	These stakeholders have the ability to lobby government (either to engage with the issue, or provide funding) but only have power to the extent that the dominant stakeholders allow
Australian exporter	Discretionary	Meat industry associations (AMIC) need to become engaged so that pressure for change can be exerted. AMIC may have power with the Australian government.

5.5 Government stakeholders: Regulatory barriers to warming frozen red meat

The following subsections provide detail and references to frozen meat requirements in various countries, comprising of major markets for Australian frozen meat and offal, and indicator markets that might be influential.

The following table (Table 12) attempts to present a summary of how favourable importing countries might be to a proposition to warm the frozen meat supply chain, based on their current regulations alone.

Table 2 Disposition of countries to warming the supply chain for meat considering only their current food regulations ('traffic light' colours: green = easy, amber = moderate, red = difficult)

Country	Frozen meat markets	Frozen offal markets	Influencers
EXPORT			
Australia			
IMPORT			
China			
USA			
Japan			
South Korea			
Indonesia			
Hong Kong			
UAE			
Europe			

5.5.1 Australia

In Australia, the Australia New Zealand Food Standards Code requires food intended to be stored frozen, to be maintained frozen and not partially thawed.[16] No temperature is specified here or in an accompanying guidance document.[17] In the Production and Processing Standard for Meat[18] reference is made to the need to follow the Australian Standard *Hygienic Production and Transportation of Meat and Meat Products for Human Consumption*.

The Australian Standard[19] specifies only that carcase parts need to be hard frozen without delay.

For meat export purposes, the Export Control (Meat and Meat Products) Rules 2021[20] enforced by the Department of Agriculture, Fisheries and Forestry, do not specify temperatures, except those required for meat safety. However, requirements of importing countries would need to be met.

[16] Federal Register of Legislation - Australia New Zealand Food Standards Code - Standard 3.2.2 - Food Safety Practices and General Requirements (Australia Only)
[17] Safe Food Australia - A guide to the Food Safety Standards | Food Standards Australia New Zealand
[18] Federal Register of Legislation - Australia New Zealand Food Standards Code - Standard 4.2.3 - Production and Processing Standard for Meat (Australia Only)
[19] AS 4696:2023 Hygienic production and transportation of meat and meat products for human consumption | Standards Australia Store 11.6 (d) (i)
[20] Federal Register of Legislation - Export Control (Meat and Meat Products) Rules 2021 5-12

5.5.2 USA

Importation of meat is controlled by the Food Safety and Inspection Service of the United States Department of Agriculture. Domestic Regulations[21] do not define frozen or specify temperature for frozen product either domestically, or at import; there is no standard of identity for frozen products. Instructions for import inspection do not mention checking of temperatures for frozen product.[22]

The lack of requirements above those of the Australian Standard is confirmed by the Australian *Manual of Importing Country Requirements* (MICoR).[23]

5.5.3 China (and Hong Kong)

China

The importing authority is the General Administration of Chinese Customs (GACC)[24] which has a decree on the safety of imported food[25] requiring that imported food shall conform with Chinese national food safety standards. The General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ) conducts imported food safety certification.[26]

The relevant national (mandatory) standards include GB 2707-2016 *National Food safety standard. Fresh and Frozen Livestock and Poultry Products*[27] which defined frozen as "has been frozen at the temperature lower than or equal to -18°C and GB 20799-2016 *National Food Safety Standards. Hygiene specifications for meat and meat product management*[28] which specifies:

> 2.3 Frozen meat. The meat that has passed through the freezing process with their core temperature not higher than -15°C.
>
> 4.4 Prior to the loading of the frozen meat and frozen edible by-products for transportation, it shall lower the core temperature of the products to -15°C and below. The temperature within the container during the transportation process shall be maintained at -15°C and below. The recording of temperature shall be carried as well.
>
> 6.3 The facilities and equipment that store the frozen meat, frozen edible by-products and frozen meat products shall be maintained at -18°C and below. The recording of temperature shall be carried out as well.

MICoR confirms the requirement for frozen meat or meat products must be –18°C or colder on arrival in China.

China does not have any mandatory shelf life requirements, but there is history of Australia negotiating shelf life for chilled meat in this market. China does have definitions for chilled meat, frozen meat, and Byproducts (which includes offal), so it is possible that China may expect shelf life validation for offal products in addition to muscle products.

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[21] Code of Federal Regulations https://www.ecfr.gov/ 9 CFR 94.29, 319, 430.1
[22] FSIS Directive 9900.2 Rev. 2 Import Reinspection of Meat Poultry and Egg Products (usda.gov)
[23] Home | Micor | Department of Agriculture, Fisheries and Forestry
[24] http://english.customs.gov.cn/
[25]https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Administrative%20Measures%20on%20Import%20and%20Export%20Food%20Safety%20-%20Decree%20249_Beijing_China%20-%20People%27s%20Republic%20of_05-01-2021.pdf
[26] https://www.aqsiq.net/what-is-aqsiq.htm
[27]https://www.aqsiq.net/pdf/Standard_for_Meat_and_Meat_Product_Management_according_to_China_GB_20799-2016.pdf
[28] https://www.aqsiq.net/pdf/Standard_for_Meat_and_Meat_Product_Management_according_to_China_GB_20799-2016.pdf

Hong Kong

The Government of the Hong Kong Special Administrative Region, Centre for Food Safety is the competent authority. Neither the basic food law[29] or the food safety ordinance[30] have any temperature requirements for meat, though the Guide to Import of Gane, Meat, Poultry and Eggs[31] does reference temperatures for chilled product. The domestic slaughter regulations[32] do not reference temperature.

MICoR does not have any specific requirements.

5.5.4 Japan

The Ministry of Health, Labour and Welfare controls meat safety under the Food Sanitation Act and Regulations for Enforcement of the Food Sanitation Act.[33]

It appears that frozen meat must be stores at -15°C or less.[34]

5.5.5 Republic of Korea

The Ministry of Food and Drug Safety is the competent authority, and requirements are found in the Food Code.[35]

A frozen product must be held and distributed at -18°C or below, except during transport to consumers.[36] There does not appear to be any differentiation between muscle meats and offals in the Food Code. While Korea maintains recommended shelf-life guidelines, there are no mandatory shelf-life requirements established by the Korean government. Food manufactures are permitted to set shelf-life for their products and may be asked by Korean authorities to provide scientific evidence supporting their claims.[37]

MICoR confirms the requirement for Korea: Once the shipping container has been sealed for export, the exporter must ensure that the container temperature is maintained at –18°C or colder during shipping until arrival in the Republic of Korea. The meat or meat products must be –18°C or colder on arrival in the Republic of Korea.

5.5.6 Indonesia

The Indonesian Food and Drug Agency (BPOM) appears to set standards for food. The food law of 2012[38] or the regulation on food safety of 2019. [39] Indonesian standards (SNI_ formulated by the National Standardization Agency (BSN) may be mandatory[40] but there do not appear to be any standards for beef or sheep meat products.[41]

MICoR does not provide any requirement beyond the Australian standards.

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[29] Cap. 132 Public Health and Municipal Services Ordinance (elegislation.gov.hk)
[30] https://www.elegislation.gov.hk/hk/cap612
[31] https://www.cfs.gov.hk/english/import/import_icfsg_04.html
[32] https://www.elegislation.gov.hk/hk/cap132BU
[33] Regulations for Enforcement of the Food Sanitation Act - Japanese/English - Japanese Law Translation
[34] Regulations for Enforcement of the Food Sanitation Act - Japanese/English - Japanese Law Translation Article 66-7 and tables 19 and 20.
[35] Food Code (No.2021-54, 2021.6.29.) Ministry of Food and Drug Safety>Our Works>Food>Regulations> View Details | Ministry of Food and Drug Safety (mfds.go.kr)
[36] Food Code (No.2021-54, 2021.6.29.) Ministry of Food and Drug Safety>Our Works>Food>Regulations> View Details | Ministry of Food and Drug Safety (mfds.go.kr) section 2.4.2.3
[37] US GAIN Report Food-and-Agricultural-Import-Regulations-and-Standards-Country-Report_12-31-2021.pdf (getusinfo.com)
[38] https://jdih.pom.go.id/ LAW OF THE REPUBLIC OF INDONESIA NUMBER 18 OF 2012 ON FOOD
[39] https://jdih.pom.go.id/ REGULATION OF THE GOVERNMENT OF THE REPUBLIC OF INDONESIA NUMBER 86 OF 2019 ON FOOD SAFETY
[40] sni-indqa-202003-e.pdf (jetro.go.jp)
[41] Home - BSN - Badan Standardisasi Nasional - National Standardization Agency of Indonesia - Setting the Standard in Indonesia ISO SNI WTO

5.5.7 UAE (and GCC)

GCC

The GCC is a regional intergovernmental union consisting of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE. Food laws are established within the GCC Gulf Standardization Organization (GSO) and adopted by participating member countries. All GCC member states, have the authority to develop and institute national food legislation in addition to those formed within the GSO.

The GSO Standard for (voluntary) shelf life of foods notes that frozen food products are to be stored at a temperature not exceeding -18°C[42]

UAE

The Ministry of Climate Change and Environment: MOCCAE is responsible for establishing and enforcing food safety regulations and laws based on recommendations from the GSO as well as the UAE National Food Safety Committee (NFSC). UAE federal laws and cabinet resolutions provide framework for regulations within each Emirate. The Ministry of Environment and Water and the Emirates Standardisation and Metrology Authority both have an interest in standards for frozen meat. For example, in Abu Dhabi[43] frozen foods must be maintained at or below -18°C, but if the temperature rises to -15°C it must be reduced as quickly as possible, and if temperatures between -15 °C and -10 °C are encountered then the product must be subjected to examination and laboratory testing. The Dubai Food Code[44] and requirements of transport vehicles[45] only mentions the -18°C requirement without any leeway.

5.5.8 EU

The Regulation on specific hygiene rules for food of animal origin[46] requires that the meat of ungulates must be frozen without undue delay to a temperature of -18°C.

MICoR confirms the temperature requirements for some meat products but suggests that there is no temperature requirement for muscle meat or offal.

Some EU member states have prescriptive requirements for frozen food temperature at -18 °C or below.

5.6 Innovation System

The systems approach has been defined in general terms as including “all important economic, social, political, organisation, institutional, and other factors that influence the development, diffusion, and use of innovations” ((Jenson, 2019), citing Edquist, 1996).

Sectoral and technological innovation system approaches have been used to understand and suggest policy approaches for encouraging the development of industry sectors and technologies, and thus are potentially applicable to food safety innovation. Sectoral innovation systems seek to understand how innovation occurs within and between firms within a sector of the economy and are acknowledged as a flexible, holistic, and interdisciplinary approach to understanding innovation of products and services within an environment influenced by multiple actors and institutions. Technological innovation systems consider the development of a technology itself, without being

[42] GSO 150-2/2013 Expiration dates for food products Part 2: voluntary expiration dates
[43] Abu Dhabi Regulation No (6) of 2010 pertaining to Food hygiene throughout the food chain reg6-en-web.pdf (adafsa.gov.ae)
[44] Dubai FOOD CODE 2020 (dm.gov.ae)
[45] Dubai DM-FSD-GU63-Requirements for food transportation and delivery vehicles guidelines
[46] CL2004R0853EN0240010.0001_cp 1..2 (europa.eu) regulation EC 853/2004 specific hygiene rules for food of animal origin Annex III Section I Chapter VII 4 ii

unduly encumbered with the constraints of national, regional, or sectoral system elements. They are considered to contain all the components necessary to influence the innovation process for a particular technology (Jenson, 2019).

5.6.1 Sectoral Innovation System analysis

The sector for analysis can be described as the frozen food sector, which could provide a lower cost product to consumers with lower environmental impact by storing and shipping frozen foods as -12 °C. The essence of sectoral innovation system analysis is to assess the actors in the system with innovation system weaknesses (Table 13). Activity has been focussed on knowledge institutes with some activity with companies. For this reason, the analysis was focussed on the Knowledge Institutes (Table 14). The M-15C may develop as a knowledge institute, but has yet to act explicitly in this direction.

The weaknesses of this innovation system are clearly that knowledge is largely within the knowledge institutes, and engagement from NGOs (including industry-based organisations) and Intergovernmental organizations is required to gain cooperation to coordinate amongst supply chains and develop international and national guidelines and standards. Engagement with the demand end of the supply chain may not only achieve permission to act, but also create an urgency to act.

Table 3 Sectoral Innovation System analysis

	Actors			
	Demand	Companies	Knowledge institutes	Third parties
[who are the actors?]	Retailers Consumers	Equipment Transport Infrastructure Meat Processors Moving to -15 Coalition	Universities Standards NGO Government Intergovernmental organisations Industry association	Insurers
Competence	Retailers (surrogate for consumers) are just beginning to know the possibilities. Identified as powerful legitimators of the idea.	The supply chain actors are just beginning to know the possibilities (but many recognise the opportunity and others are ready to hear this solution). Moving to -15 Coalition seems to be leading the agenda	Researchers are just beginning to discuss the possibilities (product, process). International organisations are becoming involved	
Capacity	Requires little change - may need to ensure consumer acceptance	Requires little effort except for coordination of supply chains	Requires work to promote and explain, and develop international norms	
Infrastructure		Equipment, transport, infrastructure will work at -12°C. Will temperature monitoring become a requirement for supply chains?	Infrastructure design models for the new reality do not exist	
Institutions (Hard)		Companies are constrained by existing rules	International and national guidelines and standards need to change	
Institutions (Soft)		Many (?most) companies do not understand how the food regulatory system works		If insurers are informed of consensus and any changes in risk they will respond appropriately
Interactions (Weak networks Strong networks)	Are not engaged in this innovation (exception: very recent engagement by Morrisons UK)	Many (?most) companies do not have good networks with Knowledge institutes. The Moving to -15 Coalition has not developed explicit networks with other actor groups	Networks within knowledge institutes are weak because they are not activated on this issue. Networks to other actors are not highly developed.	
Market	Created by utilising the carbon market Lower product cost	Cost savings in production, storage and transport are anticipated. For Australian exporters this represents about $2.5m pa in freezing costs	Will have a small impact on total carbon emission - but at no/low cost. The potential benefits for each actor are not known	

Table 4 Sectoral Innovation System analysis focussed on the Knowledge Institutes

	Knowledge institute actors			
	Universities + knowledge creators	**NGO Intergovernmental organisations**	**Government**	**Industry association**
Competence	Researchers are only starting to articulate the possibilities (product, process)	Some are involved. Others have had ideas presented - but response will take time	Not engaged - but could become engaged through climate change action	some have knowledge - and will become a topic for industry conferences in 2024 (UK, AU)
Capacity	Willing to work on funded projects	Unknown - but it is in their interests to gain an easy win for sustainability	Need to find space in international negotiation agenda to address issue	Requires little effort once permission is given. Lobbying power (government, retailers)
Infrastructure	May create more possibilities. Need to validate the proposed industry solutions			Infrastructure design models for the new reality do not exist
Institutions Hard		International and national guidelines and standards need to change	International and national guidelines and standards need to change	
Institutions Soft		Seems to fit with existing policies	Seems to fit with existing policies	Energy use is a major cost for infrastructure
Interactions Weak networks Strong networks		Engagement with decision-makers is still to occur		Are very receptive and willing to network between knowledge and their members
	Networks within academia and other institutions are not developed	Networks to other actors are not developed.	Networks to other actors are not developed.	The DP World consortium is funded and will develop
Market		The possibilities are not acknowledged by policy makers The potential benefits for each actor are not stated	Small impact carbon emissions at low/no cost The potential benefits for each actor are not stated	Will be a win for them as their members gain benefits. The potential benefits for each actor are not stated

5.6.2 Technological Innovation System analysis

The technological system can be defined as changing the temperature of frozen food supply chains from -18 °C to -12

The essence of Technological Innovation System analysis is to consider the functions of the innovation system, and how they interact and determine where the system is weak. Hekkert et al. (2007) defined 7 functions and how they might operate in cycles to increase the strength of the system (Figure 11).

Analysis of the functions leads to an identification of strengths and weaknesses, and key functions that will be likely to drive the system (Table 15).

A key function to strengthen in this innovation system is legitimation and lobbying; the idea of increasing the temperature for frozen foods must gain, at least an interest in exploration, from Government and intergovernmental organisations. Some additional entrepreneurial action and knowledge development would make the approach to Government easier (it is not advisable to approach Government with a proposition that does not have a clear chance of success and favourable outcomes). Legitimation with Government would also release resources for the additional knowledge development on 'how to' make supply chains work.

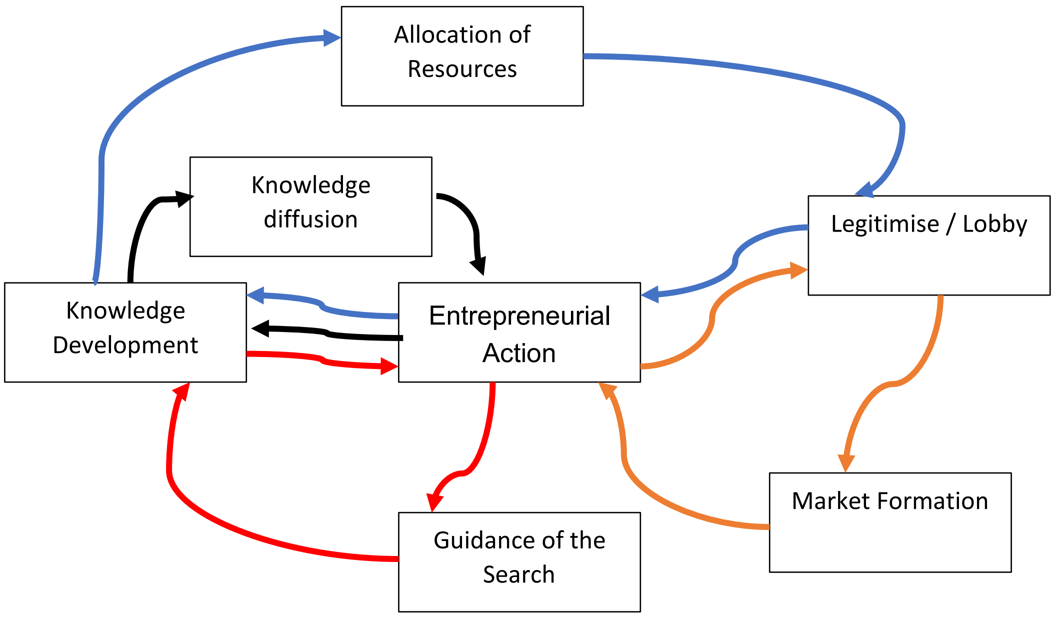

Figure 11 Technological innovation system functions and interactions
Colours represent functional interactions

Table 5 Technological Innovation System analysis

Function	Analysis
Knowledge development	• For muscle meat we DO KNOW that -12 °C for 3 years is satisfactory (James et al., 2022) • We DO KNOW that there are benefits in energy usage and carbon emissions if a change is made (this report) • For offals we DO NOT KNOW whether -12 °C is acceptable • Equipment/installations designed for -18C work will work at -12 °C (this report) • DO NOT KNOW whether -12 °C can be maintained satisfactorily and whether there is sufficient 'margin for error' either in calibration, system perturbations (e.g., defrost), over time in different locations within a container, or temperature increases moving from one storage unit to another (i.e., time out of active refrigeration) but earlier research provides a guide (McPhail and Tume, 2006) • Further knowledge development requires knowledge Externalisation and Combination (Nonaka et al., 2000) – explaining the ideas and having them combined with existing knowledge in the form of guidance and standards
Knowledge diffusion (Creating expectations)	• There is little communication about the success of -12 °C (for meat, but also other food products) other than the researchers and some knowledge institutes • Unilever is providing opportunities to competitors • Nomad has provided shelf life data which will encourage others to do the same
Guidance of the search	• Sustainability agenda which is being driven mostly from Europe is seeking opportunities to decrease carbon emissions and increase the ability of the food system to sustain the planet. • COP-associated mechanisms may provide the guidance necessary as contact is made with policy makers
Entrepreneurial activities	• Unilever – trials in Germany and Indonesia • Nomad Foods – frozen food results • Morrisons (and other M-15C member) pilot trials • Australian Red Meat can choose to present the case for change based on currently available data
Market formation	• Energy saving market is already established (reduced cost of energy) • Carbon emission market is becoming established - and this method of reducing emissions needs to be understood and accepted in the marketplace, so that the business and the product can benefit from carbon claims
Acceptance / counteract resistance to change Legitimise/Lobby	• Unilever is conducting their work 'in house' - and government by government • The M-15C is continuing to develop plans and has intentions of acting • Governmental, Intergovernmental response is lacking at this time
Resource mobilization	• European funding through University of Birmingham and ENOUGH • The development of M-15C as a corporate entity may bring further resources from members to support the proposition.

5.6.3 State of the Innovation System and actions required

The innovation system for this sectoral - technological innovation is in its early stages and the M-15C is taking a coordination role, though not all companies/organisations with an interest in the proposition are in agreement with the implicit M-15C strategy, and not all have joined the Coalition. It isn't clear what relationship the academic/COP consortium may have with the M-15C.

Those currently involved in this area need further engagement of food manufacturers and retailers, to increase the power and certainty of the consortium and proposition.

The knowledge to be developed is mostly about the "how to" of supply chain coordination, the shelf life of the products involved, and how to manage the temperature excursions that occur.

National governments and intergovernmental organizations (Codex Alimentarius Commission) need to be engaged when the coalition believes sufficient information is available to have a convincing discussion and about benefits, and before all the data considered necessary for implementation is available; there needs to be opportunity for dialogue.

5.7 Manuscript

A manuscript has been submitted to the *International Journal of Refrigeration* (*IJR*), based on the data in the James et al. (2022) report prepared for MLA (V.MFS.0428). The IJR does not publish many papers on shelf life of foods, but is believed to be a strategic choice because it is the journal of the International Institute of Refrigeration (IIR), who were central players in the *Three degrees of change* report (Allouche, et al., 2023) and have a stated intention to continue to be brokers between parties regarding the science and technology of making a change to frozen supply chain conditions.

The manuscript is to be found at Appendix 2.

5.8 Shelf life fact sheet

Meat & Livestock Australia developed a fact sheet on shelf life of beef and lamb at -18 °C that was used in acceptance of long shelf life for frozen meat in the Saudi Arabian market (Appendix 3)

A fact sheet supporting the use of -12°C as a storage and transport temperature for frozen meat was drafted (Appendix 4) with conclusions based on the 12°C manuscript.

5.9 Energy and emission fact sheet

A fact sheet on the energy and emission implications of freezing to -12°C was drafted based on the work described in this report (Appendix 5).

5.10 Communications

Communicating the opportunities for raising the temperature of the frozen supply chain is an important part of this project. AMPC has provided a communication to members and stakeholders (Appendix 6.1)

A presentation was given at the Refrigerated Warehouse and Transport Association conference in August 2022 (at their expense) to discuss the 'Three degrees' report and movement towards change.

A presentation will be given to the Dubai International Food Safety Conference in October 2024 (at their expense) (Appendix 6.3).

5.11 Acceptance by trading partners

One way that Australia's trading partners may become engaged with the idea of raising the temperature of the frozen supply chain is for the subject to be raised through the Codex Alimentarius Commission.

The *Code of Practice for the Processing and Handling of Quick Frozen Foods (CAC/RCP 8-1976)(Codex Alimentarius Commission, 2008)* (CoP) recommends distribution of quick-frozen foods should maintain a temperature of -18°C but permits competent authorities to allow -12°C during transport with the product temperature reduced to -18°C as soon as possible. The option for part of the supply chain to be at -12°C to be expanded to the entire supply chain needs to be discussed and agreed at this international forum.

A rudimentary draft of a Codex project document has been developed (Appendix 7) but much work between interested non-governmental organisations and Codex observers, and then interested Member countries would be required before submitting a document to CCFH.

6.0 Discussion

6.1 Acceptance of the proposition for warming the supply chain

The acceptance of the proposition for warming the supply chain depends on both the technical suitability of storing meat at the higher temperature and the development of a favourable innovation system to make change happen.

6.1.1 Shelf life at -12°C

Conclusion on shelf life at -12°C

The manuscript prepared for publication suggests the Practical Shelf Life of the beef and lamb products in the study. The products included loin cuts and boneless, manufacturing (trim) product, including high fat (65CL) product. Lamb trim product was stored in a plastic bag, with the top overwrapped, inside a cardboard carton, whereas all other products were vacuum packed. The manuscript concludes:

> Samples of Australian boxed frozen beef and lamb loin and beef trim of the type examined shipped to export markets by air or water can be subsequently stored at -12°C, -18°C, or -24°C without significant sensory degradation for a period of over 36 months. Frozen boxed lamb trim in this study did not degrade significantly in meat flavour or lamb odour intensity or frequently produce unacceptable sensory scores until more than 28 months of frozen storage.

Manuscript for peer review and publication

The draft manuscript has been submitted for peer review. It is worth considering, and preparing for, some of the subsequent steps.

It is recommended that, of accepted for publication, AMPC approve, and fund "gold open access" for publication in the *International Journal of Refrigeration* which means that the article will be immediately and permanently free for everyone to read and download. We recommend that downloads be subjected to a Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence which allows users to: distribute and copy the article; and include in a collective work (such as an anthology) for non-commercial purposes, and provided the user: gives appropriate credit to the author(s) (with a link to the formal publication through the relevant DOI); provides a link to the license; and does not alter or modify the article. AMPC would therefore retain the rights to derivations of the article, and involvement with any party wishing to use the article as part of any campaign to raise the temperature of the frozen supply chain. To obtain gold open access, it is necessary to pay a publication fee (Article Publishing Charge, APC) of USD 2820, excluding taxes.

6.1.2 Innovation system for warming the supply chain

The innovation system is at a formative stage. Undoubtedly more knowledge is required on shelf life at different temperatures and the impacts of temperature variation on product quality (against actual temperature variation of product in frozen supply chains). The biggest obstacle to change has been overcome by the formation of the 'Moving to 15' coalition. This organisation is new and in a formative stage, and it is yet to be seen whether it will become the dominant force and which direction it will take.

The 'Moving to -15' or other coalition must engage governments and inter-governmental organisations with information supporting the benefits of change, the lack of consequence for food safety and quality and the mechanism for change. The coalition has not been publicly active at this point.

Shelf life data for all types of food and the consequences for food safety and quality need to be examined. Measurement of actual supply chain practices and performance will need to precede design of new supply chain rules.

6.2 Energy and emission benefits

Considering the freezing costs alone (Table 8) and cost of energy at $0.20/kWh, the energy saving across the industry, for exported frozen meat and offals would amount to $1.3m pa for a change from -18 to -15°C and $2.5m for a change from -18 to -12°C.

For emissions, considering the whole cold chain, an example is presented for red meat processed near Sydney, Australia and shipped to Dalian, China (8,976 km shipping) with the cold chain maintained at -18 °C, 217.9 kg CO_2-e/t HSCW emissions would be incurred (Table 16, Figure 12) (excluding biogenic, embodied and non-fossil emissions during the producer and feedlot stage). This can be considered the base case for comparison with warmer frozen storage and transportation temperatures.

Table 16: Emissions associated with processing and shipping from Sydney to Dalian (see text)

Section of Cold Chain	Scope	kg CO_2-e / t HSCW
Processor – Power for Refrigeration	2	39.0
Storage	3	112.0
Transport	3	66.9
	Total Cold Chain	217.9
	Scope 2	39.0
	Scope 3	178.9

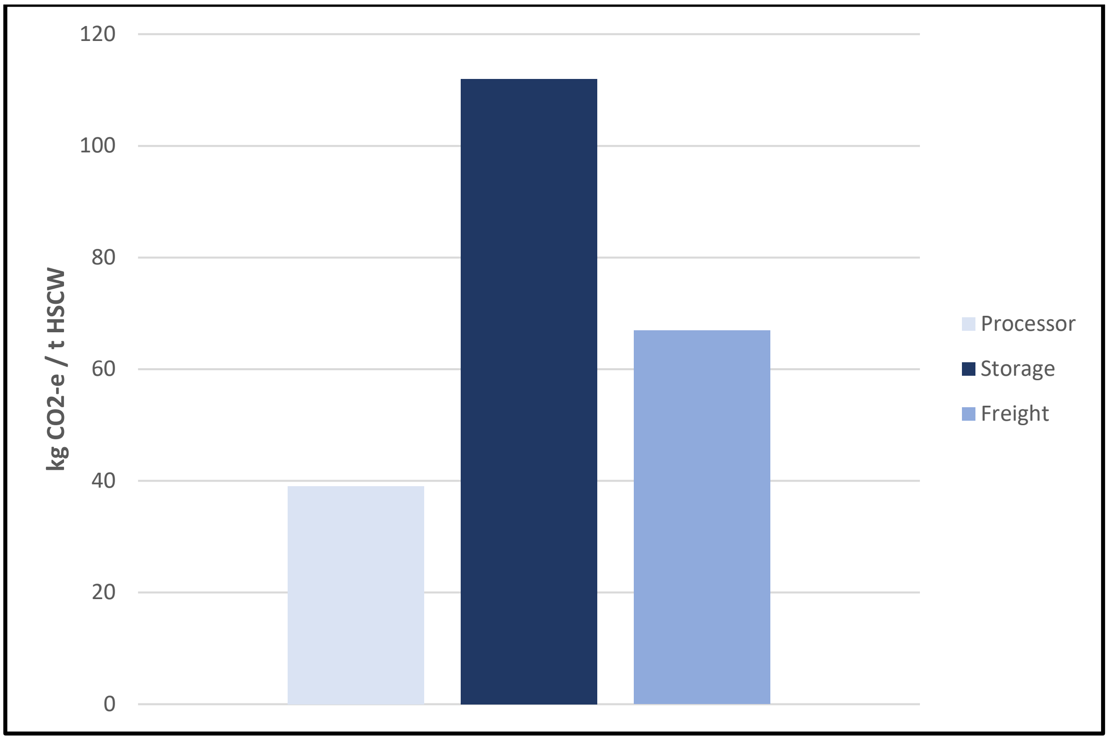

Figure 12: Emissions associated with processing and shipping from Sydney to Dalian (see text)

This 'base case' shows that emissions due to storage make up 51.3% of the total emissions, and therefore, a reduction in emissions in this part of the supply chain would be most significant to the overall reduction in emissions (Figure 12).

