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The shelf-life of Australian frozen red meat

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Abstract

Commercially produced Australian frozen beef and lamb was transported to the UK under standard commercially used conditions and then stored at -12°C, -18°C, and -24°C and instrumental, chemical, microbiological, and sensorial analyses conducted on the meat over a 38 calendar month period. Clear changes with time were found in chemical measures of rancidity that can be related to meat composition, packaging, and storage temperature. However, these changes do not appear to correlate clearly with the taste panel results in this study. Whereas the Peroxide Value (PV) and Thiobarbituric acid reactive substances (TBARS) levels (both signs of lipid oxidation/rancidity) show a clear relationship with storage temperature over time at different holding temperatures, this does not appear to be reflected in the taste panel assessment. While sensory degradation (a drop in mean scores of some characteristics) occurred over time in all meat samples this did not appear to be affected by storage temperature, but occurred at all storage temperatures, and the meat remained palatable after 38 months.

While -18°C has become established as the standard temperature for the storage of frozen foods, red meat of the type examined appears able to be stored successfully for many months or years at a temperature warmer than this threshold. Providing the meat is of sufficient hygienic quality when frozen and handled under controlled hygienic conditions, no food safety hazards exist with 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.

Executive summary

Background

Practical storage life (PSL) is the storage period of a product under specific storage condition, so long as the product maintains its organoleptic and nutritive characteristics and is suitable for human consumption or for further processing (IIR, 2006). The MLA publication on the 'Shelf life of Australian red meat' (MLA, 2014) lists the following criteria that define the usual end of shelf life for frozen ground beef and lamb chops as being 'rancid odour, flavour when cooked' and 'surface desiccation, sponginess (freezer burn)'.

There appears to be little literature, published in the last few decades, on the long-term frozen storage of beef or lamb. At the start of this project a semi-quantitate literature search was carried out to collect any published data on the subject. The search was restricted to publications produced since 1998 (i.e., publications in the last 25 years). There is an absence of reliable data on the storage life of commercially processed, frozen Australian beef and lamb, especially the relationship between its quality, storage temperatures and storage time. This lack of reliable data has limited its sales in some key export markets.

Objectives

The frozen Australian beef and lamb cuts used in this study were processed, packaged, and shipped under standard commercial refrigerated conditions. The beef was transported by sea and the lamb by air. In the UK the boxed samples were stored frozen at -12°C, -18°C (Control), and -24°C in cold storage rooms. Instrumental, chemical, microbiological, and sensorial analyses were conducted over a 38-calendar month period. Analysis was carried out on arrival (approximately 3 months post slaughter and initial freezing) and after 6, 12, 21, 24, 28, 32, 36, and 38 calendar months of storage. An assessment after 18 calendar months of storage was planned, but unfortunately could not take place due to the introduction of Covid restrictions at the time.

There were three overall objectives for this research project:

1. To determine the shelf-life of frozen Australian beef and lamb loin (strip loin and eye of loin, respectively), beef trim of 65CL, 85CL, and 95CL, and lamb trim of 65CL, 85CL, and 90CL (Chemical Lean).
2. To determine the correlation of frozen end of shelf-life (determined by taste panel) to any measurable parameters, such as oxidative rancidity (PV and TBARS).
3. To determine the rate of oxidation or development of rancidity in frozen Australian beef and lamb meat stored at -12°C, -18°C (Control), and -24°C.

Methodology

After processing and shipping, samples were stored at -12°C, -18°C (Control), and -24°C in cold storage rooms. Frozen beef and lamb samples were analysed on arrival (approx. 3 months post-production) and 6, 12, 21, 24, 28, 32, 36 and 38 calendar months after production. Samples were tested for thaw loss, colour, pH, cooking loss, texture (Warner-Bratzler shear force), microbial quality, lipid oxidation (Peroxide Value [PV], Thiobarbituric acid reactive substances [TBARS] and with gas chromatography-mass spectrometry [GC-MS]) and sensory (visual, smell, and taste).

Results/key findings

1. Determine the shelf-life of frozen Australian beef and lamb loin (strip loin and eye of loin, respectively), beef trim of 65CL, 85CL, and 95CL, and lamb trim of 65CL, 85CL, and 90CL (Chemical Lean).

While some sensory degradation occurred over time all samples remained palatable after 38 months storage at all temperatures. These results show that frozen Australian beef and lamb cuts and trim of the type examined can have a shelf-life of 36 months and longer, even when stored at -12°C.

2 Determine the correlation of frozen end of shelf-life (determined by taste panel) to any measurable parameters, such as oxidative rancidity (PV and TBARS).

Clear changes were found in chemical measures of lipid oxidation (PV and TBARS) that can be related to meat composition, packaging, and storage temperature. However, these changes did not appear to correlate clearly with the taste panel results in this study. Whereas the PV and TBARS showed a clear relationship with storage temperature over time (the lower the better), these relationships were not clearly reflected in the mean taste panel results, which showed a change in some characteristics over time but no clear relationship with storage temperature.

3 Determine the rate of oxidation or development of rancidity in frozen Australian beef and lamb meat stored at -12°C, -18°C (Control), and -24°C.

In common with other published studies, increases in lipid oxidation were observed over time. These results show a clear relationship between fat content, storage temperature and duration, and form of packaging, and lipid oxidation. Overall, the results of this study, clearly show the importance of vacuum-packaging of frozen meat for long term frozen storage, and that low storage temperature is important if the meat is intended to be stored for a long time, i.e., the lower the better. However, if meat of the type examined is to be stored for less than 24 months, storage temperature would appear to be less important.

Overall, from the results of this study, we can observe that as an 'objective' instrumental measurement TBARS and PV levels are useful indicators of the onset and development of lipid oxidation in frozen beef and lamb and a subsequent loss of 'quality' and show the effect of different storage temperatures and packaging.

In conclusion, the results of this study show that commercially produced boxed frozen beef and lamb loin and trim of the type examined can be stored for longer than 24 months and potentially up to 38 months at -12°C, -18°C, or -24°C. Particularly if vacuum-packed. These results when published should substantially improve the marketability of Australian frozen beef and lamb.

Benefits to industry

There is a lack of comprehensive scientific data to support the shelf-life for Australian frozen red meat for up to 36 months of storage. These data will provide evidence-based shelf-life claims for Australian product to respond to restrictive regulations in some importing countries and customer requests for substantiation. In 2020, 6.4 million tonnes of frozen red meat were exported around the world, the second highest volume on record and a trade worth US$28.2 billion.

Future research and recommendations

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. Providing the meat is of sufficient hygienic quality when frozen and handled under controlled hygienic conditions, no food safety hazards arise. Mandated shorter frozen shelf-life requirements (such as 12 months) should be reviewed to reflect this evidence.

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1 Background

Australia produces only 3% of global beef but is one of the world's largest exporters with almost 17% of world trade. Similarly, Australia makes up almost 40% of the global sheepmeat market, making it the largest supplier globally. In 2019 beef and sheepmeat exports were valued at A$7.96 and A$3.28 billion, respectively, with more than 60% shipped as frozen products (MLA, 2019a, 2019b). With increasing competition on the international meat export markets, ensuring the quality of frozen meat is essential for the viability of the Australian red meat industry. Industry insights conducted for MLA showed 'guaranteed safe to eat' and 'consistent quality standards' are some of the most important attributes to consumers, particularly those in Middle East and North Africa (MLA, 2015). Trims of varying chemical lean grades and whole primals make up a significant proportion of exported frozen beef and sheepmeat from Australia.

During frozen storage microbiological growth is arrested, thus no microbial spoilage can occur, but frozen food will slowly deteriorate over time due to oxidative and other changes. The International Institute of Refrigeration (IIR, 2006) 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)'. The practical storage life (PSL) of frozen food is defined as the storage period of a product under specific storage conditions, so long as the product maintains its organoleptic and nutritive characteristics and is suitable for human consumption or for further processing (IIR, 2006).

It is broadly accepted that the frozen storage life of meat is normally limited by the development of adverse flavours and odours caused by oxidative rancidity of fat (James & James, 2002). If the surface of the meat is exposed during frozen storage desiccation of the surface tissues may also occur, which produces a dry, spongy layer (commonly termed 'freezer burn') that is unattractive and does not recover after thawing and leads to rejection (James & James, 2002). While oxidation of oxymyoglobin can occur, affecting the colour of the meat (James & James, 2002), it is expected that the unacceptable changes in flavour and odour, stemming from oxidative rancidity of fat, is the most likely sensory change in frozen meat (Lawrie & Ledward, 2006). The development of oxidative rancidity is affected by both innate characteristics of the meat and the animal that the meat comes from and the treatment of the meat (James & James, 2002). Factors such as whether the meat is aged before freezing, the type and composition of the meat, the degree of saturation of the fat, the temperature of storage, and method of packaging are all believed to affect the onset and degree of these changes. The frozen storage life may also be reduced if the meat is frozen as individual cuts or comminuted, because this process exposes more meat surfaces to oxygen (James & James, 2002; MLA, 2014). There is evidence that the occurrence of rancidity in frozen bulk packed meat and large muscles is restricted to surface layers of the meat and not to the bulk muscle tissue and sub-surface fat thus may not be relatable to eating quality (Winger, 1984).

The MLA publication on the 'Shelf life of Australian red meat' (MLA, 2014) lists the following criteria that define the usual end of shelf life for frozen ground beef and lamb chops as being 'rancid odour, flavour when cooked' and 'surface desiccation, sponginess (freezer burn)'.

The first commercial modern mechanical refrigeration (ammonia based) freezing works is claimed to have been established by Thomas Mort in Sydney, Australia in 1861. While the first successful long distance shipment of frozen meat was from Buenos Aires to France in 1877, the S.S. Strathleven soon followed, shipping 40 tons of frozen beef and mutton from Sydney to London in 1880 (Critchell & Raymond, 1912). For many years frozen meat carcasses, sides, and quarters from Australia to the UK were transported to and stored in the UK at -10°C to -9°C (Cutting & Malton, 1974). According to Cutting & Malton (1974) 'occasionally a lower limit of -12°C is tolerated'. This was believed sufficient at the time to prevent any microbial growth and spoilage and maintain the quality of the frozen meat, though it is not clear how long a shelf life was expected at this temperature. It is not known when -18°C was adopted as the maximum recognised storage temperature for meat in the UK, but Cutting & Malton (1974) note at the time (the early 1970s) that practices were changing due to the requirements of regulations for 'intervention freezing'. Additionally, at the same time there was an increase in the use of general food cold stores storing different foods as well as meat, many of these foods required lower temperatures. They also note that the first edition of the International Institute of Refrigeration's 'Recommendations for the processing and handling of frozen foods' quoted expected storage lives for frozen meat for temperatures up to -12°C, whereas the second edition in 1972 included temperatures no higher than -18°C. Symons (1994) claimed that even as relatively recently as the 1980s the UK frozen meat trade was still storing meat at -10°C, although this is not the recollection of one of our authors (who is old enough to have been working at that time) of practices in the UK meat trade at the time, to their recollection -18°C was being used as standard. Lawrie (Lawrie & Ledward, 2006) notes research reporting that fats of beef and lamb are relatively resistant to oxidation and may still be good after 18 months storage at -10°C. However, it must be noted that there have been significant changes in the meat industry since the 1970s in both animal breeds and practices that make consideration of earlier research finding subject to error. Research conducted in New Zealand in the 1980s stored lamb at -10°C, -15°C and -20°C with satisfactory results (regarding rancid flavour development) for 14 to 24 months, depending upon processing conditions (Winger, 1984). The same source reported that an assessment of frozen lamb carcasses that had been stored for 30 months in commercial cold stores observed that while the external layers of these carcasses (that had been simply wrapped in stockinet) were unacceptably desiccated and rancid, the interior meat was found to be acceptable to consumers. Further research conducted in New Zealand suggested that lamb could be stored at -15°C for 15 months (Hagyard *et al.*, 1993). Recent studies by Coombs *et al.* (2017b, 2018a, b) and Holman *et al.* (2017, 2018a, b) found that long term storage of lamb and beef at -12°C for up to a year was comparable to storage at -18°C. While -18°C is widely recommended (or required) for the storage and distribution of frozen foods, many permit temperatures as high as -12°C during transport. Storage at a higher temperature would require less energy, providing economic and environmental benefits.

Many of Australia's international customers follow Codex Alimentarius guidelines and require frozen meat to be delivered at a temperature of -18°C or colder. The Australian industry's experience is that shelf lives set by other countries may be very conservative. For example, Saudi Arabia only accepts product labelled with an expiration period of up to 12-months from date of slaughter. Reliable data to show that the quality shelf life of frozen commercially produced beef and lamb is significantly longer than 12 months and that warmer distribution temperatures are not necessarily detrimental would significantly aid the marketability of Australian meat.

There appears to be relatively little recent published literature on the long-term frozen storage of beef or lamb. A semi-quantitate literature search was carried out to collect any published data on the subject. The search was restricted to publications produced since 1998 (i.e., publications in the last 25 years). Only studies that stored frozen beef or lamb for longer than 3 months were reviewed. A summary of the conditions and length of storage used in studies on the long-term storage of beef and lamb are shown in Table 1 and Table 2, respectively.

Table 1. Summary of conditions and length of storage used in studies on the long-term storage of beef published in the last 25 years

Muscle/Cut	Maximum length of storage	Temperature (°C)	Method of storage	Source
Slices of *M. Longissimus thoracis,* vacuum-packed	90 days	-20, -80	No details provided	Vieira *et al.* (2009)
Slices of *M. Longissimus dorsi* in over-wrapped tray	90 days	-20	No details provided	Popova *et al.* (2009)
Slices of ribeye rolls and inside rounds MAP, over-wrapped, vacuum-packed	90 days	-14.4	Walk-in freezer	Morgan (2004)
Fore and hind quarters (no wrap and polythene wrap) Cartoned boneless (no wrap and polythene wrap)	6 months	-10, -13, -18	(1) Pilot plant; -20°C and 0.7 m/s during freezing; -13°C and 0.4 m/s during on-shelf storage. (2) Industrial conditions; -24°C and 0.79 m/s during freezing; -10°C and 0.4 m/s storage. (3) Industrial conditions; -20°C and 0.8 m/s during freezing; storage in two pipe-cooled stores, one -13°C and the other -18°C; in both cases, the pieces were hung on hooks. (4) Industrial conditions; -25°C to -30°C and 3 m/s during freezing; -18°C and 0.5 m/s pallet storage.	Bustabad (1999)
Longissimus thoracis et lumborum Whole, diced, minced Cartoned polythene wrap	7 months	-20	No details provided	Zhang *et al.* (2005)
Slices of *M. semitendinosus*	12 months	−18, -35, -75	No details provided	Farouk *et al.* (2003)
Dry aged *longissimus lumborum,* steaks, vacuum-packed	12 months	-18	No details provided	Zhang *et al.* (2019)

Wet and dry aged *longissimus lumborum,* steaks, vacuum-packed	12 months	-18	No details provided	Zhang *et al.* (2021)
Loins, *M. longissimus lumborum*, vacuum-packed	1 year (52 weeks)	-12, -18	No details provided, stored at lab	Holman *et al.* (2017; 2018a, b)
Cuts of *Biceps femoris*	12 months	-23	No details provided	Lakehal *et al.* (2021)
Dry and wet aged *M. longissimus lumborum*; bone-in	24 months	-20	No details provided	Mungure *et al.* (2017)

Table 2. Summary of conditions and length of storage used in studies on the long-term storage of lamb published in the last 25 years

Muscle/Cut	**Maximum length of storage**	**Temperatures (°C)**	**Method of storage**	**Source**
Strips trimmed from ribs	5 months	-18, -50, -60, -80	Chest freezers (-18, -50, -60°C); Ultra low medical chest freezer (-80°C)	Choi *et al.* (2018)
Longissimus thoracis and *lumborum,* over-wrapped	6 months	−18	No details provided, stored at lab	Muela *et al.* (2010); Muela *et al.* (2012)
Longissimus thoracis and *lumborum*, over-wrapped	10 months	−18	No details provided, stored at lab	Bueno *et al.* (2013)
Longissimus dorsi, vacuum-packed	12 months	−18	Upright domestic freezer (Frost free)	Fernandes *et al.* (2013)
Longissimus thoracis et lumborum, vacuum-packed	12 months	-26	No details provided, stored at lab	Daszkiewicz *et al.* (2018)
Longissimus lumborum, vacuum-packed	12 months	-25	Upright domestic freezer	Pinheiro *et al.* (2019)
Longissimus lumborum, no details of packaging	1 year	-18	No details provided, stored at lab	Bueno *et al.* (2011)

Longissimus lumborum, vacuum-packed	1 year (52 weeks)	-12, -18	No details provided, stored at lab	Coombs *et al.* (2017b; 2018a, b)
Longissimus thoracis and *lumborum,* vacuum-packed	21 months	-18	No details provided, stored at lab	Muela *et al.* (2015, 2016)

Three of the studies identified, kept meat in frozen storage for periods approaching the 24 month and beyond target of this study. One of them (Mungure et al, 2017), stored beef for up to 24 months, while two studies (Muela *et al.*, 2015 and 2016, both by the same group) stored lamb for up to 21 months.

The Mungure *et al.* (2017) study showed that dry aged beef can be stored frozen for 24 months with no deleterious effect on conjugated linoleic acid (CLA) concentrations and tenderness. This study primarily compared wet and dry-aged beef after 24 months storage. It did not look at whether storage duration had any effect on final eating quality or at changes over the storage duration.

Studies published by Muela *et al.* (2010, 2015, 2016) on the frozen storage life of lamb were the only studies that evaluated the quality of the frozen samples with a trained sensory panel and a consumer panel. Overall, their studies indicate that panels cannot pick up differences between freezing methods, that frozen meat is often preferred over unfrozen meat, and that a difference could be detected by the panel in frozen lamb between storage periods of 15 and 21 months.

As is clear in Table 1 and Table 2, most recent published studies on the long-term storage of beef and lamb have only stored at -18°C. While these studies have usually provided details of the freezing regimes used (not reviewed here) they contain very few details on the exact storage conditions, e.g., whether temperatures were recorded, what is the actual mean, maximum, minimum temperatures were, whether there was a defrost (and if so, how regular was it, how long, and what effect did it have on product temperatures), etc. Many studies have stored samples in upright or chest freezers rather than boxed meat in walk-in cold storage rooms. The only recent studies that have looked at a range of storage temperatures are Bustabad (1999), Farouk *et al*. (2003), Holman *et al*. (2017; 2018a, b), and Coombs *et al*. (2017b; 2018a, b). Recent studies by Holman *et al*. (2017; 2018a, b), and Coombs *et al*. (2017b; 2018a, b) observed little difference to meat quality in storing beef or lamb, respectively, at temperatures of -12°C or -18°C over a 52 week period.

Reliable data on the frozen storage life of commercially produced lamb and beef, at different temperatures and storage times substantially longer than 12 months, should substantially aid the Australian frozen meat industry to expand its exports in countries that have negative views on the length of storage lives.

2 Project objectives

The overall objectives of this research project were to determine:

- The shelf-life of frozen Australian beef and lamb loin (strip loin and eye of loin, respectively), beef trim of 65CL, 85CL, and 95CL, and lamb trim of 65CL, 85CL, and 90CL (Chemical Lean).
- The correlation of frozen end of shelf-life (determined by taste panel) to any measurable parameters, such as oxidative rancidity (PV and TBARS).
- The rate of oxidation or development of rancidity in frozen Australian beef and lamb meat stored at -12°C, -18°C (Control), and -24°C.