Freezing temperature changes reduce the energy usage and hence emissions for the processor, during storage / warehousing and for the refrigeration component of transport. The overall impact on emissions can be compared with the base case of -18 °C (Table 17).

Table 17: Emissions associated with processing and shipping from Sydney to Dalian at different temperatures

Temperature °C	Estimated Cold Chain Emissions kg CO_2-e / t HSCW	Estimated Emissions Change % vs Base Case
-25	247.3	+ 13.5%
-22	235.5	+ 8.1%
-18	217.9	Base Case
-15	205.8	- 5.6 %
-12	192.7	- 11.6%

It can be observed that the difference in total cold chain emissions across a 13 °C temperature differential (-25 to -12°C) can be even more significant. However the segmentation of the cold chain and the low total contribution of processor emissions relative to freight and storage mean the major motivation for Australian processors in reducing cold chain temperature is the cost saving rather than emissions reduction.

Overall, the major impacts of total emissions will be from (not in order):

1. Reducing days in storage i.e. faster throughput
2. Reducing number of door openings in cold store / time door is open (maybe an automated proximity sensor system?)
3. Reducing number of air renewals when in freight i.e. better insulation
4. Improving packing efficiency to maximise the tonnage of product that can fit into one container

Quantifying the exclusions of this analysis, the following is noted:

Primary production and feedlots are excluded from the emissions boundary of this analysis as these two stages are not parts of the cold chain; however, these two stages contribute the majority of total supply chain emissions from the Scope 3 embodied and biogenic emissions. These stages were excluded as their magnitude and dominance of the total supply chain emissions would mask any changes as a result of cold chain temperature set points.

General discussion on the calculation of emissions in primary production:

- Primary production is the most difficult stage of the supply chain to gather high quality data and thus the calculated energy and emissions intensity is less certain here.
- Scope 1 emissions are assumed to be very minor to non-existent unless cattle trucking is under the control of the producer i.e. supply chain is vertically integrated where the producer owns and operates the trucking fleet.
- Scope 2 emissions are assumed to be predominately from pumping water for stock drinking. Rough estimate 39.8 kg CO_2-e / t HSCW[47]. Depends primarily on bore depth i.e. pumping power required per unit of water delivered
- Scope 3 emissions from transport of stock to the feedlot by a third party contractor depends primarily on distance. For 500 km round trip journey in standard semi-trailer with 25 head payload, rough estimate 125.1 kg CO_2-e / t HSCW[48]

General discussion on the calculation of emissions in feedlots:

- Some feedlot energy use benchmarks exist, however from anecdotal experience there is a large variation among individual feedlots. Primary determinant for Scope 1 and 2 emissions is whether or not grain is steam flaked, choice of thermal fuel, and duration of feeding; primary determinant of Scope 3 emissions is distance to processor.

[47] Assuming 50 L/head/day water consumption from bore 100m in depth; 1 kW pump with 0.6 isentropic efficiency can therefore deliver 2.2 kL/hr. Assuming each cow takes 2 years to reach minimum slaughter weight of 600 kg, estimated Scope 2 electricity use is 46.0 kWh / t HSCW assuming 60% carcase weight recovery

[48] Calculated 1.5 km/L diesel consumption thus 37 L / t HSCW

- Scope 1 emissions from burning LPG to steam flake grain benchmarked at 268.1 MJ/head assuming 100 day on feed and 800 kg liveweight. Equivalent to 33.9 kg CO_2-e / t HSCW
- Scope 2 emissions from consumption of grid power for milling grain and pumping drinking water. Using same Scope 2 method as above with 100 day period and 800 kg liveweight, drinking water Scope 2 emissions at feedlot estimated at 4.1 kg CO_2-e / t HSCW. Mill power consumption benchmarked at 20 kWh/head for a 100 day feed regime – equivalent to 36.0 kg CO_2-e / t HSCW
- Scope 3 emissions from transport of slaughter-ready cattle to processor

Processor Scope 1 emissions from the burning of thermal fuels are excluded from the emissions boundary:

- Reported in the 2022 sector-wide *Environmental Performance Review*[49] to be 66.0% of total energy use, or 2267.1 GJ/t HSCW
- The breakdown of site thermal fuels at red meat processing facilities reported included
    - Natural gas 45.9%
    - Coal 22.0%
    - Biomass 12.6%
    - Biogas 11.7%
    - Fuel oil 5.0%
    - LPG 2.9%
- This equates to a total Scope 1 GHG emissions intensity of 112.9 kg CO_2-e / t HSCW

Acknowledging the limitations or uncertainties of this analysis:

Some indication has been given by processors that if freezing to a higher temperature, "equipment would be run the same way as now, [we would] just stop cooling sooner". In this case, while the overall kWh of cooling work will be reduced, the peak power kW recorded and charged by the power retailer will be the same. Without digressing onto high volume consumer tariff structures, this will reduce the amount of cost savings significantly. The current underlying assumption of the calculator is that refrigeration work is reduced by reducing the % throttle on the refrigeration compressor, hence kWh and kW will be reduced by freezing to a higher temperature. The calculator assumes an equivalent cost of power factoring volume and demand charges at 20 c/kWh.

When calculating the refrigeration work at the processor by first principles thermodynamics, property data for the round primal including lean meat and fat is used. There is slight variation in properties between whole carcase and various primals due to the differences in moisture content, lean meat fraction, meat grade, and differences between US and UK primal cuts[50] however this is insignificant relative to other assumptions and does not make a material difference.

There is some variation between individual state Scope 2 grid power emissions factors and the East coast average of QLD, NSW, and VIC 0.86 t CO_2-e / MWh. This value was chosen as the majority of red meat industry throughput is produced by these three states. The variation between states reflects the proportion of renewable energy in each state's grid and varies from Tasmania at the lowest at 0.13 to QLD at the highest at 0.88 t CO_2-e / MWh.

Regarding the cost of refrigerated freight, this was consciously excluded as there is little to no transparency in freight cost modelling, meaning that finding a broadly applicable and consistent figure was not possible in this project. This will depend on a combination of factors including human labour, journey distance and/or time, fuel rates,

[49] Ridoutt, B and Sikes, A (2023) Environmental Performance Review 2022: Red meat processing industry. Australian Meat Processor Corporation Report 2023-1002. Final-Report-EPR-2022.pdf (ampc.com.au)
[50] Data was only found for US cuts

temperature, and payload. There have been indications from industry and the Moving to -15 Coalition that the anticipated economic impact of reducing to a -15 °C setpoint is 5-7% in energy savings, or as high as 12% in some areas. The energy consumption modelling during this project showed expected benefits in the same order of magnitude, but greater availability of data and more precise thermodynamic modelling could improve these estimates.

Likewise, refrigerated storage energy consumption and resultant emissions are highly specific to an individual warehouse and operating regime, and depend primarily on number of times doors are opened (i.e. air exchanges with ambient environment).

6.3 Regulatory positions and change

Some governments (China, South Korea) in major export markets would require amendments of national standards and regulations to permit transportation and storage of meat at above -18 °C. In some countries (China) there may be existing differentiation between offals and muscle meat, which could lead to expectations for additional data collection for offals. Also, if it is perceived that offal quality (e.g. nutritional properties) may deteriorate faster than muscle meat, then there may be an expectation to determine shelf life based on changes in nutrient composition (as with vitamin C in vegetables).

Countries may be more interested in reducing their carbon emissions at almost no cost, than making a change to food regulations. Promoting the climate change aspects of warming the supply chain would bring more parts of government into the quest for change and be more likely to achieve change.

Engaging with the Codex Alimentarius Commission at an early stage may help to provide a framework for change by national governments. Revision of the *Code of Practice*, taking into account the benefits for the supply chain, and contribution to the food system.

The relevant Codex technical committee is the Codex Committee on Food Hygiene (CCFH), chaired by the United States of America. Not only would the safety and quality of products needs to be considered, but also the applicability of any new CoP to all member states reflecting the differences in climate and infrastructure. A Project Proposal would need to be submitted by a Member country. Codex has a number of Observer organisations which would have an interest in the area, and could shoulder the burden of technical work, collecting data and hosting meetings etc. Observers include Economic Commission for Europe, International Frozen Foods Association, International Institute of Refrigeration, International Meat Secretariat,

There are policy issues to resolve about whether -12°C is an absolute set point or a general one. There is a lack of understanding about what happens in frozen product storage and the area will come under increased scrutiny if a change is likely to be implemented. For example, defrost cycles increase the air temperature and this is often hidden from view, but it is also most times the only measurement made. An allowance for air temperature increases might need to be made if air temperature is measured rather than product temperature. The relationship between the two temperatures would be needed. Also, product temperature might need to be considered if containers are off power, for example when moving from one storage/transport to another. The absolute minimum temperature for microbial (including fungal) growth needs to be considered, and how that may accumulate over a long period of storage – and then related to the actual temperature of product (which will be a gradient from surface to interior).

6.4 Communications materials

The manuscript on shelf life at -12°C is a major cornerstone of the proposition for warming the supply chain for frozen meat. The fact sheets provide a brief summary of the work completed and support for the proposition to move to -12°C for freezing, storage and transportation.

7.0 Conclusions / Recommendations

The proposition to raise the temperature of the frozen meat supply chain from -18°C to -12C is feasible. The proposition is feasible because the shelf life of meat at this temperature is not affected and reduced energy costs and reduced carbon emissions would result from such a change. The Australian red meat industry could save $2.5m pa annum by changing the freezing temperature, with additional savings on storage and transportation costs. A reduction in carbon emissions of about 11% would result from warming the temperature of the entire supply chain to the importing country. Furthermore, other food products may also be stored and transported at this temperature.

There is great opportunity to work with like-minded organisations (nationally and internationally, trade associations and single issue groups), emphasising the benefits in emission reductions to the world at little or no cost and no risk to consumers as the means to warming the frozen supply chain. The ‘Moving to -15’ coalition has recently formed, with a focus on collecting supply chain data, and industrial pilots before approaching governments to implement regulation. Other groups may also form with an interest in this work.

National regulation in many countries (USA, Indonesia, Hong Kong) already allows higher frozen food temperature. Lack of prescriptive temperature requirements for frozen foods in Australia may provide an opportunity for a demonstration of supply chain temperatures and any necessary new cold chain management techniques.

An approach, through the Codex Alimentarius Commission, to update the *Code of Practice for the Processing and Handling of Quick Frozen Foods*, would provide an opportunity for education, exploration and consensus-building of a change to recommended supply chain temperatures for frozen foods. This approach may be required to achieve change in countries such as China, Japan, South Korea and Europe.

Recommendations for AMPC

- Consider the benefits of paying the open access fee when manuscript is accepted to allow AMPC and others to use the published paper to support the campaign.
- Consider whether shelf life data on frozen offal stored at -12°C is required.
- Consider collection of data on air and product temperature variability in supply chains and the (lack of) impact on product quality
- Find small supply chains (perhaps between a processor and a subsidiary operation; in Australia and in international container shipping) where temperature control at a higher temperature could be piloted. This activity might require the involvement of government/s. It is likely that other organisations such as AFGC, RWTA etc may be setting up similar pilots. Data collection needs to be standardised to support national and international regulatory and practice change
- Consider working with groups such as the Moving to -15C coalition
- Consider how to engage Codex Alimentarius Commission in revising the *Code of Practice for the Processing and Handling of Quick Frozen Foods*

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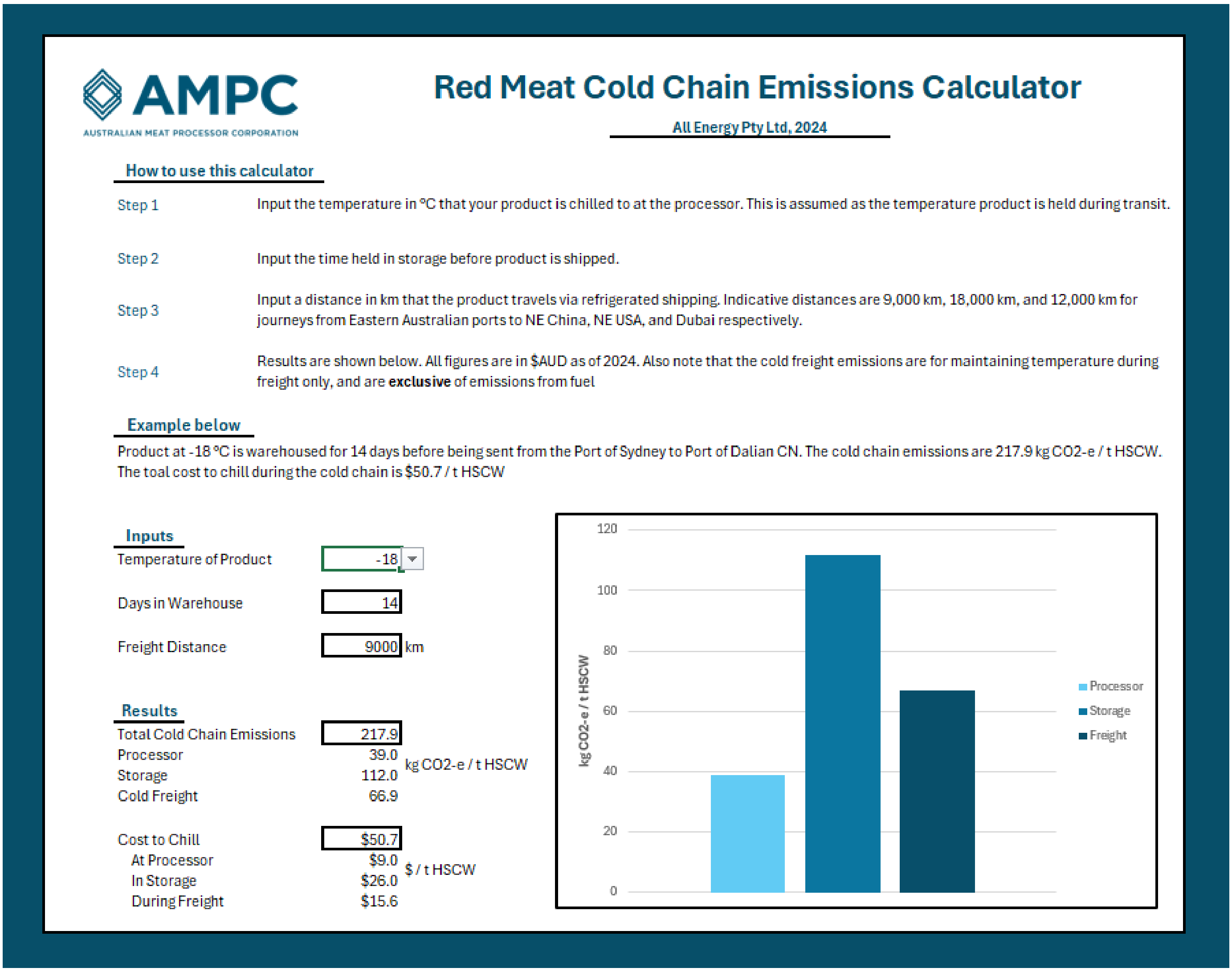
9.0 Appendices

9.1 Spreadsheet for calculating energy and emissions in a supply chain

A calculator has been developed to supplement this project. A screenshot of the user interface is shown below, where the design intent was to minimise user inputs for a maximum-streamlined experience.

Instructions are listed clearly with key input and output cells framed in dark borders. The temperature of the product, number of days warehoused before leaving cold store, and distance of journey to end importer are the key inputs by the user. Total cold chain emissions from the initial chill at the processor, cold storage, and cold freight are displayed as kg CO_2-e / t HSCW, along with the cost to chill incurred by the processor and cold store itemised separately. The cost to chill during refrigerated freight will be built into the total rate paid for freight, hence was unable to be separated out here.



9.2 Draft manuscript for submission to *International Journal of Refrigeration*

The practical storage life of Australian frozen boxed beef and lamb

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Abstract

The practical frozen shelf life of commercially produced meat has not been frequently determined. Commercially produced Australian frozen boxed beef and lamb (loin and trim with low and high fat content) was processed and frozen under standard commercial conditions and shipped (by sea and air, respectively) to the UK. In the UK, products were stored at -12°C, -18°C and -24°C, and instrumental and sensorial analyses conducted over a 38-month period from processing. No clear relationships or trends between sample type, storage temperature, and the time of storage were apparent in the majority of the measured quality parameters (colour, cook loss, texture, or microbial quality) apart from those relating to lipid oxidation (PV and TBARS) and sensory. Lipid oxidation (PV and TBARS) was observed in all products at all temperatures but not at values that would be expected to result in sensory changes. Australian boxed frozen beef and lamb loin and beef trim in vacuum packs shipped to export markets by air or water can be subsequently stored at -12°C, -18°C, or -24°C without significant sensory degradation for a period of over 36 months. Frozen boxed lamb wrapped in plastic did not degrade significantly in meat flavour or lamb odour intensity or frequently produce unacceptable sensory scores until more than 28 months of frozen storage.

Keywords

Beef; Lamb; Frozen storage; Quality

1. Introduction

Frozen meat is an important, growing, sector of the world food supply chain. The global frozen meat market was valued at USD 24.41 billion in 2023. It is predicted to grow at a Compound Annal Growth Rate (CAGR) of 4.9% from 2022 to 2030 (Coherent Market Insights, 2022). The shelf life of frozen meat is of interest to supply chains, consumers, and regulatory authorities; and the availability of safe and suitable product is the common goal. Worldwide exports of frozen beef totalled 6.92 million tons during 2022 with Brazil, India, Australia, USA, Argentina, and New Zealand accounting for over 75% of export volume and China, United States, South Korea, and Japan accounting for 57% of import volume (Workman, 2024). Australia and New Zealand accounted for 93% of export volume of mutton and lamb in 2023, with the USA, UK, and Malaysia accounting for 60% of imports (Tridge, 2024). Freezing and thawing processes exert a significant effect on product quality and novel techniques are being investigated to improve the quality of frozen meat (Zhang et al., 2023). Shelf life remains a key variable, and the international meat trade expects a frozen shelf life of 24 months or more.

The International Institute of Refrigeration defines practical storage life (PSL) of frozen food as the period of storage at a given temperature during which the product retains its characteristic properties and remains fully acceptable for consumption or the intended process (Bøgh-Sørensen, 2006). Providing the meat is of sufficient quality when frozen and handled under hygienic conditions, no food safety hazards exist with frozen meat that has been held at, or reached, a temperature lower than -10°C, no matter how long it is held as no microbial growth can take place (James and James, 2024). Many sources state that rancid odour and flavour may signal the end of PSL of frozen meat (James and James, 2002; Meat & Livestock Australia, 2016; Zhang et al., 2023).

Few studies published in the past 25 years have measured the PSL of frozen meat over ≥ 12 months. A study of frozen dry aged beef *longissimus lumborum* stored at -18°Cconcluded that it was still acceptable to consumers after 12 months (Zhang et al., 2019). Two other studies concluded, using physicochemical methods, that frozen beef was acceptable after 12 months at -18°C but they made no conclusion about consumer acceptability (Farouk et al., 2003; Holman et al., 2018a; Holman et al., 2017, 2018b). One of these studies extended the storage time to 24 months but only assessed physicochemical parameters (Holman et al., 2021). Two studies on frozen lamb concluded satisfactory consumer acceptance based on sensory panel assessment when meat was stored for 12 (de Paula Paseto Fernandes et al., 2013) and 21 months (Muela et al., 2016) at -18°C.

Storage at -18°C was codified internationally by the Codex Alimentarius Commission (CAC) in 1966 (CAC, 1966). Currently the CAC allows for -12°C during transport with the product temperature reduced to -18°C as soon as possible (CAC, 2008) but this option does not appear to be used in practice despite evidence that warmer frozen storage temperatures can maintain the quality of product. For many years frozen meat carcasses, sides, and quarters were transported from Australia to the UK at -10°C to -9°C (Cutting and Malton, 1974). Symons (1994) claimed that even as relatively recently as the 1980s the UK frozen meat trade was still storing meat at -10°C. New Zealand lamb stored at -10°C, -15°C and -20°C demonstrated no rancid flavour development for 14 to 24 months (Winger, 1984). More recently, studies of physicochemical parameters in both beef (Holman et al., 2018a; Holman et al., 2017, 2018b) and lamb (Coombs et al., 2017; Coombs et al., 2018a; Coombs et al., 2018b) stored for 12 months demonstrated comparable results at -12°C and -18°C. Other recent studies, each storing product for less than 12 months, have suggested that frozen beef (Li et al., 2018; Qian et al., 2018; Gomes et al., 2019; Qian et al., 2022; Li et al., 2024) and lamb (Liang et al., 2021) can be stored at temperatures between -9°C and -12°C without substantially impacting on meat quality. None of these studies were conducted with commercial quantities of meat frozen, stored and transported under industrial conditions.

The aims of the work described here were to measure the PSL of commercially produced Australian boxed frozen beef and lamb stored under low temperature (-24°C), conventional (-18°C), and alternative (-12°C) storage temperatures.

2. Materials and Methods

2.1 Meat

Cattle and lamb were processed in two EU listed abattoirs, operating according to the requirements of the Australian Standard AS 4696:2007 (Standards Australia, 2007). The beef meat consisted of striploins (*M. longissimus lumborum*) and boneless trim of two chemical lean grades (95CL and 65CL). The lamb consisted of short loins (*M. longissimus lumborum*) and boneless trim (90CL and 65CL). Loin products and beef trim were vacuum packed, while lamb trim was packed in plastic bag liners folded over at the top, both in standard cardboard boxes/cartons. All boxed product was frozen to -18°C following usual commercial practices using blast and plate systems within 48-72 hours of slaughter. There were no specific selection criteria for the consignment apart from the practical consideration that it was of sufficient size to supply all of the beef and lamb required for the experiment.

2.2 Transport and storage

The boxed meat was transported to the UK under standard commercial arrangements and frozen refrigerated conditions (i.e., ≤ -18°C). The beef meat was shipped by sea directly to the UK, and the lamb by air to Denmark and then by road to the UK, both arriving at the Research Centre in the UK approximately 9 and 3.5 weeks post-processing, respectively. Boxes of product were randomly assigned immediately on arrival to cold storage rooms set to -12°C, -18°C, or -24°C, and stacked and stored in pallet configurations in each room. Air temperatures were monitored during storage and fluctuated by approximately ±1°C in each room, with standard regular timed defrosts occurring approximately every 6 h causing transient air temperature spikes to approximately -8.5°C, -13°C, and -17°C in each room, respectively. However, these regular short spikes in air temperature had a negligible impact on meat temperatures.

2.3 Sampling

At each of the sampling times the frozen trim was cut into 30 mm or 60 mm cubes depending on the analysis required, and the frozen loins into 15 mm thick steaks. Cutting (using a meat cutting band saw) was conducted in small batches to ensure all samples remained frozen throughout the cutting period. Immediately after cutting the samples were bagged and kept frozen at -18 ± 1°C until analysis. Samples for texture, lipid oxidation, microbiological, and sensory analyses were allowed to thaw in a refrigerator at approximately +2 ± 1°C for 24 hours prior to analysis.

2.4 Sensory Analysis

After thawing, the loins were cut into pieces of approximately 50 mm in width and trimmed where necessary. The loins were cooked on a preheated electric hot grill plate (Double contact grill half flat, Buffalo appliances, Andover, Hampshire, United Kingdom) set to a temperature of 200 °C until a core temperature of at least 70°C was reached to achieve a medium cook. The loin pieces were turned frequently during cooking. After cooking, the loins were weighed and left to rest for approximately 5-10 minutes.

After thawing, the trim samples were minced and processed into patties of equal size and weight (approximately 100 g). Cooking was performed at 200°C in a preheated electric fan oven (AEG, Luton, Bedfordshire, United Kingdom) until the internal temperature of 70°C was achieved, which took approximately 30 minutes.

A quantitative panel evaluation (using assessors initially screened using the ISO 8586:2012 standard in ISO 8589:2007 compliant facilities) was performed using approximately ten assessors each time. A randomised and balanced sampling block design was used to serve the panellists in random order according to sample, replicate, and assessor. The parameters used in the assessments are shown in Table 1. The panel evaluated the samples on a ten-point quality scale in which intensity (having a characteristic quality in a high degree) ranged from very low (1) to very high (10) with 4 representing the point of differentiation between acceptable and unacceptable product.

Table 6. Descriptors used in the quantitative descriptive sensory analysis of beef and lamb.

Descriptors	Definition
Appearance	Appearance of the cooked meat sample associated with the species
Meat odour intensity	Odour associated with the species
Fat odour intensity	Odour associated with the fat of the species
Meat flavour intensity	Flavour associated with the species
Fat flavour intensity	Flavour associated with the fat of the species
Juiciness	Perception of water content in the sample during chewing
Tenderness/texture	Ease of chewing the sample between teeth

2.5 Physical Analysis

Drip/thaw loss was measured using a method adapted from Kim et al. (2013) based on the modified Honikel (1998) method.

Meat colour was measured on beef and lamb loin samples using a Minolta Chromameter (illuminant D65, 8 mm diameter aperture, 2° standard observer; CR-400; Konica-Minolta Corp., Tokyo, Japan). Measurements were taken on 5 steak samples cut from a frozen loin. On each of the 5 steak samples, 3 fat and 3 lean (muscle) spot measurements were taken on the newly cut surfaces (after cutting when the steak was a in a frozen state), and repeated after the steak had been thawed for 48 h at +5 ± 1°C. Muscle fibres were oriented to be perpendicular to the measured surface.

The instrumental texture of the meat samples was evaluated using shear force, which was measured with a TA.XTplus Texture Analyser (Stable Micro System, Vienna Court, UK) coupled with a Warner-Bratzler blade (Warner-Bratzler Shear Force; WBSF) on cooked meat samples, cooked according to the same, previously described, method used for the sensory assessment.

2.6 Chemical Analysis

Peroxide value was determined based on the International Dairy Federation method (Shantha and Decker, 1994). The thiobarbituric acid reactive substances (TBARS) assay was conducted using the modified method of Sørensen and Jørgensen (1996).

2.7 Microbiological Analysis

Aerobic Colony Counts (ACCs) were enumerated in samples on arrival and after 6, 12, 21, 24, 28, 32, 36, and 38 months of frozen storage following ISO 4833-2:2013. *Escherichia coli* and *Salmonella* were measured at 24 months following ISO 16649-1:2001, and ISO 6579-1:2017, respectively.

2.8 Statistical analysis

All results are reported as means and standard deviations (SD). All results were analysed through analysis of variance (one-Way ANOVA) using StatPlus: mac Pro8.0.1.0 (AnalystSoft Inc., Walnut, CA, US). *P* values of 0.05 and below were considered to be significant. To determine whether individual comparisons (e.g., drip/thaw loss -12°C 65CL trim samples at 9 vs 12 months) were significant, Fisher LSD post-hoc test was conducted.

3. Results and discussion

3.1 Sensory

When assessed visually after 6 months of frozen storage there were slight signs of freezer burn (surface desiccation and discolouration) on some the over-wrapped boxed lamb trim samples stored at -12°C. This was more apparent on samples analysed after 12 months of frozen storage (and in all subsequently analysed samples stored at -12°C). Freezer burn was particularly apparent where the blocks had not been fully wrapped. There were no significant signs of discolouration on lamb trim stored at -18°C and -24°C, or on any of the vacuum-packed lamb or beef samples. The samples from the trim used for the chemical lipid oxidation analysis and sensory analysis were cut from the inside of the blocks which were unaffected by the surface freezer burn.

The sensory analysis (Table 2 to Table 8) of the beef samples showed that while there was a slight variation (in some cases statistically significant [$P<0.05$]) between some individual mean scores for some characteristics at different months, overall, there was no significant ($P>0.05$) change in mean meat odour intensity (Table 3), fat odour intensity (Table 4), meat flavour intensity (Table 5), or tenderness/texture (Table 6) scores for all types of beef samples stored at all temperatures over the full storage duration. There was more variation in juiciness scores (Table 7) than the other characteristics for the different beef samples over the assessment period, but again no clear overall change in mean juiciness scores with storage duration in samples stored at any of the three storage temperatures. Variations in score at different sampling times are highly likely to be due to a combination of box-to-box variation in the samples selected for analysis and drifts in the sensory panel perceptions over time. This explanation for some of the variation is supported by the observation that significant differences between samples stored at different temperatures but tested at the same time rarely occurred, and rarely resulted in a trend over time.

Table 7. Effect of frozen storage duration and temperature on mean (SD) sensory scores for appearance of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Storage temp. (°C)	Frozen storage duration (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12	6.2 (1.5)^{a}	4.4 (0.8)$^{a}_{A}$	6.6 (1.7)$^{b}_{A}$	4.1 (1.8)$^{a}_{A}$	4.7 (1.5)$^{a}_{A}$	4.3 (1.2)$^{a}_{A}$	4.3 (0.9)$^{a}_{A}$	4.2 (1.0)$^{a}_{A}$	4.0 (1.2)$^{a}_{A}$
	-18		5.7 (0.7)$^{abc}_{B}$	5.8 (1.8)$^{ab}_{A}$	4.8 (1.3)$^{bc}_{A}$	5.3 (1.3)$^{abc}_{A}$	4.5 (1.1)$^{c}_{A}$	4.6 (0.5)$^{bc}_{A}$	4.6 (1.5)$^{bc}_{A}$	4.6 (1.1)$^{abc}_{A}$
	-24		6.1 (0.9)$^{a}_{B}$	5.0 (1.8)$^{ab}_{A}$	5.2 (1.3)$^{ab}_{A}$	4.6 (0.9)$^{b}_{A}$	4.1 (1.3)$^{b}_{A}$	3.8 (1.8)$^{b}_{A}$	4.8 (1.1)$^{ab}_{A}$	4.0 (1.2)$^{b}_{A}$
Beef trim 95CL	-12	6.7 (1.5)^{a}	4.5 (1.6)$^{a}_{A}$	5.2 (1.3)$^{ab}_{A}$	4.3 (1.8)$^{a}_{A}$	6.1 (1.4)$^{b}_{A}$	5.6 (0.8)$^{ab}_{A}$	5.4 (0.7)$^{ab}_{A}$	5.3 (0.5)$^{ab}_{A}$	4.6 (1.3)$^{a}_{A}$
	-18		4.1 (1.7)$^{bc}_{A}$	5.7 (1.3)$^{ab}_{A}$	4.9 (1.4)$^{b}_{A}$	3.0 (2.0)$^{c}_{B}$	5.2 (0.9)$^{b}_{A}$	4.8 (1.2)$^{b}_{A}$	5.7 (0.9)$^{a}_{A}$	5.3 (1.6)$^{ab}_{A}$
	-24		4.0 (1.4)$^{a}_{A}$	5.1 (0.7)$^{ab}_{A}$	4.9 (1.5)$^{ab}_{A}$	5.9 (1.9)$^{b}_{A}$	5.4 (0.7)$^{b}_{A}$	5.6 (1.6)$^{b}_{A}$	3.7 (0.9)$^{a}_{B}$	4.7 (0.8)$^{ab}_{A}$
Beef trim 65CL	-12	6.6 (1.8)^{ab}	-	5.8 (1.2)$^{a}_{A}$	4.0 (1.2)$^{b}_{A}$	5.6 (1.7)$^{a}_{A}$	5.7 (1.8)$^{a}_{A}$	4.6 (0.7)$^{ab}_{A}$	2.8 (1.0)$^{b}_{A}$	3.2 (1.0)$^{b}_{A}$
	-18		-	5.3 (2.1)$^{ab}_{A}$	4.7 (0.9)$^{a}_{A}$	5.1 (1.9)$^{ab}_{A}$	6.4 (1.6)$^{b}_{A}$	5.1 (0.8)$^{ab}_{A}$	4.9 (1.2)$^{ab}_{B}$	2.9 (1.5)$^{c}_{A}$
	-24		-	5.7 (2.1)$^{a}_{A}$	3.9 (0.8)$^{bc}_{A}$	4.3 (1.8)$^{abc}_{A}$	5.1 (1.3)$^{ac}_{A}$	4.4 (1.8)$^{abc}_{A}$	4.4 (1.1)$^{abc}_{B}$	3.3 (1.0)$^{b}_{A}$
Lamb loin	-12	5.7 (1.0)^{ab}	6.1 (0.9)$^{a}_{A}$	5.8 (1.4)$^{ab}_{A}$	4.2 (1.0)$^{c}_{A}$	4.7 (1.2)$^{cd}_{AB}$	4.8 (0.8)$^{bc}_{A}$	4.8 (1.0)$^{bc}_{A}$	4.8 (0.5)$^{bc}_{A}$	5.3 (0.8)$^{abd}_{A}$
	-18		6.1 (1.3)$^{ac}_{A}$	6.4 (2.0)$^{a}_{A}$	5.1 (1.3)$^{bc}_{A}$	5.2 (0.7)$^{bc}_{A}$	5.2 (0.7)$^{bc}_{A}$	4.5 (0.5)$^{b}_{A}$	4.8 (0.5)$^{b}_{A}$	5.2 (0.6)$^{bc}_{A}$
	-24		5.8 (1.1)$^{a}_{A}$	5.2 (1.1)$^{a}_{A}$	5.0 (0.9)$^{a}_{A}$	3.4 (1.7)$^{b}_{B}$	4.8 (0.7)$^{a}_{A}$	5.4 (0.9)$^{a}_{A}$	5.1 (0.6)$^{a}_{A}$	5.3 (0.7)$^{a}_{A}$
Lamb trim 90CL	-12	5.3 (1.1)^{a}	6.3 (1.4)$^{a}_{A}$	4.7 (0.5)$^{b}_{A}$	3.6 (1.4)$^{bc}_{A}$	3.1 (1.3)$^{c}_{A}$	3.8 (1.2)$^{bc}_{A}$	3.3 (1.0)$^{bc}_{A}$	3.8 (1.3)$^{bc}_{A}$	3.6 (1.2)$^{bc}_{A}$
	-18		5.0 (1.3)$^{ab}_{B}$	4.6 (0.7)$^{ac}_{A}$	3.4 (0.9)$^{c}_{A}$	4.3 (1.7)$^{ac}_{A}$	4.7 (1.3)$^{ac}_{A}$	3.7 (1.4)$^{bc}_{A}$	4.0 (1.2)$^{bc}_{A}$	4.1 (1.0)$^{ac}_{A}$
	-24		5.3 (1.0)$^{a}_{AB}$	4.7 (1.3)$^{ab}_{A}$	3.7 (1.2)$^{bc}_{A}$	4.0 (1.2)$^{bc}_{A}$	4.1 (1.1)$^{bc}_{A}$	3.2 (1.5)$^{c}_{A}$	3.8 (1.2)$^{bc}_{A}$	3.7 (1.1)$^{bc}_{A}$
Lamb trim 65CL	-12	5.6 (0.5)^{a}	-	3.7 (1.3)$^{a}_{A}$	4.4 (0.9)$^{ab}_{Ab}$	5.2 (1.8)$^{bc}_{A}$	5.9 (1.0)$^{c}_{A}$	5.4 (0.9)$^{bc}_{A}$	4.9 (0.7)$^{ac}_{A}$	4.8 (0.5)$^{ac}_{A}$
	-18		-	5.1 (1.2)$^{a}_{B}$	3.8 (1.0)$^{b}_{A}$	5.2 (1.7)$^{a}_{A}$	5.2 (1.2)$^{a}_{AB}$	5.1 (1.1)$^{a}_{A}$	4.6 (0.5)$^{ab}_{A}$	4.6 (1.3)$^{ab}_{A}$
	-24		-	5.9 (1.1)$^{a}_{B}$	5.7 (2.1)$^{a}_{B}$	5.8 (1.9)$^{a}_{A}$	3.9 (1.7)$^{b}_{B}$	5.3 (1.3)$^{ab}_{A}$	4.1 (1.2)$^{b}_{A}$	4.1 (1.1)$^{b}_{A}$

N=10; Within a row, means that do not share superscripts significantly differ (P<0.05); Within a column, for a specific sample type, means that do not share subscripts significantly differ (P<0.05).

Table 8. Effect of frozen storage duration and temperature on mean (SD) sensory scores for meat odour intensity of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Storage temp. (°C)	Frozen storage time (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12		4.6 (1.2)$^{a}_{A}$	6.1 (1.6)$^{b}_{A}$	4.4 (1.7)$^{a}_{A}$	4.4 (2.1)$^{a}_{A}$	4.5 (1.3)$^{a}_{A}$	4.1 (1.0)$^{a}_{A}$	4.4 (1.5)$^{a}_{A}$	4.4 (2.3)$^{ab}_{A}$
	-18	4.8 (0.8)^{a}	5.5 (2.0)$^{a}_{A}$	5.5 (2.0)$^{a}_{A}$	4.8 (1.9)$^{a}_{A}$	5.0 (2.0)$^{a}_{A}$	4.3 (1.3)$^{a}_{A}$	5.1 (1.0)$^{a}_{A}$	4.6 (1.6)$^{a}_{A}$	4.0 (1.6)$^{a}_{A}$
	-24		5.3 (1.6)$^{ab}_{A}$	5.6 (1.4)$^{a}_{A}$	5.6 (1.4)$^{ac}_{A}$	4.7 (1.7)$^{ab}_{A}$	4.4 (1.6)$^{ab}_{A}$	4.0 (1.1)$^{b}_{A}$	4.1 (1.4)$^{bc}_{A}$	4.2 (1.5)$^{a}_{A}$
Beef trim 95CL	-12		4.2 (1.8)$^{a}_{A}$	4.5 (2.0)$^{a}_{A}$	4.3 (1.1)$^{a}_{A}$	5.0 (1.6)$^{a}_{A}$	4.5 (1.6)$^{a}_{A}$	5.0 (1.3)$^{a}_{A}$	4.8 (1.6)$^{a}_{A}$	5.0 (1.6)$^{a}_{A}$
	-18	4.9 (1.1)^{a}	4.4 (2.1)$^{a}_{A}$	4.7 (1.3)$^{a}_{A}$	4.7 (1.1)$^{a}_{A}$	4.6 (2.8)$^{a}_{A}$	4.8 (1.4)$^{a}_{A}$	4.5 (0.9)$^{a}_{A}$	5.1 (1.4)$^{a}_{A}$	5.3 (1.5)$^{a}_{A}$
	-24		4.8 (2.1)$^{a}_{A}$	4.8 (1.0)$^{a}_{A}$	4.8 (1.6)$^{a}_{A}$	5.4 (1.4)$^{a}_{A}$	5.2 (1.9)$^{a}_{A}$	4.6 (0.9)$^{a}_{A}$	5.4 (1.3)$^{a}_{A}$	4.3 (1.1)$^{a}_{A}$
Beef trim 65CL	-12		-	6.1 (1.7)$^{a}_{A}$	4.8 (1.7)$^{ab}_{A}$	4.9 (1.5)$^{ab}_{A}$	4.8 (2.0)$^{ab}_{A}$	4.1 (2.0)$^{b}_{A}$	4.8 (1.7)$^{ab}_{A}$	4.8 (1.7)$^{ab}_{A}$
	-18	4.8 (1.3)^{a}	-	5.2 (0.8)$^{a}_{A}$	4.7 (1.5)$^{a}_{A}$	5.1 (1.5)$^{a}_{A}$	5.8 (2.2)$^{a}_{A}$	4.9 (1.6)$^{a}_{A}$	4.5 (1.4)$^{a}_{A}$	4.3 (1.4)$^{a}_{A}$
	-24		-	5.8 (0.7)$^{a}_{A}$	4.6 (1.4)$^{a}_{A}$	4.5 (2.2)$^{a}_{A}$	4.4 (1.3)$^{a}_{A}$	4.5 (1.6)$^{a}_{A}$	5.1 (1.6)$^{a}_{A}$	4.8 (1.6)$^{a}_{A}$
Lamb loin	-12		5.7 (1.3)$^{a}_{A}$	4.3 (0.9)$^{bc}_{A}$	5.4 (1.8)$^{ab}_{A}$	4.7 (2.0)$^{abc}_{A}$	4.0 (1.2)$^{bc}_{A}$	4.3 (0.8)$^{abc}_{A}$	4.5 (1.1)$^{abc}_{A}$	4.0 (1.2)$^{c}_{A}$
	-18	4.9 (1.1)^{ab}	5.5 (1.8)$^{a}_{A}$	4.8 (0.8)$^{ab}_{A}$	5.8 (1.2)$^{a}_{A}$	4.3 (1.9)$^{ab}_{A}$	4.3 (1.3)$^{ab}_{A}$	4.3 (0.8)$^{ab}_{A}$	4.4 (1.4)$^{ab}_{A}$	3.8 (1.2)$^{b}_{A}$
	-24		5.6 (1.8)$^{a}_{A}$	4.5 (1.4)$^{a}_{A}$	5.4 (1.6)$^{a}_{A}$	4.2 (1.6)$^{a}_{A}$	4.4 (1.2)$^{a}_{A}$	5.4 (0.9)$^{a}_{A}$	4.4 (1.2)$^{a}_{A}$	4.5 (1.5)$^{a}_{A}$
Lamb trim 90CL	-12		5.5 (1.7)$^{a}_{A}$	4.1 (0.7)$^{a}_{A}$	4.7 (1.9)$^{a}_{A}$	5.3 (1.6)$^{a}_{A}$	4.4 (1.7)$^{a}_{A}$	4.2 (0.8)$^{a}_{A}$	4.6 (1.9)$^{a}_{A}$	4.3 (1.5)$^{a}_{A}$
	-18	4.7 (1.2)^{a}	5.7 (1.1)$^{a}_{A}$	4.7 (1.1)$^{a}_{A}$	5.0 (1.3)$^{a}_{A}$	5.6 (1.6)$^{a}_{A}$	4.6 (1.4)$^{a}_{A}$	4.7 (1.5)$^{a}_{A}$	4.6 (2.3)$^{a}_{A}$	4.4 (1.6)$^{a}_{A}$
	-24		5.0 (1.4)$^{a}_{A}$	4.7 (1.4)$^{a}_{A}$	4.8 (1.3)$^{a}_{A}$	4.8 (2.6)$^{a}_{A}$	4.2 (1.6)$^{a}_{A}$	3.7 (1.2)$^{a}_{A}$	4.9 (2.1)$^{a}_{A}$	4.2 (1.4)$^{a}_{A}$
Lamb trim 65CL	-12		-	4.3 (1.9)$^{ab}_{A}$	6.0 (2.1)$^{a}_{A}$	4.4 (2.3)$^{ab}_{A}$	4.2 (1.5)$^{b}_{A}$	4.4 (1.2)$^{ab}_{A}$	4.3 (1.4)$^{ab}_{A}$	4.0 (1.1)$^{b}_{A}$
	-18	5.8 (1.3)$^{a}_{A}$	-	5.3 (1.7)$^{a}_{A}$	4.5 (1.7)$^{a}_{A}$	4.2 (2.5)$^{a}_{A}$	4.5 (1.7)$^{a}_{A}$	4.6 (1.4)$^{a}_{A}$	4.4 (1.5)$^{a}_{A}$	3.6 (1.5)$^{a}_{A}$
	-24		-	5.4 (1.9)$^{a}_{A}$	5.1 (1.9)$^{a}_{A}$	4.8 (1.9)$^{a}_{A}$	4.6 (1.3)$^{a}_{A}$	4.1 (1.5)$^{a}_{A}$	3.9 (1.3)$^{a}_{A}$	3.9 (1.6)$^{a}_{A}$

N=10; Within a row, means that do not share superscripts significantly differ ($P<0.05$); Within a column, for a specific sample type, means that do not share subscripts significantly differ ($P<0.05$).

Table 9. Effect of frozen storage duration and temperature on mean (SD) sensory scores for fat odour intensity of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Storage temp. (°C)	Frozen storage duration (Months)								
		3	6	12	21	24	28	32	36	38
Beef loin	-12		4.3 (0.9)$^{a}_{A}$	5.0 (1.5)$^{a}_{A}$	4.8 (1.6)$^{a}_{A}$	4.8 (2.2)$^{a}_{A}$	4.0 (1.4)$^{a}_{A}$	4.6 (1.4)$^{a}_{A}$	4.4 (1.5)$^{a}_{A}$	4.6 (1.5)$^{a}_{A}$
	-18	5.2 (0.8)$^{a}_{A}$	5.1 (1.5)$^{ab}_{A}$	5.6 (2.2)$^{a}_{A}$	4.4 (1.6)$^{ab}_{A}$	4.4 (1.7)$^{ab}_{A}$	3.6 (1.7)$^{b}_{A}$	5.3 (0.7)$^{a}_{A}$	4.3 (1.1)$^{a}_{A}$	3.4 (1.1)$^{b}_{A}$
	-24		4.7 (0.8)$^{ab}_{A}$	5.0 (1.6)$^{a}_{A}$	4.4 (1.2)$^{ab}_{A}$	4.3 (1.9)$^{ab}_{A}$	3.5 (1.6)$^{b}_{A}$	4.3 (1.0)$^{ab}_{A}$	3.8 (1.0)$^{ab}_{A}$	3.8 (1.1)$^{ab}_{A}$
Beef trim 95CL	-12		3.9 (1.7)$^{a}_{A}$	4.4 (1.9)$^{a}_{A}$	4.3 (1.0)$^{a}_{A}$	4.4 (1.6)$^{a}_{A}$	4.0 (1.5)$^{a}_{A}$	4.5 (0.5)$^{a}_{A}$	3.6 (1.2)$^{a}_{A}$	4.0 (1.5)$^{a}_{A}$
	-18	4.5 (1.4)$^{a}_{A}$	4.0 (1.9)$^{a}_{A}$	4.2 (1.5)$^{a}_{A}$	4.3 (1.3)$^{a}_{A}$	4.2 (2.3)$^{a}_{A}$	4.2 (1.6)$^{a}_{A}$	4.4 (0.9)$^{a}_{A}$	4.2 (1.4)$^{a}_{A}$	4.4 (1.5)$^{a}_{A}$
	-24		4.3 (1.8)$^{a}_{A}$	4.3 (1.7)$^{a}_{A}$	4.0 (1.8)$^{a}_{A}$	5.1 (1.4)$^{a}_{A}$	4.3 (1.6)$^{a}_{A}$	4.6 (1.1)$^{a}_{A}$	4.6 (1.3)$^{a}_{A}$	4.0 (1.0)$^{a}_{A}$
Beef trim 65CL	-12		-	4.8 (1.6)$^{a}_{A}$	4.7 (1.7)$^{a}_{A}$	4.1 (1.5)$^{a}_{A}$	3.7 (0.8)$^{a}_{A}$	3.9 (1.5)$^{a}_{A}$	3.8 (1.5)$^{a}_{A}$	4.0 (1.8)$^{a}_{A}$
	-18	5.8 (1.8)$^{a}_{A}$	-	5.6 (1.6)$^{a}_{A}$	4.4 (1.9)$^{a}_{A}$	4.4 (1.3)$^{a}_{A}$	4.5 (1.8)$^{a}_{A}$	4.5 (2.0)$^{a}_{A}$	4.0 (2.8)$^{a}_{A}$	3.8 (1.3)$^{a}_{A}$
	-24		-	5.2 (1.3)$^{a}_{A}$	4.2 (1.6)$^{a}_{A}$	3.8 (1.8)$^{a}_{A}$	4.3 (1.3)$^{a}_{A}$	4.1 (1.7)$^{a}_{A}$	4.9 (2.2)$^{a}_{A}$	4.4 (1.4)$^{a}_{A}$
Lamb loin	-12		6.0 (1.2)$^{a}_{A}$	5.4 (1.7)$^{a}_{AB}$	5.7 (1.9)$^{a}_{A}$	4.9 (1.6)$^{a}_{A}$	4.6 (1.2)$^{a}_{A}$	5.0 (1.7)$^{a}_{A}$	4.3 (2.0)$^{a}_{A}$	4.4 (1.5)$^{a}_{A}$
	-18	4.9 (1.7)$^{abc}_{A}$	5.0 (0.8)$^{abc}_{A}$	5.8 (0.8)$^{ab}_{A}$	6.0 (1.7)$^{b}_{A}$	4.8 (2.4)$^{ab}_{A}$	4.0 (1.5)$^{c}_{A}$	4.2 (1.2)$^{ac}_{A}$	3.5 (1.2)$^{c}_{A}$	4.4 (1.0)$^{ac}_{A}$
	-24		5.2 (1.0)$^{a}_{A}$	4.4 (1.2)$^{a}_{B}$	5.4 (1.3)$^{a}_{A}$	4.9 (2.1)$^{a}_{A}$	5.0 (1.3)$^{a}_{A}$	5.0 (1.0)$^{a}_{A}$	4.1 (1.1)$^{a}_{A}$	4.7 (1.6)$^{a}_{A}$
Lamb trim 90CL	-12		5.3 (1.2)$^{a}_{A}$	4.4 (1.1)$^{ab}_{A}$	4.1 (2.0)$^{ab}_{A}$	4.9 (1.7)$^{ab}_{A}$	4.1 (2.0)$^{ab}_{A}$	3.7 (1.6)$^{ab}_{A}$	3.6 (1.2)$^{b}_{A}$	3.7 (1.2)$^{b}_{A}$
	-18	4.5 (1.4)$^{a}_{A}$	4.9 (1.2)$^{a}_{A}$	5.1 (1.0)$^{a}_{A}$	4.0 (1.2)$^{a}_{A}$	4.6 (1.3)$^{a}_{A}$	4.0 (1.9)$^{a}_{A}$	4.2 (1.5)$^{a}_{A}$	3.8 (1.3)$^{a}_{A}$	3.8 (1.6)$^{a}_{A}$
	-24		5.6 (1.2)$^{a}_{A}$	4.8 (1.5)$^{ab}_{A}$	4.4 (1.1)$^{ab}_{A}$	4.5 (2.4)$^{ab}_{A}$	4.0 (1.7)$^{b}_{A}$	3.3 (1.6)$^{b}_{A}$	3.8 (1.3)$^{b}_{A}$	3.8 (1.4)$^{b}_{A}$
Lamb trim 65CL	-12		-	5.4 (3.0)$^{ab}_{A}$	6.4 (2.2)$^{a}_{A}$	5.6 (2.1)$^{ab}_{A}$	4.4 (1.5)$^{ab}_{A}$	4.4 (1.6)$^{ab}_{A}$	4.0 (1.0)$^{b}_{A}$	4.0 (1.2)$^{b}_{A}$
	-18	7.0 (1.9)$^{a}_{A}$	-	6.2 (1.4)$^{ab}_{A}$	5.9 (2.6)$^{ac}_{A}$	5.0 (2.5)$^{ac}_{A}$	4.2 (1.8)$^{bc}_{A}$	4.6 (1.9)$^{ac}_{A}$	4.4 (1.1)$^{bc}_{A}$	3.8 (1.4)$^{c}_{A}$
	-24		-	5.6 (2.1)$^{a}_{A}$	5.1 (2.0)$^{a}_{A}$	5.0 (1.4)$^{a}_{A}$	4.2 (1.0)$^{a}_{A}$	4.5 (2.0)$^{a}_{A}$	3.7 (1.0)$^{a}_{A}$	4.1 (1.1)$^{a}_{A}$

N=10; Within a row, means that do not share superscripts significantly differ ($P<0.05$); Within a column, for a specific sample type, means that do not share subscripts significantly differ ($P<0.05$).

Table 10. Effect of frozen storage duration and temperature on mean (SD) sensory scores for meat flavour intensity of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Temp (°C)	Frozen storage duration (Months)								
		3	6	12	21	24	28	32	36	38
Beef loin	-12		4.6 (1.3)$^{a}_{A}$	5.4 (1.4)$^{a}_{A}$	4.3 (1.7)$^{a}_{A}$	5.4 (1.2)$^{a}_{A}$	4.7 (0.8)$^{a}_{A}$	4.1 (1.1)$^{a}_{A}$	4.8 (1.6)$^{a}_{A}$	5.2 (0.8)$^{a}_{A}$
	-18	4.7 (1.1)$^{a}_{A}$	4.9 (1.4)$^{a}_{A}$	5.7 (1.6)$^{a}_{A}$	4.9 (1.6)$^{a}_{A}$	5.1 (1.4)$^{a}_{A}$	4.7 (0.8)$^{a}_{A}$	4.6 (1.1)$^{a}_{A}$	5.7 (1.7)$^{a}_{A}$	4.2 (0.8)$^{a}_{A}$
	-24		3.9 (1.7)$^{a}_{A}$	5.1 (2.5)$^{a}_{A}$	5.9 (1.5)$^{a}_{A}$	5.1 (0.9)$^{a}_{A}$	4.8 (1.1)$^{a}_{A}$	4.4 (0.5)$^{a}_{A}$	5.1 (1.5)$^{a}_{A}$	4.4 (0.5)$^{a}_{A}$
Beef trim 95CL	-12		3.3 (1.8)$^{a}_{A}$	4.5 (1.6)$^{a}_{A}$	3.2 (1.6)$^{a}_{A}$	4.4 (1.5)$^{a}_{A}$	4.6 (1.4)$^{a}_{A}$	4.5 (1.8)$^{a}_{A}$	4.7 (1.4)$^{a}_{A}$	3.7 (1.3)$^{a}_{A}$
	-18	4.3 (1.4)$^{a}_{A}$	3.7 (1.9)$^{a}_{A}$	4.6 (2.0)$^{a}_{A}$	4.0 (1.1)$^{a}_{A}$	-	5.1 (1.6)$^{a}_{A}$	4.3 (1.2)$^{a}_{A}$	5.1 (0.6)$^{a}_{A}$	4.7 (1.9)$^{a}_{A}$
	-24		4.0 (2.0)$^{a}_{A}$	4.6 (2.1)$^{a}_{A}$	4.3 (1.0)$^{a}_{A}$	4.7 (1.6)$^{a}_{A}$	4.8 (1.8)$^{a}_{A}$	4.9 (1.0)$^{a}_{A}$	4.4 (1.0)$^{a}_{A}$	4.1 (1.2)$^{a}_{A}$
Beef trim 65CL	-12		-	5.4 (0.7)$^{a}_{A}$	4.2 (1.2)$^{ab}_{A}$	-	4.5 (1.2)$^{ab}_{AB}$	4.8 (0.7)$^{ab}_{A}$	4.0 (1.4)$^{b}_{A}$	4.6 (1.4)$^{ab}_{A}$
	-18	5.2 (0.8)$^{ab}_{A}$	-	5.9 (1.1)$^{a}_{A}$	4.9 (1.4)$^{ab}_{A}$	-	3.4 (1.0)$^{b}_{A}$	4.8 (2.4)$^{ab}_{A}$	4.9 (1.7)$^{ab}_{A}$	3.9 (1.5)$^{b}_{A}$
	-24		-	6.0 (1.4)$^{a}_{A}$	4.4 (1.7)$^{ab}_{A}$	-	5.2 (1.1)$^{ab}_{B}$	4.8 (1.5)$^{ab}_{A}$	5.1 (1.2)$^{ab}_{A}$	4.6 (1.0)$^{b}_{A}$
Lamb loin	-12		5.6 (1.2)$^{a}_{A}$	5.4 (1.8)$^{ab}_{A}$	5.4 (1.1)$^{ab}_{A}$	4.7 (1.4)$^{abc}_{A}$	4.6 (1.3)$^{abc}_{A}$	3.8 (1.0)$^{bc}_{A}$	4.6 (1.8)$^{abc}_{A}$	3.7 (1.3)$^{c}_{A}$
	-18	5.3 (1.1)$^{a}_{A}$	5.4 (1.3)$^{a}_{A}$	5.3 (0.9)$^{a}_{A}$	5.7 (1.7)$^{a}_{A}$	4.7 (1.9)$^{a}_{A}$	5.3 (1.0)$^{a}_{A}$	5.0 (0.9)$^{a}_{A}$	5.1 (1.9)$^{a}_{A}$	4.2 (1.7)$^{a}_{A}$
	-24		5.6 (1.3)$^{a}_{A}$	4.9 (1.5)$^{ab}_{A}$	5.0 (1.1)$^{ab}_{A}$	4.4 (1.8)$^{ab}_{A}$	4.0 (1.5)$^{b}_{A}$	4.6 (1.9)$^{ab}_{A}$	4.5 (1.5)$^{ab}_{A}$	3.8 (0.8)$^{b}_{A}$
Lamb trim 90CL	-12		5.5 (1.9)$^{a}_{A}$	4.9 (1.7)$^{ab}_{A}$	4.4 (1.9)$^{ab}_{A}$	4.5 (2.0)$^{ab}_{A}$	4.4 (1.6)$^{ab}_{A}$	3.5 (1.4)$^{b}_{A}$	4.8 (1.0)$^{ab}_{A}$	3.7 (1.5)$^{b}_{A}$
	-18	4.3 (1.3)$^{a}_{A}$	4.4 (1.6)$^{a}_{A}$	4.6 (1.3)$^{a}_{A}$	4.9 (1.9)$^{a}_{A}$	5.3 (2.1)$^{a}_{A}$	4.6 (1.1)$^{a}_{A}$	3.7 (1.8)$^{a}_{A}$	4.8 (1.8)$^{a}_{A}$	3.9 (1.4)$^{a}_{A}$
	-24		5.0 (1.9)$^{a}_{A}$	4.9 (1.8)$^{a}_{A}$	5.2 (1.6)$^{a}_{A}$	5.7 (1.6)$^{a}_{A}$	5.1 (2.0)$^{a}_{A}$	3.8 (1.0)$^{a}_{A}$	4.5 (1.5)$^{a}_{A}$	4.7 (1.4)$^{a}_{A}$
Lamb trim 65CL	-12		-	4.6 (2.2)$^{ab}_{A}$	5.7 (2.2)$^{a}_{A}$	-	4.4 (1.6)$^{ab}_{A}$	4.0 (1.5)$^{ab}_{A}$	4.0 (0.8)$^{ab}_{A}$	3.1 (1.6)$^{b}_{A}$
	-18	7.0 (1.9)$^{a}_{A}$	-	4.9 (1.6)$^{ab}_{A}$	4.1 (2.5)$^{b}_{A}$	-	4.8 (1.5)$^{ab}_{A}$	5.0 (1.8)$^{ab}_{A}$	3.7 (1.5)$^{b}_{A}$	3.6 (1.3)$^{b}_{A}$
	-24		-	5.4 (2.5)$^{a}_{A}$	5.3 (2.2)$^{a}_{A}$	-	4.6 (1.6)$^{a}_{A}$	4.1 (1.2)$^{a}_{A}$	3.7 (1.1)$^{a}_{A}$	4.0 (1.5)$^{a}_{A}$

N=10; Within a row, means that do not share superscripts significantly differ (P<0.05); Within a column, for a specific sample type, means that do not share subscripts significantly differ (P<0.05).