3 Methodology

Frozen beef and lamb samples were analysed on arrival (approximately 3 months post-production) and 6, 12, 21, 24, 28, 32, 36 and 38 calendar months after production. An assessment after 18 calendar months of storage was planned, but unfortunately could not take place due to the introduction of Covid restrictions in the UK at the time.

3.1 Sample receival and storage

The beef and lamb were sourced and provided by Meat & Livestock Australia (MLA). Production and transport dates are shown in the table below (Table 3). Beef samples consisted of strip loins (*M. longissimus lumborum*) and trims of various chemical lean (CL) grades (65CL, 85CL, and 95CL). Lamb samples consisted of short (eye of) loins (*M. longissimus lumborum*) and trims of various chemical lean grades (65CL, 85CL, and 90CL). The frozen meats were commercially processed and produced as standard at two different meat processing plants in Victoria. The beef and lamb were conventionally frozen in commercial blast and plate systems approximately 48 to 72 hours after slaughter. Each group of the samples were packed in standard cardboard cartons. Each carton of beef loin contained 4 individual loins per carton, each loin weighing approximately 4 kg. Each carton of lamb loin contained 20 individual loins per carton, each loin weighing approximately 0.75 kg. Each carton of beef trim contained 2 individual bags of trim, each weighing approximately 10 kg. Each carton of lamb trim contained individual blocks of trim weighing approximately 27.2 kg. The beef and lamb loins, and beef trim were vacuum-packed within the boxes, while lamb trims were over-wrapped in bag liners. All meat samples were transported to the Food Refrigeration & Process Engineering Research Centre (FRPERC) at the Grimsby Institute (Grimsby, North East Lincolnshire, UK) under standard commercial frozen refrigerated conditions (i.e., <-18°C). The beef was shipped from Australia to the UK by sea and the lamb by air to Denmark and then by lorry to the UK. Upon receival, the cartons were split into equal groups and immediately stored at -12°C, -18°C, and -24°C in cold storage chambers until sampling and testing. The temperatures of the cold storage chambers were monitored and recorded using temperature data loggers. Air temperatures in the storage rooms fluctuated by approximately ±1°C during storage with automatic defrosts occurring every 6 h in the rooms set at -12°C and -18°C, and 7 h in the room set at -24°C. Initial (arrival) instrumental, chemical, microbiological, and sensorial analyses were conducted within 2 months of receival (approximately 3 months after production), while further analyses were conducted 6, 12, 21, 24, 28, 32, 36, and 38 calendar months after initial freezing (production).

Table 3. Beef and lamb slaughter, pack, and transport dates

Frozen Lamb	Frozen Beef
Trim Slaughter date: 25/09/18 Production date: 26/09/18 Eye of short loin Slaughter date: 26/09/18 Production date: 27/09/18 Delivery date: 15/10/18 (Australia) Entered Denmark: 16/10/18 Trucked to Grimsby: 22/10/18	Trim and loins Slaughter date: 11/09/18 Production date: 12/09/18 Delivery date: 17/09/18 (Brisbane port) Entered UK: 28/10/18 Trucked to Grimsby: 15/11/18

3.2 Sampling protocol

All frozen beef and lamb samples were cut, while still frozen, under ambient conditions (+18 ± 2°C). Multiple samples were collected from each carton using an AEW Thurne meat cutting band saw (Model 250). The trim was cut into 30 mm cubes for measurement of drip / thaw loss, colour, cooking loss, and 60 mm cubes for measurement of lipid oxidation, microbiology, shear force (Warner-Bratzler), volatile organic compounds, and sensory evaluation. The loins were cut into 15 mm thick steaks. Cutting was carried 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. The frozen colour of samples used to measure drip loss were measured prior to thawing then thawed in an unilluminated refrigerated display cabinet with a nightblind at approximately +5 ± 1°C for 48 h, then also used for pH, colour, and cook loss analysis. Samples for texture, lipid oxidation, and microbiological analyses were allowed to thaw in a refrigerator at approximately +2 ± 1°C for 24 hours prior to analysis.

3.3 Drip / thaw loss method

A method adapted from Kim *et al.* (2013) based on a modified Honikel (1998) method was used to measure drip / thaw loss.

Trim: 30 mm cuboid samples were cut in a frozen state from a block of frozen trim using an industrial food band saw (AEW Thurne (Model 250). The samples were then returned to the frozen storage condition for at least 2 hours before being tested to return to temperature. Once equalised back to its initial storage temperature a 30 mm cuboid trim sample was placed in a plastic net and then suspended within a closed container without contacting any side of the container. After 48 h of suspension at approximately +5 ± 1°C, the sample was removed from the container, blotted dry and then reweighed. The drip loss (%) was calculated as weight lost expressed as a percentage of the original sample weight.

Loin: 15 mm thick steak samples were cut in a frozen state from a frozen loin using an industrial food band saw (AEW Thurne (Model 250). The samples were then returned to the frozen storage condition for at least 2 hours before being tested to return to temperature. Once equalised back to its initial storage temperature a 15 mm thick steak sample was placed in a plastic net and then suspended within a closed container without contacting any side of the container. After 48 h of suspension at approximately +5 ± 1°C, the sample was removed from the container, blotted dry and then reweighed. The drip loss (%) was calculated as weight lost expressed as a percentage of the original sample weight, according to the following equation:

$$Drip/thaw\ loss\ (\%) = \frac{(frozen\ weight - thawed\ weight)}{frozen\ weight} \times 100$$

Means and standard deviations were calculated from 5 samples. The same samples used for the drip loss analysis were then also used for the pH, colour (loin only), and cooking loss analysis.

3.4 Colour method

Due to the mixture of different muscle and fat in the boxed trim samples instrumental colour measurements were only taken on beef and lamb loin samples. Colour measurements were taken on 5 steak samples (15 mm thick) cut from a frozen loin using an industrial food band saw (AEW Thurne (Model 250). On each of 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.

Meat sample colour was measured using a Minolta Chromameter (illuminant D65, 8 mm diameter aperture, 2° standard observer; CR-400; Konica-Minolta Corp., Tokyo, Japan). Colour was measured using the Commission Internationale de L'Éclairage (1978) (CIE) colour space (L*, a* and b*) after calibrating the instrument using a standard white tile. In the CIELAB colour space, L* denoting lightness to darkness, a* denoting the redness to green (positive red, to negative green) and b* denoting yellowness to blue (positive yellow to negative blue,). The CIE L* a* b* values were used to calculate saturation index / chroma and hue angle (AMSA, 2012). Hue angle (degrees) denoting the base colour (0° = red, 90° = yellow, 180° = green, 270° = blue). Chroma denoting the difference between pure grey (chroma = 0) to very high colour purity (chroma = 100). Chroma and hue were calculated using the following equations:

$$\text{Chroma} = \text{sqrt}(a^{*2}+b^{*2})$$

$$\text{Hue angle} = \arctan(b^*/a^*)$$

3.5 pH method

The pH of the centre of a thawed meat sample was measured using a Testo 205 pH meter (Testo AG, Germany) fitted with a meat probe (automatic adjustment for temperature) that was inserted into the meat sample perpendicular to the muscle fibres. The pH meter was calibrated at 18°C using pH 4 and pH 7 buffers.

Means and standard deviations were calculated from 5 samples.

3.6 Cooking loss method

A method adapted from Honikel (1998) method was used to measure cooking loss.

Each thawed meat sample (loin: rectangular strips 15mm x 20 mm x 40 mm of lean cut from thawed steaks; trim: 30 mm cuboid samples) was weighed, placed in a thin-walled plastic bag then placed in a continuously boiling stirred beaker of water, with the bag opening extending above the water surface. Samples were cooked to an internal temperature of 75°C. Once cooked the bag containing the sample was removed and cooled in an ice slurry and held at chill conditions (1 to 5°C) until the sample equilibrated to the holding condition. The meat sample was then taken from the bag, blotted dry, and weighed. The cooking loss was expressed as a percentage of the initial sample weight, according to the following equation:

$$Cooking\ loss\ (\%) = \frac{(thawed\ weight - cooked\ weight)}{thawed\ weight} \times 100$$

Means and standard deviations were calculated from 5 samples.

3.7 Texture method - Warner–Bratzler shear force (WBSF)

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. The frozen meat samples were thawed at +2±1°C for at least 24 h in a refrigerator. Steak samples were approximately 15 mm in thickness. The steak samples were kept at ambient temperature (approximately 20°C) for 60 minutes before cooking. The sample was cooked at 200°C for 3 min 20 s for double side cooking to obtain a 'medium' cooked steak. Pattie samples (from loin and trim) were also made from 150 g minced meat samples. Patties were cooked in the oven at 200°C for 35 minutes to reach core temperature 75°C. Rectangular strips of 20 mm x 20 mm were cut. WBSF was measured using a shear blade (V-shaped) adapted to a texture analyser with a 500 N load cell, and the shearing speed was set at 300 mm/min. The 'Firmness' (N), maximum shear force, and 'Toughness' (Ns^{-1}), total work of shear, were measured and recorded. Means and standard deviations were calculated from 5 samples.

3.8 Microbiological methods

Aerobic Colony Counts (ACCs) were measured in samples on arrival and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage. A more detailed analysis of microbial quality was carried out on the samples at 24 months.

The method used for the sample preparation of meat and meat products for microbiological examination followed ISO 6887-2:2017. The analysis of meat samples for Aerobic Colony Count (ACC) followed ISO 4833-2:2013. The additional analysis of meat samples for *Enterobacteriaceae* (EB), Coliforms (CF), *Staphylococcus aureus* (SA), *Escherichia coli* counts (EC) and presence of *Salmonella* (SAL) carried out at 24 months also followed standardised ISO protocols for the enumeration or detection of these organisms, these being: ISO 21528-2:2017, ISO 4832:2006, ISO 6888-1:2021, ISO 16649-1:2001, and ISO 6579-1:2017, respectively.

The general protocol was as follows. The meat samples were thawed overnight at +2±1°C (up to 24 h). Samples of 25±1 g of trim or steak were weighed and individually placed in sterile stomacher bags, to which 225 ml of Buffered Peptone Water (BPW) was added. For the trims the sample was homogenised in a stomacher set at 260 rpm 'High' for 2 minutes before conducting serial dilution in 9 ml BPW bottles and plating. For the beef and lamb loin samples, after adding the BPW to the stomacher bags the bag was heat sealed and the content shaken (to detach any microbial cell on the meat surface) for 2 minutes before conducting serial dilution in 9 ml BPW bottles and plating.

Liquid from the stomacher bags and individual serial dilution bottles were sampled in volumes of 0.1 ml with a sterile pipette and deposited on the surface of individual plates (of the appropriate growth media) corresponding to the dilution factor of handled sample, then spread with a sterile spreader. Duplicate plating was carried out for each dilution. Plates were left to rest on the lab bench for 15 minutes before inverting and incubating at the appropriate temperature and time for the organism (according to ISO protocol).

Colonies were counted with a manual plate counter. Plates with fewer than 300 colonies were used for the result calculation. Results were calculated according to the following equation:

$$N = \frac{A + B}{V \times 1.1 \times d}$$

Where,

A = Mean count of microorganisms on plates with fewer than 300 colonies,

B = Mean count of microorganisms on plates with more than 10 colonies,

V = Volume of inoculum (0.1 ml),

d = dilution factor corresponding to plates with less than 300 colonies (expressed as a fraction).

Counts were transformed into log values and means and standard deviations were calculated from counts on 5 samples.

3.9 Lipid oxidation analysis methods

Lipid oxidation was assessed by measuring peroxide value (PV) as indicative of primary oxidation; and thiobarbituric acid reactive substances (TBARS), mainly malondialdehyde (MDA), as indicative of secondary oxidation.

3.9.1 Peroxide Value (PV) analysis

This methodology was based on the IDF method to determine lipid peroxides in meat, poultry, fish, and vegetable oils.

Fat was extracted from the meat sample with a mixture of hexane-isopropanol (3 + 2 v/v) in a 1:2 ratio, after which the sample was homogenised in a Silverson Shear mixer homogeniser (Silverson machines Ltd, UK) at 5000 rpm for 1 minutes. The sample was then filtered using a Whatman No.1 filter paper and mixed with sodium sulphate solution (6.66% w/v) in a 1:1 ratio to facilitate hexane layer separation. The hexane layer containing the fat was then transferred to a beaker and evaporated at 45°C to purify the fat. To determine the peroxide value (PV), the extracted fat sample (0.15 g) in the liquid state was mixed with approximately 5ml of chloroform-methanol (7 + 3, v/v) on a vortex mixer for 2-4 s. Ammonium thiocyanate (25 µl) and iron (II) chloride solution (25 µl) were added and the sample vortexed for 2-4 s to complete the reaction. The absorbance at 500 nm using a 1510 UV-Vis spectrophotometer was recorded after 5 minutes incubation at room temperature against a blank (5 ml chloroform-methanol (7 + 3, v/v), ammonium thiocyanate (25 µl) and iron (II) chloride solution (25 µl)).

The hydroperoxide concentration was determined using a Fe^{+3} standard curve with an iron concentration varying from 1 to 20 mg. The peroxide value, expressed as milliequivalents of peroxide per kilogram of oil, was calculated using the following equation:

$$Peroxide\ Value\ (PV) = \frac{[(As - Ab) * m]}{[55.84 * \ m0 * 2]}$$

Where,

As = absorbance of the sample,

Ab = absorbance of the blank,

m = slope of the calibration curve (41.52),

*m*0 = mass (g) of the oily extracted sample (0.15 g),

55.84 = atomic weight of iron.

The result was divided by a factor of 2 to express the peroxide value as milliequivalents of peroxide instead of milliequivalents of oxygen.

Means and standard deviations were calculated from 9 samples.

3.9.2 Thiobarbituric Acid Reactive Substances (TBARS) analysis

The thiobarbituric acid reactive substances (TBARS) assay was conducted using the modified method of Sørensen & Jørgensen (1996) as a measure of the secondary lipid oxidation. The meat samples were thawed at 4°C, then 5 g was homogenised in a Silverson Shear mixer homogeniser (Silverson machines Ltd, UK) at 5000 rpm for 1 minutes in 15 ml trichloroacetic acid (TCA) solution (10% TCA, 0.1% propyl gallate and 0.1% ethylenediaminetetraacetic acid [EDTA]). The mixture was filtered through a Whatman No.1 filter paper and 5 ml of filtrate was mixed with 5 ml 20mM 2-thiobarbituric acid (TBA) and incubated at 95°C for 30 minutes. The absorbance at 532 nm was measured on a 1510 UV–Vis spectrophotometer against a blank sample (5 ml of 10% TCA solution with 5 ml of 20mM TBA solution). Results were reported as mg malondialdehyde (MDA) equivalent/kg sample. Concentrations of TBARS were calculated from a standard curve prepared using 1,1,3,3-tetraethoxypropane and presented as mg malondialdehyde (MDA)/kg. Means and standard deviations were calculated from 9 samples.

3.10 Analysis of ratio of hexanal to nonanal by Gas Chromatography–Mass Spectrometry (GC-MS)

The ratio of hexanal to nonanal was used as an indicator of lipid oxidation.

3.10.1 Reagent and Sample preparation

The Internal standard (IS) preparation (2-Methylpentanal) was prepared in the following manner. A stock solution of the IS was prepared by adding 1.237 ml of 98% purity 2-Methylpentanal into 100 ml deionised water. From the stock of IS 1 ml was pipetted into 99 ml H_2O to make the final solution. The final/working solution was then added to the homogenised meat sample.

The antioxidant Butylated hydroxyanisole (BHA) was prepared in the following manner. To dissolve the BHA powder, 1 ml of ethanol was added to 100 mg of BHA powder was added in an Eppendorf tube to make a 100 mg/ml stock solution. The dissolved BHA was then added to 99 ml of H_2O in a volumetric flask to make a final volume of 100 ml of final/working solution.

The meat sample was prepared in the following manner. Approximately 50 g of meat sample was weighed out and defrosted for the GC-MS analysis. After defrosting the meat was then minced in a mincer. From the 50 g minced meat sample, 5 g samples were then weighed and placed into 3 separate stomacher bags. To each sample bag, 25 ml of deionised water was added, the content of the bag was then put in the stomacher for 3 minutes at 230 rpm. After stomaching, the content of the stomacher bag was dispensed into a 50 ml centrifuge tube. To each tube 0.5 ml BHA and 0.5 ml 2-Methylpentanal were added to the homogenate in the tube. The tube was then mixed well by vortexing for 1 minute. The tube was then incubated in a water bath for 5 minutes at 40°C. It was then removed from the water bath and vortexed again for another minute. The centrifuge tube was left to settle for 5 minutes before pipetting out 3 ml of clear solution was pipetted into a 5 ml screw GC-MS head vial. The vial was then warmed at 30°C in a heating block for 5 minutes before introducing the SPME fibre for Head Space (HS) analysis.

3.10.2 VOC extraction by head space analysis

GC–MS analysis was performed on a Shimadzu GCMS-QP2010 Plus, fitted with an Agilent DB-1MS UI capillary Column with film thickness of 0.25 µm, internal diameter of 0.25 mm and length of 30.0 m with a column helium flow rate of 1.0 mL min^{-1}.

Solid-phase microextraction (SPME) was used to analyse the head space volatile compounds of the sample vial prepared above. With the use of an SPME fibre, VOCs relating to the meat samples were collected and analysed with GC-MS.

A 65 µm SPME fibre with Divinylbenzene/Polydimethylsiloxane (DVB/PDMS) phase, PDMS/DVB was used for analyte group volatiles, amines, and nitroaromatic compounds (MW 50-300). This fibre was used to extract VOCs from the headspace of each vial. After the 5 minute heat up to 30°C, the fibre was introduced into the sample vial for 20 minutes.

The injection port temperature was 250°C, run in splitless mode with a sampling time of 1 minute. The injection port was fitted with an SPME liner. The SPME fibre was desorbed in the injection port for 1 minute. The GC oven temperature programme was an initial hold at 40°C for 1 minute, followed by a ramp at 10°C/min to 250°C, followed by a hold for 12 minutes.

The mass spectrometer was operated in Electron Ionization (EI) mode with an energy of 70 eV and a source temperature of 200°C. The interface temperature was 270°C and ions were measured in the mass/charge (m/z) range of 33 to 500 with a scan speed of 2500.

The identification of compounds, hexanal and nonanal, was achieved by comparing the mass spectra of the chromatographic peaks with those of the National Institute of Standards and Technology (NIST) Atomic Spectra Database/Standard Reference Database. The ratio of these compounds for individual samples was calculated and means and standard deviations were calculated from 3 samples.

3.11 Sensory testing

3.11.1 Sensory evaluation plan, product preparation and cooking plan

The frozen loins (beef strip loin and lamb eye of loin) were thawed for at least 24 h in a refrigerator (0-4°C). After thawing the loins were cut into pieces of approximately 5 cm in width. Where necessary trimming was carried out. Prior to cooking, the loins were kept at ambient temperature (20°C) for approximately 20 minutes before grilling to achieve an internal muscle temperature of 13-15°C. The loins were cooked on a preheated electric hot grill plate (Buffalo double contact grill half flat) set to a temperature of 200 °C until a core temperature of at least 70°C was achieved 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. Samples were kept warm at 70°C until served (<15 minutes after being cooked).

The frozen trims were thawed for at least 24 h in a refrigerator (0-4°C). After thawing the beef and lamb trims were minced and processed into patties of equal size and weight (approximately 100 g). Weights for raw and cooked samples were recorded and photos taken to ensure consistency throughout the testing period. Cooking was performed at 200°C in a preheated electric fan oven until the internal temperature of 70°C was achieved, after approximately 30 minutes. Samples were kept warm at 70°C until they were served (<15 minutes after being cooked).

3.11.2 Evaluation area

This consisted of six individual booths that were equipped with an iPad and lighting. The assessors were provided with a set of forks and knives, water, and crackers for palate cleansing. The sensory booths were situated within close proximity, but out of view, of the preparation area. The samples were kept in a warm cabinet set at 70°C and were served warm. The sensory area was well lit, set at an ambient temperature of between 18-20°C, and conformed to the ISO 8589:2007 standards for sensory testing facilities.

3.11.3 Sampling plan and experimental design

The assessors were asked to cleanse their palate with mineral water at the beginning of the sensory evaluation and between samples to make the palate conditions similar for each sample. Assessors were advised to avoid any form of communication while the test was in progress to avoid any bias. A randomised and balanced sampling block were generated using the RedJade Sensory software (RedJade Sensory Solutions LLC, Redwood City, CA, USA). This was used to serve the panellist in random order according to sample, replicate, and assessor. The assessors were asked to log in to the system to carry out the sensory assessment of the sample of meat provided. Each panellist was provided with a standardized amount of each sample. When finished the assessors were free to leave the sensory suite.

3.11.4 Sensory method

A quantitative panel evaluation was carried out on the meat using approximately ten assessors each time (however, due to Covid restrictions a smaller number of assessors (5 to 8 depending on sample) were available to assess at month 32 and 38). Intensity scales and just about right (JAR) scales were used to determine if products differed significantly in the levels of specific attributes. The assessors were initially screened using the ISO 8586:2012 standard.

3.11.5 Descriptors

Descriptors used in the sensory analysis of beef and lamb meat were:

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

3.11.6 Procedure when assessing samples

Assessors were asked to read instructions thoroughly before any task and to adhere to them throughout the analysis. The assessors were asked to examine attributes in the following order:

1. Appearance
2. Odour
3. Flavour
4. Juiciness
5. Tenderness/texture

The assessors waited 10-15 s before tasting another sample. The time gap being sufficient to permit recovery, but not so long as to prejudice the ability to discriminate. 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) as exemplified below:

3.11.7 Cooked beef specifications

	RATING		
Characteristics	**(1-4)**	**(4-8)**	**(8-10)**
Appearance	Dark brown on the outer, hard, and with a brown and dry consistency on the inside	Slightly Brown on the outer, firm with consistent pinkish brown on the inside	Outer brown in colour, firm and roasted evenly with a consistent pinkish-brown colour on the inside
Odour	Rancid, tart, bitter and strong pungent warm off-odour	Mild beef aroma	Strong beef aroma, fresh
Flavour	Stale, gamey or livery off-flavour, metallic	Slightly dense beef flavour, sour, umami and mild buttery taste	Strong beefy flavour, salty and sweet (umami), sweet hay, Buttery dense flavour
Juiciness	Very dry	Slightly moist	Much too moist
Tenderness/texture	Rubbery, brittle, gritty and tough	Slightly tender and clear juices oozing	Tender and juicy (light red juices)

3.11.8 Cooked lamb specifications

	RATING		
Characteristics	**(1-4)**	**(4-8)**	**(8-10)**
Appearance	Dark brown, burnt, hard and dry	Firm, slightly brown in colour	Brown in colour and roasted evenly
Odour	Rancid, sour, acidic odour with a strong pungent warm off-flavour	Mild lamb aroma with grassy notes	Strong fresh lamb like odour with grassy notes
Flavour	Stale, metallic taste with sour and bitter notes with liver like off flavour and cardboard like taste	Slightly dense lamb like flavour, earthy and umami	Strong lamb like flavour, umami with buttery dense flavour
Juiciness	Very dry	Slightly moist	Much too moist
Tenderness/texture	Rubbery, brittle, gritty and tough	Clear juices oozing, slightly tender and firm	Tender and juicy and easy to cut and chew, melts in the mouth

3.11.9 Cooked beef and lamb patties scoring

Characteristics	Sensory Attributes	Scoring
Appearance	Too light in colour Moderately coloured, brown lightly Too dark in colour, overcooked	1 – 4 4 – 8 8 – 10
Odour	Very weak odour intensity Slightly weak odour intensity Very high odour intensity	1 – 4 4 – 8 8 – 10

Flavour	Weak flavour Slightly good/strong characteristic flavour Strong characteristic flavour	1 – 4 4 – 8 8 – 10
Juiciness	Very dry Slightly moist Much too moist	1 – 4 4 – 8 8 – 10
Tenderness/texture	Very tough Moderately tender Very tender	1 – 4 4 – 8 8 – 10

3.12 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 Pro 8.0.1.0 (AnalystSoft Inc., Walnut, CA, US). *P* values of 0.05 and below were determined to be significant. To determine whether individual comparisons (e.g., cooking loss -12°C 65CL trim samples at 9 vs 12 months) were significant, Fisher LSD post-hoc test was conducted.

4 Results and discussion

4.1.1 Drip / thaw loss

Mean drip/thaw losses measured in samples on arrival (approximately 3 months post-production) and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage are shown in Table 4. A graphical comparison of mean % drip/thaw loss results is shown in Figure 1. Also shown is the day 0 analysis performed by the University of Melbourne (Ha & Warner, 2018) that was carried out on frozen meat from the same batches soon after production. 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. 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. Consequently, most of the drip/thaw loss (in the form of both drip and moisture loss) will be from the muscle only.

Mean drip/thaw losses measured in all samples after 38 months frozen storage were similar to those measured initially by the University of Melbourne (Ha & Warner, 2018). In most cases mean drip/thaw losses measured in samples after 38 months storage were not significantly different ($P>0.05$) to that measured in samples at 3 to 6 months post-production. In some cases, there was a slight increase in drip/thaw loss with storage duration for particular sample groups, but these increases were not consistent over the entire duration of storage. For example, drip/thaw losses in beef loin stored at -24°C appeared to increase with storage duration for up to 21 months of storage, but then decreased and stabilised. Lamb trim 90CL (-12°C and -18°C samples) also appeared to show an increase in drip/thaw losses over time for up to 21/24 months of storage, but then decreased. Storage temperature also appeared to have 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 -12°C, -18°C, or -24°C. Differences, such as those between lamb trim 90CL samples measured at 24 and 32 months are likely to be due to box-to-box variation and differences in trim composition rather than an effect of storage temperature.

Recent published studies on the long term frozen storage of beef and lamb report conflicting findings on whether drip/thaw loss is affected by storage duration or temperature. Farouk *et al.* (2003) observed an increase in drip/thaw loss measured in beef (*m. semitendinosus*) with a frozen storage duration of up to 12 months (stored at -18°C, -35°C, -75°C). Pinheiro *et al.* (2019) and Muela *et al.* (2015) also reported an increase in drip/thaw losses over time in vacuum-packed lamb (*L. thoracis et lumborum*) stored up to 12 months or 21 months, respectively, at -25°C or -18°C, respectively. Other studies have observed no change. Daszkiewicz *et al.* (2018) observed no change in drip/thaw loss in vacuum-packed lamb (*L. thoracis et lumborum*) measured after 6 and 12 months storage at -26°C. Nor did Coombs *et al.* (2017a) or Holman *et al.* (2017) observe any effect of storage period or temperature upon drip/thaw loss in vacuum-packed lamb (*M. longissimus lumborum*) or beef (*M. longissimus lumborum*), respectively, stored for up to 12 months at -12°C or -18°C. None of these studies stored frozen meat beyond 24 months.

Table 4. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) drip / thaw loss (%) from beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Initial*	3 (arrival)	Frozen storage duration (Months) 6	12	21	24	28	32	36	38
Beef	-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)$^{ac}_{AB}$
loin	-18	8.1 (1.3)	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	-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)$^{ad}_{A}$
trim	-18	6.5 (3.4)	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)$^{a}_{B}$
95CL	-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	-12			2.1 (1.3)$^{a}_{A}$	8.1 (3.8)$^{b}_{A}$	5.0 (3.4)$^{ab}_{A}$	8.7 (4.4)$^{b}_{A}$	6.7 (3.6)$^{ab}_{A}$	11.4 (4.1)$^{b}_{A}$	11.9 (4.9)$^{b}_{A}$	5.8 (3.5)$^{a}_{A}$
trim	-18	4.6 (2.7)	4.3 (0.7)^{ab}	7.1 (2.7)$^{abc}_{B}$	3.7 (3.7)$^{ab}_{A}$	9.4 (4.5)$^{c}_{A}$	3.1 (1.5)$^{a}_{A}$	7.3 (2.4)$^{bc}_{A}$	5.1 (1.8)$^{abd}_{A}$	6.8 (2.5)$^{abc}_{AB}$	8.8 (2.9)$^{cd}_{A}$
85CL	-24			5.1 (3.1)$^{ab}_{AB}$	4.8 (3.3)$^{ab}_{A}$	5.0 (4.7)$^{ab}_{A}$	6.2 (4.5)$^{ab}_{A}$	5.2 (3.5)$^{ab}_{A}$	10.6 (8.6)$^{a}_{A}$	5.9 (2.3)$^{ab}_{B}$	3.8 (3.7)$^{b}_{A}$
Beef	-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)$^{a}_{A}$
trim	-18	3.6 (1.3)	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)$^{ab}_{A}$
65CL	-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	-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)$^{a}_{A}$
loin	-18	6.5 (3.4)	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	-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)$^{bc}_{A}$
trim	-18	10.8 (0.8)	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)$^{abc}_{A}$
90CL	-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	-12			11.5 (6.2)$^{ab}_{A}$	13.8 (1.3)$^{ab}_{A}$	16.2 (4.1)$^{a}_{A}$	14.5 (4.9)$^{ab}_{A}$	13.0 (4.8)$^{ab}_{A}$	8.5 (4.4)$^{b}_{A}$	8.6 (2.6)$^{b}_{A}$	11.0 (3.7)$^{ab}_{A}$
trim	-18	9.4 (2.5)	6.9 (4.4)^{a}	12.6 (5.9)$^{bcde}_{A}$	17.5 (0.9)$^{c}_{A}$	16.2 (2.0)$^{bcd}_{A}$	11.0 (2.9)$^{ab}_{A}$	16.1 (3.8)$^{bcd}_{A}$	18.5 (4.0)$^{c}_{B}$	11.6 (4.5)$^{ad}_{A}$	11.3 (1.4)$^{ae}_{A}$
85CL	-24			13.8 (2.4)$^{a}_{A}$	12.7 (5.3)$^{ab}_{A}$	6.9 (2.5)$^{b}_{B}$	13.6 (5.8)$^{a}_{A}$	13.9 (2.1)$^{a}_{A}$	13.2 (4.5)$^{a}_{AB}$	8.1 (5.0)$^{ab}_{A}$	11.1 (2.9)$^{ab}_{A}$
Lamb	-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)$^{a}_{A}$
trim	-18	3.7 (2.2)	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)$^{a}_{A}$
65CL	-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)$^{b}_{A}$

* Ha & Warner (2018); 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)

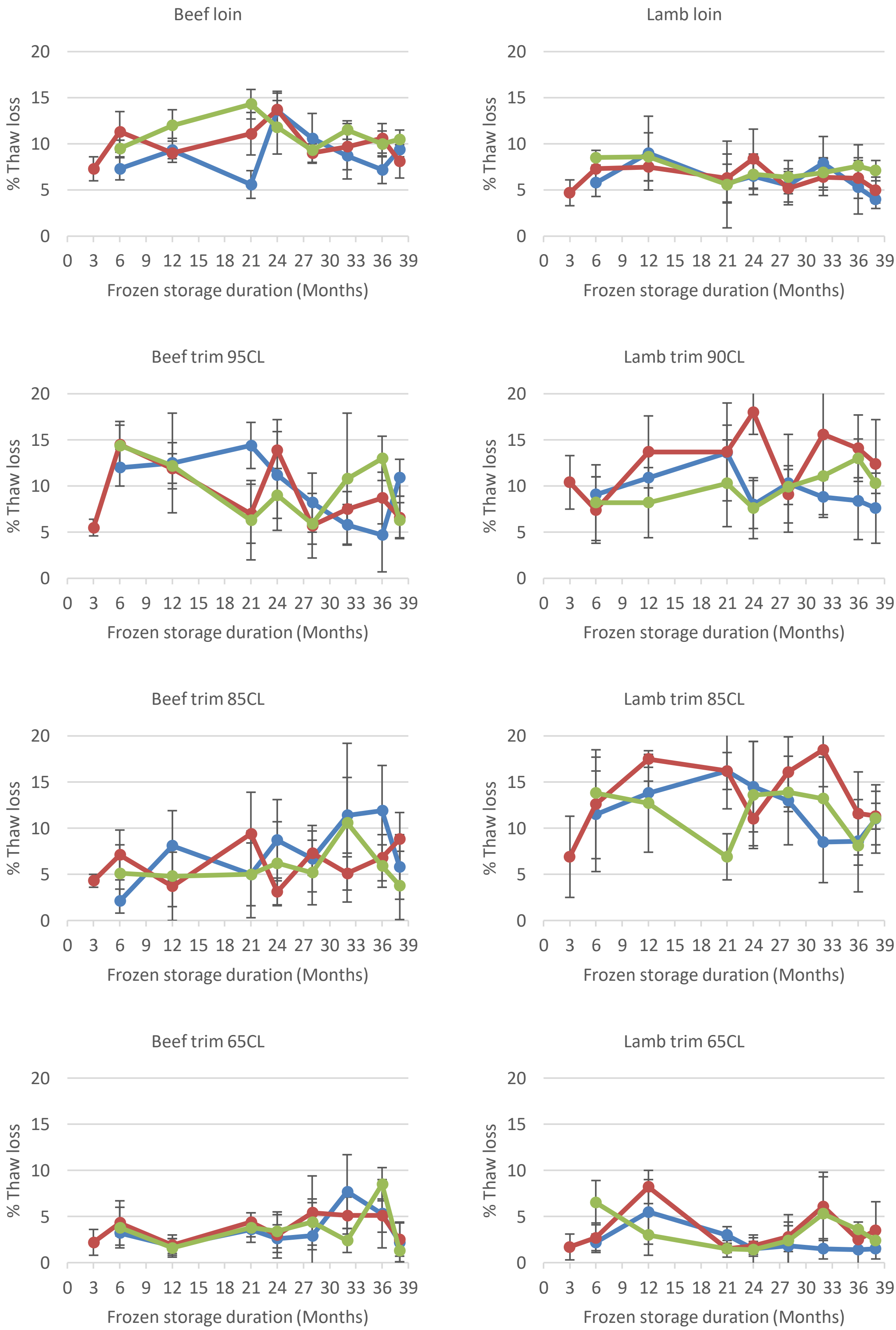


Figure 1. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean drip / thaw loss (%) from beef/lamb loin and trim (Vertical bars: ±1SD)

4.1.2 Colour

When assessed visually after 6 months storage there were slight signs of freezer burn (surface desiccation and discolouration) on the over-wrapped boxed lamb trim samples stored at -12°C. This was more apparent on samples analysed after 12 months of storage (and in all subsequently analysed samples stored at -12°C). Freezer burn was particularly apparent where the blocks had not been fully wrapped (Figure 2). There were no significant signs of discolouration on lamb trim stored at -18°C and -24°C, or on any of the vacuum-packed samples (i.e., lamb loin and all beef samples). Excessive freezer burn was apparent in the 90CL lamb trim sample that had been stored at -12°C assessed at 28 months, and to a lesser extent to the 85CL lamb trim sample (Figure 3). Samples, especially the 90CL lamb trim showed clear signs of freezer burn over upper and side surfaces. In our opinion the 90CL at 28 months would probably be rejected as having excessive freezer burn. No severe freezer burn was observed in boxed lamb trim samples cut for the 24 month assessment. 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.

Figure 2. Examples of freezer burn on poorly over-wrapped frozen lamb trim

Figure 3. Excessive freezer burn on frozen 90CL (left) and 85CL (right) lamb trim sample that had been stored at -12°C assessed at 28 months

Due to the mixture of muscle and fat in trim samples only chroma levels taken on beef and lamb loin fat and lean (muscle) measured on frozen and thawed samples are presented and will be discussed.

L*, a*, and b* levels measured on frozen and thawed loin samples on arrival and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage are shown in Table 5, Table 6, and Table 7 respectively. This data is compared graphically in Figure 4, Figure 5, and Figure 6. Overall saturation and hue angle levels are shown in Table 8 and Table 9, respectively, and graphically in Figure 7 and Figure 8. Overall, there were no clear trends in colour characteristics measured on the muscles or fat the beef or lamb loins with storage duration or temperature. There was considerable scatter in measurements made at different assessment times, which again is most likely due to box-to-box variation in the commercially produced meat.

Other recent published studies on long term frozen storage of beef or lamb have also generally observed few changes in colour characteristics (with a few exceptions). Lightness (L*) has been reported to be stable during frozen storage in lamb (Muela *et al.*, 2015; Pinheiro *et al.*, 2019), and a value <34 considered unacceptably dark in lamb (Khliji *et al.*, 2010). A decrease in redness (a*) has been observed in some studies on frozen beef (Farouk *et al.*, 2003) and lamb (Muela *et al.*, 2010; Pinheiro *et al.*, 2019). While Muela *et al.* (2015) found no clear trend in redness (a*) in vacuum-packed lamb (*L. thoracis et lumborum*) stored up to 21 months at -18°C. Fernandes *et al.* (2013) reported no change in brightness (L*) or redness (a*) in vacuum-packed lamb (*L. dorsi*) with frozen storage duration, stored for up to 12 months at -18°C. Similarly, Daszkiewicz *et al.* (2018) observed no change in any colour characteristics in vacuum-packed lamb (*L. thoracis et lumborum*) between 6 and 12 months storage at -26°C. Farouk *et al.* (2003) reported a decrease in hue angle measured in thawed beef (*M. semitendinosus*) with frozen storage duration (stored for up to 12 months at -18°C, -35°C, -75°C). None of these studies stored frozen meat beyond 24 months.