Table 11. Effect of frozen storage duration and temperature on mean (SD) sensory scores for fat flavour intensity of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Temp (°C)	Frozen storage duration (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12		4.8 (1.7)$^{a}_{A}$	5.2 (0.8)$^{a}_{A}$	4.9 (1.6)$^{a}_{A}$	5.2 (1.9)$^{a}_{A}$	4.5 (1.2)$^{a}_{A}$	4.9 (1.0)$^{a}_{A}$	4.3 (1.7)$^{a}_{A}$	4.4 (1.1)$^{a}_{A}$
	-18	5.4 (1.4)$^{ab}_{A}$	4.6 (2.0)$^{ac}_{A}$	6.3 (1.9)$^{b}_{A}$	4.9 (1.1)$^{abc}_{A}$	5.3 (1.0)$^{ab}_{A}$	4.4 (1.0)$^{ac}_{A}$	4.6 (1.3)$^{ac}_{A}$	5.1 (1.6)$^{abc}_{A}$	3.4 (1.1)$^{c}_{A}$
	-24		4.9 (1.9)$^{a}_{A}$	5.1 (2.1)$^{a}_{A}$	5.3 (1.3)$^{a}_{A}$	5.2 (0.8)$^{a}_{A}$	4.8 (1.2)$^{a}_{A}$	5.5 (1.9)$^{a}_{A}$	5.2 (2.0)$^{a}_{A}$	4.8 (1.5)$^{a}_{A}$
Beef trim 95CL	-12		3.7 (2.0)$^{a}_{A}$	4.2 (1.6)$^{ab}_{A}$	3.1 (1.8)$^{a}_{A}$	5.6 (1.3)$^{ab}_{A}$	4.7 (1.5)$^{ab}_{A}$	5.9 (1.6)$^{b}_{A}$	4.8 (2.3)$^{ab}_{A}$	3.3 (1.5)$^{a}_{A}$
	-18	4.2 (1.0)$^{a}_{A}$	4.0 (2.2)$^{a}_{A}$	3.7 (1.6)$^{a}_{A}$	3.7 (1.7)$^{a}_{A}$	-	4.2 (1.6)$^{a}_{A}$	5.1 (1.5)$^{a}_{A}$	3.8 (1.2)$^{a}_{A}$	3.9 (1.9)$^{a}_{A}$
	-24		4.4 (1.9)$^{a}_{A}$	4.5 (2.3)$^{a}_{A}$	4.5 (1.1)$^{a}_{A}$	5.0 (2.0)$^{a}_{A}$	4.6 (1.3)$^{a}_{A}$	5.6 (1.5)$^{a}_{A}$	4.0 (2.6)$^{a}_{A}$	3.7 (1.7)$^{a}_{A}$
Beef trim 65CL	-12		-	5.6 (1.9)$^{a}_{A}$	4.8 (2.3)$^{a}_{A}$	-	4.8 (1.2)$^{a}_{A}$	4.8 (0.7)$^{a}_{A}$	4.6 (2.1)$^{a}_{A}$	4.1 (1.5)$^{a}_{A}$
	-18	6.2 (0.8)$^{a}_{A}$	-	5.2 (1.6)$^{ab}_{A}$	4.8 (1.6)$^{ab}_{A}$	-	4.2 (1.0)$^{ab}_{A}$	6.0 (2.4)$^{a}_{A}$	4.9 (2.5)$^{ab}_{A}$	3.6 (1.5)$^{b}_{A}$
	-24		-	5.7 (1.9)$^{ab}_{A}$	5.1 (1.6)$^{ab}_{A}$	-	4.4 (1.7)$^{ab}_{A}$	6.1 (1.5)$^{a}_{A}$	4.9 (2.5)$^{ab}_{A}$	4.1 (1.3)$^{b}_{A}$
Lamb loin	-12		5.7 (1.8)$^{a}_{A}$	5.1 (1.8)$^{a}_{A}$	5.7 (1.3)$^{a}_{A}$	5.4 (1.4)$^{a}_{A}$	5.0 (1.2)$^{a}_{A}$	5.0 (1.4)$^{a}_{A}$	4.5 (1.6)$^{a}_{A}$	4.9 (1.9)$^{a}_{A}$
	-18	5.1 (1.1)$^{ab}_{A}$	5.3 (1.7)$^{ab}_{A}$	6.0 (1.6)$^{ab}_{A}$	6.1 (2.0)$^{a}_{A}$	5.3 (2.1)$^{ab}_{A}$	4.7 (1.5)$^{ab}_{A}$	5.2 (1.5)$^{ab}_{A}$	4.3 (1.8)$^{b}_{A}$	4.4 (1.3)$^{ab}_{A}$
	-24		5.5 (0.7)$^{ab}_{A}$	5.2 (1.1)$^{ab}_{A}$	5.3 (1.1)$^{ab}_{A}$	6.1 (1.8)$^{b}_{A}$	4.4 (1.7)$^{a}_{A}$	4.0 (2.1)$^{a}_{A}$	4.5 (1.7)$^{a}_{A}$	4.5 (1.5)$^{a}_{A}$
Lamb trim 90CL	-12		4.1 (1.5)$^{a}_{A}$	5.3 (2.0)$^{a}_{A}$	4.7 (1.8)$^{a}_{A}$	5.1 (2.7)$^{a}_{A}$	4.1 (1.6)$^{a}_{A}$	4.7 (1.9)$^{a}_{A}$	4.6 (2.3)$^{a}_{A}$	4.0 (1.5)$^{a}_{A}$
	-18	3.8 (1.7)$^{a}_{A}$	3.8 (1.4)$^{a}_{A}$	5.5 (1.5)$^{b}_{A}$	4.2 (1.2)$^{ab}_{A}$	5.1 (1.7)$^{ab}_{A}$	4.1 (1.8)$^{ab}_{A}$	4.5 (1.8)$^{ab}_{A}$	4.1 (0.8)$^{ab}_{A}$	4.0 (1.3)$^{ab}_{A}$
	-24		4.7 (1.7)$^{a}_{A}$	4.5 (1.9)$^{a}_{A}$	4.2 (1.4)$^{a}_{A}$	5.7 (1.6)$^{a}_{A}$	4.7 (2.1)$^{a}_{A}$	3.8 (1.8)$^{a}_{A}$	4.4 (0.9)$^{a}_{A}$	4.4 (1.3)$^{a}_{A}$
Lamb trim 65CL	-12		-	7.4 (1.7)$^{a}_{A}$	7.1 (2.3)$^{ab}_{A}$	-	4.6 (1.6)$^{c}_{A}$	4.0 (1.5)$^{c}_{A}$	5.0 (1.5)$^{bc}_{A}$	5.4 (2.1)$^{c}_{A}$
	-18	7.8 (1.6)$^{a}_{A}$	-	6.8 (1.5)$^{ab}_{AB}$	7.4 (3.2)$^{a}_{A}$	-	5.1 (1.6)$^{bc}_{A}$	4.3 (1.7)$^{c}_{A}$	4.6 (1.3)$^{c}_{A}$	4.9 (0.8)$^{bc}_{A}$
	-24		-	5.0 (2.0)$^{ab}_{B}$	6.4 (2.7)$^{a}_{A}$	-	4.9 (1.4)$^{ab}_{A}$	5.6 (1.8)$^{ab}_{A}$	5.1 (2.3)$^{ab}_{A}$	4.3 (0.9)$^{b}_{A}$

N=10; Within a row, means that do not share superscripts significantly differ (P<0.05); Within a column, for a specific sample type, means that do not share subscripts significantly differ (P<0.05).

Table 12. Effect of frozen storage duration and temperature on mean (SD) sensory scores for juiciness of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Temp (°C)	Frozen storage duration (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12		3.8 (1.8)$^{a}_{A}$	4.5 (1.9)$^{a}_{A}$	5.1 (2.1)$^{a}_{A}$	5.6 (1.3)$^{a}_{A}$	4.3 (0.9)$^{a}_{A}$	4.6 (1.9)$^{a}_{A}$	3.8 (2.1)$^{a}_{A}$	4.8 (0.8)$^{a}_{A}$
	-18	4.7 (1.3)$^{a}_{A}$	4.2 (1.5)$^{a}_{A}$	4.0 (1.5)$^{a}_{A}$	4.6 (1.1)$^{a}_{A}$	5.2 (1.6)$^{a}_{A}$	5.3 (1.3)$^{a}_{A}$	4.9 (0.6)$^{a}_{A}$	5.3 (1.4)$^{a}_{A}$	4.4 (0.5)$^{a}_{A}$
	-24		3.5 (1.3)$^{a}_{A}$	4.4 (0.8)$^{ab}_{A}$	4.4 (1.7)$^{ab}_{A}$	6.0 (1.6)$^{c}_{A}$	5.3 (1.2)$^{bc}_{A}$	4.8 (0.5)$^{ac}_{A}$	4.4 (1.8)$^{a}_{A}$	4.6 (1.3)$^{ac}_{A}$
Beef trim 95CL	-12		2.1 (1.2)$^{a}_{A}$	3.3 (1.2)$^{ab}_{A}$	2.0 (1.3)$^{a}_{A}$	5.2 (1.2)$^{c}_{A}$	4.0 (0.9)$^{bc}_{A}$	4.5 (0.8)$^{bc}_{A}$	5.3 (2.1)$^{c}_{A}$	2.7 (1.6)$^{a}_{A}$
	-18	3.8 (1.7)$^{abc}_{A}$	2.5 (1.7)$^{b}_{A}$	2.7 (1.1)$^{bd}_{A}$	3.0 (1.7)$^{ab}_{A}$	-	4.0 (0.9)$^{adc}_{A}$	3.8 (0.9)$^{abc}_{A}$	3.9 (1.2)$^{abc}_{AB}$	4.7 (1.5)$^{c}_{B}$
	-24		2.6 (1.6)$^{ab}_{A}$	2.8 (1.3)$^{ab}_{A}$	3.6 (2.2)$^{abc}_{A}$	4.0 (1.5)$^{ac}_{A}$	3.8 (1.0)$^{abc}_{A}$	3.8 (0.7)$^{abc}_{A}$	2.3 (1.4)$^{b}_{B}$	4.6 (1.3)$^{c}_{AB}$
Beef trim 65CL	-12		-	4.6 (2.2)$^{a}_{A}$	4.7 (1.6)$^{a}_{A}$	-	4.0 (1.5)$^{a}_{A}$	4.1 (0.4)$^{a}_{A}$	4.5 (1.6)$^{a}_{A}$	4.3 (1.2)$^{a}_{A}$
	-18	4.6 (0.9)$^{abc}_{A}$	-	4.8 (2.1)$^{abc}_{A}$	4.9 (1.5)$^{ab}_{A}$	-	3.6 (1.4)$^{ac}_{A}$	6.1 (1.2)$^{b}_{B}$	3.3 (1.4)$^{c}_{A}$	4.2 (0.8)$^{ac}_{A}$
	-24		-	5.0 (1.5)$^{ab}_{A}$	5.8 (2.2)$^{a}_{A}$	-	3.6 (1.5)$^{bc}_{A}$	6.4 (1.2)$^{a}_{B}$	2.9 (1.8)$^{c}_{A}$	4.3 (1.0)$^{bc}_{A}$
Lamb loin	-12		5.7 (1.3)$^{a}_{A}$	4.5 (1.6)$^{a}_{A}$	4.3 (1.0)$^{a}_{A}$	4.8 (1.5)$^{a}_{A}$	4.9 (1.4)$^{a}_{A}$	4.8 (1.5)$^{a}_{A}$	5.5 (2.1)$^{a}_{A}$	4.4 (1.7)$^{a}_{A}$
	-18	5.0 (1.5)$^{a}_{A}$	5.0 (1.5)$^{a}_{A}$	5.1 (1.6)$^{a}_{A}$	5.1 (2.0)$^{a}_{A}$	6.0 (1.7)$^{a}_{A}$	5.8 (1.1)$^{a}_{A}$	5.5 (2.1)$^{a}_{A}$	5.8 (1.8)$^{a}_{A}$	5.2 (0.8)$^{a}_{A}$
	-24		4.7 (1.7)$^{ab}_{A}$	4.4 (1.4)$^{a}_{A}$	5.8 (1.4)$^{ab}_{A}$	5.8 (1.2)$^{ab}_{A}$	5.9 (0.8)$^{b}_{A}$	5.4 (1.9)$^{ab}_{A}$	5.0 (1.4)$^{ab}_{A}$	4.5 (1.1)$^{ab}_{A}$
Lamb trim 90CL	-12		3.4 (2.1)$^{a}_{A}$	3.9 (1.5)$^{a}_{A}$	4.3 (1.9)$^{a}_{A}$	4.6 (2.1)$^{a}_{A}$	3.3 (1.5)$^{a}_{A}$	4.8 (2.1)$^{a}_{A}$	2.9 (1.2)$^{a}_{A}$	3.1 (1.0)$^{a}_{A}$
	-18	3.8 (1.5)$^{a}_{A}$	3.5 (1.8)$^{a}_{A}$	4.3 (1.6)$^{a}_{A}$	4.0 (1.6)$^{a}_{A}$	4.8 (1.9)$^{a}_{A}$	3.4 (1.0)$^{a}_{A}$	4.3 (1.0)$^{a}_{A}$	3.5 (1.5)$^{a}_{A}$	3.4 (1.1)$^{a}_{A}$
	-24		4.3 (2.1)$^{ab}_{A}$	3.6 (1.6)$^{a}_{A}$	3.9 (2.2)$^{a}_{A}$	6.0 (2.3)$^{b}_{A}$	3.6 (1.0)$^{a}_{A}$	3.7 (1.2)$^{a}_{A}$	4.5 (1.6)$^{ab}_{A}$	3.8 (1.5)$^{a}_{A}$
Lamb trim 65CL	-12		-	6.3 (1.7)$^{a}_{A}$	7.1 (1.8)$^{a}_{A}$	-	4.3 (0.9)$^{bc}_{A}$	5.6 (1.6)$^{ab}_{A}$	5.3 (1.7)$^{abc}_{A}$	3.5 (1.2)$^{c}_{A}$
	-18	6.0 (2.6)$^{ab}_{A}$	-	5.6 (2.1)$^{ab}_{A}$	7.4 (2.3)$^{a}_{A}$	-	4.5 (1.1)$^{b}_{A}$	4.9 (1.2)$^{b}_{A}$	5.6 (1.7)$^{ab}_{A}$	4.5 (1.6)$^{b}_{A}$
	-24		-	5.2 (2.1)$^{ab}_{A}$	6.8 (2.3)$^{a}_{A}$	-	4.7 (1.5)$^{b}_{A}$	4.9 (1.2)$^{ab}_{A}$	5.4 (1.9)$^{ab}_{A}$	3.9 (1.6)$^{b}_{A}$

N=10; Within a row, means that do not share superscripts significantly differ (P<0.05); Within a column, for a specific sample type, means that do not share subscripts significantly differ (P<0.05).

Table 13. Effect of frozen storage duration and temperature on mean (SD) sensory scores for tenderness/texture of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Storage temp. (°C)	Frozen storage duration (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12		4.1 (1.7)$^{ab}_{A}$	4.5 (1.6)$^{a}_{A}$	4.8 (1.6)$^{a}_{A}$	4.4 (1.7)$^{ab}_{A}$	3.4 (1.3)$^{ab}_{A}$	3.6 (1.2)$^{ab}_{A}$	2.9 (1.8)$^{b}_{A}$	4.0 (1.2)$^{ab}_{A}$
	-18	3.9 (1.4)$^{ab}_{A}$	4.0 (1.6)$^{ab}_{A}$	3.5 (1.7)$^{b}_{A}$	4.3 (1.7)$^{ab}_{A}$	4.3 (1.4)$^{ab}_{A}$	5.0 (1.3)$^{a}_{B}$	4.4 (1.2)$^{ab}_{A}$	5.1 (1.5)$^{a}_{B}$	5.2 (1.3)$^{ab}_{A}$
	-24		4.0 (2.1)$^{a}_{A}$	3.9 (1.4)$^{a}_{A}$	4.7 (1.9)$^{a}_{A}$	5.2 (1.2)$^{a}_{A}$	4.7 (1.3)$^{a}_{AB}$	3.6 (1.3)$^{a}_{A}$	4.0 (1.9)$^{a}_{AB}$	5.0 (1.4)$^{a}_{A}$
Beef trim 95CL	-12		3.8 (2.4)$^{a}_{A}$	4.4 (1.4)$^{ab}_{A}$	4.1 (2.0)$^{ab}_{A}$	5.8 (1.5)$^{b}_{A}$	5.0 (1.2)$^{ab}_{A}$	5.4 (1.3)$^{ab}_{A}$	5.3 (1.7)$^{ab}_{A}$	4.6 (2.0)$^{ab}_{A}$
	-18	4.6 (1.6)$^{a}_{A}$	4.7 (2.5)$^{a}_{A}$	4.8 (1.1)$^{a}_{A}$	5.0 (2.1)$^{a}_{A}$	-	4.8 (0.9)$^{a}_{A}$	5.4 (1.5)$^{a}_{A}$	5.0 (1.4)$^{a}_{A}$	5.4 (1.5)$^{a}_{A}$
	-24		4.6 (2.5)$^{a}_{A}$	4.0 (1.1)$^{a}_{A}$	5.6 (2.1)$^{a}_{A}$	5.2 (1.1)$^{a}_{A}$	4.6 (1.1)$^{a}_{A}$	4.5 (0.5)$^{a}_{A}$	4.0 (1.7)$^{a}_{A}$	4.9 (1.2)$^{a}_{A}$
Beef trim 65CL	-12		-	5.1 (2.3)$^{a}_{A}$	5.0 (1.7)$^{a}_{A}$	-	4.3 (1.3)$^{a}_{A}$	5.0 (0.5)$^{a}_{A}$	5.5 (1.6)$^{a}_{A}$	5.8 (1.6)$^{a}_{A}$
	-18	4.6 (0.5)$^{a}_{A}$	-	5.7 (1.4)$^{a}_{A}$	5.1 (1.3)$^{a}_{A}$	-	4.7 (1.3)$^{a}_{A}$	6.1 (1.5)$^{a}_{AB}$	5.9 (1.7)$^{a}_{A}$	5.2 (1.6)$^{a}_{A}$
	-24		-	5.6 (1.4)$^{ab}_{A}$	5.7 (1.7)$^{ab}_{A}$	-	4.7 (1.8)$^{a}_{A}$	6.5 (1.4)$^{b}_{B}$	4.9 (1.7)$^{ab}_{A}$	5.8 (1.8)$^{ab}_{A}$
Lamb loin	-12		5.3 (1.4)$^{a}_{A}$	4.2 (1.7)$^{ab}_{A}$	4.2 (1.6)$^{ab}_{A}$	4.0 (1.5)$^{ab}_{A}$	4.3 (1.1)$^{ab}_{A}$	3.8 (1.2)$^{ab}_{A}$	4.6 (1.1)$^{ab}_{A}$	3.6 (1.0)$^{b}_{A}$
	-18	5.0 (1.5)$^{a}_{A}$	4.2 (2.3)$^{a}_{AB}$	3.9 (1.5)$^{a}_{A}$	5.1 (2.0)$^{a}_{A}$	4.9 (1.5)$^{a}_{A}$	5.0 (1.4)$^{a}_{A}$	4.8 (1.7)$^{a}_{A}$	4.6 (1.7)$^{a}_{A}$	4.1 (0.9)$^{a}_{A}$
	-24		3.1 (1.4)$^{a}_{B}$	4.5 (1.1)$^{bc}_{A}$	5.8 (1.7)$^{b}_{A}$	5.0 (1.2)$^{bc}_{A}$	5.6 (1.1)$^{b}_{A}$	4.2 (2.0)$^{ab}_{A}$	4.4 (0.5)$^{ab}_{A}$	4.1 (0.9)$^{ac}_{A}$
Lamb trim 90CL	-12		5.6 (2.0)$^{ab}_{A}$	5.8 (1.1)$^{a}_{A}$	4.9 (1.7)$^{ab}_{A}$	5.0 (1.6)$^{ab}_{A}$	4.0 (1.3)$^{b}_{A}$	4.8 (1.9)$^{ab}_{A}$	4.1 (1.5)$^{ab}_{A}$	5.2 (1.5)$^{ab}_{A}$
	-18	5.5 (1.6)$^{a}_{A}$	5.6 (2.2)$^{a}_{A}$	5.5 (1.4)$^{a}_{A}$	4.8 (1.7)$^{a}_{A}$	5.3 (1.3)$^{a}_{A}$	4.1 (1.5)$^{a}_{A}$	5.5 (1.4)$^{a}_{A}$	4.9 (1.1)$^{a}_{A}$	5.2 (1.8)$^{a}_{A}$
	-24		6.2 (2.0)$^{a}_{A}$	5.0 (1.4)$^{ab}_{A}$	5.3 (1.9)$^{ab}_{A}$	5.7 (1.7)$^{ab}_{A}$	4.4 (1.2)$^{b}_{A}$	5.3 (2.2)$^{ab}_{A}$	5.3 (1.7)$^{ab}_{A}$	5.5 (1.3)$^{ab}_{A}$
Lamb trim 65CL	-12		-	7.2 (1.1)$^{a}_{A}$	6.8 (2.1)$^{a}_{A}$	-	5.1 (1.3)$^{b}_{A}$	6.0 (2.1)$^{ab}_{A}$	5.9 (1.5)$^{ab}_{A}$	4.6 (1.3)$^{b}_{A}$
	-18	5.8 (2.5)$^{a}_{A}$	-	6.3 (1.6)$^{a}_{A}$	7.1 (2.2)$^{a}_{A}$	-	5.7 (1.4)$^{a}_{A}$	5.3 (1.5)$^{a}_{A}$	6.1 (1.5)$^{a}_{A}$	5.8 (1.7)$^{a}_{A}$
	-24		-	6.8 (1.6)$^{a}_{A}$	6.4 (2.1)$^{a}_{A}$	-	6.2 (1.7)$^{a}_{A}$	6.1 (1.1)$^{a}_{A}$	6.1 (1.5)$^{a}_{A}$	5.1 (1.7)$^{a}_{A}$

N=10; Within a row, means that do not share superscripts significantly differ (P<0.05); Within a column, for a specific sample type, means that do not share subscripts significantly differ (P<0.05).

There was a decline in mean scores for certain characteristics in lamb trim with storage duration at all storage temperatures (Table 2 to Table 8). Sensory panel scores for meat flavour intensity (Table 4) and fat odour intensity (Table 5) decreased significantly after 28 months for lamb trim, though differences between storage temperatures were not significant. As with the beef, there was more variation in juiciness scores (Table 7) than the other characteristics, but again, in common with the beef, no clear effect of frozen storage temperature. The mean scores for all parameters were acceptable (>4) for at least 28 months of frozen storage and did not become convincingly unacceptable for lamb loin during the entire 38 months of storage. Trim was more affected than the loin cuts, though the higher fat 65CL trim was not always the most adversely affected. As with the beef samples, some of the variations in score at different sampling times are highly likely to be due to variation in the samples selected and drifts in sensory panel perceptions.

Few studies have been published in the last 25 years on the frozen storage of lamb that assessed the effect frozen storage duration or temperature have on final eating quality after cooking, and none on beef as far as we are aware. Studies published by Muela et al. (2010, 2015, 2016) on the frozen storage life of lamb at -18°C were one of the few studies that evaluated the quality of the frozen samples with a trained sensory panel and a consumer panel. There was a significant change in scores (for tenderness, flavour, and overall acceptability) recorded by the untrained sensory panel in frozen lamb between storage periods of 15 and 21 months, but this was not reflected by the trained sensory panel scores which did not show significant differences with frozen storage duration. While the untrained panel noted a drop in quality, they still considered the samples to be of acceptable eating quality after 21 months of frozen storage. Daszkiewicz et al. (2018) observed a decrease in taste intensity in vacuum packaged lamb (*L. thoracis et lumborum*) measured after 6 and 12 months storage at -26°C though no change in other sensory attributes, while Fernandes et al. (2013) observed no changes in sensory attributes of vacuum-packed lamb loin (*L. dorsi*) stored for up to 1 year. None of these studies used commercially frozen bulk boxed meat.

3.2 Physical

Overall, there were no clear trends in colour characteristics (L*, a*, and b* levels) measured on the muscles or fat of the beef or lamb loins with frozen storage duration or temperature (see Supplementary data). Previous studies on long term frozen storage of beef or lamb have also generally observed few changes in colour characteristics. Holman et al. (2017) observed a decrease in lightness (L*), and a rise in redness (a*) during storage in frozen beef. Farouk et al. (2003) reported a decrease in hue angle measured in thawed beef (*M. semitendinosus*) with frozen storage duration. Lightness (L*) and redness (a*) have generally been reported to be stable during frozen storage in lamb (Fernandes et al., 2013; Muela et al., 2015; Daszkiewicz et al., 2018; Pinheiro et al., 2019). Although some studies have reported a decrease in redness (a*) in frozen beef (Farouk et al., 2003) and lamb (Muela et al., 2010; Pinheiro et al., 2019) during storage.

Instrumental texture (Warner–Bratzler shear force [WBSF]) results (see Supplementary data) showed no trend for firmness (shear force) or toughness with storage duration, with the highest mean values being recorded at different storage durations at all storage temperatures in the different meat types. In most cases there was no statistical difference ($P>0.05$) between the firmness or toughness of samples held at -12°C, -18°C, or -24°C. Though there was considerable variation in mean measurements made at different assessment periods (a number of which were statistically significant [$P<0.05$]). This is most likely due to box-to-box variation in the commercially produced meat, particularly differences in the composition of the trim. As noted by Muela et al. (2015), there is conflicting evidence in the literature on the effect of freezing and frozen storage duration on texture (shear force). It has been reported to have no effect (Pinheiro et al., 2019), decrease toughness (Farouk et al., 2003; Lagerstedt et al., 2008; Coombs et al., 2017), or increase toughness (Fernandes et al., 2013; Holman et al., 2017; Muela et al., 2015). This may be due to an effect of differences in initial freezing rates (Wheeler et al., 1990), different ageing prior to freezing (Vieira et al., 2009; Jacob et al., 2010), or how soon after thawing the texture is measured (Pinheiro et al., 2019).