Table 5. Effect of frozen storage duration and temperature on mean (SD) L* values measured on frozen beef/lamb loin

Sample	Surface	Temp (°C)	Frozen storage duration (Months) 3 (arrival)*	6	12	21	24	28	32	36	38
Beef loin	Lean, frozen	-12		40.7 (4.7)$^{a}_{A}$	40.0 (2.7)$^{b}_{A}$	45.8 (6.8)$^{ab}_{A}$	39.6 (4.3)$^{c}_{A}$	45.6 (7.2)$^{a}_{A}$	45.3 (3.5)$^{a}_{A}$	42.6 (2.5)$^{bc}_{A}$	46.8 (3.4)$^{a}_{AB}$
		-18	40.9 (4.5)^{ab}	42.7 (2.8)$^{ab}_{A}$	45.9 (2.8)$^{a}_{B}$	45.7 (7.4)$^{a}_{A}$	42.3 (6.3)$^{ab}_{AB}$	44.5 (4.4)$^{ab}_{A}$	40.8 (4.2)$^{b}_{B}$	42.9 (2.4)$^{ab}_{A}$	45.8 (3.3)$^{a}_{A}$
		-24		39.3 (4.6)$^{a}_{A}$	51.5 (3.9)$^{b}_{C}$	47.5 (4.0)$^{c}_{A}$	46.4 (3.6)$^{cd}_{B}$	43.2 (3.5)$^{d}_{A}$	45.8 (5.6)$^{cd}_{A}$	47.9 (3.3)$^{c}_{B}$	49.1 (3.9)$^{bc}_{B}$
Beef loin	Lean, thawed	-12		33.6 (2.3)$^{a}_{A}$	35.9 (2.5)$^{ab}_{A}$	35.0 (4.3)$^{ab}_{A}$	34.9 (2.1)$^{ab}_{A}$	41.6 (5.0)$^{c}_{A}$	40.3 (2.6)$^{c}_{AB}$	36.4 (2.8)$^{b}_{A}$	39.5 (2.9)$^{c}_{A}$
		-18		34.1 (3.0)$^{a}_{B}$	37.8 (2.8)$^{b}_{AB}$	39.7 (2.5)$^{b}_{B}$	38.1 (2.9)$^{b}_{B}$	38.9 (2.6)$^{b}_{AB}$	39.1 (2.7)$^{b}_{A}$	38.9 (3.0)$^{b}_{B}$	34.0 (3.3)$^{a}_{B}$
		-24		37.1 (4.0)$^{ab}_{AB}$	38.3 (2.2)$^{abc}_{B}$	39.7 (2.9)$^{cd}_{B}$	39.5 (2.7)$^{ac}_{B}$	37.9 (3.1)$^{abd}_{B}$	41.6 (2.4)$^{c}_{B}$	36.7 (2.8)$^{b}_{AB}$	40.0 (3.2)$^{c}_{A}$
Beef loin	Fat, frozen	-12		78.0 (2.7)$^{ab}_{A}$	76.6 (1.8)$^{ac}_{AB}$	76.5 (2.1)$^{ac}_{A}$	74.9 (4.8)$^{c}_{A}$	75.9 (2.9)$^{ac}_{A}$	76.0 (3.3)$^{ac}_{A}$	78.0 (1.6)$^{ad}_{A}$	79.7 (1.6)$^{bd}_{A}$
		-18	73.3 (2.0)^{abc}	75.5 (2.0)$^{abd}_{B}$	77.8 (1.0)$^{d}_{A}$	73.9 (4.3)$^{ac}_{B}$	75.5 (3.3)$^{ad}_{A}$	74.9 (3.0)$^{ac}_{A}$	76.2 (4.0)$^{bd}_{A}$	72.7 (2.2)$^{c}_{B}$	76.3 (1.5)$^{abd}_{B}$
		-24		76.0 (1.9)$^{a}_{B}$	75.4 (4.3)$^{a}_{B}$	74.3 (1.3)$^{ab}_{AB}$	73.8 (2.1)$^{ab}_{A}$	78.6 (2.7)$^{c}_{B}$	75.4 (2.2)$^{a}_{A}$	74.4 (1.7)$^{ab}_{C}$	72.8 (3.9)$^{b}_{C}$
Beef loin	Fat, thawed	-12		72.7 (4.5)$^{a}_{A}$	70.6 (4.0)$^{ab}_{A}$	72.8 (2.5)$^{a}_{A}$	65.4 (16.6)$^{b}_{A}$	72.2 (3.2)$^{a}_{A}$	70.7 (5.0)$^{ab}_{A}$	71.1 (3.9)$^{ab}_{A}$	73.3 (8.7)$^{a}_{A}$
		-18		66.6 (5.6)$^{a}_{AB}$	69.8 (8.2)$^{a}_{A}$	69.6 (5.1)$^{a}_{AB}$	68.6 (7.2)$^{a}_{A}$	70.2 (3.6)$^{a}_{A}$	66.3 (3.1)$^{a}_{AB}$	67.6 (4.2)$^{a}_{B}$	69.5 (3.6)$^{a}_{A}$
		-24		71.3 (2.0)$^{ab}_{B}$	70.6 (3.6)$^{ab}_{A}$	68.4 (4.4)$^{ac}_{B}$	64.7 (5.4)$^{d}_{A}$	72.6 (3.5)$^{b}_{A}$	65.3 (8.7)$^{cd}_{B}$	67.7 (3.4)$^{ad}_{B}$	68.4 (5.0)$^{ad}_{A}$
Lamb loin	Lean, frozen	-12		43.8 (2.2)$^{a}_{A}$	40.0 (2.7)$^{b}_{A}$	44.4 (1.8)$^{ac}_{A}$	42.9 (4.8)$^{a}_{A}$	46.0 (4.1)$^{cd}_{A}$	47.4 (3.0)$^{d}_{A}$	44.8 (5.1)$^{ad}_{A}$	42.8 (2.5)$^{ab}_{A}$
		-18	38.3 (3.2)^{a}	39.4 (3.1)$^{a}_{AB}$	45.9 (2.8)$^{bc}_{B}$	50.7 (4.1)$^{d}_{B}$	40.6 (6.0)$^{ae}_{A}$	47.2 (2.7)$^{bcd}_{A}$	49.0 (6.4)$^{bd}_{A}$	43.6 (4.1)$^{ce}_{A}$	44.2 (6.6)$^{ce}_{A}$
		-24		46.0 (3.2)$^{ab}_{B}$	51.5 (3.9)$^{c}_{C}$	47.8 (3.6)$^{a}_{C}$	39.8 (4.9)$^{d}_{A}$	47.0 (3.1)$^{ae}_{A}$	49.9 (5.2)$^{cef}_{A}$	46.9 (5.7)$^{af}_{A}$	42.8 (4.3)$^{bd}_{A}$
Lamb loin	Lean, thawed	-12		39.3 (11.1)$^{ab}_{A}$	35.9 (2.5)$^{bcd}_{A}$	42.3 (2.5)$^{ae}_{A}$	36.8 (3.7)$^{abc}_{A}$	38.4 (3.6)$^{abe}_{A}$	34.9 (4.2)$^{cf}_{A}$	32.8 (2.7)$^{c}_{A}$	38.6 (2.0)$^{adef}_{A}$
		-18		31.1 (3.2)$^{a}_{B}$	37.8 (2.8)$^{bc}_{A}$	38.9 (3.4)$^{bc}_{B}$	38.4 (3.6)$^{bc}_{A}$	38.1 (4.0)$^{bc}_{A}$	37.8 (3.5)$^{bc}_{AB}$	39.5 (3.1)$^{b}_{B}$	36.6 (3.3)$^{c}_{A}$
		-24		32.3 (3.4)$^{a}_{B}$	38.0 (2.3)$^{bc}_{A}$	39.7 (5.0)$^{b}_{B}$	37.5 (3.6)$^{bc}_{A}$	35.5 (2.8)$^{c}_{A}$	38.7 (4.5)$^{b}_{B}$	37.8 (3.0)$^{bc}_{B}$	36.4 (3.3)$^{c}_{A}$
Lamb loin	Fat, frozen	-12		70.5 (4.8)$^{a}_{A}$	76.6 (1.8)$^{b}_{AB}$	76.0 (5.7)$^{b}_{A}$	71.3 (4.8)$^{a}_{A}$	76.3 (3.6)$^{b}_{A}$	71.9 (4.9)$^{a}_{A}$	75.6 (4.2)$^{b}_{A}$	77.9 (6.8)$^{b}_{A}$
		-18	70.3 (3.0)^{a}	69.0 (4.3)$^{a}_{B}$	77.8 (1.0)$^{bc}_{A}$	77.1 (4.1)$^{b}_{A}$	74.3 (3.8)$^{a}_{A}$	80.4 (3.2)$^{c}_{B}$	78.6 (3.4)$^{bc}_{B}$	72.8 (4.7)$^{a}_{A}$	73.9 (5.0)$^{a}_{AB}$
		-24		74.4 (4.7)$^{a}_{B}$	75.4 (4.3)$^{ab}_{B}$	75.7 (4.3)$^{ab}_{A}$	74.3 (3.5)$^{a}_{A}$	78.3 (3.4)$^{b}_{AB}$	75.7 (6.4)$^{ab}_{AB}$	75.6 (4.5)$^{ab}_{A}$	78.5 (3.6)$^{b}_{B}$
Lamb loin	Fat, thawed	-12		54.5 (13.4)$^{a}_{A}$	70.6 (4.0)$^{bcd}_{A}$	70.1 (7.1)$^{bcd}_{A}$	67.0 (4.1)$^{be}_{A}$	73.3 (2.7)$^{c}_{A}$	65.7 (4.9)$^{de}_{A}$	63.3 (6.4)$^{e}_{A}$	72.3 (5.9)$^{bc}_{A}$
		-18		66.6 (4.6)$^{a}_{B}$	69.8 (8.2)$^{ab}_{A}$	69.7 (4.5)$^{ab}_{A}$	66.9 (3.1)$^{a}_{A}$	72.7 (5.4)$^{b}_{A}$	68.6 (3.2)$^{a}_{A}$	69.3 (2.8)$^{ab}_{B}$	66.5 (3.1)$^{a}_{B}$
		-24		69.6 (3.7)$^{a}_{B}$	66.8 (7.6)$^{a}_{A}$	68.4 (5.9)$^{a}_{A}$	67.0 (5.5)$^{a}_{A}$	71.0 (4.8)$^{a}_{A}$	66.8 (5.2)$^{a}_{A}$	71.1 (5.5)$^{a}_{B}$	71.0 (4.5)$^{a}_{A}$

N=15, 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 ($P<0.05$)

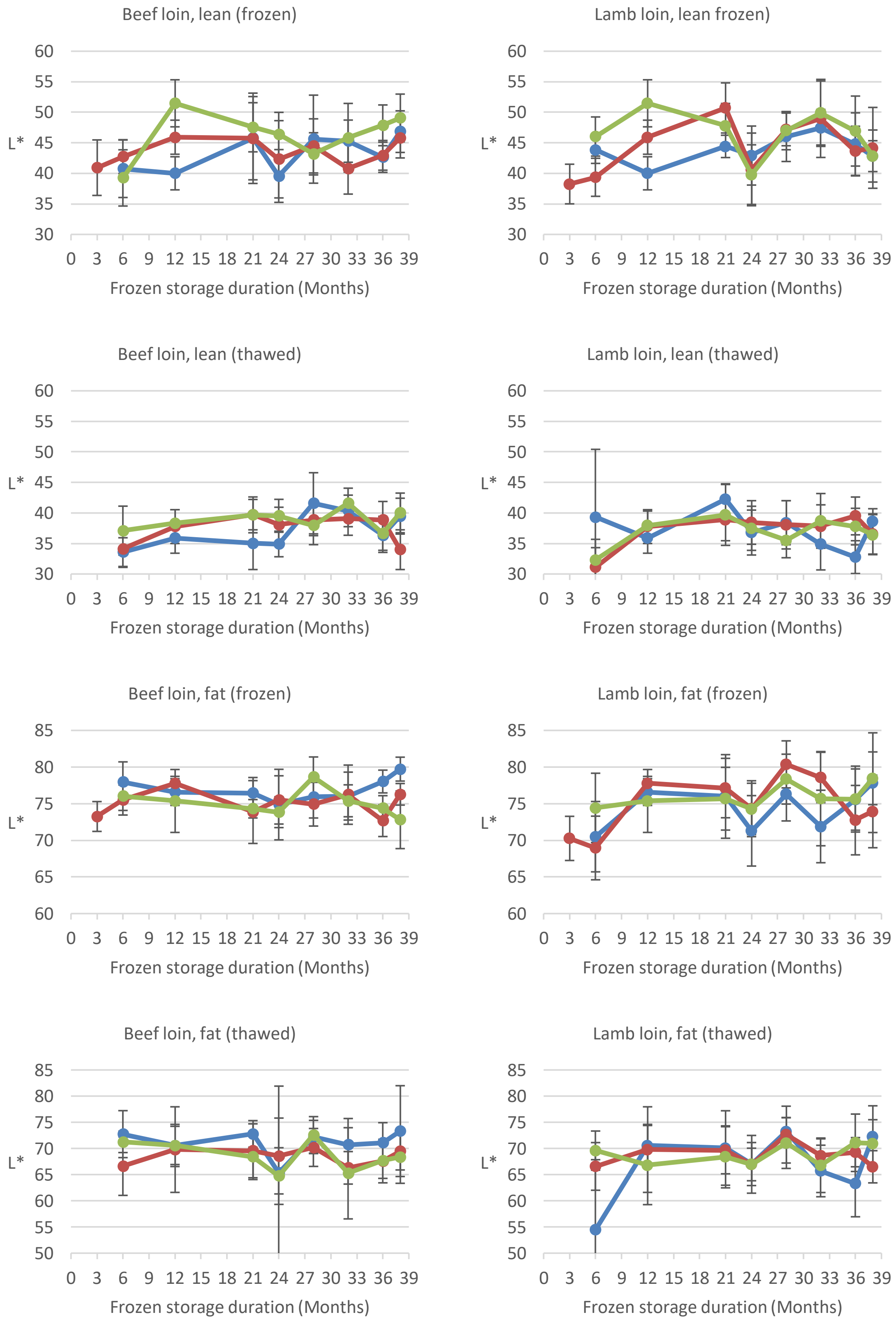


Figure 4. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean L* values measured on frozen beef/lamb loin, N.B. lean and fat results are presented on a different scale (Vertical bars: ±1SD)

Table 6. Effect of frozen storage duration and temperature on mean (SD) a values measured on frozen beef/lamb loin*

Sample	Surface	Temp (°C)	Frozen storage duration (Months)								
			3 (arrival)*	6	12	21	24	28	32	36	38
		-12		15.3 (1.7)$^{ab}_{A}$	17.1 (1.5)$^{a}_{A}$	11.9 (3.2)$^{c}_{A}$	16.5 (2.7)$^{ad}_{A}$	13.9 (3.5)$^{be}_{A}$	14.8 (1.6)$^{bd}_{A}$	14.0 (1.9)$^{be}_{A}$	12.5 (1.2)$^{ce}_{A}$
Beef loin	Lean, frozen	-18	16.3 (3.0)^{a}	14.2 (1.7)$^{ab}_{A}$	15.9 (2.1)$^{a}_{A}$	13.4 (3.4)$^{c}_{A}$	14.1 (2.4)$^{ac}_{B}$	11.2 (3.0)$^{d}_{B}$	14.3 (2.3)$^{ac}_{A}$	12.8 (1.4)$^{bcd}_{A}$	11.3 (1.7)$^{d}_{A}$
		-24		15.7 (2.4)$^{a}_{A}$	12.7 (2.0)$^{bc}_{B}$	11.6 (1.8)$^{b}_{A}$	11.5 (1.7)$^{b}_{C}$	13.5 (1.9)$^{c}_{AB}$	13.9 (2.0)$^{c}_{A}$	13.7 (2.1)$^{c}_{A}$	11.9 (1.5)$^{b}_{A}$
		-12		19.7 (2.1)$^{a}_{A}$	17.1 (2.3)$^{bcd}_{A}$	18.6 (3.6)$^{abd}_{A}$	18.5 (1.2)$^{abd}_{A}$	16.0 (2.1)$^{cd}_{A}$	15.5 (1.6)$^{c}_{A}$	17.4 (2.2)$^{de}_{A}$	16.5 (1.5)$^{ce}_{A}$
Beef loin	Lean, thawed	-18		19.5 (3.0)$^{a}_{A}$	16.6 (1.6)$^{bc}_{B}$	15.6 (2.4)$^{b}_{AB}$	17.6 (1.5)$^{ab}_{A}$	18.2 (1.9)$^{acd}_{B}$	18.2 (4.1)$^{acd}_{B}$	17.4 (2.4)$^{bd}_{A}$	16.8 (2.0)$^{bd}_{A}$
		-24		18.3 (2.9)$^{a}_{A}$	19.0 (1.8)$^{a}_{AB}$	15.4 (4.5)$^{b}_{B}$	18.3 (1.8)$^{a}_{A}$	17.7 (1.6)$^{a}_{B}$	17.9 (1.9)$^{a}_{B}$	17.5 (1.2)$^{a}_{A}$	17.4 (2.2)$^{ab}_{A}$
		-12		6.7 (1.3)$^{ab}_{A}$	7.0 (1.1)$^{a}_{A}$	1.1 (0.4)$^{c}_{A}$	4.2 (2.1)$^{d}_{A}$	6.6 (1.9)$^{ab}_{AB}$	3.9 (1.2)$^{d}_{A}$	5.6 (1.7)$^{b}_{A}$	0.1 (0.4)$^{c}_{A}$
Beef loin	Fat, frozen	-18	8.2 (2.1)^{a}	7.1 (0.8)$^{a}_{A}$	7.4 (0.5)$^{a}_{B}$	4.4 (2.1)$^{bc}_{B}$	4.4 (2.3)$^{bc}_{A}$	7.8 (2.5)$^{a}_{A}$	3.8 (1.7)$^{c}_{A}$	7.6 (2.8)$^{a}_{B}$	5.6 (1.7)$^{b}_{B}$
		-24		6.3 (1.0)$^{ab}_{A}$	6.3 (1.8)$^{ab}_{B}$	6.0 (1.6)$^{abc}_{C}$	6.6 (0.8)$^{b}_{B}$	5.2 (0.9)$^{ac}_{B}$	5.0 (1.4)$^{c}_{A}$	7.0 (1.7)$^{bd}_{AB}$	8.0 (2.0)$^{d}_{C}$
		-12		8.8 (2.7)$^{a}_{A}$	8.0 (1.7)$^{ab}_{A}$	1.9 (1.3)$^{c}_{A}$	6.2 (2.4)$^{bd}_{A}$	6.2 (1.8)$^{bd}_{A}$	5.2 (1.8)$^{d}_{A}$	7.2 (2.6)$^{ab}_{A}$	1.7 (3.9)$^{c}_{A}$
Beef loin	Fat, thawed	-18		8.7 (3.0)$^{ab}_{A}$	7.8 (3.1)$^{abc}_{A}$	5.9 (3.3)$^{c}_{B}$	5.7 (2.8)$^{c}_{A}$	9.1 (2.4)$^{a}_{B}$	6.2 (3.1)$^{c}_{A}$	9.5 (2.0)$^{a}_{B}$	6.5 (1.9)$^{b}_{B}$
		-24		8.1 (1.5)$^{a}_{A}$	9.9 (3.7)$^{a}_{A}$	9.1 (3.2)$^{a}_{C}$	9.1 (2.8)$^{a}_{B}$	8.1 (2.5)$^{a}_{AB}$	8.0 (5.1)$^{a}_{A}$	7.8 (2.1)$^{a}_{AB}$	10.1 (3.1)$^{a}_{C}$
		-12		14.9 (1.5)$^{a}_{A}$	17.1 (1.5)$^{b}_{A}$	14.3 (1.4)$^{a}_{A}$	13.3 (2.7)$^{c}_{AB}$	11.6 (1.9)$^{d}_{A}$	13.6 (1.2)$^{ac}_{A}$	13.4 (2.2)$^{ac}_{AB}$	13.5 (1.6)$^{ac}_{AB}$
Lamb loin	Lean, frozen	-18	14.4 (2.6)^{abc}	16.7 (1.9)$^{a}_{B}$	15.9 (2.1)$^{b}_{A}$	12.1 (2.0)$^{c}_{B}$	12.6 (2.7)$^{cd}_{A}$	14.1 (2.0)$^{bd}_{B}$	13.0 (2.9)$^{cd}_{A}$	14.6 (2.3)$^{bd}_{A}$	12.0 (2.8)$^{c}_{A}$
		-24		13.3 (1.7)$^{abcd}_{C}$	12.7 (2.0)$^{acd}_{B}$	12.1 (2.4)$^{ac}_{B}$	14.9 (2.3)$^{be}_{B}$	13.8 (1.9)$^{a}_{B}$	12.9 (3.0)$^{ac}_{A}$	11.9 (2.7)$^{c}_{B}$	14.2 (1.8)$^{de}_{B}$
		-12		17.0 (2.6)$^{a}_{A}$	17.1 (2.3)$^{a}_{A}$	12.1 (1.7)$^{b}_{A}$	13.8 (1.7)$^{cd}_{A}$	14.5 (1.6)$^{cd}_{A}$	14.2 (2.0)$^{c}_{A}$	16.1 (1.4)$^{a}_{A}$	13.7 (2.0)$^{bd}_{A}$
Lamb loin	Lean, thawed	-18		16.5 (2.6)$^{ab}_{A}$	16.6 (1.6)$^{a}_{A}$	15.3 (2.8)$^{ac}_{B}$	14.5 (2.1)$^{c}_{A}$	16.9 (2.5)$^{a}_{B}$	16.2 (2.1)$^{a}_{B}$	14.1 (2.0)$^{c}_{B}$	14.7 (1.6)$^{bc}_{A}$
		-24		15.9 (2.4)$^{ab}_{A}$	13.3 (1.7)$^{c}_{B}$	13.7 (2.9)$^{c}_{AB}$	14.4 (2.9)$^{ad}_{A}$	16.6 (1.7)$^{be}_{B}$	14.4 (2.4)$^{ac}_{AB}$	13.8 (1.4)$^{cd}_{B}$	17.8 (1.9)$^{e}_{B}$
		-12		8.2 (2.0)$^{a}_{A}$	7.0 (1.1)$^{ab}_{AB}$	6.2 (2.3)$^{ab}_{A}$	6.8 (2.7)$^{ab}_{A}$	6.9 (1.6)$^{ab}_{A}$	5.9 (2.8)$^{b}_{A}$	5.9 (2.0)$^{b}_{A}$	6.5 (4.2)$^{ab}_{A}$
Lamb loin	Fat, frozen	-18	9.5 (2.7)^{ab}	9.9 (2.2)$^{a}_{A}$	7.4 (0.5)$^{c}_{B}$	5.2 (1.3)$^{de}_{A}$	6.9 (1.9)$^{c}_{A}$	4.1 (0.8)$^{d}_{B}$	6.5 (1.6)$^{ce}_{A}$	8.0 (2.1)$^{bc}_{B}$	9.3 (2.4)$^{ab}_{B}$
		-24		6.1 (2.9)$^{a}_{B}$	6.3 (1.8)$^{a}_{A}$	5.2 (2.7)$^{ab}_{A}$	6.3 (1.7)$^{a}_{A}$	5.8 (3.0)$^{ab}_{A}$	5.8 (2.0)$^{ab}_{A}$	4.0 (1.5)$^{b}_{C}$	5.7 (1.4)$^{ab}_{A}$
		-12		14.7 (5.1)$^{a}_{A}$	8.0 (1.7)$^{b}_{A}$	8.7 (3.6)$^{b}_{A}$	7.1 (3.6)$^{b}_{A}$	6.9 (2.5)$^{b}_{A}$	7.4 (2.5)$^{b}_{A}$	8.5 (2.7)$^{b}_{A}$	6.6 (3.9)$^{b}_{A}$
Lamb loin	Fat, thawed	-18		10.4 (3.4)$^{ab}_{A}$	7.8 (3.1)$^{c}_{A}$	8.6 (3.3)$^{abc}_{A}$	7.8 (2.5)$^{c}_{A}$	6.3 (3.6)$^{c}_{A}$	8.3 (2.4)$^{ac}_{A}$	7.2 (1.7)$^{c}_{A}$	11.0 (2.9)$^{b}_{A}$
		-24		9.0 (3.0)$^{a}_{A}$	8.0 (2.7)$^{ab}_{A}$	9.4 (3.6)$^{a}_{A}$	8.6 (1.9)$^{ab}_{A}$	8.4 (4.0)$^{ab}_{A}$	8.5 (3.4)$^{ab}_{A}$	6.4 (2.7)$^{b}_{A}$	7.9 (2.7)$^{ab}_{A}$

N=15, 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 ($P<0.05$)

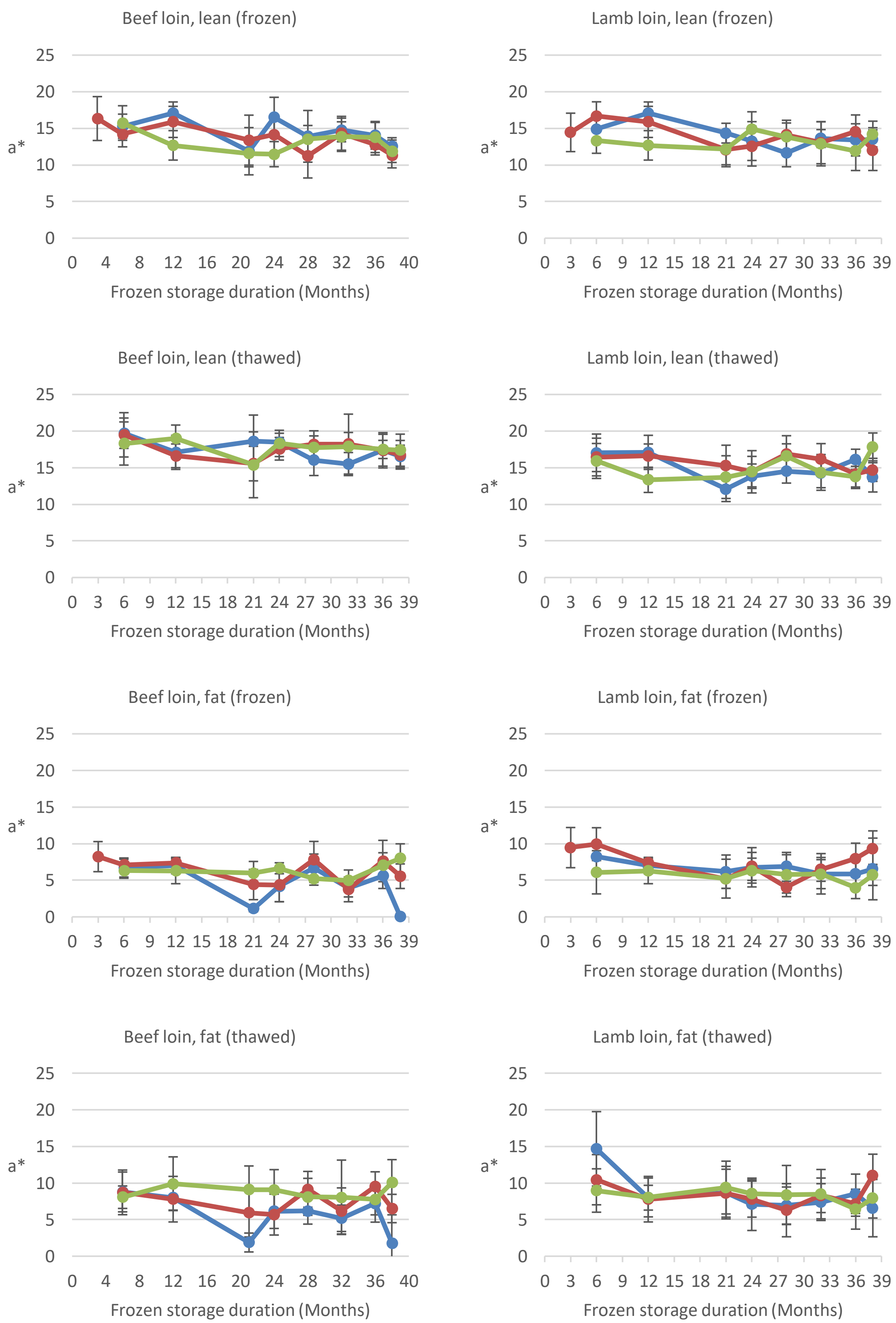


Figure 5. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean a* values measured on frozen beef/lamb loin (Vertical bars: ±1SD)

Table 7. Effect of frozen storage duration and temperature on mean (SD) b* values measured on frozen beef/lamb loin

Sample	Surface	Temp	Frozen storage duration (Months)								
		(°C)	3 (arrival)*	6	12	21	24	28	32	36	38
Beef loin	Lean, frozen	-12		0.3 (2.8)$^{a}_{A}$	2.5 (1.7)$^{b}_{A}$	-0.4 (2.0)$^{ac}_{A}$	2.4 (1.0)$^{b}_{A}$	0.2 (2.0)$^{a}_{A}$	0.8 (0.9)$^{a}_{A}$	-1.8 (1.9)$^{cd}_{A}$	-1.9 (0.9)$^{d}_{A}$
		-18	-0.2 (1.2)^{ab}	-1.9 (1.4)$^{a}_{B}$	3.1 (0.9)$^{c}_{A}$	2.2 (2.1)$^{c}_{B}$	0.3 (1.7)$^{b}_{B}$	-1.8 (1.4)$^{ad}_{B}$	-0.9 (1.6)$^{ab}_{B}$	-2.3 (1.2)$^{d}_{A}$	-1.5 (1.5)$^{ad}_{A}$
		-24		0.7 (2.4)$^{ab}_{A}$	1.4 (0.9)$^{a}_{B}$	-0.4 (1.0)$^{bc}_{A}$	-1.4 (0.9)$^{cd}_{C}$	-2.1 (0.8)$^{d}_{B}$	-0.8 (2.0)$^{c}_{B}$	0.5 (1.3)$^{ab}_{B}$	-1.0 (0.9)$^{cd}_{A}$
Beef loin	Lean, thawed	-12		0.4 (0.9)$^{ab}_{A}$	0.4 (1.2)$^{ab}_{A}$	0.4 (2.6)$^{ab}_{A}$	0.4 (1.6)$^{ab}_{A}$	0.0 (0.8)$^{ab}_{A}$	0.2 (0.8)$^{ab}_{A}$	-0.2 (1.0)$^{a}_{A}$	1.0 (1.1)$^{b}_{A}$
		-18		0.1 (1.3)$^{ab}_{A}$	-0.8 (1.1)$^{a}_{B}$	0.3 (0.9)$^{bc}_{A}$	1.2 (1.5)$^{c}_{AB}$	0.9 (1.1)$^{bc}_{B}$	0.1 (1.2)$^{ab}_{A}$	0.8 (0.9)$^{bc}_{B}$	-1.8 (1.4)$^{d}_{B}$
		-24		0.8 (0.9)$^{ab}_{A}$	1.0 (1.2)$^{ab}_{A}$	1.0 (1.4)$^{ab}_{A}$	2.3 (1.2)$^{c}_{B}$	0.3 (1.1)$^{a}_{AB}$	2.1 (1.3)$^{c}_{B}$	-0.8 (1.3)$^{d}_{A}$	1.5 (1.2)$^{bc}_{A}$
Beef loin	Fat, frozen	-12		6.6 (0.8)$^{ab}_{A}$	5.8 (0.4)$^{a}_{A}$	7.2 (0.9)$^{bc}_{A}$	6.4 (1.6)$^{abc}_{A}$	6.4 (0.7)$^{ab}_{A}$	6.8 (1.6)$^{b}_{A}$	6.4 (0.8)$^{ab}_{A}$	8.0 (0.9)$^{c}_{A}$
		-18	6.6 (1.4)^{a}	6.7 (0.3)$^{a}_{A}$	6.8 (0.7)$^{a}_{B}$	6.7 (1.4)$^{a}_{A}$	6.9 (0.5)$^{a}_{A}$	7.9 (0.9)$^{b}_{B}$	6.8 (1.4)$^{a}_{A}$	6.8 (0.6)$^{a}_{A}$	6.1 (0.7)$^{a}_{B}$
		-24		6.4 (0.8)$^{ab}_{A}$	5.0 (1.1)$^{c}_{C}$	6.7 (1.1)$^{ab}_{A}$	4.4 (0.7)$^{c}_{B}$	6.1 (1.0)$^{a}_{A}$	6.1 (0.5)$^{a}_{A}$	7.1 (1.1)$^{bd}_{A}$	6.5 (1.3)$^{ad}_{B}$
Beef loin	Fat, thawed	-12		8.3 (1.7)$^{a}_{A}$	6.7 (0.8)$^{b}_{A}$	6.9 (0.9)$^{bc}_{A}$	7.0 (1.5)$^{bc}_{A}$	6.3 (0.7)$^{a}_{A}$	6.5 (1.0)$^{b}_{A}$	7.9 (1.2)$^{ac}_{A}$	7.3 (2.3)$^{ac}_{A}$
		-18		7.5 (1.0)$^{a}_{AB}$	5.7 (1.5)$^{b}_{A}$	6.5 (1.4)$^{ab}_{A}$	7.1 (1.8)$^{a}_{A}$	7.5 (1.2)$^{a}_{B}$	5.7 (1.4)$^{b}_{AB}$	6.6 (1.3)$^{a}_{B}$	6.7 (1.2)$^{ab}_{A}$
		-24		7.2 (0.8)$^{ab}_{B}$	6.2 (1.1)$^{a}_{A}$	7.4 (1.5)$^{b}_{A}$	6.2 (1.4)$^{a}_{A}$	7.0 (1.4)$^{ab}_{AB}$	5.0 (1.1)$^{c}_{B}$	6.3 (0.9)$^{a}_{B}$	7.9 (1.8)$^{b}_{A}$
Lamb loin	Lean, frozen	-12		1.4 (1.0)$^{a}_{A}$	2.5 (1.7)$^{b}_{A}$	-1.0 (0.7)$^{c}_{A}$	-1.0 (1.5)$^{cd}_{A}$	-0.2 (1.0)$^{c}_{A}$	-2.0 (1.2)$^{de}_{A}$	-2.4 (1.6)$^{e}_{A}$	1.0 (0.8)$^{b}_{A}$
		-18	-1.2 (1.4)^{ab}	0.4 (1.8)$^{cd}_{AB}$	3.1 (0.9)$^{e}_{A}$	-1.5 (0.8)$^{ab}_{A}$	-1.3 (1.6)$^{ab}_{A}$	0.4 (1.3)$^{d}_{A}$	-0.3 (1.8)$^{acd}_{B}$	-0.7 (0.9)$^{abc}_{B}$	-1.8 (1.1)$^{b}_{B}$
		-24		-0.6 (2.2)$^{ab}_{B}$	1.4 (0.9)$^{c}_{B}$	-1.7 (1.3)$^{a}_{A}$	0.1 (2.3)$^{b}_{A}$	-0.2 (1.0)$^{b}_{A}$	-0.7 (1.9)$^{ab}_{AB}$	-0.9 (1.7)$^{ab}_{B}$	-0.6 (1.9)$^{ab}_{C}$
Lamb loin	Lean, thawed	-12		3.1 (3.8)$^{a}_{A}$	0.4 (1.2)$^{b}_{A}$	-2.2 (1.0)$^{c}_{A}$	-1.3 (1.4)$^{cd}_{A}$	-0.5 (0.9)$^{bd}_{AB}$	-1.8 (0.7)$^{ce}_{A}$	-1.9 (1.0)$^{ce}_{A}$	-0.6 (1.7)$^{bde}_{A}$
		-18		-2.1 (1.4)$^{a}_{B}$	-0.8 (1.1)$^{bc}_{B}$	-1.2 (1.8)$^{ab}_{A}$	-0.4 (1.0)$^{bc}_{A}$	0.1 (0.7)$^{c}_{B}$	-0.3 (1.1)$^{bc}_{B}$	0.2 (1.1)$^{c}_{B}$	-0.6 (1.6)$^{bc}_{A}$
		-24		-1.9 (1.1)$^{a}_{B}$	-1.5 (0.9)$^{ab}_{B}$	-1.6 (2.2)$^{ac}_{A}$	-0.6 (1.4)$^{bcde}_{A}$	-0.7 (0.8)$^{bcd}_{A}$	-1.0 (1.2)$^{ad}_{AB}$	0.0 (1.1)$^{de}_{B}$	0.5 (1.6)$^{e}_{A}$
Lamb loin	Fat, frozen	-12		7.6 (1.7)$^{a}_{A}$	5.8 (0.4)$^{bc}_{A}$	4.8 (1.8)$^{bd}_{A}$	7.8 (2.6)$^{a}_{A}$	6.6 (1.6)$^{ac}_{A}$	7.3 (2.4)$^{ac}_{A}$	5.8 (2.3)$^{cd}_{A}$	8.0 (2.3)$^{a}_{A}$
		-18	8.3 (1.6)^{ab}	11.8 (2.7)$^{c}_{B}$	6.8 (0.7)$^{a}_{B}$	9.3 (1.1)$^{bd}_{B}$	7.4 (2.2)$^{a}_{A}$	10.6 (1.5)$^{cd}_{B}$	7.1 (0.9)$^{a}_{A}$	8.0 (1.7)$^{ab}_{B}$	7.4 (1.4)$^{a}_{A}$
		-24		6.9 (2.8)$^{a}_{A}$	5.0 (1.1)$^{bc}_{C}$	4.8 (2.2)$^{b}_{A}$	8.0 (2.1)$^{ad}_{A}$	6.7 (2.0)$^{a}_{A}$	6.5 (2.0)$^{ac}_{A}$	9.2 (1.5)$^{d}_{B}$	7.9 (1.0)$^{ad}_{A}$
Lamb loin	Fat, thawed	-12		7.7 (3.9)$^{ab}_{A}$	6.7 (0.8)$^{ac}_{A}$	5.4 (1.3)$^{c}_{A}$	8.7 (3.3)$^{bd}_{A}$	6.7 (0.7)$^{ac}_{A}$	9.9 (1.8)$^{d}_{A}$	8.4 (1.6)$^{abd}_{AB}$	8.5 (1.9)$^{abd}_{A}$
		-18		10.4 (1.7)$^{a}_{B}$	5.7 (1.5)$^{b}_{A}$	8.4 (1.5)$^{c}_{B}$	8.1 (1.8)$^{c}_{A}$	11.0 (1.0)$^{a}_{B}$	8.3 (1.6)$^{c}_{B}$	7.6 (1.1)$^{c}_{A}$	8.2 (1.4)$^{c}_{A}$
		-24		8.8 (1.8)$^{ab}_{AB}$	6.7 (1.9)$^{cd}_{A}$	6.1 (1.5)$^{c}_{A}$	7.9 (1.5)$^{ad}_{A}$	8.8 (1.9)$^{ab}_{C}$	8.0 (1.3)$^{ad}_{B}$	9.4 (1.4)$^{b}_{B}$	7.9 (1.2)$^{ad}_{A}$

N=15, 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)