Overall, the results showed no statistical trend for drip/thaw loss to increase with storage duration or any consistent effect of storage temperature on drip/thaw loss (Table 9). In both beef and lamb samples, drip/thaw loss increased with the level of chemical lean. Loins had higher drip/thaw loss than the 65CL trim. This was as expected, since fat has a very low water content compared to lean. Storage temperature also had little effect on drip/thaw losses over the evaluated storage period. In most cases there was no statistical difference (P>0.05) between mean drip/thaw losses of samples held at different temperatures. There is conflicting evidence on the effect of frozen storage duration on drip/thaw loss from frozen meat (James and James, 2012). Some recent studies have observed no change in drip/thaw loss during long term frozen storage of beef (Holman et al., 2017) or lamb (Coombs et al., 2017; Daszkiewicz et al., 2018); while others have observed an increase in drip/thaw loss in beef (Farouk et al.,2003; Gonza et al., 2023) and lamb (Pinheiro et al., 2019; Muela et al., 2015) stored at -18°C over time. Qian et al. (2021) observed no difference in drip from beef stored at either -12°C or -18°C for 6 months. There is some evidence that initial freezing rate may affect drip (James and James, 2012), but in industrial practice freezing rates in boxed meat are slow and there will be considerable variation in the rate of freezing within a block of meat. It is likely that any changes in the structure of this slow frozen meat during frozen storage will have less effect on drip than in small pieces of "fast" frozen meat as would typically be seen in small scale laboratory studies.

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Table 14. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) drip/thaw loss (%) from commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Temp (°C)	Frozen storage duration (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12		7.3 (1.2)$^{ab}_{A}$	9.3 (1.3)$^{ac}_{A}$	5.6 (1.5)$^{b}_{A}$	13.6 (2.1)$^{d}_{A}$	10.6 (2.7)$^{c}_{A}$	8.7 (2.5)$^{ac}_{A}$	7.2 (1.5)$^{ab}_{A}$	9.4 (0.8)$^{ac}_{AB}$
	-18	7.3 (1.3)^{a}	11.3 (2.2)$^{b}_{B}$	9.0 (0.6)$^{a}_{A}$	11.1 (2.3)$^{ab}_{B}$	13.7 (1.8)$^{b}_{A}$	9.0 (1.0)$^{a}_{A}$	9.7 (2.5)$^{ab}_{A}$	10.6 (1.6)$^{ab}_{B}$	8.1 (1.8)$^{a}_{A}$
	-24		9.5 (0.9)$^{ad}_{AB}$	12.0 (1.7)$^{bcd}_{B}$	14.3 (1.6)$^{c}_{C}$	11.8 (2.9)$^{bd}_{A}$	9.3 (1.3)$^{a}_{A}$	11.5 (1.0)$^{abd}_{A}$	10.0 (1.4)$^{abd}_{B}$	10.5 (1.0)$^{abd}_{B}$
Beef trim 95CL	-12		12.0 (2.0)$^{ab}_{A}$	12.5 (5.4)$^{ab}_{A}$	14.4 (2.5)$^{b}_{A}$	11.2 (6.0)$^{ab}_{A}$	8.2 (3.2)$^{ac}_{A}$	5.8 (2.2)$^{cd}_{A}$	4.7 (4.0)$^{c}_{A}$	10.9 (2.0)$^{ad}_{A}$
	-18	5.5 (0.9)^{a}	14.5 (2.5)$^{b}_{A}$	11.9 (1.6)$^{bc}_{A}$	7.0 (3.2)$^{a}_{B}$	13.9 (2.0)$^{b}_{A}$	5.7 (3.5)$^{a}_{A}$	7.5 (1.9)$^{a}_{A}$	8.7 (2.8)$^{ac}_{AB}$	6.6 (2.3)$^{a}_{B}$
	-24		14.4 (2.2)$^{a}_{A}$	12.2 (2.5)$^{ab}_{A}$	6.3 (4.3)$^{cde}_{B}$	9.0 (2.5)$^{bcde}_{A}$	5.9 (2.2)$^{ce}_{A}$	10.8 (7.1)$^{ade}_{A}$	13.0 (2.4)$^{ad}_{B}$	6.3 (1.9)$^{e}_{B}$
Beef trim 65CL	-12		3.2 (0.3)$^{a}_{A}$	1.8 (0.8)$^{a}_{A}$	3.6 (0.8)$^{a}_{A}$	2.6 (1.5)$^{a}_{A}$	2.9 (3.6)$^{a}_{A}$	7.7 (4.0)$^{b}_{A}$	5.3 (3.7)$^{a}_{A}$	2.2 (2.2)$^{a}_{A}$
	-18	2.2 (1.4)^{a}	4.3 (2.4)$^{ab}_{A}$	1.9 (1.1)$^{a}_{A}$	4.4 (1.0)$^{ab}_{A}$	3.0 (2.5)$^{ab}_{A}$	5.4 (4.0)$^{b}_{A}$	5.1 (2.0)$^{ab}_{AB}$	5.1 (1.8)$^{ab}_{A}$	2.5 (1.8)$^{ab}_{A}$
	-24		3.8 (2.2)$^{ab}_{A}$	1.6 (1.0)$^{a}_{A}$	3.8 (1.6)$^{ab}_{A}$	3.4 (1.8)$^{a}_{A}$	4.4 (2.5)$^{b}_{A}$	2.4 (1.3)$^{ab}_{B}$	8.5 (1.8)$^{c}_{A}$	1.3 (1.2)$^{a}_{A}$
Lamb loin	-12		5.8 (1.5)$^{ab}_{A}$	9.0 (4.0)$^{b}_{A}$	5.7 (2.1)$^{ab}_{A}$	6.5 (1.4)$^{ab}_{A}$	5.5 (1.8)$^{a}_{A}$	7.9 (2.9)$^{b}_{A}$	5.3 (2.9)$^{ab}_{A}$	4.0 (1.0)$^{a}_{A}$
	-18	4.7(1.4)^{a}	7.3 (1.2)$^{ab}_{AB}$	7.5 (1.5)$^{ab}_{A}$	6.3 (2.6)$^{ab}_{A}$	8.4 (3.2)$^{b}_{A}$	5.2 (1.8)$^{a}_{A}$	6.4 (2.0)$^{ab}_{A}$	6.3 (2.2)$^{ab}_{A}$	5.0 (1.4)$^{a}_{A}$
	-24		8.5 (0.8)$^{a}_{B}$	8.6 (2.6)$^{a}_{A}$	5.6 (4.7)$^{a}_{A}$	6.7 (2.2)$^{a}_{A}$	6.4 (1.8)$^{a}_{A}$	6.9 (1.6)$^{a}_{A}$	7.6 (2.3)$^{a}_{A}$	7.1 (1.1)$^{a}_{B}$
Lamb trim 90CL	-12		9.1 (1.9)$^{abc}_{A}$	10.9 (2.7)$^{abc}_{A}$	13.6 (3.0)$^{a}_{A}$	8.0 (2.6)$^{b}_{A}$	10.3 (5.3)$^{ac}_{A}$	8.8 (1.9)$^{a}_{A}$	8.4 (4.2)$^{bc}_{A}$	7.6 (3.8)$^{bc}_{A}$
	-18	10.4 (2.9)^{ab}	7.4 (3.6)$^{a}_{A}$	13.7 (3.9)$^{bc}_{A}$	13.7 (5.3)$^{bc}_{A}$	18.0 (2.4)$^{b}_{B}$	9.1 (3.1)$^{ac}_{A}$	15.6 (4.7)$^{b}_{B}$	14.1 (3.6)$^{bc}_{B}$	12.4 (4.8)$^{abc}_{A}$
	-24		8.2 (4.1)$^{ab}_{A}$	8.2 (3.8)$^{ab}_{A}$	10.3 (4.7)$^{ab}_{A}$	7.6 (3.3)$^{a}_{A}$	9.9 (1.9)$^{ab}_{A}$	11.1 (4.5)$^{ab}_{AB}$	13.0 (2.1)$^{b}_{AB}$	10.3 (1.1)$^{ab}_{A}$
Lamb trim 65CL	-12		2.2 (0.9)$^{a}_{A}$	5.5 (3.5)$^{b}_{AB}$	3.0 (0.9)$^{a}_{A}$	1.5 (0.8)$^{a}_{A}$	1.8 (2.2)$^{a}_{A}$	1.5 (1.1)$^{a}_{A}$	1.4 (1.7)$^{a}_{A}$	1.5 (0.9)$^{a}_{A}$
	-18	1.7 (1.4)^{a}	2.7 (1.6)$^{a}_{A}$	8.2 (1.8)$^{b}_{A}$	1.5 (0.4)$^{a}_{B}$	1.8 (0.9)$^{a}_{A}$	2.8 (1.6)$^{a}_{A}$	6.1 (3.7)$^{b}_{A}$	2.5 (1.1)$^{a}_{AB}$	3.5 (3.1)$^{a}_{A}$
	-24		6.5 (2.4)$^{a}_{B}$	3.0 (2.2)$^{b}_{B}$	1.5 (0.9)$^{b}_{B}$	1.4 (1.6)$^{b}_{A}$	2.4 (2.8)$^{b}_{A}$	5.3 (4.0)$^{a}_{A}$	3.6 (0.8)$^{ab}_{B}$	2.4 (1.2)$^{b}_{A}$

N=5; Within a row, means that do not share superscripts significantly differ ($P<0.05$); Within a column, for a specific sample type, means that do not share subscripts significantly differ ($P<0.05$).

3.3 Chemical

Lipid oxidation was assessed by measuring peroxide value (PV) as indicative of primary lipid oxidation; and thiobarbituric acid reactive substances (TBARS) as a measure of secondary lipid oxidation products (aldehydes, ketones, alcohols, others) represented by malondialdehyde [MDA] (Domínguez et al., 2019). It should be noted that while peroxides indicate the start of lipid oxidation, unlike TBARS, peroxides are tasteless and odourless compounds, thus TBARS better suit comparisons to the sensory assessment and consumer thresholds (Holman et al., 2018a).

The beef and lamb results (Table 10) showed very clear relationships in PVs and fat content (CL), storage temperature, duration, and method of packing (whether vacuum-packed or over-wrapped). Low PVs were observed in the beef loins throughout the storage period with no significant differences (P>0.05) between samples stored at different temperatures, except for a spike measured in beef loins stored at -12°C, where PV peaked at 24 months then decreased (Figure 1). PVs in 95CL beef trim followed a similar trend to beef loins however, a spike in the -12°C trim was observed at 28 months rather than at 24 months. 65CL beef trim showed a similar trend of no considerable changes up to 21 months, after which there was a progressive increase (Figure 2). Although all beef samples stored at the three temperatures showed a rise in PVs after 21 months, samples stored at -18°C and -24°C (with some exceptions) were the most stable throughout the whole storage period.

All beef and the lamb loin samples were vacuum-packed, whereas the lamb trim was simply over-wrapped. PVs in the lamb loin were initially similar, though slightly higher, to those measured in the beef loin, but showed an increase with storage duration and an effect of storage temperature, particularly in the loin stored at -12°C (Figure 1). PVs were much higher in loin stored at -12°C at 21 months and for the remaining storage period. The lamb trim samples showed clear signs of oxidation earlier than the other samples, a clear rise with storage duration, and a clear effect of storage temperature. There was a clear effect of storage temperature, with the lowest mean PVs being consistently measured in the samples stored at -24°C and the highest PVs in the trim stored at -12°C. Mean PVs of 65CL lamb trim stored at -12°C were at a level of 2.62 meq kg^{-1} at 6 months showing a further significant (P<0.05) increase up to 24 months and then significantly decreased over the rest of the storage period (Figure 2). Recent studies on beef (Holman, et al., 2018a) and lamb (Coombs et al., 2018a) also found an increase in PV over 12 months of storage but neither study found any significant effect of storage temperature.

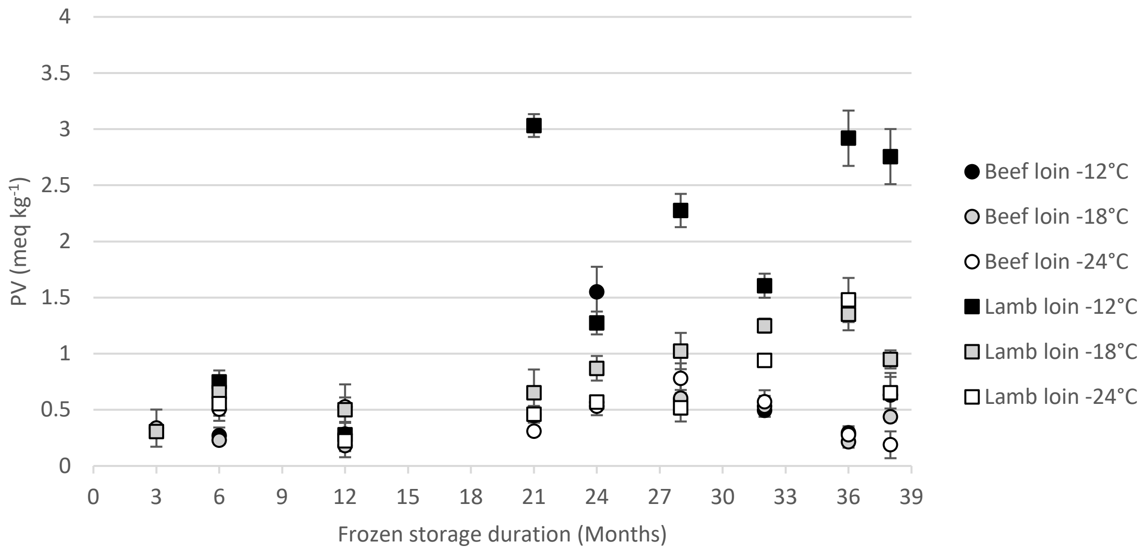

Figure 8. Effect of frozen storage duration and temperature on mean PV (Milliequivalent/kg of fat) of commercially produced frozen boxed beef and lamb loin (Vertical bars: ±1SD).

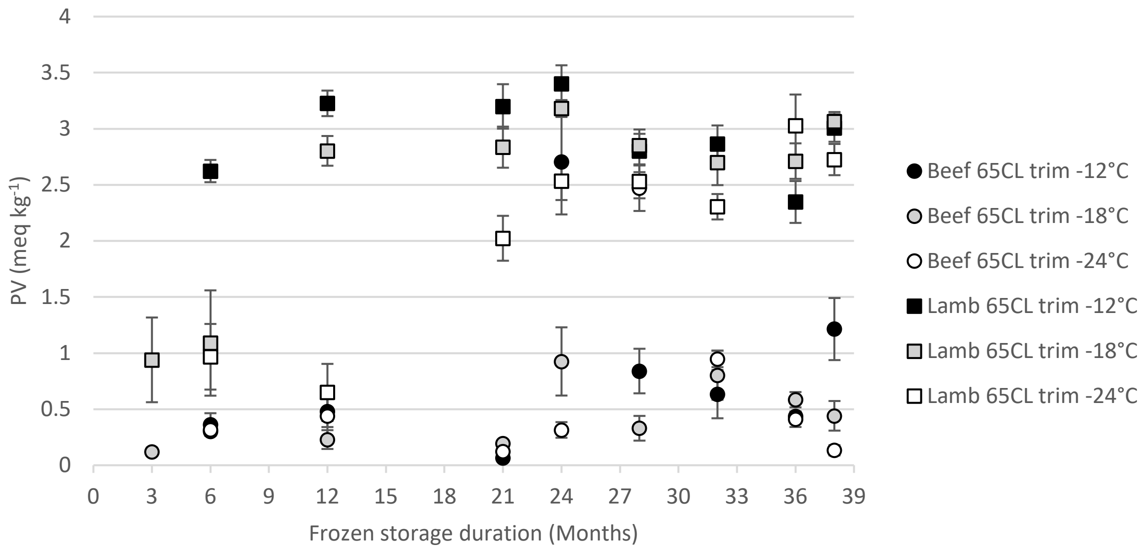

Figure 9. Effect of frozen storage duration and temperature on mean PV (Milliequivalent/kg of fat) of commercially produced frozen boxed beef and lamb 65CL trim (Vertical bars: ±1SD).

Table 15. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) Peroxide value (PV) (meq kg^{-1}) of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Temp (°C)	Frozen storage duration (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12		0.27 (0.07)$^{a}_{A}$	0.28 (0.21)$^{a}_{A}$	0.46 (0.05)$^{b}_{A}$	1.55 (0.22)$^{c}_{A}$	0.59 (0.09)$^{bd}_{A}$	0.50 (0.06)$^{be}_{A}$	0.30 (0.06)$^{a}_{A}$	0.63 (0.20)$^{de}_{A}$
	-18	0.34 (0.17)^{a}	0.23 (0.04)$^{b}_{A}$	0.18 (0.05)$^{b}_{A}$	0.45 (0.06)$^{c}_{A}$	0.57 (0.04)$^{d}_{B}$	0.60 (0.15)$^{d}_{A}$	0.53 (0.09)$^{cd}_{A}$	0.22 (0.05)$^{b}_{B}$	0.44 (0.04)$^{c}_{B}$
	-24		0.51 (0.11)$^{a}_{B}$	0.53 (0.20)$^{a}_{B}$	0.31 (0.04)$^{b}_{B}$	0.53 (0.08)$^{a}_{B}$	0.78 (0.13)$^{c}_{B}$	0.57 (0.10)$^{a}_{A}$	0.28 (0.06)$^{b}_{AB}$	0.19 (0.12)$^{b}_{C}$
Beef trim 95CL	-12		0.55 (0.07)$^{a}_{AB}$	0.19 (0.09)$^{b}_{A}$	0.90 (0.23)$^{c}_{AC}$	0.69 (0.09)$^{a}_{AC}$	2.68 (0.33)$^{d}_{A}$	0.62 (0.11)$^{a}_{A}$	0.21 (0.02)$^{b}_{A}$	1.96 (0.26)$^{e}_{A}$
	-18	0.17 (0.03)^{a}	0.63 (0.09)$^{b}_{B}$	0.63 (0.38)$^{b}_{BC}$	0.47 (0.13)$^{b}_{B}$	1.03 (0.24)$^{c}_{B}$	0.43 (0.10)$^{ab}_{BC}$	0.61 (0.29)$^{b}_{A}$	0.20 (0.05)$^{a}_{A}$	1.13 (0.36)$^{c}_{BC}$
	-24		0.29 (0.02)$^{ad}_{C}$	0.51 (0.14)$^{b}_{C}$	0.97 (0.43)$^{c}_{C}$	0.43 (0.10)$^{bd}_{C}$	0.51 (0.08)$^{b}_{C}$	0.51 (0.07)$^{b}_{A}$	0.22 (0.03)$^{a}_{A}$	1.48 (0.32)$^{e}_{C}$
Beef trim 65CL	-12		0.36 (0.10)$^{a}_{A}$	0.48 (0.14)$^{a}_{A}$	0.06 (0.03)$^{b}_{A}$	2.71 (0.47)$^{c}_{A}$	0.84 (0.20)$^{d}_{A}$	0.63 (0.21)$^{ad}_{A}$	0.44 (0.04)$^{ae}_{A}$	1.21 (0.28)$^{f}_{A}$
	-18	0.12 (0.04)^{a}	0.30 (0.02)$^{b}_{A}$	0.23 (0.08)$^{ab}_{B}$	0.19 (0.03)$^{ab}_{B}$	0.93 (0.30)$^{c}_{B}$	0.33 (0.11)$^{bd}_{B}$	0.80 (0.22)$^{c}_{AB}$	0.58 (0.07)$^{d}_{B}$	0.44 (0.13)$^{de}_{B}$
	-24		0.32 (0.04)$^{ab}_{A}$	0.44 (0.24)$^{a}_{AC}$	0.12 (0.04)$^{c}_{C}$	0.31 (0.07)$^{b}_{C}$	2.47 (0.20)$^{d}_{C}$	0.95 (0.07)$^{e}_{B}$	0.41 (0.07)$^{ab}_{AC}$	0.13 (0.05)$^{c}_{C}$
Lamb loin	-12		0.75 (0.10)$^{a}_{A}$	0.28 (0.11)$^{b}_{A}$	3.03 (0.10)$^{c}_{A}$	1.27 (0.10)$^{d}_{A}$	2.28 (0.15)$^{e}_{A}$	1.61 (0.11)$^{f}_{A}$	2.92 (0.25)$^{c}_{A}$	2.76 (0.25)$^{g}_{A}$
	-18	0.31 (0.03)^{a}	0.66 (0.12)$^{b}_{AB}$	0.50 (0.11)$^{c}_{B}$	0.65 (0.21)$^{b}_{B}$	0.87 (0.11)$^{d}_{B}$	1.02 (0.16)$^{e}_{B}$	1.25 (0.06)$^{f}_{B}$	1.35 (0.14)$^{f}_{B}$	0.95 (0.08)$^{de}_{B}$
	-24		0.56 (0.11)$^{acd}_{B}$	0.22 (0.09)$^{b}_{AC}$	0.46 (0.07)$^{c}_{C}$	0.57 (0.05)$^{acd}_{C}$	0.52 (0.12)$^{ac}_{C}$	0.94 (0.05)$^{e}_{C}$	1.48 (0.20)$^{f}_{B}$	0.65 (0.14)$^{d}_{C}$
Lamb trim 90CL	-12		1.22 (0.43)$^{a}_{A}$	3.07 (0.14)$^{b}_{A}$	1.96 (0.18)$^{c}_{A}$	2.55 (0.29)$^{d}_{A}$	2.83 (0.19)$^{b}_{A}$	2.48 (0.09)$^{de}_{A}$	2.96 (0.18)$^{b}_{A}$	2.51 (0.20)$^{de}_{A}$
	-18	0.97 (0.03)^{a}	1.15 (0.07)$^{b}_{AB}$	1.80 (0.23)$^{c}_{B}$	2.10 (0.09)$^{d}_{A}$	2.47 (0.13)$^{e}_{A}$	2.97 (0.19)$^{c}_{A}$	1.85 (0.10)$^{f}_{AB}$	2.32 (0.08)$^{g}_{B}$	2.26 (0.14)$^{g}_{B}$
	-24		1.24 (0.16)$^{a}_{B}$	0.33 (0.14)$^{b}_{C}$	1.37 (0.13)$^{a}_{B}$	1.76 (0.15)$^{c}_{B}$	1.77 (0.14)$^{c}_{B}$	1.78 (0.03)$^{c}_{B}$	1.54 (0.13)$^{d}_{C}$	1.95 (0.10)$^{e}_{C}$
Lamb trim 65CL	-12		2.62 (0.10)$^{a}_{A}$	3.23 (0.11)$^{b}_{A}$	3.20 (0.20)$^{bc}_{A}$	3.40 (0.17)$^{b}_{A}$	2.80 (0.19)$^{ad}_{A}$	2.87 (0.16)$^{d}_{A}$	2.35 (0.19)$^{e}_{A}$	3.01 (0.12)$^{cd}_{A}$
	-18	0.94 (0.38)^{a}	1.09 (0.47)$^{a}_{B}$	2.80 (0.13)$^{b}_{B}$	2.84 (0.18)$^{bc}_{B}$	3.18 (0.08)$^{d}_{B}$	2.85 (0.10)$^{bc}_{AB}$	2.70 (0.20)$^{b}_{A}$	2.71 (0.16)$^{b}_{B}$	3.06 (0.08)$^{cd}_{AB}$
	-24		0.97 (0.29)$^{a}_{B}$	0.65 (0.25)$^{b}_{C}$	2.02 (0.20)$^{c}_{C}$	2.53 (0.17)$^{de}_{C}$	2.53 (0.15)$^{de}_{B}$	2.30 (0.11)$^{d}_{B}$	3.03 (0.28)$^{f}_{C}$	2.73 (0.14)$^{e}_{B}$

N=9; Within a row, means that do not share superscripts significantly differ ($P<0.05$); Within a column, for a specific sample type, means that do not share subscripts significantly differ ($P<0.05$).

Table 16. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) TBARS (mg malondialdehyde (MDA) kg^{-1}) of commercially produced frozen boxed beef/lamb loin and trim stored for up to 38 months.

Sample	Temp	Frozen storage duration (Months)								
	(°C)	3	6	12	21	24	28	32	36	38
Beef loin	-12		0.06 (0.00)$^{a}_{AB}$	0.08 (0.00)$^{b}_{A}$	0.07 (0.00)$^{c}_{A}$	0.10 (0.00)$^{d}_{A}$	0.09 (0.02)$^{d}_{A}$	0.09 (0.01)$^{bd}_{A}$	0.06 (0.01)$^{ac}_{A}$	0.09 (0.02)$^{d}_{AB}$
	-18	0.07 (0.00)^{a}	0.06 (0.01)$^{b}_{A}$	0.05 (0.00)$^{c}_{B}$	0.07 (0.00)$^{a}_{A}$	0.06 (0.00)$^{ab}_{B}$	0.08 (0.01)$^{de}_{A}$	0.08 (0.00)$^{d}_{A}$	0.08 (0.01)$^{e}_{B}$	0.09 (0.01)$^{d}_{A}$
	-24		0.05 (0.00)$^{ab}_{B}$	0.05 (0.00)$^{a}_{B}$	0.06 (0.00)$^{b}_{B}$	0.07 (0.00)$^{c}_{C}$	0.08 (0.01)$^{d}_{A}$	0.09 (0.01)$^{e}_{A}$	0.08 (0.01)$^{d}_{B}$	0.10 (0.01)$^{f}_{B}$
Beef trim 95CL	-12		0.06 (0.00)$^{a}_{A}$	0.06 (0.00)$^{ab}_{A}$	0.07 (0.01)$^{ab}_{A}$	0.09 (0.00)$^{c}_{A}$	0.07 (0.00)$^{ab}_{A}$	0.07 (0.03)$^{ab}_{A}$	0.07 (0.00)$^{bc}_{A}$	0.11 (0.04)$^{d}_{A}$
	-18	0.04 (0.00)^{a}	0.05 (0.00)$^{ade}_{B}$	0.05 (0.00)$^{abeg}_{B}$	0.06 (0.00)$^{cdehi}_{B}$	0.08 (0.01)$^{f}_{B}$	0.08 (0.03)$^{f}_{A}$	0.04 (0.01)$^{ag}_{B}$	0.08 (0.03)$^{fhi}_{A}$	0.06 (0.01)$^{bcde}_{B}$
	-24		0.04 (0.00)$^{a}_{C}$	0.05 (0.01)$^{b}_{B}$	0.06 (0.01)$^{b}_{B}$	0.06 (0.00)$^{b}_{C}$	0.08 (0.02)$^{c}_{A}$	0.03 (0.00)$^{d}_{B}$	0.08 (0.02)$^{c}_{A}$	0.04 (0.00)$^{a}_{B}$
Beef trim 65CL	-12		0.04 (0.00)$^{a}_{A}$	0.10 (0.02)$^{b}_{A}$	0.10 (0.00)$^{b}_{A}$	0.11 (0.03)$^{b}_{A}$	0.12 (0.02)$^{bc}_{A}$	0.20 (0.03)$^{d}_{A}$	0.07 (0.01)$^{e}_{A}$	0.17 (0.02)$^{f}_{A}$
	-18	0.08 (0.01)^{acd}	0.04 (0.00)$^{b}_{A}$	0.08 (0.00)$^{acd}_{B}$	0.07 (0.00)$^{ac}_{B}$	0.10 (0.01)$^{e}_{A}$	0.12 (0.01)$^{f}_{A}$	0.17 (0.03)$^{g}_{A}$	0.08 (0.01)$^{c}_{B}$	0.09 (0.01)$^{de}_{B}$
	-24		0.08 (0.01)$^{a}_{B}$	0.07 (0.01)$^{ab}_{C}$	0.06 (0.01)$^{b}_{C}$	0.10 (0.00)$^{c}_{A}$	0.10 (0.01)$^{c}_{B}$	0.18 (0.02)$^{d}_{A}$	0.04 (0.00)$^{e}_{C}$	0.07 (0.01)$^{ab}_{C}$
Lamb loin	-12		0.04 (0.00)$^{a}_{A}$	0.11 (0.00)$^{b}_{A}$	0.16 (0.00)$^{c}_{A}$	0.08 (0.00)$^{d}_{A}$	0.13 (0.00)$^{e}_{A}$	0.13 (0.01)$^{e}_{A}$	0.10 (0.02)$^{b}_{A}$	0.39 (0.03)$^{f}_{A}$
	-18	0.07 (0.00)^{a}	0.05 (0.00)$^{b}_{AB}$	0.05 (0.00)$^{b}_{B}$	0.13 (0.00)$^{c}_{B}$	0.09 (0.00)$^{d}_{B}$	0.16 (0.01)$^{e}_{B}$	0.12 (0.01)$^{f}_{B}$	0.09 (0.01)$^{d}_{A}$	0.18 (0.02)$^{g}_{B}$
	-24		0.05 (0.00)$^{a}_{B}$	0.07 (0.01)$^{b}_{C}$	0.15 (0.00)$^{c}_{C}$	0.09 (0.00)$^{d}_{B}$	0.09 (0.00)$^{d}_{C}$	0.09 (0.00)$^{d}_{C}$	0.14 (0.02)$^{e}_{B}$	0.13 (0.01)$^{e}_{C}$
Lamb trim 90CL	-12		0.05 (0.00)$^{a}_{A}$	0.27 (0.02)$^{b}_{A}$	0.64 (0.09)$^{c}_{A}$	0.23 (0.02)$^{b}_{A}$	0.87 (0.06)$^{d}_{A}$	0.44 (0.03)$^{e}_{A}$	0.17 (0.03)$^{f}_{A}$	0.13 (0.02)$^{f}_{A}$
	-18	0.15 (0.00)^{a}	0.05 (0.00)$^{b}_{A}$	0.25 (0.01)$^{c}_{B}$	0.38 (0.02)$^{d}_{B}$	0.20 (0.01)$^{e}_{B}$	0.36 (0.01)$^{f}_{B}$	0.29 (0.01)$^{g}_{B}$	0.21 (0.01)$^{h}_{B}$	0.10 (0.00)$^{i}_{B}$
	-24		0.04 (0.01)$^{a}_{B}$	0.12 (0.01)$^{b}_{C}$	0.12 (0.01)$^{b}_{C}$	0.14 (0.00)$^{c}_{C}$	0.21 (0.01)$^{d}_{C}$	0.20 (0.01)$^{d}_{C}$	0.15 (0.01)$^{c}_{C}$	0.11 (0.01)$^{e}_{B}$
Lamb trim 65CL	-12		0.12 (0.01)$^{a}_{A}$	0.91 (0.06)$^{b}_{A}$	0.94 (0.08)$^{b}_{A}$	0.51 (0.03)$^{c}_{A}$	0.56 (0.04)$^{d}_{A}$	0.44 (0.05)$^{e}_{A}$	0.28 (0.05)$^{f}_{A}$	0.56 (0.02)$^{d}_{A}$
	-18	0.18 (0.01)^{a}	0.07 (0.00)$^{b}_{B}$	0.26 (0.02)$^{c}_{B}$	1.22 (0.02)$^{d}_{B}$	0.62 (0.05)$^{e}_{B}$	0.40 (0.03)$^{f}_{B}$	0.45 (0.02)$^{gh}_{A}$	0.48 (0.03)$^{h}_{B}$	0.43 (0.05)$^{fg}_{B}$
	-24		0.06 (0.00)$^{a}_{C}$	0.13 (0.01)$^{b}_{C}$	0.24 (0.02)$^{c}_{C}$	0.28 (0.01)$^{d}_{C}$	0.26 (0.01)$^{c}_{C}$	0.36 (0.04)$^{e}_{B}$	0.35 (0.01)$^{e}_{C}$	0.22 (0.01)$^{f}_{C}$

N=9; Within a row, means that do not share superscripts significantly differ (P<0.05); Within a column, for a specific sample type, means that do not share subscripts significantly differ (P<0.05).

As in many other studies, a general rise in TBARS was observed in all meat samples over the storage period (Table 11), with that rise being higher in the lamb samples than the beef samples (Figure 3 and Figure 4), especially in the lamb trim (Figure 4). TBARS were generally higher in samples with a higher fat content (lower CL). TBARS were also generally lower in meat stored at -24°C than in meat stored at -12°C or -18°C. The highest TBARS were in meat stored at -12°C, which also showed the greatest rise. TBARS in the vacuum-packed lamb loins were much lower than in the over-wrapped lamb trim. TBARS measured in some samples, particularly the 65CL lamb trim held at -12°C, showed an increase in TBARS over time (sample dependent) followed by a decrease after which TBARS remained constant. As noted by Coombs et al. (2018a), TBARS have been observed to decrease or stabilise when storage periods exceed 6 months in some cases, though they did not observe this in lamb stored for up to a year. A decrease in TBARS was attributed by Ozen et al. (2011) to be due to the reaction rate of carbonyls with proteins through cross-linking being greater than the rate of TBARS formation. The decrease observed in TBARS over storage duration could also be due the formation of tertiary oxidation products, such as organic acids and alcohols, not determined by TBARS.

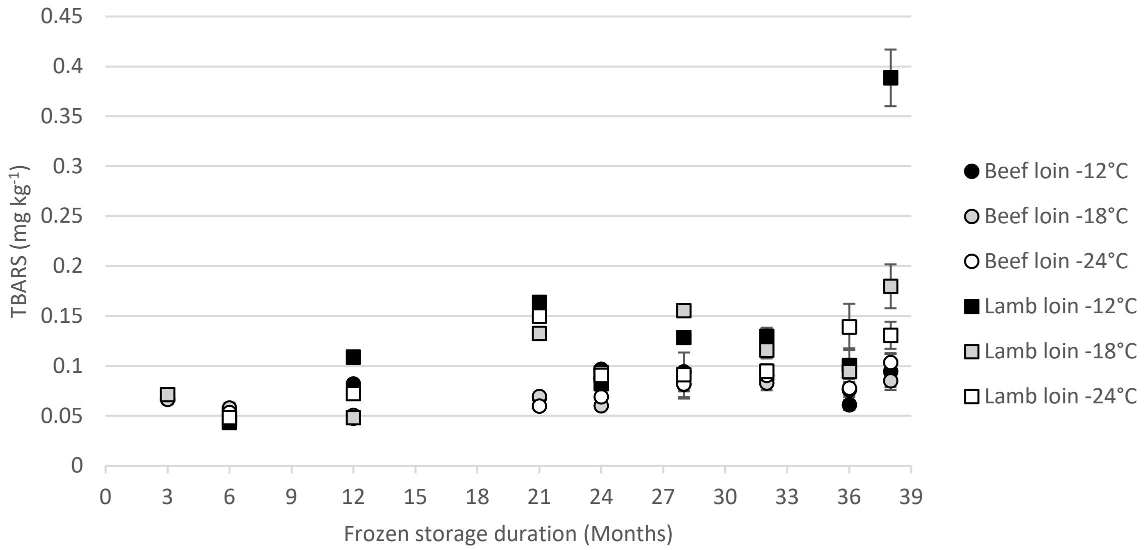

Figure 10. Effect of frozen storage duration and temperature on mean TBARS (mg MDA kg^{-1}) of commercially produced frozen boxed beef and lamb loin (Vertical bars: ±1SD).

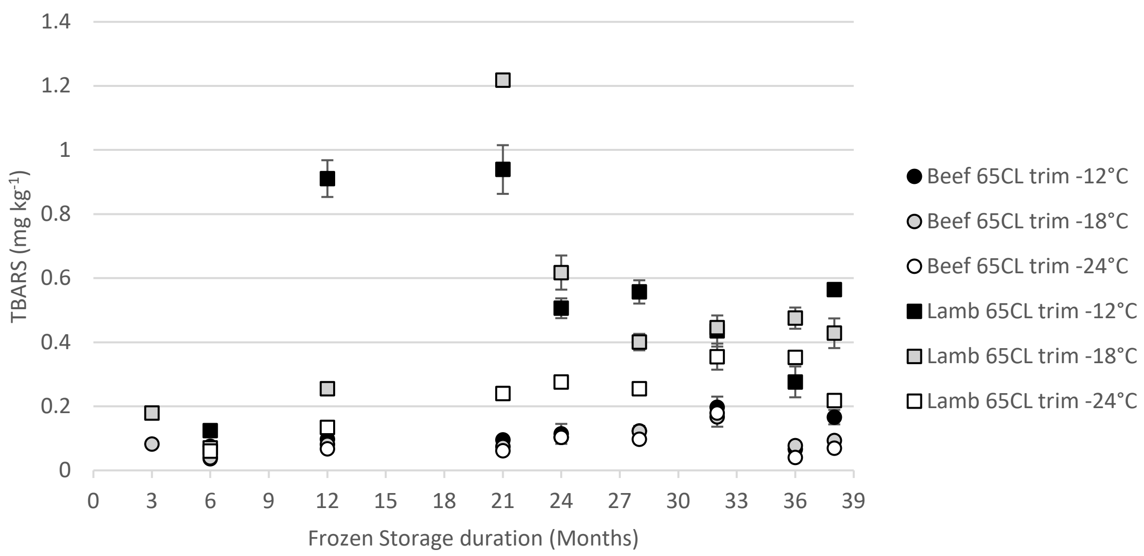

Figure 11. Effect of frozen storage duration and temperature on mean TBARS (mg MDA kg^{-1}) of commercially produced frozen boxed beef and lamb trim (Vertical bars: ±1SD).

There appears to be no clear agreement in the published literature on the threshold for TBARS values at which consumers may begin to detect a rancid off-flavour in beef and lamb. Campo et al. (2006) reported TBARS in beef to be a good predictor of the perception of rancidity by sensory panels and suggested a threshold of 2.0 mg MDA kg^{-1}. Other researchers (Igene et al., 1979; Ripoll et al., 2011; McKenna et al., 2005) have used a lower 'arbitrary' TBARS threshold of 1.0 mg MDA kg^{-1}. Except for 65CL lamb trim at 21 months (1.2 mg MDA kg^{-1}), TBARS measured in our study were below the lowest threshold where rancidity would be likely to be detected by sensory analysis.

Other studies have observed an increase in TBARS in frozen meat during storage. TBARS in beef increased over 12 months frozen storage (Holman, et al., 2018a) but did not exceed the threshold of Campo et al. (2006). In studies of frozen lamb stored at -18°C an increase in TBARS was observed over a 12-month period, but again never exceeded the threshold of Campo et al. (2006) (Coombs et al., 2018a, Muela et al., 2016, Fernandes, et al., 2013). Neither of these studies observed an effect of storage temperature (-12°C or -18°C)

3.4 Microbiological

The overall microbial quality of all of the meat, in terms of ACC, was found to be acceptable., There was no consistent effect of frozen storage temperature on microbial counts (ACC) (Table 12), confirming that the -12°C storage temperature used in this study was sufficient to prevent the growth of bacteria and that any transient temperature rise or fluctuation during the regular defrosts at this temperature (as is standard practice in frozen storage) had no impact on microbial quality or safety.

Microbial analysis to quantify *E. coli* and detect the presence of *Salmonella* spp. in the samples was performed at 24 months. In 14 of18 sample groups (meat type x storage temperature) all 5 samples were found to contain <100 *E. coli*/g and in only 1 of18 did the average of 5 samples exceed 100/g. No *Salmonella* was detected in the samples.

The results obtained in this study were consistent with those obtained in Australian national surveys of beef and lamb microbiological quality (Phillips et al., 2012, Phillips et al., 2013).

Table 172. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) aerobic colony counts (ACC; log_{10} CFU g^{-1}) of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months) 3	6	12	21	24	28	32	36	38
Beef loin	-12		$3.43 (0.19)^{ab}_{AB}$	$3.03 (0.11)^{cd}_{A}$	$1.75 (0.26)^{e}_{A}$	$2.15 (0.27)^{ef}_{A}$	$2.80 (0.55)^{acf}_{A}$	$2.69 (0.91)^{cf}_{AB}$	$3.56 (0.10)^{bd}_{A}$	$2.49 (0.42)^{cf}_{A}$
	-18	$2.12 (0.62)^{ab}$	$3.89 (0.14)^{c}_{A}$	$2.70 (0.28)^{d}_{A}$	$1.70 (0.00)^{a}_{A}$	$1.77 (0.10)^{ae}_{A}$	$2.34 (0.53)^{bd}_{A}$	$3.28 (0.17)^{f}_{A}$	$3.55 (0.05)^{c}_{A}$	$2.26 (0.56)^{bef}_{A}$
	-24		$3.12 (0.79)^{a}_{B}$	$2.73 (0.25)^{ab}_{A}$	$1.89 (0.26)^{c}_{A}$	$1.98 (0.32)^{c}_{A}$	$2.22 (0.73)^{bc}_{A}$	$1.88 (0.27)^{c}_{B}$	$2.93 (0.26)^{a}_{B}$	$2.50 (0.26)^{ac}_{A}$
Beef trim 95CL	-12		$2.85 (0.30)^{a}_{A}$	$2.64 (0.13)^{a}_{A}$	$1.95 (0.36)^{b}_{A}$	$1.99 (0.11)^{bc}_{A}$	$2.61 (0.71)^{a}_{A}$	$1.76 (0.13)^{b}_{A}$	$3.79 (0.15)^{d}_{A}$	$2.42 (0.18)^{ac}_{A}$
	-18	$2.56 (0.32)^{ab}$	$2.96 (0.16)^{a}_{A}$	$2.66 (0.05)^{a}_{B}$	$1.82 (0.27)^{c}_{A}$	$1.85 (0.33)^{c}_{A}$	$2.05 (0.47)^{c}_{A}$	$2.18 (0.34)^{bc}_{B}$	$4.11 (0.08)^{d}_{A}$	$3.69 (0.35)^{d}_{B}$
	-24		$2.43 (0.26)^{a}_{B}$	$3.01 (0.13)^{bc}_{AB}$	$1.76 (0.13)^{d}_{A}$	$2.54 (0.49)^{ab}_{B}$	$1.88 (0.27)^{d}_{A}$	$1.76 (0.13)^{d}_{A}$	$3.07 (0.63)^{c}_{B}$	$4.01 (0.31)^{e}_{B}$
Beef trim 65CL	-12		$3.91 (0.13)^{a}_{A}$	$2.60 (0.14)^{b}_{A}$	$1.76 (0.13)^{c}_{A}$	$2.38 (0.50)^{bd}_{A}$	$2.59 (1.00)^{b}_{A}$	$1.82 (0.16)^{cd}_{A}$	$2.00 (0.00)^{cd}_{A}$	$4.64 (0.11)^{e}_{A}$
	-18	$3.35 (0.09)^{a}$	$3.89 (0.20)^{bc}_{A}$	$2.73 (0.21)^{d}_{AB}$	$1.70 (0.00)^{e}_{A}$	$3.42 (0.13)^{a}_{B}$	$2.00 (0.37)^{e}_{A}$	$1.76 (0.13)^{e}_{A}$	$4.29 (0.04)^{b}_{B}$	$3.69 (0.62)^{ac}_{B}$
	-24		$3.11 (0.25)^{a}_{B}$	$2.95 (0.09)^{ab}_{B}$	$1.93 (0.37)^{c}_{A}$	$4.65 (0.25)^{d}_{C}$	$2.26 (0.29)^{c}_{A}$	$2.18 (0.16)^{c}_{B}$	$2.57 (0.47)^{bc}_{C}$	$3.85 (0.46)^{e}_{B}$
Lamb loin	-12		$2.10 (0.33)^{a}_{A}$	$4.16 (0.07)^{b}_{A}$	$2.33 (0.37)^{ac}_{A}$	$2.54 (0.30)^{acd}_{A}$	$3.08 (0.90)^{d}_{A}$	$2.04 (0.44)^{a}_{A}$	$2.68 (0.23)^{ad}_{A}$	$2.97 (0.64)^{cd}_{A}$
	-18	$2.82 (0.57)^{ab}$	$3.31 (0.41)^{a}_{B}$	$4.48 (0.04)^{c}_{A}$	$1.92 (0.50)^{d}_{A}$	$2.13 (0.45)^{d}_{A}$	$2.18 (0.53)^{bd}_{A}$	$2.04 (0.46)^{d}_{A}$	$3.02 (0.60)^{a}_{AB}$	$2.98 (0.23)^{a}_{A}$
	-24		$3.07 (0.45)^{ab}_{B}$	$3.96 (0.20)^{c}_{A}$	$2.47 (0.24)^{ad}_{A}$	$3.67 (0.59)^{bc}_{B}$	$2.38 (0.55)^{d}_{A}$	$2.55 (0.45)^{ade}_{A}$	$3.30 (0.08)^{b}_{B}$	$3.09 (0.22)^{be}_{A}$
Lamb trim 90CL	-12		$3.80 (0.12)^{a}_{A}$	$2.53 (0.04)^{bc}_{A}$	$2.18 (0.38)^{b}_{A}$	$3.15 (0.10)^{ac}_{AB}$	$3.15 (0.99)^{acde}_{A}$	$2.39 (1.00)^{bd}_{A}$	$3.82 (0.22)^{ae}_{A}$	$2.54 (0.33)^{b}_{A}$
	-18	$3.30 (0.77)^{ab}$	$3.45 (0.11)^{a}_{B}$	$3.02 (0.11)^{ac}_{B}$	$1.70 (0.00)^{d}_{B}$	$2.72 (0.29)^{ce}_{A}$	$2.81 (0.25)^{bce}_{A}$	$1.82 (0.27)^{d}_{A}$	$2.56 (0.56)^{c}_{B}$	$2.94 (0.48)^{ae}_{A}$
	-24		$3.03 (0.25)^{ab}_{C}$	$2.59 (0.12)^{ac}_{A}$	$1.76 (0.13)^{d}_{B}$	$3.54 (0.58)^{be}_{B}$	$2.00 (0.30)^{cd}_{AB}$	$2.36 (0.79)^{cd}_{A}$	$3.36 (0.13)^{bf}_{A}$	$3.79 (0.21)^{ef}_{B}$
Lamb trim 65CL	-12		$4.00 (0.22)^{a}_{A}$	$2.53 (0.04)^{bc}_{A}$	$2.80 (0.24)^{b}_{AB}$	$3.36 (0.93)^{a}_{AB}$	$2.44 (0.42)^{b}_{A}$	$2.33 (0.75)^{b}_{A}$	$3.16 (0.10)^{c}_{AB}$	$2.46 (0.55)^{b}_{A}$
	-18	$3.34 (0.15)^{a}$	$4.15 (0.51)^{b}_{A}$	$2.66 (0.08)^{cd}_{A}$	$3.37 (0.61)^{a}_{A}$	$2.48 (0.27)^{c}_{A}$	$2.28 (0.44)^{c}_{B}$	$2.34 (0.23)^{c}_{A}$	$3.66 (0.11)^{ab}_{A}$	$3.17 (0.34)^{ad}_{B}$
	-24		$4.22 (0.22)^{a}_{A}$	$2.75 (0.31)^{b}_{A}$	$2.46 (0.46)^{b}_{B}$	$3.93 (0.51)^{a}_{B}$	$1.88 (0.27)^{c}_{B}$	$2.55 (0.45)^{b}_{A}$	$3.02 (0.60)^{b}_{B}$	$4.09 (0.28)^{a}_{C}$

N=5; Within a row, means that do not share superscripts significantly differ ($P<0.05$); Within a column, for a specific sample type, means that do not share subscripts significantly differ ($P<0.05$)

4. Overall discussion

In this study no clear relationships or trends between sample type, storage temperature, and duration were apparent in the majority of the measured quality parameters, apart from those relating to lipid oxidation and sensory, which remained acceptable for at least 28 months in lamb trim and 38 months in beef and lamb loin, and beef trim. This study used commercially produced bulk product, in standard commercial packaging which was stored in bulk in cold rooms subjected to standard regular defrosts every 6 h. While some published studies have shown some of these characteristics to change with time, this has been from instrumental assessment only; sensory analysis has frequently been lacking. It is probable that differences in type and size of meat sample, time between slaughter and freezing, packaging, storage conditions, and study protocols account for many of the differences reported in the literature. The products were stored as boxed entire loins or blocks of trim, and samples for analysis were cut from these whole samples. In the case of the blocks of trim all analysed samples came from the centre of the blocks. In comparison most recent published studies have stored relatively small, prepared meat samples under laboratory conditions in chest freezers.

Sensory decline for lamb, particularly for meat flavour and fat odour for lamb trim may have marked the end of PSL for these products after 28 months of frozen storage at all temperatures. The sensory decline was not marked, but statistically significant with a proportion of average sensory scores in the unacceptable (<4) range. The packaging method (overwrap) may have contributed to the degradation in the lamb trim and may have been prevented by vacuum packing (Zhang et al., 2023). It must be noted that all trim (both beef and lamb) was minced and cooked and provided for sensory assessment without further enhancement such as with flavouring, sauces or condiments. The patties provided for sensory analysis (10% and 35% fat) were not at an optimal level for flavour (15% fat) or overall satisfaction (20% fat) (Carpenter and King, 1969). TBARS (Table 11) showed clear signs of lipid oxidation but not at a level that would be detectable by a sensory panel (Campo et al., 2006). The same decline in sensory scores over storage duration was observed for samples held at all storage temperatures. However, the instrumental lipid oxidation analysis showed more degradation over time in samples stored at -12°C. While there may have been some oxidation of the surface layers of the lamb trim over time, as already mentioned the samples used for sensory analysis were cut from the centre of blocks of the trim and thus were unlikely to have been affected by surface desiccation and oxidation. This is supported in the literature where there is evidence that the eating quality of long term stored meat is more influenced by the bulk muscle tissue and sub-surface fat than by changes to the surface layers of the meat (Winger, 1984).

The boxed lamb trim was simply over-wrapped prior to freezing. While the beef loin and trim, and lamb loins, which were vacuum-packed and boxed. Thus, it is not unexpected that the lamb trim samples showed clear signs of lipid oxidation earlier than the other samples. The importance of secure packaging during frozen storage to prevent oxidative changes has been known and highlighted since the advent of the modern freezing of meat (James and James, 2002). In common with the literature, the lipid oxidation showed a clear relationship between lamb trim fat content (CL), storage temperature, and duration. The level of lipid oxidation (as measured by PV and TBARS) was highest in the 65CL samples, and generally higher in samples stored at -12°C and -18°C than in samples stored at -24°C, it also increased with storage duration. In the lamb trim stored at -24°C, values were generally lower in all types of trim samples but did increase over time. A similar trend was observed in the beef samples, but values were lower. Overall, the observations of this study show that vacuum-packaging of frozen boxed meat rather than over-wrapping is more effective in maintaining quality if meat is intended for long term frozen storage.

A limitation to this study, and of all other recent studies on the long term frozen storage of beef and lamb, may be the neglect of nutritional parameters. Wood (2023) identifies lean red meats as good sources of several micronutrients: B vitamins, iron, zinc and long chain omega 3 polyunsaturated fatty acids

(PUFAs). Changes in the nutritional properties of meat over storage (chilled or frozen) are not frequently assessed. B vitamins appear to be relatively stable in frozen meat (Engler and Bowers, 1976). PUFAs appear to slowly degrade (Holman, et al., 2018a; Feng et al., 2022). Mineral content is expected to be constant. Nutrient concentrations are thus, not likely to limit the PSL.

5. Conclusions

The world trade in bulk frozen meat has moved away from whole carcasses, sides, quarters and bone in primals to predominantly boned out primals, sub primals, mince and trim packed in cartons with an approximate weight of 25 kg and a height of 15cm. As far as we are aware this is the first study which looks at the frozen storage life of a range of commercially produced beef and lamb, cuts, and trim in 25 kg cartons transported and stored under commercial conditions. The PSL of the meat was measured using a variety of physical and chemical tests and presented to a sensory panel.

Clear changes over time were found in chemical measures of rancidity (lipid oxidation) that can be related to meat composition, packaging, and storage temperature. These changes were greater in over-wrapped meat compared to vacuum-packed meat, and occurred more in frozen meat held at -12°C than in meat held at -18°C or -24°C. However, these changes did not reach thresholds that would be expected to be detected by a sensory panel and did not appear to correlate clearly with any of the sensory panel results in this study. The sensory assessment showed a general change in some sensory characteristics over time in the meat but no clear relationship with storage temperature. Overall, the results of this study demonstrate that commercially produced Australian boxed frozen beef and lamb loin and beef trim in vacuum packs shipped to export markets by air or water can be subsequently stored at -12°C, -18°C, or -24°C without significant sensory degradation for a period of over 36 months. Frozen boxed lamb trim wrapped in plastic did not degrade significantly in meat flavour or lamb odour intensity or frequently produce unacceptable sensory scores until more than 28 months of frozen storage at -12°C, -18°C, or -24°C. This study, along with previous studies on lamb (Coombs et al., 2017, 2018a, b) and beef (Holman et al., 2017, 2018a, b), suggests that, provided good temperature control is used, warmer (potentially as high as -12°C) frozen temperatures than -18°C (as currently used) may be used for the distribution and storage of frozen meat of the type examined without having a significant impact on quality, safety or PSL. The use of warmer frozen storage temperatures would lower energy costs and reduce the carbon footprint of frozen meat.

Author contributions (CRediT taxonomy)

Christian James: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Stephen J. James:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Graham Purnell:** Conceptualization, Methodology, Investigation, Resources, Data curation, Supervision, Funding acquisition. **Luke Talbot:** Investigation, Resources, Data curation. **Essam Hebishy:** Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Supervision. **Sophie Bowers:** Investigation, Data curation. **Bukola Onarinde:** Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Supervision, Project administration, Funding acquisition. **Long Huynh:** Conceptualization, Methodology, Supervision, Funding acquisition. **Ian Jenson:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

Ian Jenson and Long Huynh were employees of Meat & Livestock Australia (MLA) at the time the work was conducted. The other 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 statement

Data will be made available on request.

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9.3 Fact sheet on Shelf life of frozen Australian red meat products (-18 °C)

SHELF LIFE OF FROZEN AUSTRALIAN RED MEAT PRODUCTS

1. Frozen meat trade

History

Freezing, as a method of preserving food, was known prior to modern technology enabled its widespread application.[1] Modern commercial mechanical refrigeration is suggested to have commenced in Sydney, Australia in 1861 and the first shipment of frozen meat from Sydney to London followed in 1868.[2] Over many years, frozen food and international trade in meat has flourished and enabled more countries to participate in global food chains.

Volume

In 2020, 6.4 million tonnes of frozen red meat[3] was exported around the world, the second highest volume on record and a trade worth US$28.2 billion. As highlighted in Figure 1, the global trade in frozen meat has more than doubled since 2000.

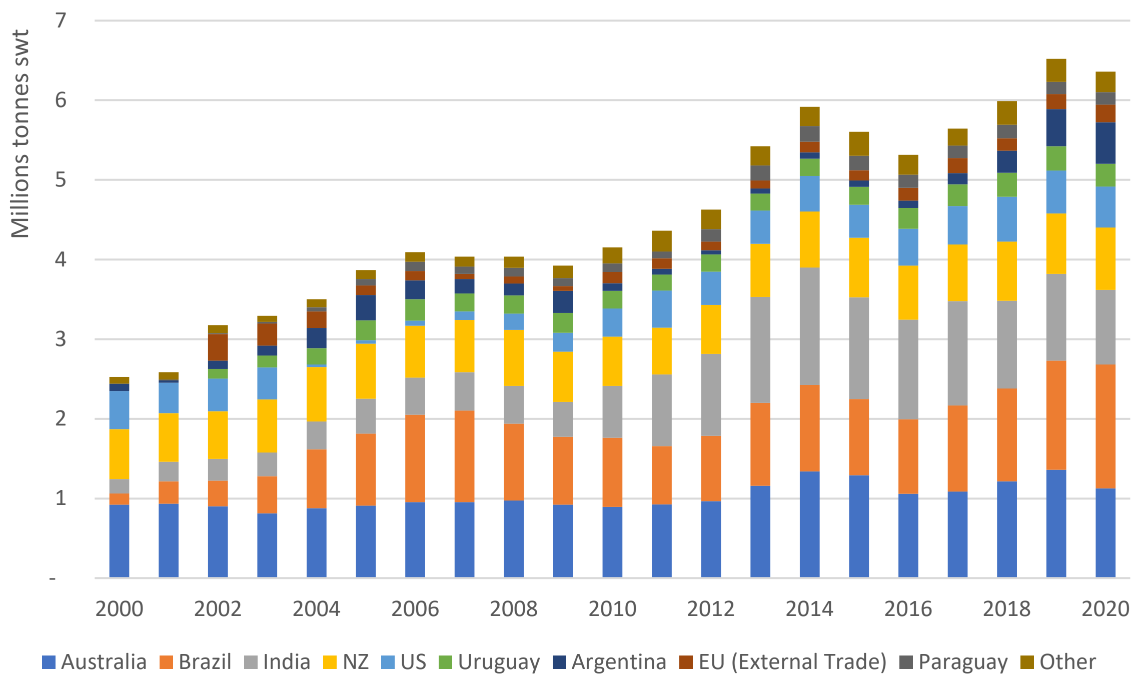

Figure 1. Frozen red meat exports by major exporting countries: includes frozen beef, buffalo meat and sheepmeat from major exporting countries (excludes intra-EU trade) in shipped weight (swt)

Australia is a major exporter of frozen meat and has a rich history of shipping product to over one hundred markets worldwide. Australia is consistently among the top-three exporters of frozen beef and sheepmeat over the last decade.