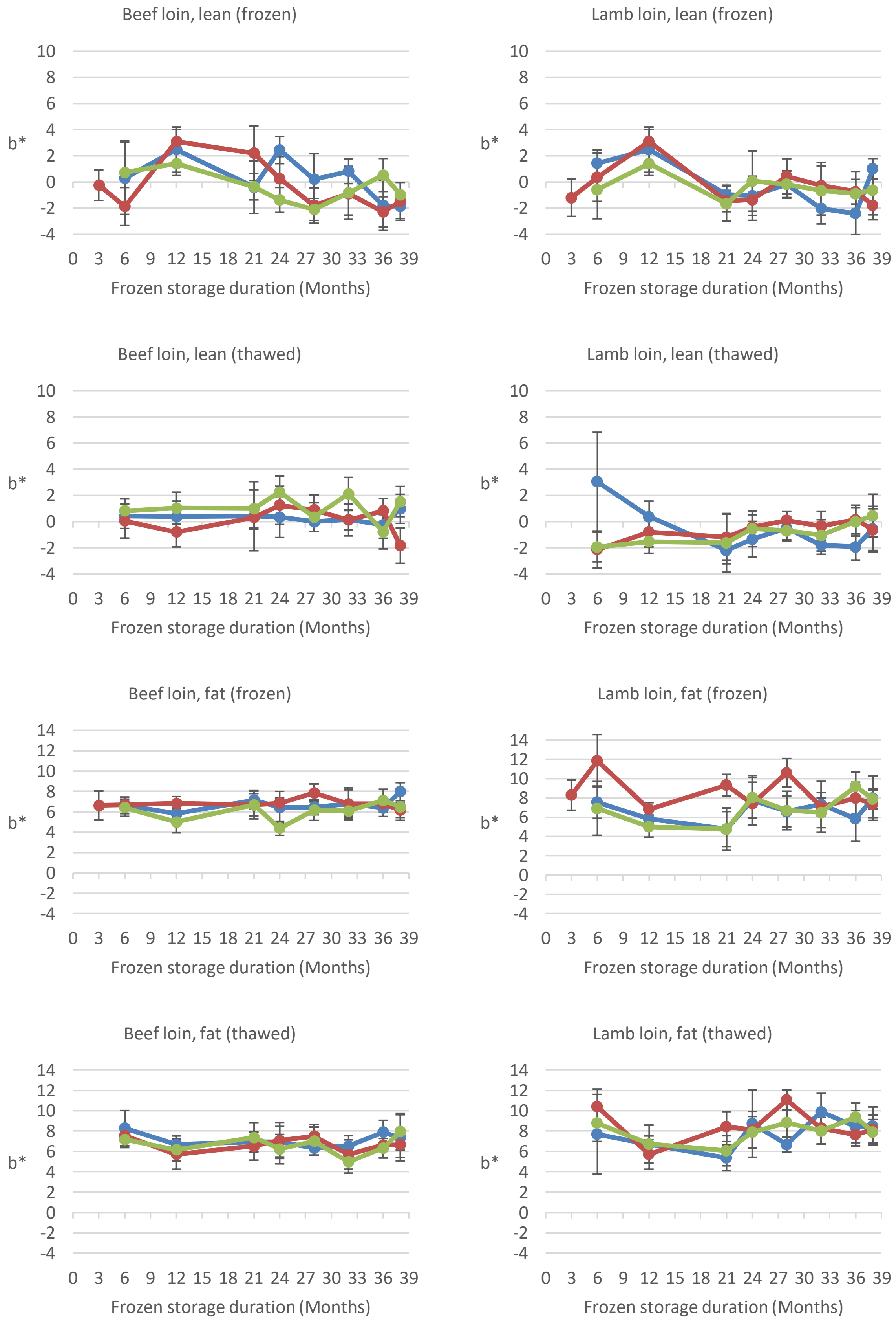


Figure 6. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean b* values measured on frozen beef/lamb loin, N.B. lean and fat results are presented on a different scale (Vertical bars: ±1SD)

Table 8. Effect of frozen storage duration and temperature on mean (SD) saturation values measured on frozen beef/lamb loin

Sample	Surface	Temp (°C)	Frozen storage duration (Months) 3 (arrival)*	6	12	21	24	28	32	36	38
Beef loin	Lean, frozen	-12		15.5 (1.6)$^{abc}_{A}$	17.3 (1.7)$^{a}_{A}$	12.1 (3.2)$^{d}_{A}$	16.7 (2.8)$^{ab}_{A}$	14.1 (3.4)$^{c}_{A}$	14.8 (1.6)$^{bc}_{A}$	14.3 (1.8)$^{ce}_{A}$	12.7 (1.2)$^{de}_{A}$
		-18	16.4 (3.0)$^{a}_{A}$	14.4 (1.7)$^{ab}_{A}$	16.2 (2.2)$^{a}_{A}$	13.7 (3.4)$^{bc}_{A}$	14.2 (2.4)$^{ac}_{A}$	11.5 (3.0)$^{d}_{A}$	14.5 (2.2)$^{ac}_{A}$	13.0 (1.3)$^{bcd}_{A}$	11.5 (1.7)$^{d}_{A}$
		-24		15.9 (2.3)$^{a}_{A}$	12.8 (2.0)$^{bc}_{B}$	11.6 (1.8)$^{b}_{A}$	11.6 (1.6)$^{b}_{A}$	13.7 (1.9)$^{c}_{A}$	14.0 (2.0)$^{c}_{A}$	13.8 (2.1)$^{c}_{A}$	11.9 (1.6)$^{b}_{A}$
Beef loin	Lean, thawed	-12		19.7 (2.1)$^{a}_{A}$	17.1 (2.3)$^{bc}_{A}$	18.8 (3.6)$^{ab}_{A}$	18.5 (1.2)$^{ab}_{A}$	16.0 (2.1)$^{cd}_{A}$	15.5 (1.6)$^{c}_{A}$	17.4 (2.2)$^{bd}_{A}$	16.6 (1.5)$^{cd}_{A}$
		-18		19.5 (3.0)$^{a}_{A}$	16.7 (1.6)$^{a}_{A}$	15.6 (2.4)$^{a}_{B}$	17.7 (1.5)$^{a}_{A}$	18.2 (1.9)$^{a}_{B}$	18.3 (4.1)$^{a}_{B}$	17.4 (2.4)$^{a}_{A}$	16.9 (1.9)$^{a}_{A}$
		-24		18.3 (2.9)$^{a}_{A}$	19.1 (1.9)$^{bc}_{B}$	15.5 (4.5)$^{b}_{B}$	18.5 (1.8)$^{ac}_{A}$	17.8 (1.6)$^{ac}_{B}$	18.0 (2.0)$^{ac}_{B}$	17.6 (1.3)$^{bc}_{A}$	17.5 (2.1)$^{bc}_{A}$
Beef loin	Fat, frozen	-12		9.5 (1.4)$^{a}_{A}$	9.1 (0.9)$^{a}_{AB}$	7.3 (0.9)$^{b}_{A}$	8.0 (1.0)$^{bc}_{A}$	9.4 (1.0)$^{a}_{A}$	8.0 (1.4)$^{bc}_{A}$	8.6 (1.2)$^{ac}_{A}$	8.0 (0.9)$^{bc}_{A}$
		-18	10.6 (2.2)$^{ab}_{A}$	9.8 (0.7)$^{a}_{A}$	10.1 (0.7)$^{ab}_{A}$	8.2 (2.0)$^{c}_{AB}$	8.4 (1.2)$^{c}_{A}$	11.3 (1.7)$^{b}_{B}$	7.9 (1.2)$^{c}_{A}$	10.4 (2.0)$^{ab}_{B}$	8.4 (1.0)$^{c}_{A}$
		-24		9.0 (1.2)$^{ab}_{A}$	8.1 (1.8)$^{a}_{B}$	9.1 (1.3)$^{ab}_{B}$	8.0 (0.9)$^{a}_{A}$	8.1 (1.1)$^{a}_{C}$	7.9 (0.9)$^{a}_{A}$	10.1 (1.1)$^{bc}_{B}$	10.3 (2.1)$^{c}_{B}$
Beef loin	Fat, thawed	-12		12.2 (2.8)$^{a}_{A}$	10.5 (1.6)$^{bc}_{A}$	7.3 (1.0)$^{d}_{A}$	9.5 (1.8)$^{bce}_{A}$	8.9 (1.7)$^{bf}_{A}$	8.5 (1.3)$^{def}_{A}$	10.8 (2.4)$^{ac}_{A}$	8.5 (2.2)$^{def}_{A}$
		-18		11.6 (2.8)$^{a}_{A}$	9.9 (2.7)$^{abcd}_{A}$	9.1 (2.7)$^{bd}_{A}$	9.3 (2.4)$^{abd}_{A}$	11.9 (2.5)$^{ac}_{B}$	8.7 (2.7)$^{d}_{A}$	11.7 (2.0)$^{ac}_{A}$	9.4 (2.0)$^{d}_{A}$
		-24		10.8 (1.4)$^{ab}_{A}$	11.7 (3.6)$^{ab}_{A}$	11.8 (3.3)$^{ab}_{B}$	11.0 (3.0)$^{ab}_{A}$	10.7 (2.8)$^{ab}_{AB}$	9.8 (4.5)$^{a}_{A}$	10.1 (1.9)$^{a}_{A}$	12.9 (3.4)$^{b}_{B}$
Lamb loin	Lean, frozen	-12		15.0 (1.5)$^{a}_{A}$	17.3 (1.7)$^{b}_{A}$	14.4 (1.3)$^{ab}_{A}$	13.4 (2.7)$^{b}_{AB}$	11.7 (1.9)$_{A}$	13.8 (1.3)$^{ab}_{A}$	13.7 (2.4)$^{ab}_{AB}$	13.6 (1.6)$^{ab}_{AB}$
		-18	14.6 (2.5)$^{abcd}_{A}$	16.8 (1.9)$^{a}_{B}$	16.2 (2.2)$^{ab}_{A}$	12.2 (2.1)$^{c}_{B}$	12.7 (2.8)$^{cd}_{A}$	14.2 (2.0)$^{cd}_{B}$	13.2 (2.9)$^{cd}_{A}$	14.6 (2.3)$^{bd}_{A}$	12.2 (2.7)$^{c}_{A}$
		-24		13.5 (1.6)$^{abc}_{C}$	12.8 (2.0)$^{ac}_{B}$	12.3 (2.4)$^{a}_{B}$	15.1 (2.4)$^{bc}_{B}$	13.9 (1.9)$^{abc}_{B}$	13.0 (3.0)$^{ac}_{A}$	12.0 (2.6)$^{a}_{B}$	14.4 (1.7)$^{c}_{B}$
Lamb loin	Lean, thawed	-12		17.7 (2.1)$^{a}_{A}$	17.1 (2.3)$^{a}_{A}$	12.3 (1.6)$^{b}_{A}$	14.0 (1.6)$^{c}_{A}$	14.5 (1.6)$^{c}_{A}$	14.4 (2.0)$^{c}_{A}$	16.3 (1.4)$^{a}_{A}$	13.8 (1.9)$^{bc}_{A}$
		-18		16.6 (2.6)$^{a}_{A}$	16.7 (1.6)$^{a}_{A}$	15.4 (2.6)$^{ab}_{B}$	14.5 (2.1)$^{bc}_{A}$	16.9 (2.5)$^{a}_{B}$	16.2 (2.1)$^{ac}_{A}$	14.2 (2.0)$^{b}_{B}$	14.8 (1.6)$^{bc}_{A}$
		-24		16.1 (2.4)$^{ab}_{A}$	13.5 (1.7)$^{c}_{B}$	14.0 (2.8)$^{c}_{AB}$	14.5 (2.8)$^{ac}_{A}$	16.6 (1.7)$^{bd}_{B}$	14.4 (2.4)$^{ac}_{A}$	13.8 (1.4)$^{c}_{B}$	17.9 (1.9)$^{d}_{B}$
Lamb loin	Fat, frozen	-12		11.2 (2.3)$^{a}_{A}$	9.1 (0.9)$^{ab}_{AB}$	7.8 (2.8)$^{b}_{A}$	10.6 (2.6)$^{ac}_{A}$	9.7 (1.6)$^{abc}_{AB}$	9.6 (3.1)$^{ab}_{A}$	8.4 (2.7)$^{bc}_{A}$	10.5 (4.3)$^{ac}_{A}$
		-18	12.6 (3.0)$^{a}_{A}$	15.5 (3.2)$^{b}_{B}$	10.1 (0.7)$^{cd}_{A}$	10.7 (1.2)$^{acd}_{B}$	10.3 (2.1)$^{cde}_{A}$	11.4 (1.4)$^{ac}_{A}$	9.7 (1.5)$^{d}_{A}$	11.3 (2.3)$^{acd}_{B}$	12.0 (2.3)$^{ae}_{A}$
		-24		9.5 (3.2)$^{ab}_{A}$	8.1 (1.8)$^{ac}_{B}$	7.2 (3.1)$^{c}_{A}$	10.5 (1.4)$^{b}_{A}$	9.1 (2.9)$^{abc}_{B}$	8.8 (2.6)$^{abc}_{A}$	10.1 (1.8)$^{ab}_{AB}$	9.8 (1.3)$^{ab}_{A}$
Lamb loin	Fat, thawed	-12		17.4 (3.3)$^{a}_{A}$	10.5 (1.6)$^{b}_{A}$	10.3 (3.4)$^{b}_{A}$	11.4 (4.5)$^{b}_{A}$	9.8 (1.9)$^{b}_{A}$	12.4 (2.7)$^{b}_{A}$	12.1 (2.7)$^{b}_{A}$	10.9 (3.7)$^{b}_{A}$
		-18		14.8 (3.4)$^{a}_{AB}$	9.9 (2.7)$^{b}_{A}$	12.2 (2.9)$^{cd}_{A}$	11.4 (2.3)$^{bc}_{A}$	13.1 (2.1)$^{ac}_{B}$	11.8 (2.6)$^{bc}_{A}$	10.5 (1.7)$^{bd}_{A}$	13.9 (2.6)$^{ac}_{B}$
		-24		12.7 (2.7)$^{a}_{B}$	10.7 (2.2)$^{a}_{A}$	11.3 (3.5)$^{a}_{A}$	11.7 (1.9)$^{a}_{A}$	12.3 (3.9)$^{a}_{B}$	11.8 (3.2)$^{a}_{A}$	11.6 (2.0)$^{a}_{A}$	11.3 (2.6)$^{a}_{A}$

N=15, 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)

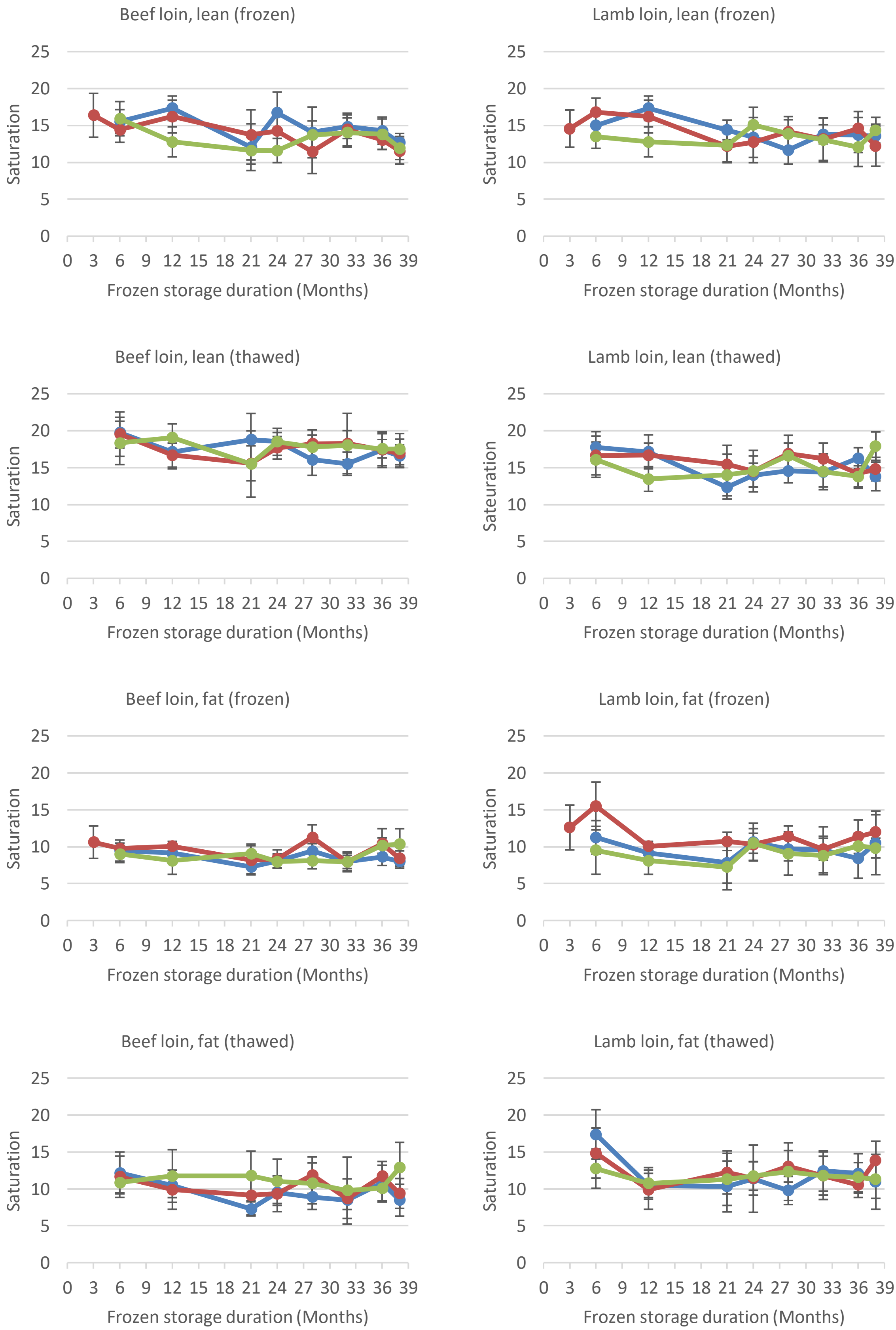


Figure 7. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean saturation values measured on frozen beef/lamb loin (Vertical bars: ±1SD)

Table 9. Effect of frozen storage duration and temperature on mean (SD) Hue Angle (°) values measured on frozen beef/lamb loin

Sample	**Surface**	**Temp**	**Frozen storage duration (Months)**								
		(°C)	**3 (arrival)***	**6**	**12**	**21**	**24**	**28**	**32**	**36**	**38**
Beef loin	Lean, frozen	-12		89.2 (10.4)$^{a}_{A}$	82.1 (5.4)$^{b}_{AB}$	89.6 (11.2)$^{a}_{A}$	81.8 (2.5)$^{b}_{A}$	88.9 (9.9)$^{a}_{A}$	86.7 (3.7)$^{ab}_{A}$	97.5 (7.9)$^{c}_{A}$	98.4 (4.0)$^{c}_{A}$
		-18	90.9 (4.6)$^{ab}_{A}$	97.9 (5.6)$^{ac}_{B}$	79.1 (2.4)$^{d}_{A}$	80.1 (9.0)$^{d}_{B}$	88.7 (7.1)$^{b}_{B}$	99.6 (7.2)$^{ce}_{B}$	94.1 (7.3)$^{abe}_{B}$	100.4 (5.8)$^{c}_{A}$	97.8 (6.8)$^{ac}_{A}$
		-24		87.7 (9.2)$^{ab}_{A}$	83.6 (4.0)$^{a}_{B}$	91.4 (4.8)$^{bc}_{A}$	97.2 (5.7)$^{de}_{C}$	98.7 (3.2)$^{df}_{B}$	93.1 (8.8)$^{ce}_{B}$	87.8 (5.1)$^{ab}_{B}$	94.5 (4.2)$^{cf}_{A}$
Beef loin	Lean, thawed	-12		88.9 (2.7)$^{ab}_{AB}$	88.6 (4.3)$^{ab}_{A}$	89.3 (8.5)$^{ab}_{A}$	88.9 (4.9)$^{ab}_{A}$	90.2 (2.7)$^{ab}_{A}$	89.6 (2.8)$^{ab}_{A}$	90.9 (3.4)$^{ab}_{A}$	86.5 (4.1)$^{b}_{A}$
		-18		90.2 (4.2)$^{ab}_{A}$	92.9 (3.9)$^{a}_{B}$	89.1 (3.1)$^{bc}_{A}$	86.0 (4.9)$^{c}_{AB}$	87.3 (3.6)$^{bc}_{B}$	89.9 (4.0)$^{ab}_{A}$	87.3 (3.1)$^{abc}_{B}$	96.3 (4.8)$^{d}_{B}$
		-24		87.2 (3.1)$^{ab}_{B}$	87.1 (3.6)$^{ab}_{A}$	85.3 (7.4)$^{bc}_{A}$	83.0 (3.6)$^{c}_{B}$	89.0 (3.4)$^{a}_{AB}$	83.4 (4.0)$^{c}_{B}$	92.6 (4.1)$^{d}_{A}$	84.7 (4.4)$^{ab}_{A}$
Beef loin	Fat, frozen	-12		45.2 (3.3)$^{ab}_{A}$	49.9 (5.0)$^{a}_{A}$	8.9 (2.8)$^{c}_{A}$	33.1 (17.5)$^{de}_{A}$	44.9 (12.0)$^{ab}_{A}$	30.8 (10.1)$^{d}_{AB}$	40.4 (10.6)$^{be}_{A}$	0.6 (3.0)$^{f}_{A}$
		-18	50.8 (6.8)$^{a}_{A}$	46.6 (2.7)$^{a}_{A}$	47.3 (3.2)$^{a}_{A}$	32.2 (10.7)$^{b}_{B}$	30.8 (14.1)$^{b}_{A}$	43.8 (10.9)$^{a}_{A}$	28.7 (13.7)$^{b}_{A}$	46.1 (12.1)$^{a}_{A}$	41.3 (10.5)$^{a}_{B}$
		-24		44.4 (4.2)$^{a}_{A}$	50.8 (7.4)$^{b}_{A}$	41.2 (10.0)$^{a}_{C}$	56.6 (4.2)$^{b}_{B}$	40.4 (5.3)$^{a}_{A}$	38.5 (9.1)$^{a}_{B}$	44.4 (9.9)$^{a}_{A}$	50.6 (7.0)$^{b}_{C}$
Beef loin	Fat, thawed	-12		46.1 (7.6)$^{ab}_{A}$	49.6 (4.9)$^{a}_{A}$	14.8 (10.1)$^{c}_{A}$	40.6 (13.4)$^{ab}_{A}$	43.4 (5.9)$^{ab}_{A}$	37.7 (10.8)$^{b}_{A}$	41.3 (7.6)$^{ab}_{A}$	11.1 (23.1)$^{c}_{A}$
		-18		47.6 (7.9)$^{abc}_{A}$	51.3 (13.1)$^{ac}_{A}$	39.6 (16.1)$^{b}_{B}$	37.0 (13.6)$^{d}_{B}$	50.0 (5.4)$^{ac}_{B}$	45.1 (15.8)$^{abd}_{AB}$	54.9 (6.1)$^{c}_{B}$	43.6 (7.1)$^{abd}_{B}$
		-24		48.0 (5.6)$^{a}_{A}$	56.7 (6.1)$^{b}_{A}$	50.0 (5.2)$^{a}_{C}$	55.0 (4.3)$^{bc}_{C}$	48.5 (4.0)$^{a}_{B}$	52.0 (15.2)$^{ab}_{B}$	49.9 (7.8)$^{ac}_{B}$	51.1 (4.9)$^{ab}_{B}$
Lamb loin	Lean, frozen	-12		84.6 (3.8)$^{a}_{A}$	82.1 (5.4)$^{a}_{AB}$	94.0 (3.0)$^{b}_{A}$	94.2 (5.8)$^{b}_{A}$	90.9 (4.7)$^{b}_{A}$	98.2 (4.5)$^{c}_{A}$	99.6 (5.5)$^{c}_{A}$	85.9 (2.9)$^{a}_{A}$
		-18	95.6 (6.4)$^{ab}_{A}$	88.5 (6.5)$^{c}_{AB}$	79.1 (2.4)$^{d}_{B}$	96.7 (3.1)$^{ab}_{AB}$	95.6 (7.0)$^{ab}_{A}$	88.6 (5.1)$^{c}_{A}$	91.5 (7.6)$^{ac}_{B}$	92.7 (3.7)$^{ac}_{B}$	98.9 (6.0)$^{b}_{B}$
		-24		93.4 (10.0)$^{ab}_{B}$	83.6 (4.0)$^{c}_{A}$	98.0 (6.3)$^{a}_{B}$	89.7 (8.5)$^{bc}_{A}$	90.9 (4.3)$^{b}_{A}$	93.6 (8.9)$^{ab}_{AB}$	93.9 (9.1)$^{ab}_{B}$	92.8 (7.6)$^{ab}_{C}$
Lamb loin	Lean, thawed	-12		79.5 (13.7)$^{a}_{A}$	88.6 (4.3)$^{b}_{A}$	100.7 (5.6)$^{c}_{A}$	95.7 (5.9)$^{cd}_{A}$	91.9 (3.6)$^{bd}_{AB}$	97.2 (2.6)$^{cd}_{A}$	96.7 (3.5)$^{cd}_{A}$	92.7 (7.7)$^{bd}_{A}$
		-18		97.4 (4.4)$^{a}_{B}$	92.9 (3.9)$^{bc}_{B}$	95.6 (8.3)$^{b}_{A}$	91.8 (3.9)$^{bc}_{A}$	89.7 (2.3)$^{c}_{A}$	91.4 (4.0)$^{c}_{B}$	89.4 (4.5)$^{c}_{B}$	92.3 (6.1)$^{bc}_{A}$
		-24		97.0 (3.9)$^{a}_{B}$	96.7 (4.4)$^{ab}_{C}$	97.2 (9.9)$^{a}_{A}$	92.8 (6.6)$^{abc}_{A}$	92.3 (2.4)$^{bc}_{B}$	94.2 (4.9)$^{abd}_{AB}$	90.1 (4.3)$^{cd}_{B}$	88.7 (5.2)$^{c}_{A}$
Lamb loin	Fat, frozen	-12		47.2 (6.9)$^{ab}_{A}$	49.9 (5.0)$^{a}_{A}$	52.2 (6.2)$^{a}_{A}$	41.0 (14.9)$^{bcd}_{A}$	46.5 (9.6)$^{ac}_{A}$	37.8 (12.3)$^{d}_{A}$	45.8 (10.2)$^{ab}_{A}$	36.6 (11.5)$^{d}_{A}$
		-18	48.1 (3.9)$^{ab}_{A}$	40.2 (5.2)$^{c}_{A}$	47.3 (3.2)$^{ab}_{A}$	28.9 (6.3)$^{d}_{B}$	43.1 (11.2)$^{ac}_{A}$	21.1 (4.7)$^{e}_{B}$	41.9 (7.3)$^{ac}_{A}$	44.8 (7.3)$^{ac}_{A}$	51.1 (6.8)$^{b}_{B}$
		-24		41.4 (13.8)$^{ab}_{A}$	50.8 (7.4)$^{c}_{A}$	45.8 (12.4)$^{ac}_{A}$	38.8 (12.8)$^{ab}_{A}$	38.6 (13.5)$^{ab}_{A}$	41.7 (7.9)$^{ab}_{A}$	23.3 (6.7)$^{d}_{B}$	35.6 (7.0)$^{b}_{A}$
Lamb loin	Fat, thawed	-12		59.7 (19.3)$^{a}_{A}$	49.6 (4.9)$^{b}_{A}$	56.4 (9.1)$^{ab}_{A}$	37.1 (9.9)$^{cd}_{A}$	44.2 (11.7)$^{bc}_{A}$	35.9 (6.5)$^{cd}_{A}$	44.3 (7.8)$^{bc}_{A}$	34.9 (11.7)$^{d}_{A}$
		-18		44.2 (6.9)$^{ab}_{B}$	51.3 (13.1)$^{bc}_{A}$	44.2 (9.6)$^{ab}_{B}$	43.5 (10.1)$^{ab}_{AB}$	28.0 (13.3)$^{d}_{B}$	44.5 (5.3)$^{ab}_{B}$	42.6 (6.5)$^{a}_{A}$	52.6 (7.5)$^{c}_{B}$
		-24		44.8 (10.3)$^{a}_{B}$	49.1 (12.9)$^{ab}_{A}$	55.6 (8.4)$^{b}_{A}$	47.0 (7.5)$^{a}_{B}$	41.5 (9.8)$^{ac}_{A}$	44.8 (8.2)$^{a}_{B}$	33.4 (12.0)$^{c}_{B}$	44.1 (7.0)$^{a}_{C}$

N=15, 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)

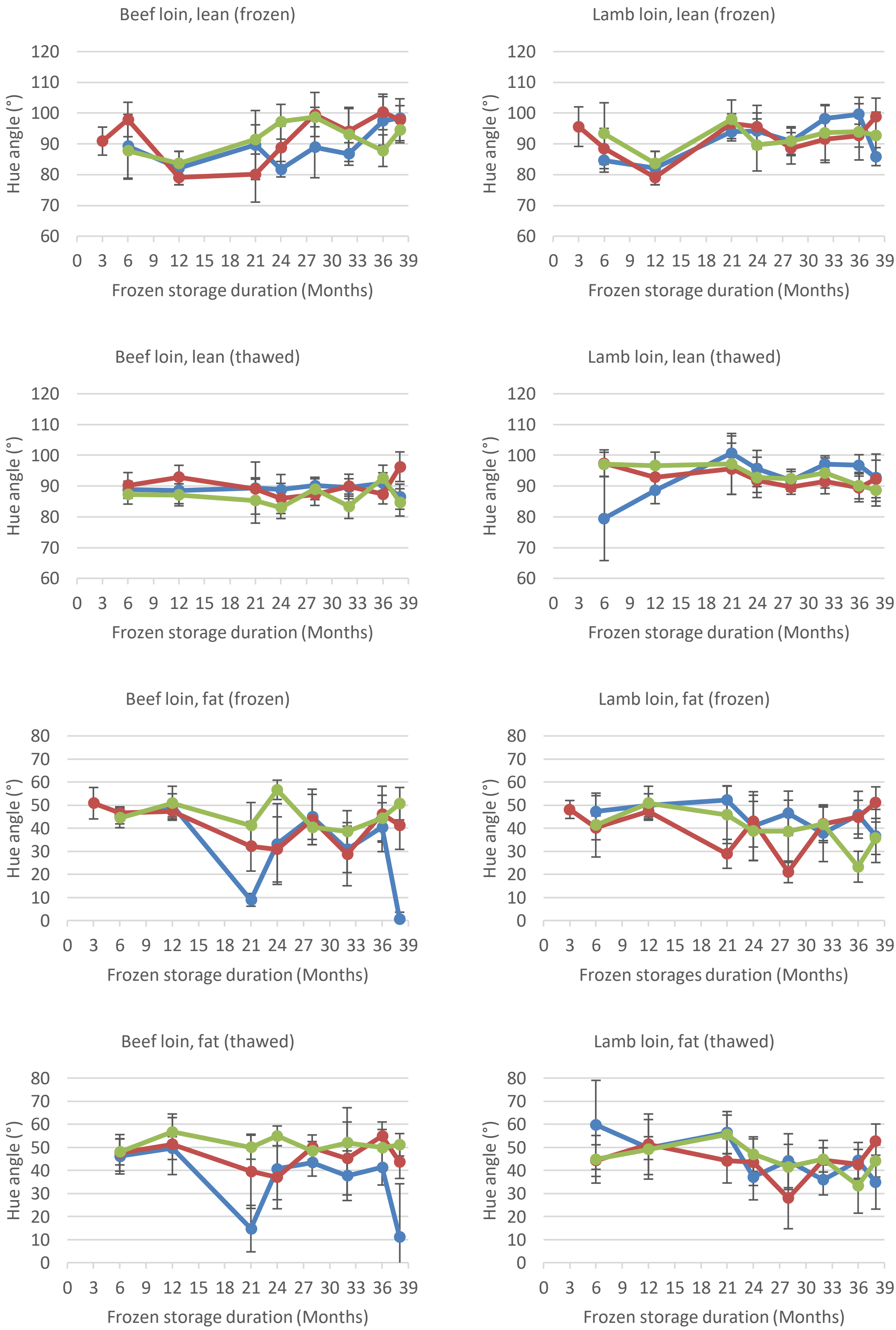


Figure 8. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean hue angle values measured on frozen beef/lamb loin, N.B. lean and fat results are presented on a different scale (Vertical bars: ±1SD)

4.1.3 pH

A summary of pH measured in samples on arrival and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage are shown in Table 10, and graphically in Figure 9. There is no clear trend for pH to change with storage duration or any effect of storage temperature.

As also shown is the day 0 analysis performed by the University of Melbourne (Ha & Warner, 2018), the pH of the beef loins in the 0 analysis were all under 5.7, meeting the pH requirement of MSA grading. The pH of the lamb loins varied widely, with some of the samples falling into dark cutting category. Except for the lamb loin stored at -12°C and -18°C sampled on month 38, none of the lamb loin samples were above the highest pH of <5.8 considered normal for lamb (Devine *et al.*, 1993), but some were close to that value. As also reported by the University of Melbourne (Ha & Warner, 2018) the pH values of trim samples varied dramatically. With some samples falling into dark cutting category, above 5.8 which is likely to affect the functionality of the meat.

While there were some significant differences (P<0.05) between beef and lamb loin samples measured after different storage durations and stored at different storage temperatures these differences were not consistent and were likely due to box-to-box variation. No clear consistent change in pH over storage duration or with storage temperature was observed. More variation was observed in pH of the trim samples, but again no consistent change in pH over time or difference between storage temperature. It is likely that any differences are due to natural variation in the samples.

Recent published studies on the long term storage of frozen beef and lamb report conflicting findings on whether pH is affected by frozen storage duration or temperature. Farouk *et al.* (2003) reported no trend in change of pH in beef (*M. semitendinosus*) with frozen storage duration of up to 12 months (stored at -18, -35, -75°C). While Fernandes *et al.* (2013) and Pinheiro *et al.* (2015) reported no change pH in vacuum-packed lamb (*L. dorsi* or *L. lumborum*, respectively) with frozen storage duration, stored for up to 12 months at -18°C and -25°C, respectively. Similarly, Coombs *et al.* (2017a) and Holman *et al.* (2017) observed no significant effect of storage period or temperature on pH in vacuum-packed lamb (*M. longissimus lumborum*) or beef (*M. longissimus lumborum*), respectively, stored for up to 12 months at -12°C or -18°C. Muela *et al.* (2015) observed a general light decrease of pH in vacuum-packed lamb (*L. thoracis et lumborum*) stored up to 21 months at -18°C, although this was no higher than 0.1 units. Daszkiewicz *et al.* (2018) observed a slight rise in pH in vacuum-packed lamb (*L. thoracis et lumborum*) between 6 and 12 months storage at -26°C. Again, none of these studies stored frozen meat beyond 24 months.