[1] Lawrie, R.A. and D.A. Ledward (2006) Lawrie's meat science. 7th ed. Cambridge: Woodhead. p.213
[2] Frozen food - Wikipedia accessed 21.10.2021
[3] MLA calculations based on IHS Markit Global Trade Atlas data; includes frozen beef, buffalo meat and sheepmeat from major exporting countries

Australia exported more than 1.13 million tonnes of frozen beef and sheepmeat in 2020, with the bulk of shipments spread across North Asia, Southeast Asia, North America, the Middle East and Europe.

Table 1: Australian frozen meat and offal exports by country 2020 in Tonnes[4]

Export market	Beef	Pork	Sheepmeat	Offal	Total
China	186,676	0	145,819	11,549	344,044
US	144,488	0	38,104	5,712	188,304
Japan	152,046	630	7,377	14,486	174,539
Korea	134,103	1,303	10,058	22,944	168,407
Indonesia	57,568	25	1,202	42,900	101,696
Philippines	28,702	891	216	10,630	40,440
Malaysia	7,971	307	25,303	3,434	37,015
Vietnam	17,594	3,972	299	8,785	30,650
Taiwan	19,903	0	5,810	4,009	29,722
Hong Kong	3,379	886	4,141	20,096	28,502
PNG	3,302	4,031	12,564	5,302	25,198
Saudi Arabia	8,079	0	8,894	6,985	23,958
Singapore	6,276	1,106	11,043	3,156	21,582
Canada	11,077	0	5,363	1,447	17,888
UAE	3,981	11	7,238	3,972	15,201
Other	19,067	3,841	37,876	36,902	97,686
Total	**804,210**	**17,004**	**321,309**	**202,308**	**1,344,831**

2. Safety and quality of frozen meat

The International Institute of Refrigeration (IIR)[5] notes that ‘the physical and biochemical reactions which take place in frozen food products lead to a gradual, cumulative and irreversible reduction in product quality such that after a period of time the product is no longer suitable for consumption (or the intended process)’.

During frozen storage microbiological growth is arrested, but meat will slowly deteriorate due to oxidative and other changes. Frozen storage life is normally limited by the development of adverse flavours caused by oxidative rancidity of fat. The temperature of storage, method of packaging and degree of saturation of the fat all affect the

[4] MLA calculations based on IHS Markit Global Trade Atlas data
[5] Bøgh-Sørensen, L. (ed.) (2006) Recommendations for the Processing and Handling of Frozen Foods. Paris: International Institute of Refrigeration. p. 10

onset of these changes. The frozen storage life may also be reduced if the product is comminuted, because this process exposes more meat surfaces to oxygen.[6]

Microbiology

Many factors influence the growth and survival of microorganisms (bacteria, mould) in meat during freezing and frozen storage. However, the main factor affecting the growth of microorganisms during freezing is the availability of water (expressed as water activity). The transformation of water into ice significantly modifies the growth environment for microorganisms because water activity is progressively reduced preventing microbial growth.[7]

Microorganisms do not grow below about -10°C (mould growth being most noticeable on meat held at low temperatures), thus spoilage is only normally relevant to handling before freezing or during/after thawing.[8]

Chemistry

It is broadly accepted that fat oxidation remains the obstacle to very long-term storage of frozen meat.[9] The initial reaction is between a molecule of oxygen and a fatty acid to form a peroxide. The presence of peroxides in fat does not change the flavour; rather, it is the breakdown products of the peroxides which produce the unpleasant rancid odour and flavour and determines the acceptable shelf life of the meat.

Sensory

In cartons, 'freezer burn' is the main appearance problem that may frequently affect the appearance of meat. Freezer burn results from the desiccation of the surface tissues, which produces a dry, spongy layer that is unattractive and does not recover after thawing.[10]

While oxidation of oxymyoglobin can occur, affecting the colour of the meat,[11] it is expected that the unacceptable changes in flavour, stemming from oxidative rancidity of fat, is the most likely sensory change in product.[12]

3. Storage conditions

Temperature

Early last century, -10°C was regarded as a suitable temperature for storing frozen food. However, lower temperatures were recognised as being more suitable. In the late 1930s, the American Fruit and Vegetable Coalition advocated that a freezing temperature of 0°F (equivalent to -17.8°C) be maintained, largely on the basis that 0°F was a round number, rather than for scientific reasons[13]. The IIR note that -10°C is a satisfactory temperature for meat storage.[14] Lawrie[15] reported that it is customary in Britain to store frozen meat at -10°C and notes research reporting that fats of beef and lamb are relatively resistant to such oxidation and may still be good after 18 months storage at -10°C. Research conducted in New Zealand in the 1980s stored lamb at -10°C with satisfactory results for 14-18 months, depending upon processing conditions.[16] Storage at a higher temperature would require less energy, providing economic and environmental benefits.

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[6] Food Science Australia (2002) Shelf life of meat. https://meatupdate.csiro.au/Storage-Life-of-Meat.pdf
[7] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.7
[8] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.11
[9] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.216
[10] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.76-77
[11] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.76-77
[12] Lawrie and Ledward. Lawrie's meat science. 7th ed. Cambridge: Woodhead. p. 226
[13] https://blog.liebherr.com/appliances/my/ideal-freezer-temperature/
[14] Bøgh-Sørensen, L. (ed.) (2006) Recommendations for the Processing and Handling of Frozen Foods. Paris: International Institute of Refrigeration. p. 117
[15] Lawrie and Ledward. Lawrie's meat science. 7th ed. Cambridge: Woodhead. p. 220, 226
[16] Winger, R. J. (1984). Storage life and eating-related quality of New-Zealand frozen lamb: A compendium of irrepressible longevity. In P. Zeuthen (Ed.), *Thermal processing and quality of foods* (pp. 541–543). London: Elsevier

In 1964, the International Institute of Refrigeration recommended a minimum temperature of -18°C for frozen food.[17] By 1966 the Codex Alimentarius Commission was considering standards on frozen foods and recommended that the temperature of product should be maintained at -18°C (0°F) and that any rise in the temperature of product during transportation and unloading should be limited to very brief periods and never be warmer than -15°C.[18]

The current Codex Alimentarius *Code of Practice* recommends distribution of quick-frozen foods should maintain a temperature of -18°C but permits competent authorities to allow -12°C during transport with the product temperature reduced to -18°C as soon as possible.[19]

Time of storage

The IIR notes that ‘storage life of nearly all frozen foods is dependent on the temperature of storage' and makes recommendations on practical storage life (PSL). PSL is defined as ‘the period of frozen storage at a given temperature during which the product retains its characteristic properties and remains suitable for consumption or the intended process'.[20] Few scientific publications present data on the PSL of meat at different storage temperatures.[21]

The practical storage life suggested by the IIR (Table 2) should be subject to qualification:

Storage life for carcases are stated for unpackaged products. This may have reflected international trade in 2006 but changes in packaging practices may be expected to extend storage periods from those stated.

The IIR frames disclaimers around storage periods stating that their recommendations only provide a “*very rough guide* to their storage potential" and "*should not* be constructed as *absolute limits* to be applied rigidly”

Table 2: Practical storage life (PSL) in months of some frozen meat products

Product	-12°C	-18°C	-24°C
Beef carcass (unpackaged)	8	15	24
Beef cuts	8	18	24
Lamb carcass, grass fed (unpackaged)	18	24	>24
Lamb cuts	12	18	24
Veal carcass (unpackaged)	6	12	15
Ground beef	6	10	15

Regulation

[17] https://blog.liebherr.com/appliances/my/ideal-freezer-temperature
[18] Joint FAO/WHO Program on Food Standards. Codex Alimentarius Commission. (1966) Report of the Second Session of the Joint ECE/Codex Alimentarius Group of Experts on Standardization of Quick (Deep) Frozen Foods. Annex I. Proposed Draft Provisional General Standard for Quick (deep) Frozen Foods at Step 3. ALINORM 66/25 October 1966.
[19] Codex Alimentarius Commission (2008). Code of Practice for the Processing and Handling of Quick Frozen Foods CAC/RCP8-1976. adopted 2008.
[20] Bøgh-Sørensen, L. (ed.) (2006) Recommendations for the Processing and Handling of Frozen Foods. Paris: International Institute of Refrigeration. p. 10
[21] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.208,221

Regulatory authorities in most countries do not mandate expiry dates, except where it can be scientifically shown that there is a food safety concern; rather, the convention in international trade is for the supplier to nominate a shelf life, which is usually applied to the product label (Table 3).

Table 3: Expiry date considerations for selected countries importing Australian frozen meats

Country	Requirements[22]
USA	Use-by dates may be printed on the label
EU	Labels on consumer-ready edible products must include the date of minimum durability, or, in the case of foodstuffs, which from a microbiological point of view are highly perishable, the 'use-by' date and any special storage conditions or conditions of use.
China	No requirements for frozen meat.
Japan	No known specific requirements for use-by dates and/or shelf life restrictions.
Korea	No known requirements for frozen meat. The shelf life for chilled beef must be determined by the manufacturer. [23]

4. Data on frozen storage of Australian Red Meat

Meat & Livestock Australia, the designated Australian Government research and development corporation for red meat production, conducted a study to establish the practical shelf life (PSL) of frozen beef and lamb, such as would be exported from Australia.

Experiment design

Australian beef and lamb cuts (strip loin and eye of loin, respectively) and manufacturing meat of varying fat levels were frozen at -18°C prior to transport to the Food Refrigeration & Process Engineering Research Centre (FRPERC) at the Grimsby Institute (UK). The cartons were then stored at -12°C, -18 °C, and -24°C until sampling and testing.

The data for highest fat-containing manufacturing meat are presented below, with literature suggesting that these products will deteriorate the quickest. Sensory scores for fat flavour in minced, cooked patties and a measure of oxidative rancidity (TBARS) are presented here as sensitive indicators of shelf life (Figures 2 and 3). Campo et al.[24] investigated the flavour perceptions in beef and suggested that, as rancid flavours develop, there is a loss of desirable flavour notes. They reported that the higher the TBARS the less beef flavour could be perceived sensorially, with a strong relationship between TBARS level and perception of rancidity. They suggested that a TBARS value of around 2 could be considered the limiting threshold for the acceptability of oxidised beef.

[22] Australian Government, Department of Agriculture, Water and the Environment. Manual of Importing Country Requirements.
[23] WTO case (DS-5,1995) United States v Korea. agreement to allow manufacturers of various products to determine their own shelf-life. https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds5_e.htm
[24] Campo MM, Nute GR, Hughes SI, Enser M, Wood JD, Richardson RI. Flavour perception of oxidation in beef. Meat Sci. 2006 Feb;72(2):303-11. doi: 10.1016/j.meatsci.2005.07.015

A quantitative panel evaluation was carried out on the meat using approximately ten assessors. The panel evaluated the samples on a ten-point quality scale in which intensity (having a characteristic quality in a high degree) ranged from very low (1) to very high (10). Scores less than 4 represent samples approaching unacceptable flavour.

Results

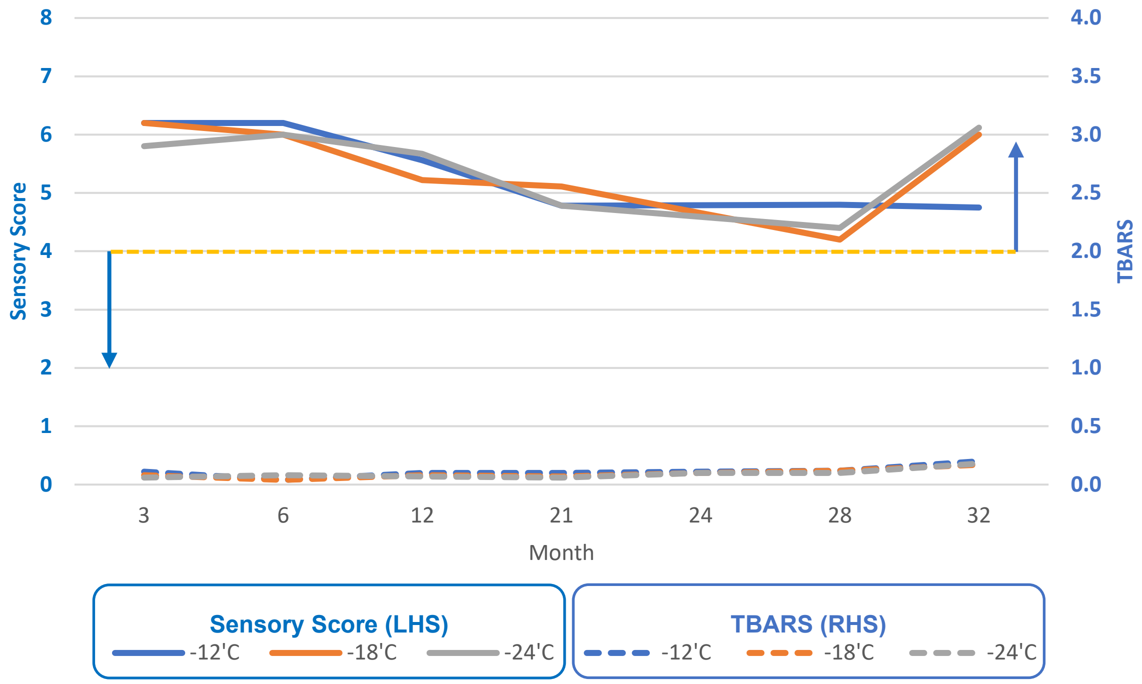

Figure 2. Frozen 65CL beef made into patties: mean sensory (solid line) and measure of oxidative rancidity [thiobarbituric acid reactive substances (TBARS) (mg malondialdehyde (MDA)/kg)] (Dashed lines) of samples measured at 3 (arrival), 6, 12, 21, 24, 28, and 32 months, stored at -12°C (green), -18°C (yellow) and -24°C (grey). The red dashed line represents a score approaching unfavourable sensory and oxidative rancidity (TBARS) results.

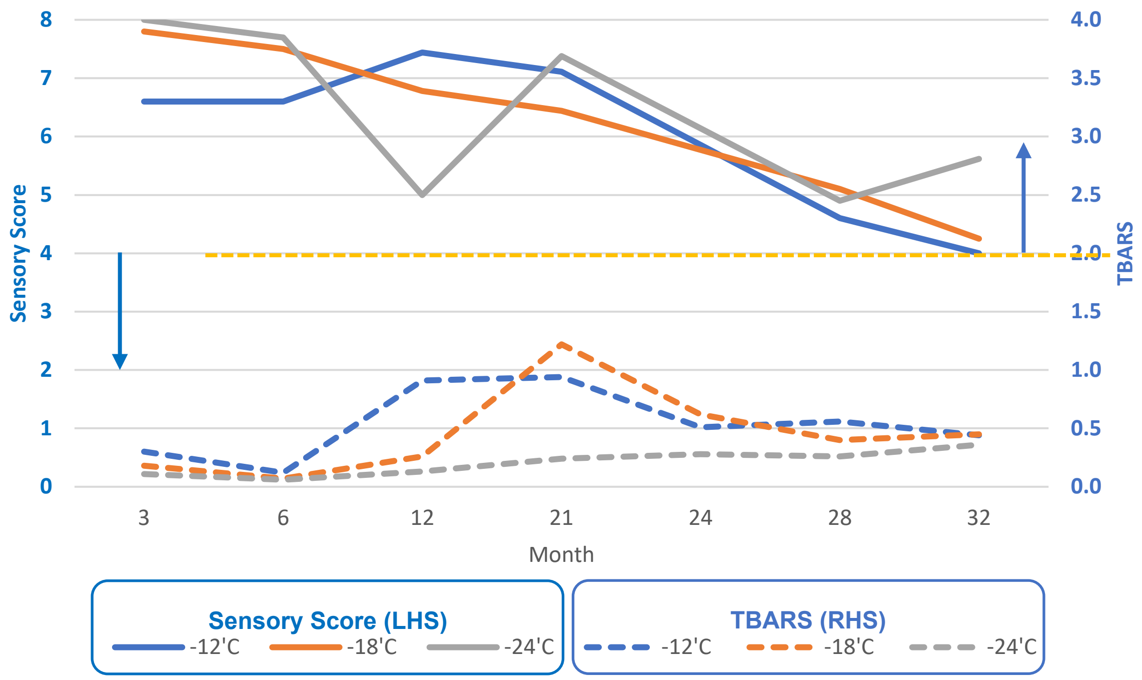

Figure 3. Frozen 65CL lamb made into patties: mean sensory (solid line) and measure of oxidative rancidity [thiobarbituric acid reactive substances (TBARS) (mg malondialdehyde (MDA)/kg)] (Dashed lines) of samples measured at 3 (arrival), 6, 12, 21, 24, 28, and 32 months, stored at -12°C (green), -18°C (yellow) and -24°C (grey). The red dashed line represents a score approaching unfavourable sensory and oxidative rancidity (TBARS) results.

In this work, no clear relationships/trends between sample type, storage temperature, and time of storage were apparent in the majority of the measured quality parameters, apart from those relating to lipid oxidation and sensory evaluation.

5. Recommendations

Storage temperature

While -18°C has become the standard temperature for the storage of frozen foods, red meat appears able to be stored successfully for many months or years at a temperature warmer than this threshold. No food safety hazards exist on frozen meat that has been held at, or reached, a temperature between -10°C and -18°C. Sensory degradation occurs only slowly at these temperatures and no food safety hazards arise.

Shelf life at -18°C

The world-leading Australian study demonstrated that if held at, or around, -18°C, frozen beef and lamb can be stored without significant sensory degradation for a period of over 30 months, and possibly, over 36 months. No food safety hazards arise. Mandated shorter frozen shelf life requirements (such as 12 months) should be reviewed to reflect this evidence.

9.4 Shelf life fact sheet

SUCCESSFUL STORAGE OF FROZEN AUSTRALIAN RED MEAT PRODUCTS at -12°C

1. Frozen meat trade

Freezing, as a method of preserving food, was known prior to modern technology enabled its widespread application.[1] Modern commercial mechanical refrigeration is suggested to have commenced in Sydney, Australia in 1861 and the first shipment of frozen meat from Sydney to London followed in 1868.[2] Over many years, frozen food and international trade in meat has flourished and enabled more countries to benefit from a more varied diet.

Australia is a major exporter of frozen meat and has a rich history of shipping product to over one hundred markets worldwide. Australia is consistently among the top-three exporters of frozen beef and sheepmeat over the last decade.

Australia exported more than 1.4 million tonnes of frozen beef and sheepmeat in 2023, with the bulk of shipments spread across North Asia, Southeast Asia, North America, the Middle East and Europe.

2. Safety and quality of frozen meat

During frozen storage microbiological growth is arrested, but meat will slowly deteriorate due to oxidative and other changes. The temperature of storage, method of packaging and degree of saturation of the fat all affect the onset of these changes. The frozen storage life may also be reduced if the product is ground, because this process exposes more meat surfaces to oxygen.[3]

Microbiology

Many factors influence the growth and survival of microorganisms (bacteria, mould) in meat during freezing and frozen storage. The transformation of water into ice significantly modifies the growth environment for microorganisms because water is no longer available as a medium for microbial growth.[4]

Microorganisms do not grow below about -10°C (mould growth being most noticeable on meat held at low temperatures), thus spoilage is only normally relevant to handling before freezing or during/after thawing.[5]

Chemistry

It is broadly accepted that fat oxidation remains the obstacle to very long-term storage of frozen meat.[6] The initial reaction is between a molecule of oxygen and a fatty acid to form a peroxide. The presence of peroxides in fat does not change the flavour; rather, it is the breakdown products of the peroxides which produce the unpleasant rancid odour and flavour and determines the acceptable shelf life of the meat.

[1] Lawrie, R.A. and D.A. Ledward (2006) Lawrie's meat science. 7th ed. Cambridge: Woodhead. p.213
[2] Frozen food - Wikipedia accessed 19.6.2024
[3] Food Science Australia (2002) Shelf life of meat. https://meatupdate.csiro.au/Storage-Life-of-Meat.pdf
[4] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.7
[5] James, S. J., & James, C. (2023). Food Technologies: Freezing. In Y. Motarjemi (Ed.), *Encyclopedia of Food Safety* (pp. 187-195). Waltham: Academic Press.
[6] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.216

Sensory

In cartons, 'freezer burn' is the main appearance problem that may frequently affect the appearance of meat. Freezer burn results from the desiccation of the surface tissues, which produces a dry, spongy layer that is unattractive and does not recover after thawing.[7]

While oxidation of oxymyoglobin can occur, affecting the colour of the meat,[8] it is expected that the unacceptable changes in flavour, stemming from oxidative rancidity of fat, is the most likely sensory change in product.[9]

3. Storage conditions

Temperature

Early last century, -10°C was regarded as a suitable temperature for storing frozen food. However, lower temperatures were recognised as being more suitable. In the late 1930s, the American Fruit and Vegetable Coalition advocated that a freezing temperature of 0°F (equivalent to -17.8°C) be maintained, largely on the basis that 0°F was a round number, rather than for scientific reasons[10]. The IIR note that -10°C is a satisfactory temperature for meat storage.[11] Lawrie[12] reported that it was customary in Britain to store frozen meat at -10°C and notes research reporting that fats of beef and lamb are relatively resistant to such oxidation and may still be good after 18 months storage at -10°C. Research conducted in New Zealand in the 1980s stored lamb at -10°C with satisfactory results for 14-18 months, depending upon processing conditions.[13]

Regulation

Regulatory authorities in many countries do not mandate storage temperatures for frozen foods, or may regulate non-specific requirements, such a food being maintained in a frozen state. If temperatures are specified, then a temperature higher than -18°C may be chosen, and allowances for food moving between one form of storage or transport and another might be given.

4. Data on frozen storage of Australian Red Meat

Meat & Livestock Australia, the designated Australian Government research and development corporation for red meat production, conducted a study to establish the practical shelf life (PSL) of frozen beef and lamb, such as would be exported from Australia.

Experiment design

Australian beef and lamb cuts (strip loin and eye of loin, respectively) and manufacturing meat of varying fat levels were packed in the usual way and frozen at -18°C prior to transport to the Food Refrigeration & Process Engineering Research Centre (FRPERC) at the Grimsby Institute (UK). The cartons were then stored at -12°C, -18 °C, and -24°C until sampling and testing. The product was stored in commercial cold storage rooms with frequent defrost cycles which transiently increased the air temperature to approximately -8.5°C, -13°C, and -17°C, not sufficiently to affect product temperature.

[7] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.76-77
[8] James, SJ and C James (2002) Meat Refrigeration. Cambridge: Woodhead p.76-77
[9] Lawrie and Ledward. Lawrie's meat science. 7th ed. Cambridge: Woodhead. p. 226
[10] https://blog.liebherr.com/appliances/my/ideal-freezer-temperature/
[11] Bøgh-Sørensen, L. (ed.) (2006) Recommendations for the Processing and Handling of Frozen Foods. Paris: International Institute of Refrigeration. p. 117
[12] Lawrie and Ledward. Lawrie's meat science. 7th ed. Cambridge: Woodhead. p. 220, 226
[13] Winger, R. J. (1984). Storage life and eating-related quality of New-Zealand frozen lamb: A compendium of irrepressible longevity. In P. Zeuthen (Ed.), *Thermal processing and quality of foods* (pp. 541–543). London: Elsevier

The data for highest fat-containing manufacturing meat are presented below, with literature suggesting that these products will deteriorate the quickest. Sensory scores for fat flavour in minced, cooked patties and a measure of oxidative rancidity [thiobarbituric acid reactive substances (TBARS) (mg malondialdehyde (MDA)/kg)] are presented here as sensitive indicators of shelf life (Figures 1 and 2). Campo et al.[14] investigated the flavour perceptions in beef and suggested that, as rancid flavours develop, there is a loss of desirable flavour notes. They reported a strong relationship between TBARS level and perception of rancidity. They suggested that a TBARS value of around 2 could be considered the limiting threshold for the acceptability of oxidised beef.

A sensory evaluation was carried out on the meat using approximately ten assessors. The panel evaluated the samples on a ten-point quality scale in which intensity (having a characteristic quality in a high degree) ranged from very low (1) to very high (10). Scores less than 4 represent samples approaching unacceptable flavour.

A complete description of the work and presentation of the results is available.[15]

Results

For both beef (Figure 1) and lamb (Figure 2) the mean sensory scores for fat flavour are shown on a scale of 1-10 (only 1-8 is shown), with a score of 4 being considered the minimum acceptable result. The TBARS result, a chemical indicator of oxidation of fat, is shown on a scale of 0-4, with 2 being estimated as the point that consumers perceive as rancid.

It is clear that for these tests, that acceptable results were obtained throughout the 38 month frozen storage period (approximately, 36-37 months at the temperature shown after initial -18°C freezing and transport).

It is also clear that the three temperatures gave rise to product with very similar results. In other words, -12°C was as suitable for long term storage of frozen beef and lamb as -18°C.

5. Recommendations

Storage temperature

While -18°C has become the standard temperature for the storage of frozen foods, red meat appears able to be stored successfully for years at a temperature of -12°C. No food safety hazards exist on frozen meat that has been held at, or reached, a temperature between -10°C and -18°C. Sensory degradation occurs only slowly at these temperatures and no food safety hazards arise.

Temperature specification

Specification of storage temperatures must take account of the cycles of refrigeration equipment and ensure that product temperature is addressed rather than air temperature.

[14] Campo MM, Nute GR, Hughes SI, Enser M, Wood JD, Richardson RI. Flavour perception of oxidation in beef. Meat Sci. 2006 Feb;72(2):303-11. doi: 10.1016/j.meatsci.2005.07.015

[15] Christian James, Stephen James, Graham Purnell, Luke Talbot, Essam Hebishy, Sophie Bowers and Bukola Onarinde (2022) The shelf-life of Australian frozen red meat | Meat & Livestock Australia (mla.com.au) North Sydney Australia.

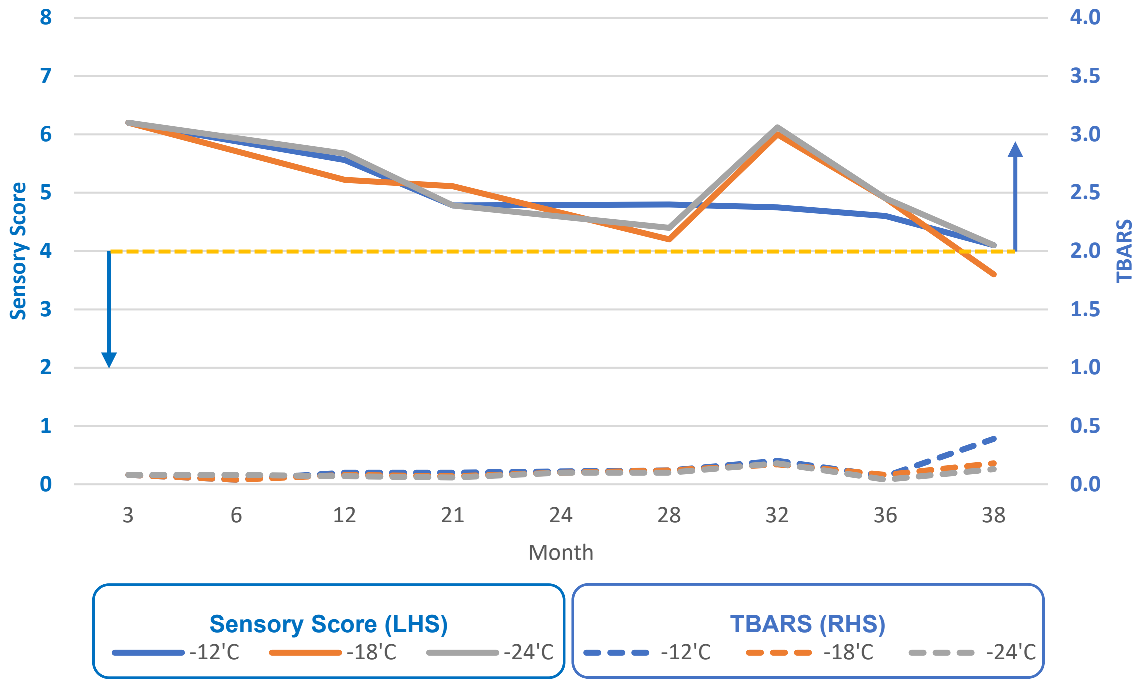

Figure 1. Frozen 65CL beef made into patties: mean sensory (solid line) and measure of oxidative rancidity (TBARS) (Dashed lines) of samples, stored at -12°C (green), -18°C (yellow) and -24°C (grey). The red dashed line represents a score approaching unfavourable sensory and oxidative rancidity (TBARS) results.

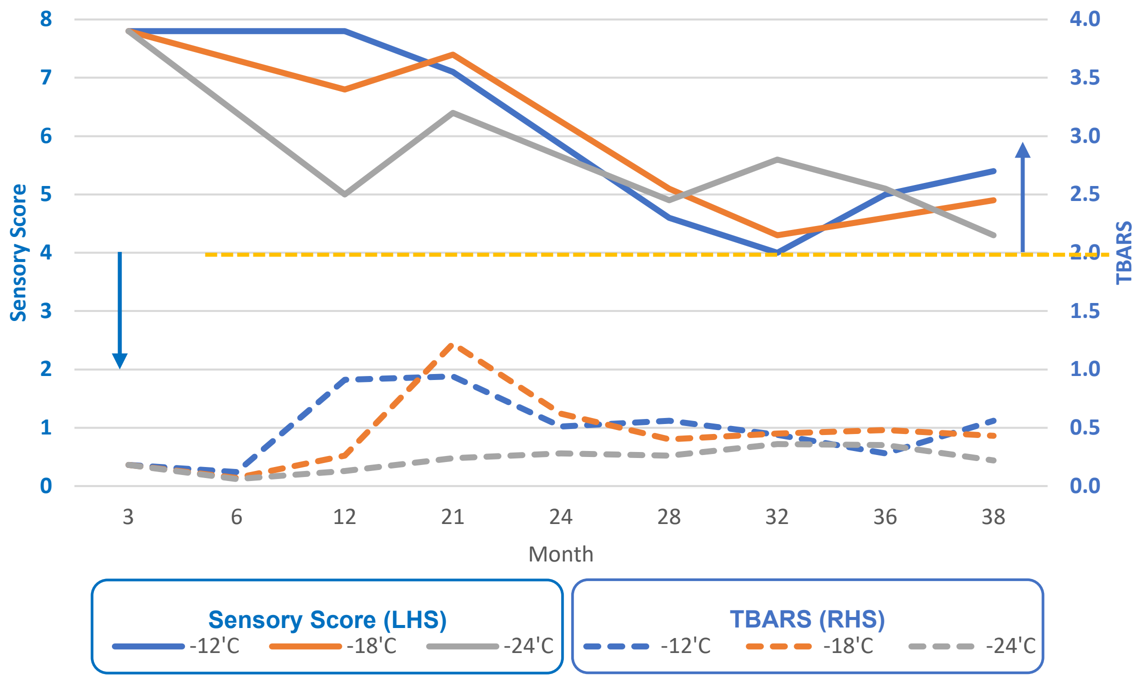

Figure 2. Frozen 65CL lamb made into patties: mean sensory (solid line) and measure of oxidative rancidity (TBARS) (Dashed lines) of samples, stored at -12°C (green), -18°C (yellow) and -24°C (grey). The red dashed line represents a score approaching unfavourable sensory and oxidative rancidity (TBARS) results.

9.5 Energy and Emissions fact sheet

SAVING ENERGY AND REDUCING CARBON EMISSIONS BY STORING FROZEN RED MEAT PRODUCTS at -12°C

1. Frozen meat trade

History

Modern commercial mechanical refrigeration is suggested to have commenced in Sydney, Australia in 1861 and the first shipment of frozen meat from Sydney to London followed in 1868.[1] Over many years, frozen food and international trade in meat has flourished and enabled more countries to benefit from a varied diet.

Australia is a major exporter of frozen meat and has a rich history of shipping product to over one hundred markets worldwide. Australia is consistently among the top-three exporters of frozen beef and sheepmeat over the last decade.

Australia exported more than 1.4 million tonnes of frozen beef and sheepmeat in 2023, with the bulk of shipments spread across North Asia, Southeast Asia, North America, the Middle East and Europe.

2. Storing frozen meat at -12°C

Recent studies of Australian beef and lamb frozen at -12°C demonstrate that deterioration is slow, and even after more than 36 months storage, product held mostly at -12°C are not significantly different in sensory properties to product stored at -18°C. Some chemical tests show differences, but these are not reflected in the sensory properties, or safety of the product.

3. History of storage temperature

Early last century, -10°C was regarded as a suitable temperature for storing frozen food. However, lower temperatures were recognised as being more suitable. In the late 1930s, the American Fruit and Vegetable Coalition advocated that a freezing temperature of 0°F (equivalent to -17.8°C) be maintained, largely on the basis of preserving vitamin C levels in fruit juice and that 0°F was a round number[2]. The International Institute of Refrigeration (IIR) note that -10°C is a satisfactory temperature for meat storage.[3] Lawrie[4] reported that it was customary in Britain to store frozen meat at -10°C and notes research reporting that fats of beef and lamb are relatively resistant to such oxidation and may still be good after 18 months storage at -10°C. Research conducted in New Zealand in the 1980s stored lamb at -10°C with satisfactory results for 14-18 months, depending upon processing conditions.[5]

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[1] Frozen food - Wikipedia accessed 21.10.2021

[2] https://blog.liebherr.com/appliances/my/ideal-freezer-temperature/

[3] Bøgh-Sørensen, L. (ed.) (2006) Recommendations for the Processing and Handling of Frozen Foods. Paris: International Institute of Refrigeration. p. 117

[4] Lawrie and Ledward. Lawrie's meat science. 7th ed. Cambridge: Woodhead. p. 220, 226

[5] Winger, R. J. (1984). Storage life and eating-related quality of New-Zealand frozen lamb: A compendium of irrepressible longevity. In P. Zeuthen (Ed.), *Thermal processing and quality of foods* (pp. 541–543). London: Elsevier

Internationally, standards and Codes of Practice, acknowledged the possibility of higher temperature storage, at least for a time, but tended to settle towards -18°C, probably due to the ability of refrigeration systems to reliably achieve this result.

In 1964, the International Institute of Refrigeration recommended a minimum temperature of -18°C for frozen food.[6] By 1966 the Codex Alimentarius Commission was considering standards on frozen foods and recommended that the temperature of product should be maintained at -18°C (0°F) and that any rise in the temperature of product during transportation and unloading should be limited to very brief periods and never be warmer than -15°C.[7]

The current Codex Alimentarius *Code of Practice* recommends distribution of quick-frozen foods should maintain a temperature of -18°C but permits competent authorities to allow -12°C during transport with the product temperature reduced to -18°C as soon as possible.[8]

Regulation

Regulatory authorities in many countries do not mandate a storage or transportation temperature, but some specify -18°C. There are a few countries that specify 'never more than' a particular temperature. The specification of -18°C is not supported by past experience and a growing number of current studies. The absolute prescription of a maximum temperature is not risk-based. A summary of the requirements for meat in different countries/regions is provided below:

	Maximum temperature for frozen meat (°C)	Level of prescription
Australia	Not specified	
China	-18	Lower than or equal to
USA	Not specified	
Japan	-15	Less than
South Korea	-18	Or below – except during transport to consumers
Europe	-18	Implied – but depends on product
United Arab Emirates	-18	But allowance for -15 or -10 in some Emirates, subject to conditions

4. Energy consumption for freezing and frozen storage at -12°C compared to -18°C

[6] https://blog.liebherr.com/appliances/my/ideal-freezer-temperature

[7] Joint FAO/WHO Program on Food Standards. Codex Alimentarius Commission. (1966) Report of the Second Session of the Joint ECE/Codex Alimentarius Group of Experts on Standardization of Quick (Deep) Frozen Foods. Annex I. Proposed Draft Provisional General Standard for Quick (deep) Frozen Foods at Step 3. ALINORM 66/25 October 1966.

[8] Codex Alimentarius Commission (2008). Code of Practice for the Processing and Handling of Quick Frozen Foods CAC/RCP8-1976. adopted 2008.

Energy consumption and emissions production can be conveniently divided into three processes in the cold chain:

- Electrical refrigeration work for initial freezing at the processor
- Electrical refrigeration work for maintaining temperature during storage (e.g. in a warehouse)
- Electrical refrigeration work for maintaining temperature during transport (e.g., shipping container) and exclusive of transport fuel

Initial freezing - emissions

Based on an average Australian meat processing establishment, the energy emissions generated from freezing would be:

to -18°C: 39.0 kg CO_2-e / t HSCW[9]

to -12°C: 32.4 kg CO_2-e / t HSCW

a reduction of 17%

Warehouse storage emissions

at -18°C: 8.0 kg CO_2-e / t HSCW / day

at -12°C: 7.2 kg CO_2-e / t HSCW / day

a reduction of 10%

During refrigerated shipping[10]

at -18°C: 7.4 g CO_2-e / t HSCW / km or 7.4 kg CO_2-e / t HSCW / 1,000 km

at -12°C: 6.6 g CO_2-e / t HSCW / 1,000 km

a reduction of 10.8%

An example scenario:

A journey from the Port of Sydney to the Port of Dalian, China is 8,976 km and can take about 14 days. Additionally, the product may spend about 14 days not in a refrigerated container in storage at the processor, waiting at the port for loading, or for government inspection.

at -18°C: 217.8 kg CO_2-e / t HSCW

at -12°C: 192.5 kg CO_2-e / t HSCW kg CO_2-e / t HSCW

a reduction of 11.6%

A reduction similar to this would occur for other sea freight journeys. Further data is required to be able to make better predictions of emission reductions.

5. Implementation

[9] Kilograms carbon dioxide equivalent per tonne of hot standard carcase [weight] assuming 0.3 t carcase weight yield per head

[10] Cost for maintaining temperature of fresh chilled (i.e. not frozen) product with dry ice during air freight will be significantly higher

Changes in frozen meat temperatures could be implemented with no change to equipment. Coordination of the supply chain would be required to manage the change. Possibly, more careful management of the time that product is not under active refrigeration would be required.

6. Recommendations

While -18°C has become the standard temperature for the storage of frozen foods, red meat appears able to be stored successfully for many months or years at a temperature of -12°C. No food safety hazards exist on frozen meat that has been held at, or reached, a temperature between -10°C and -12°C.

Temperature

Freezing meat to a temperature of -12°C would reduce the emissions required to maintain the cold chain compared to -18°C by 11-12% at little to no cost.

9.6 Communications

9.6.1 AMPC communication

Higher temps means lower costs

24 May 2024

The cost of getting meat products to the standard -18C freezing temperature – and keeping them there – is high. AMPC is currently investigating the implications of lifting the freezing temperature to -12C to reduce energy consumption while maintaining our world leading food quality and safety standards.

AMPC Program Manager Ann McDonald says there are cost and environmental benefits thanks to reduced energy usage, and -12C has already been demonstrated to provide good shelf life for frozen meats, but many markets require a -18C temperature.

“We have set out to understand the positions of stakeholders in the meat supply chain, especially regulators and international government and semi-government standard setting bodies, to determine whether change from the conventional storage temperature is feasible. The financial and environmental benefits will be weighed against the feasibility and actions required to achieve change.”

Meat & Livestock Australia conducted a study to establish the practical shelf life of frozen beef and lamb, such as would be exported from Australia.

“The results at -12°C demonstrated no meaningful differences in quality and no food safety hazards were detected,” Ann says.

The cost savings for industry could be very significant: up to 20 per cent less to freeze product to -12C and about 60 per cent less for ongoing warehouse storage costs. The costs to maintain temperature during shipping could fall by about 30 per cent.

There is already some scope in the regulations to store some product at -12C, though it rarely happens.

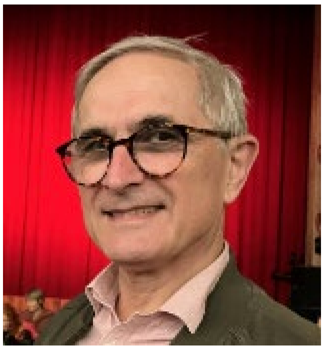
“The current Codex Alimentarius Code of Practice recommends distribution of quick-frozen foods should maintain a temperature of -18°C but permits competent authorities to allow -12°C during transport, with the product temperature reduced to -18°C as soon as possible. This has not typically been common practice, but some large international frozen food producers have recently announced an intention to store some of their products at -12°C,” Ann says.

“From this investigative phase our next step would be to develop a scientific paper and submission to regulators and others along the supply chain to have the change agreed. The challenge will be to reach consensus across stakeholder groups but there is potential for significant savings in energy costs if this can be achieved.”

For more information contact a.mcdonald@ampc.com.au

9.6.2 Refrigerated Warehouse and Transport Association of Australia (RWTA)

Conference 2024: Set Point 3 Degrees of Difference, Expert Dr Ian Jenson Presenting



Dr Ian Jenson

We are on the brink of a Cold Storage Revolution.

Ian Jenson will unpack groundbreaking findings that challenge the long-held standard of -18°C for frozen food.

Discover how emerging scientific insights propose not only potential cost reductions and lower carbon emissions, but also foster global trade efficiencies.

Three degrees difference to make the cold chain a more sustainable sector is a robust international conversation taking place.

Dr Ian Jenson is a food microbiologist who has worked in the areas of industrial fermentation, fermented foods, and meat safety over his entire career.

He is the Principal of FIRST Management Pty Ltd, a consulting company dedicated to Food Innovation Research Science and Technology Management.

True or False?

- Frozen foods are unsafe if stored above -18°C
- The c… lost if store…
- The s… less if store…
- -18°C … ice cream
- Refreezing foods is unsafe

FALSE

Outline

- Can frozen food temperatures be raised?
- What are the barriers to raising frozen food temperatures?
- What is the agenda to achieve change?

Raising the temperature

- Shelf life of frozen foods
- Benefits of raising the temperature
- Infrastructure required

Raising the temperature Shelf life

Frozen beef and lamb	>24 months at -12°C
Crumbed chicken Salmon fillets Peas Spinach Meatballs Pizza	18 months at -15°C unless 'best before' <18 months
Ice cream	-12°C in retail freezer cabinets

Shelf life is not affected by the raising of frozen food temperatures

Raising the temperature Benefits


Three Degrees
Of Change
FROZEN FOOD IN A RESILIENT AND SUSTAINABLE FOOD SYSTEM
Summary report & initial findings
November 2023

The savings that can be achieved by shifting frozen food set-point temperatures from -18°C to -15°C …estimate electrical energy savings of approximately 10%

Frozen meat - Eastern Australia to Dalian, China

	-18	-15	-12
emissions (kg CO2-e)			
processor	39	36	32
storage	16	15	14
freight	67	63	59
costs ($)			
processor	9	8	7.5
storage	3.7	3.6	3.4
freight	16	15	14

per tonne hot standard carcase weight

Data: Australian Meat Processor Corporation 2024 -1058

Raising the temperature will reduce energy costs and carbon emissions

Raising the temperature

Infrastructure

Most existing refrigeration equipment will be able to operate satisfactorily at a higher temperature, but some may need to undergo modification to increase efficiency and/or be recommissioned.

3 degrees of change report

RWTA member survey:

How would your operation need to adapt?

"easy to adapt to, no foreseeable issues"
"we would need to be cautious..."
"may require a change from operations"

Engineering of current storage and transport is not a problem

Raising the temperature

Shelf life is not affected by the raising of frozen food temperature

Raising the temperature will reduce energy costs and carbon emissions

Engineering of current storage and transport is not a problem

Raising the temperature for storage and transportation of frozen foods can be easily achieved with significant benefits and without the need for capital investment

Barriers to raising the temperature

FIRST M

- Australian regulation
- International regulation
- Supply chain practices

Barriers

Australian regulation

FIRST M

FOOD STANDARDS Australia • New Zealand
Te Mana Kounga Kai – Ahitereiria me Aotearoa

Cwuvtcnkc'Pgy'\ gcncpf'Hqqf'Ucpf ctfu'Eqfg

STANDARD 3.2.2

FOOD SAFETY PRACTICES AND GENERAL REQUIREMENTS

- Food intended to be received frozen, **is frozen**
- A food that is intended to be stored frozen.. **remains frozen**
- A food intended to be displayed frozen … **remains frozen**
- Food which is intended to be transported frozen **remains frozen**
- **Frozen does not include partly thawed**

- The Guidelines are **advisory** only
- It is the responsibility of **the manufacturer or producer, in consultation with its clients**, to set the Cold Chain requirements for any particular food
- Frozen foods …. Never warmer than -18°C [temperature of the product]

There is no regulatory barrier to raising the temperature of the frozen food chain

Barriers

International regulation

FIRST M

CODEX ALIMENTARIUS
INTERNATIONAL FOOD STANDARDS
Food and Agriculture Organization of the United Nations
World Health Organization

CAC/RCP 8- 1976 Page 1 of 14

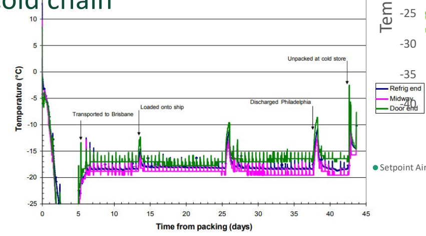
CODE OF PRACTICE FOR THE PROCESSING AND HANDLING OF QUICK FROZEN FOODS
(CAC/RCP 8-1976)

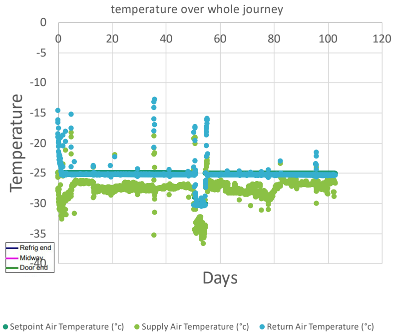
- The product temperature should be at -18°C or colder at the beginning of the transport
- Any rise above -18°C be kept to a minimum ….not…be warmer than -12°C
- Many countries set -18°C as the maximum temperature for frozen food

Gaining international acceptance of higher temperatures is a major challenge

Barriers **Practices**

- Product vs. Air temperature
- Temperature variations
  - Defrost
  - Refrigeration issues
- Breaks in cold chain





Cold chain practices must be validated tobe effective

Barriers to raising the temperature

There is no regulatory barrier to raising temperature in Australia

International acceptance is a major challenge

Cold chain practices must be validated to be effective

Developing and validating new practices for a warmer frozen food chain and gaining acceptance by customers and governments

Agenda for change

- **International**
- **Australia**
- **RWTA**

Agenda

International

The Move to Minus 15°C

Is a campaign to build a coalition of industry partners to change the temperature that frozen food is stored and transported at around the world.

DP WORLD
MAERSK
DAIKIN
GLOBAL COLD CHAIN ALLIANCE
Nomad Foods
Danish Crown
Morrisons
americold
Lineage

An international coalition to advocate for change has formed

Agenda

National

AMPC AUSTRALIAN MEAT PROCESSOR CORPORATION

- Research and development corporation for red meat sector
- Focus on international trade

Simplot AUSTRALIA

- Early discussions with multiple organisations on how to operationalise the change in Australia

AUSTRALIAN FOOD & GROCERY COUNCIL

- Considering how to approach the issue and how to bring all the supply chain actors together

Australian food businesses and corporations are keen for change

Agenda

RWTA

RWTA survey: building consensus amongst stakeholders

- Major food producers and food retailers need to be onboard with the temperature changes.
- Unanimous international support is needed
- Key considerations would include –
  a. Staging times on loading docks
  b. Loading dock temps
  c. How to treat products that required lower temps

rwta Confidence in food quality, every day.

RWTA can represent the sector in building the system and advocating for change

Agenda for change

An international coalition for change has formed

Australian food businesses and corporations are keen for change

RWTA can represent the sector in building the systems and advocating for change

Coordinated efforts to advocate for change will be required nationally and internationally

Conclusion

- **Can frozen food temperatures be raised?**

  easily achieved with significant benefits and without the need for capital investment

- **What are the barriers to raising frozen food temperatures?**

  Developing and validating new practices for a warmer frozen food chain and gaining acceptance by customers and governments

- **What is the agenda to achieve change?**

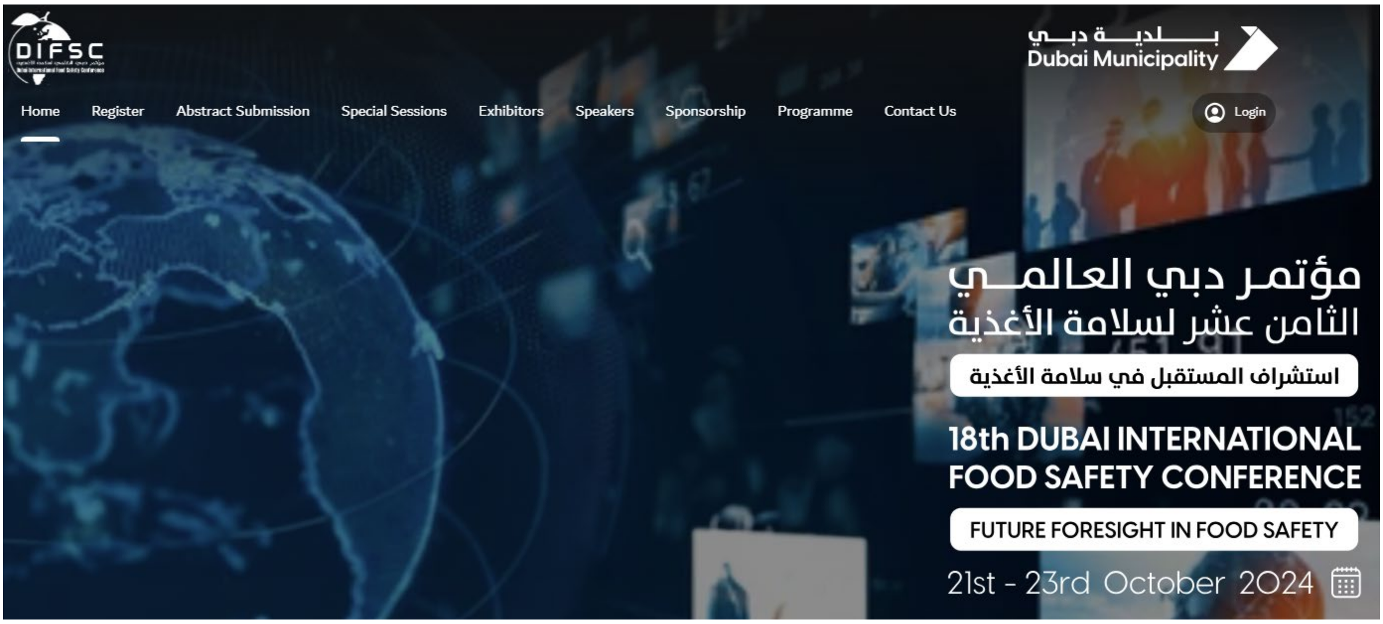
  Coordinated effort to advocate for change will be required

FIRST M
Food Innovation Research
Science Technology Management

mla
MEAT & LIVESTOCK AUSTRALIA

AMPC
AUSTRALIAN MEAT PROCESSOR CORPORATION

9.6.3 Dubai International Food Safety Conference



The future of frozen meat: high quality, energy-saving, and sustainable.

Ian Jenson

FIRST Management Pty Ltd, North Parramatta, NSW, Australia

Frozen meat is popular due to its long shelf life, resilience of its quality in supply chains that may not be well-controlled, and enduring low microbial load. There is a substantial international trade in frozen meat. One problem is that frozen meat is more expensive to produce, due to the additional costs of freezing, and the cost of maintaining the product at temperatures well below the freezing point.

Since the 1960s, -18°C has been the focal temperature for the storage and transportation of frozen foods of all kinds. As refrigeration technology and supply chains have improved, the desirability of food being rapidly frozen at -18°C and never again exceeding this temperature has been reinforced in government regulations and industry specifications.

Recently an international consortium of food industry and logistics sector companies, with academic support, has formed seeking to increase the standard frozen food storage and transportation temperature from -18°C to -15°C and beyond. This idea is motivated by the saving of energy, and therefore carbon emissions, when reducing the heat that needs to be removed in the freezing process, and the reduced energy to maintain that temperature. It is supported by data demonstrating the safety and quality of food stored at a higher than standard temperature.

The practical shelf life of Australian beef and lamb cuts as well as boneless manufacturing product has been determined to be over 2 years, even at -12°C and the safety of product is maintained. Data are being collected on other foods. There is a clear opportunity to lower the carbon emissions necessary to supply frozen meat. The challenge for the whole supply chain, from meat processor to retailer, is implementing change and coordination along the supply chain. The benefits are large, with essentially no implementation costs. Pilot trials are being implemented to explore how best to implement a warmer supply chain and ensure that product quality and safety is maintained.

9.7 Codex Alimentarius project document

Project document[100]

Code of Practice for the Processing and Handling of Quick Frozen Foods

CAC/RCP 8-1976 revision 2008

1. The purposes and the scope of the standard

The Code of Practice (CoP) has not been substantially revised for over 40 years. Opportunities for significant change in frozen food supply chains are presenting and this adherence to this CoP stands in the way of developing a more sustainable, safe and suitable food supply.

The scope is 'quick frozen foods', but excluding edible ices, ice creams and milk.

2. Its relevance and timeliness

- The CoP has high relevance because many Members regulate and enforce the '-18°C or colder' provision of the CoP. The default position, in many Member countries is that all frozen foods (not only Quick Frozen Foods) follow the requirements of this CoP.[101]
- Several studies are demonstrating that practical shelf life can be maintained for long periods at temperatures well above -18°C and as high as -12°C[102].
- The opportunity to raise the temperature of frozen food processing, handling, storage, transportation, and presentation for retail sale from -18°C to -12°C is impeded by the CoP
- -18°C as a default temperature results in larger carbon emissions than necessary to ensure a safe and suitable food supply[103]

3. The main aspects to be covered

- The scope of the CoP (inclusion of dairy products)
- The definition of quick freezing process
- Temperature control during the processing, handling, storage, transportation, export, import, and sale of (quick) frozen foods

4. An assessment against *Criteria for the establishment of work priorities*

- -18°C is not a risk-based parameter for determining the safety and suitability of food.
- It is not clear why some dairy products are excluded from the CoP, and it is an opportune time to consider which, if any, products should be excluded.[104]
- The CoP overstates the importance of -18°C as a key temperature (and implies that it is sometimes a critical limit in hazard control) and the opportunity afforded by the CoP for transport up to 12°C is rarely, if ever, taken because it is too restrictive. [105]

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[100] Procedures for the elaboration of Codex standards and related texts. CAC Procedural Manual. 28th ed.
[101] AMPC Project 2024-1058 Milestone 2 report
[102] Nomad Foods, Unilever, MLA (beef and lamb). AMPC Project 2024-1058 Milestone 2 report
[103] ALLOUCHE, Y., EVANS, J., SAYIN, L., FALAGAN, N., HETTERSCHEID, B. & PETER, T. 2023. Three Degrees of Change: Frozen food in a resilient and sustainable food system. FOX, T. (ed.) Summary report & initial findings ed.: International Institute of Refrigeration; Centre for Sustainable Cooling.
[104] Excluded from this CoP but caught up by Member countries provisions – Unilever. AMPC Project 2024-1058 Milestone 2 report
[105] AMPC Project 2024-1058 Milestone 2 report

- The default position, in many Member countries is that all frozen foods are covered by this CoP's general provision of '-18°C or colder'.[106] The definition of 'quick freezing process' is not easily applied to determine which foods are within scope of the CoP.
- Revision of the CoP could allow less developed countries participate in global frozen food supply chains, strengthen their agricultural base, improve their financial position, and contribute to achievement of SDGs.

5. Information on the relation between the proposal and other existing Codex documents as well as other ongoing work

- No other relevant work in Codex.
- The CAC Observer organisation, International Institute of Refrigeration, has an interest in this subject and may be engaged in ongoing work.[107]
- United Nations Economic Commission for Europe facilitates an agreement on international carriage of perishable foods.[108]

6. Identification of any requirement for and availability of expert scientific advice

- Expert advice may be necessary to better identify the products that should be covered by the CoP and how to define them (definition of 'quick frozen process').
- Expert advice may be necessary to determine the upper limit for temperature, possibly in combination with other parameters, to ensure the safety and suitability of food being stored frozen
- Expert advice may be necessary to define the criteria for demonstrating the practical shelf life of a product at a particular temperature or under particular conditions

7. Identification of any need for technical input to the standard from external bodies so that this can be planned for

- International Institute of Refrigeration
- United Nations Economic Commission for Europe

8. The proposed timeline for completion of the new work, including the start date, the proposed date for adoption at Step 5, and the proposed date for adoption by the Commission; the time frame for developing a standard should not normally exceed five years

[106] AMPC Project 2024-1058 Milestone 2 report

[107] IIR was a key organisation in the production of the report *Three Degrees of Change: Frozen food in a resilient and sustainable food system.*

[108] Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage (ATP). Text and Status of the Agreement | UNECE