Table 10. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) pH of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months)									
		Initial*	3 (arrival)	6	12	21	24	28	32	36	38
Beef loin	-12			-	5.52 (0.04)$^{a}_{A}$	5.50 (0.04)$^{a}_{A}$	5.47 (0.01)$^{a}_{A}$	5.53 (0.07)$^{a}_{A}$	5.33 (0.08)$^{b}_{A}$	5.55 (0.10)$^{a}_{A}$	5.67 (0.10)$^{c}_{A}$
	-18	5.43 (0.04)	5.43 (0.05)^{a}	5.53 (0.07)$^{bcd}_{A}$	5.60 (0.02)$^{de}_{B}$	5.52 (0.03)$^{ac}_{A}$	5.48 (0.04)$^{ab}_{A}$	5.60 (0.05)$^{bde}_{A}$	5.35 (0.03)$^{f}_{AB}$	5.42 (0.06)$^{af}_{B}$	5.57 (0.06)$^{bd}_{A}$
	-24			5.46 (0.06)$^{ab}_{A}$	5.46 (0.03)$^{abc}_{C}$	5.44 (0.02)$^{ab}_{B}$	5.37 (0.01)$^{b}_{B}$	5.60 (0.03)$^{c}_{A}$	5.43 (0.04)$^{ab}_{B}$	5.49 (0.04)$^{a}_{AB}$	5.54 (0.21)$^{ac}_{A}$
Beef trim 95CL	-12			5.62 (0.14)$^{a}_{A}$	5.57 (0.03)$^{a}_{A}$	5.86 (0.21)$^{bc}_{A}$	5.92 (0.20)$^{c}_{A}$	5.94 (0.23)$^{bc}_{A}$	6.05 (0.16)$^{bc}_{A}$	5.98 (0.10)$^{bc}_{A}$	5.68 (0.06)$^{ab}_{A}$
	-18	5.78 (0.19)	5.81 (0.12)^{abc}	5.70 (0.18)$^{bc}_{A}$	5.66 (0.05)$^{c}_{B}$	5.75 (0.21)$^{abc}_{A}$	5.48 (0.01)$^{b}_{B}$	6.03 (0.13)$^{d}_{A}$	6.00 (0.09)$^{ad}_{AB}$	6.11 (0.13)$^{d}_{A}$	5.98 (0.15)$^{ad}_{B}$
	-24			5.56 (0.01)$^{ab}_{A}$	5.57 (0.03)$^{ac}_{A}$	5.76 (0.05)$^{bcd}_{A}$	5.76 (0.26)$^{bce}_{AB}$	6.02 (0.18)$^{f}_{A}$	5.82 (0.17)$^{bf}_{B}$	5.48 (0.04)$^{a}_{B}$	5.85 (0.13)$^{def}_{B}$
Beef trim 85CL	-12			6.00 (0.22)$^{ab}_{A}$	5.97 (0.22)$^{ab}_{A}$	6.07 (0.07)$^{b}_{A}$	5.60 (0.03)$^{c}_{A}$	5.77 (0.10)$^{cd}_{A}$	5.90 (0.08)$^{abd}_{A}$	5.71 (0.11)$^{c}_{AB}$	5.81 (0.14)$^{ac}_{A}$
	-18	5.90 (0.30)	5.73 (0.23)^{a}	5.92 (0.19)$^{ab}_{A}$	6.04 (0.08)$^{b}_{A}$	5.71 (0.13)$^{a}_{B}$	5.71 (0.10)$^{a}_{A}$	5.78 (0.13)$^{a}_{A}$	5.89 (0.12)$^{ab}_{A}$	5.87 (0.17)$^{ab}_{A}$	5.92 (0.15)$^{ab}_{A}$
	-24			5.85 (0.14)$^{ab}_{A}$	5.62 (0.13)$^{ac}_{B}$	6.09 (0.25)$^{b}_{A}$	5.94 (0.20)$^{bd}_{B}$	5.77 (0.11)$^{ad}_{A}$	5.49 (0.05)$^{c}_{B}$	5.54 (0.04)$^{c}_{B}$	5.73 (0.09)$^{ad}_{A}$
Beef trim 65CL	-12			5.71 (0.16)$^{a}_{A}$	5.72 (0.05)$^{a}_{A}$	6.07 (0.14)$^{b}_{A}$	5.79 (0.09)$^{a}_{A}$	5.80 (0.08)$^{a}_{A}$	5.44 (0.04)$^{c}_{A}$	5.53 (0.03)$^{c}_{A}$	5.77 (0.06)$^{a}_{A}$
	-18	5.69 (0.09)	5.58 (0.07)^{a}	5.76 (0.06)$^{b}_{A}$	5.72 (0.06)$^{b}_{A}$	5.80 (0.13)$^{b}_{B}$	5.60 (0.08)$^{a}_{B}$	6.01 (0.19)$^{c}_{B}$	5.51 (0.03)$^{a}_{A}$	5.78 (0.06)$^{b}_{B}$	5.95 (0.03)$^{c}_{B}$
	-24			5.83 (0.19)$^{a}_{A}$	5.88 (0.25)$^{a}_{A}$	5.89 (0.19)$^{a}_{A}$	5.59 (0.07)$^{bc}_{B}$	5.62 (0.04)$^{bc}_{A}$	5.36 (0.06)$^{d}_{B}$	5.47 (0.02)$^{bd}_{A}$	5.71 (0.02)$^{ac}_{A}$
Lamb loin	-12			-	5.70 (0.05)$^{abcd}_{A}$	5.67 (0.04)$^{b}_{A}$	5.63 (0.01)$^{bc}_{A}$	5.68 (0.04)$^{ab}_{AB}$	5.65 (0.04)$^{ab}_{A}$	5.76 (0.07)$^{d}_{A}$	5.88 (0.10)$^{e}_{A}$
	-18	5.74 (0.14)	5.50 (0.06)^{a}	5.78 (0.06)$^{b}_{A}$	5.77 (0.11)$^{bc}_{A}$	5.60 (0.05)$^{d}_{B}$	5.64 (0.05)$^{de}_{A}$	5.63 (0.02)$^{df}_{A}$	5.58 (0.08)$^{ad}_{A}$	5.70 (0.06)$^{bcef}_{A}$	5.91 (0.06)$^{g}_{A}$
	-24			5.47 (0.09)$^{a}_{B}$	5.75 (0.11)$^{b}_{A}$	5.55 (0.01)$^{a}_{B}$	5.57 (0.03)$^{a}_{B}$	5.73 (0.09)$^{b}_{B}$	5.55 (0.06)$^{a}_{A}$	5.65 (0.10)$^{b}_{A}$	5.69 (0.10)$^{b}_{B}$
Lamb trim 90CL	-12			6.02 (0.16)$^{a}_{A}$	5.87 (0.24)$^{ab}_{A}$	5.77 (0.06)$^{bcd}_{A}$	5.67 (0.05)$^{bd}_{AB}$	5.76 (0.13)$^{bd}_{A}$	5.65 (0.07)$^{d}_{A}$	5.90 (0.08)$^{ac}_{A}$	5.83 (0.03)$^{b}_{A}$
	-18	5.72 (0.09)	5.58 (0.07)^{a}	5.83 (0.12)$^{bc}_{A}$	5.77 (0.09)$^{bc}_{A}$	6.10 (0.14)$^{d}_{B}$	5.55 (0.06)$^{a}_{B}$	5.92 (0.15)$^{bc}_{A}$	5.70 (0.09)$^{ab}_{A}$	5.71 (0.11)$^{ab}_{B}$	5.87 (0.11)$^{c}_{AB}$
	-24			5.89 (0.22)$^{abc}_{A}$	5.77 (0.11)$^{ab}_{A}$	5.84 (0.02)$^{abc}_{A}$	5.73 (0.12)$^{ac}_{A}$	5.82 (0.25)$^{abc}_{A}$	5.97 (0.11)$^{bc}_{B}$	5.85 (0.09)$^{abc}_{AB}$	5.99 (0.12)$^{c}_{B}$
Lamb trim 85CL	-12			5.89 (0.35)$^{ab}_{A}$	5.95 (0.16)$^{a}_{A}$	5.54 (0.05)$^{c}_{A}$	5.60 (0.07)$^{c}_{A}$	5.78 (0.10)$^{ab}_{A}$	5.70 (0.09)$^{bc}_{A}$	6.05 (0.08)$^{a}_{A}$	5.84 (0.08)$^{ab}_{AB}$
	-18	5.76 (0.12)	5.66 (0.08)^{ab}	5.77 (0.12)$^{ab}_{A}$	5.75 (0.29)$^{ab}_{A}$	5.71 (0.12)$^{ab}_{AB}$	5.81 (0.17)$^{ab}_{B}$	5.63 (0.03)$^{a}_{B}$	5.71 (0.10)$^{ab}_{A}$	5.84 (0.09)$^{b}_{B}$	5.77 (0.11)$^{ab}_{A}$
	-24			5.74 (0.05)$^{ab}_{A}$	5.89 (0.15)$^{ac}_{A}$	5.76 (0.15)$^{ab}_{B}$	5.68 (0.06)$^{b}_{AB}$	5.79 (0.06)$^{abd}_{AB}$	5.90 (0.12)$^{cd}_{B}$	5.95 (0.09)$^{c}_{AB}$	5.95 (0.12)$^{c}_{B}$
Lamb trim 65CL	-12			5.87 (0.11)$^{ab}_{A}$	5.80 (0.14)$^{ab}_{A}$	5.76 (0.12)$^{a}_{A}$	5.82 (0.05)$^{ab}_{A}$	5.80 (0.06)$^{ab}_{A}$	5.91 (0.08)$^{b}_{A}$	6.08 (0.12)$^{c}_{A}$	5.85 (0.06)$^{ab}_{AB}$
	-18	5.87 (0.06)	5.59 (0.11)^{a}	5.85 (0.11)$^{bcd}_{A}$	5.98 (0.17)$^{cd}_{A}$	6.00 (0.20)$^{d}_{A}$	5.82 (0.06)$^{bc}_{A}$	5.81 (0.03)$^{bc}_{A}$	5.77 (0.09)$^{b}_{B}$	5.89 (0.08)$^{bcd}_{B}$	5.80 (0.08)$^{b}_{A}$
	-24			5.93 (0.05)$^{a}_{A}$	5.84 (0.05)$^{ab}_{A}$	5.82 (0.19)$^{ab}_{A}$	5.93 (0.10)$^{a}_{A}$	5.83 (0.17)$^{ab}_{A}$	5.74 (0.13)$^{b}_{AB}$	5.74 (0.08)$^{b}_{B}$	5.92 (0.05)$^{a}_{B}$

* Ha & Warner (2018); 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)

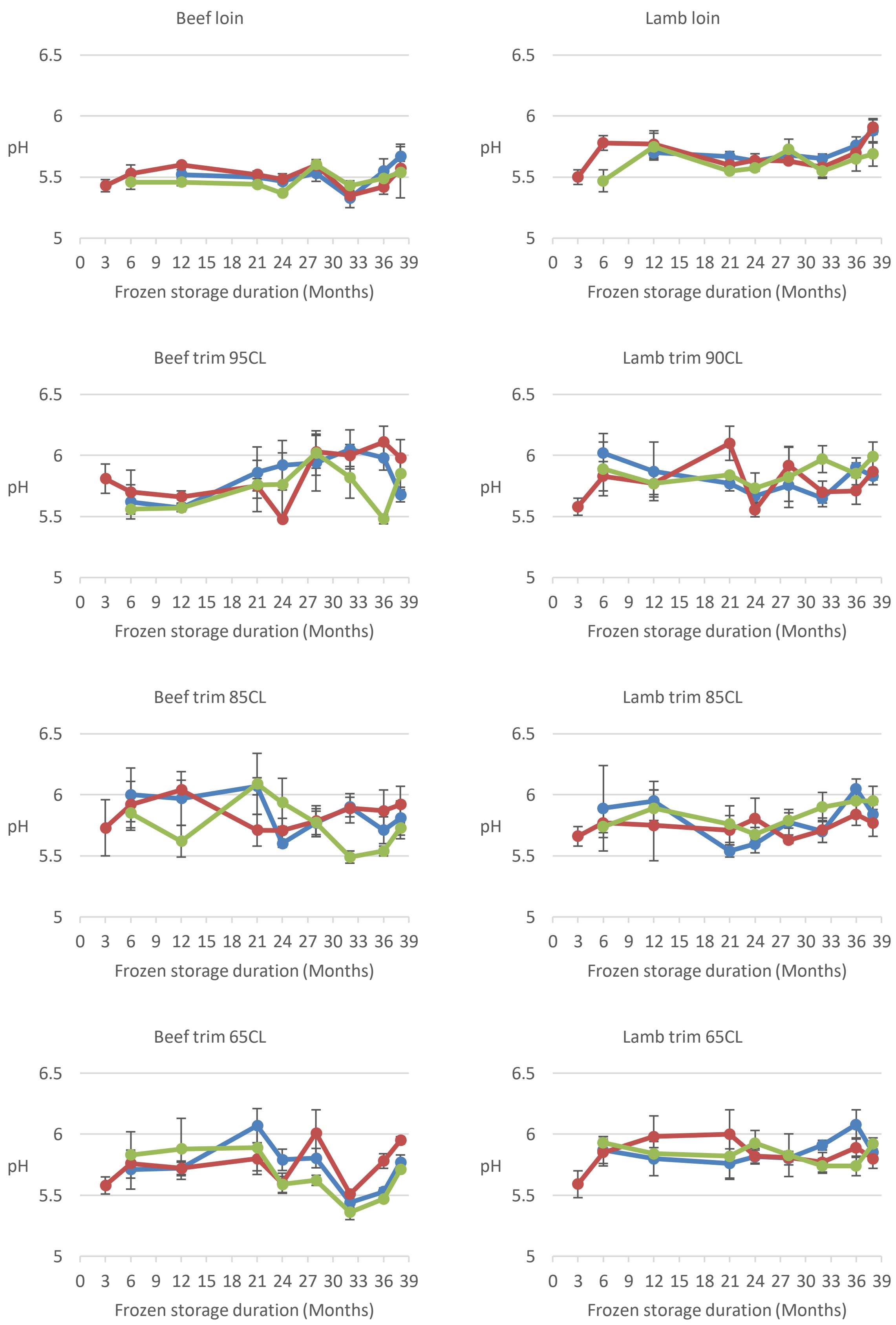


Figure 9. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean pH of beef/lamb loin and trim (Vertical bars: ±1SD)

4.1.4 Cooking loss

Cooking loss measured in samples on arrival and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage are shown in Table 11 and Figure 10. Cooking loss values were higher than those reported by Ha & Warner (2018). However, the method used to measure cooking loss differed from that used by the University of Melbourne (Ha & Warner, 2018), so a direct comparison of values is not possible. They only carried out their analysis on loin samples and reported cooking losses of 15.4 (2.3) % and 15.8 (2.2) % in beef loin and lamb loin, respectively. Their method cooked the samples to 71°C, whereas the method used in our analysis heated the samples to 75°C in boiling water. This may account for the higher values recorded in our analysis and the higher degree of variability in results. In common with the thawing loss results, in both beef and lamb samples cooking losses increased with the level of chemical lean. This indicates, as would be expected, that there is more cooking loss from the muscle than the fat in the samples. Except for the beef and lamb loin, higher cooking losses were measured in all the other samples at 3 months, in comparison to that measured after all other storage durations. We believe that this was due to refinements made to the experimental method used to analyse the samples after the initial analysis on arrival of the samples.

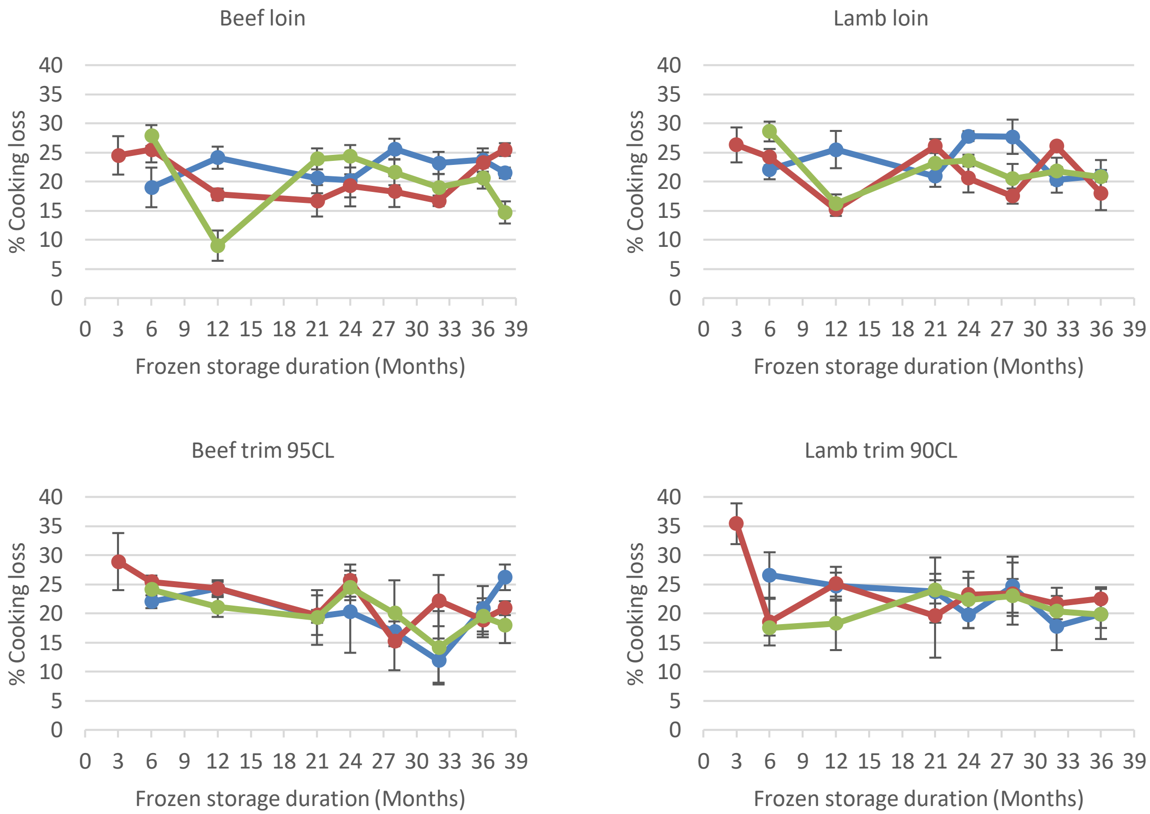
After 38 months of frozen storage, in several sample types small but statistically significant differences ($P<0.05$) were measured in cooking losses between different frozen storage durations and temperatures. However, no repeatable trend between storage duration and temperature was observed over the evaluated storage period, with the highest cooking loss being recorded at different storage durations at all three different storage temperatures in different groups. Overall, there was little difference between cooking losses measured in the beef and lamb loin after 6, 12, 21, 24, 28, 32, 36, and 38 months storage. In most cases there was no statistical difference ($P>0.05$) between mean cooking losses of samples held at -12°C, -18°C, or -24°C. Significantly lower ($P \leq 0.05$) cooking losses were measured at month 12 in beef loin samples stored at -24°C, and lamb loin samples stored at -18°C and -24°C at 12 months, but these differences were not repeated and are likely to be due to box-to-box variation in the commercially processed meat.

While this study did not observe any significant change in cooking loss with frozen storage duration from beef and lamb samples some published studies have reported an increase in cooking loss in these meats with frozen storage duration, while others have observed no change, or a decrease with time. Farouk *et al.* (2003) observed an increase in cooking loss in beef (*m. semitendinosus*) with frozen storage duration of up to 12 months stored at -18°C, -35°C, and -75°C. Fernandes *et al.* (2013) and Muela *et al.* (2015) also observed an increase in cooking losses in vacuum-packed lamb (*L. dorsi* and *L. thoracis et lumborum*, respectively) with frozen storage duration, stored for up to 12 and 21 months, respectively, at -18°C. However, Coombs *et al.* (2017a) and Holman *et al.* (2017) observed no significant effect of storage period or temperature on cooking loss in vacuum-packed lamb (*M. longissimus lumborum*) or beef (*M. longissimus lumborum*), respectively, stored for up to 12 months at -12°C or -18°C. Conversely, Pinheiro *et al.* (2015) observed a decrease in cooking loss over time in vacuum-packed lamb (*L. lumborum*) held for up to 12 months at -25°C. None of these studies stored frozen meat beyond 24 months.

Table 11. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) cooking loss (%) from beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	6	12	21	24	28	32	36	38
Beef loin	-12		19.0 (3.4)$^{a}_{A}$	24.1 (1.9)$^{bcd}_{A}$	20.6 (2.6)$^{abc}_{A}$	20.2 (4.4)$^{abc}_{AB}$	25.6 (1.7)$^{d}_{A}$	23.2 (1.9)$^{bd}_{A}$	23.7 (2.0)$^{bd}_{A}$	21.5 (0.9)$^{ab}_{A}$
	-18	24.5 (3.3)^{a}	25.5 (2.2)$^{a}_{B}$	17.8 (1.0)$^{b}_{B}$	16.7 (2.7)$^{b}_{B}$	19.3 (2.0)$^{b}_{A}$	18.3 (2.7)$^{b}_{B}$	16.7 (0.9)$^{b}_{B}$	23.3 (1.7)$^{a}_{AB}$	25.5 (1.1)$^{a}_{B}$
	-24		27.9 (1.8)$^{a}_{B}$	9.0 (2.6)$^{b}_{C}$	23.9 (1.8)$^{c}_{A}$	24.3 (1.9)$^{c}_{B}$	21.6 (2.2)$^{cd}_{B}$	19.0 (2.3)$^{d}_{B}$	20.6 (1.8)$^{d}_{B}$	14.7 (1.9)$^{e}_{C}$
Beef trim 95CL	-12		22.0 (1.1)$^{abc}_{A}$	24.3 (1.1)$^{ac}_{A}$	19.5 (1.1)$^{ab}_{A}$	20.3 (7.1)$^{ab}_{A}$	16.9 (1.8)$^{b}_{A}$	11.9 (3.8)$^{d}_{A}$	20.8 (3.9)$^{ab}_{A}$	26.2 (2.2)$^{c}_{A}$
	-18	28.9 (4.9)^{a}	25.4 (1.1)$^{ab}_{B}$	24.3 (1.4)$^{acd}_{A}$	19.7 (3.4)$^{de}_{A}$	25.6 (2.8)$^{ac}_{A}$	15.2 (5.0)$^{e}_{A}$	22.2 (4.4)$^{bcdf}_{B}$	18.9 (3.0)$^{ef}_{A}$	20.9 (1.2)$^{bcf}_{B}$
	-24		24.1 (1.7)$^{a}_{AB}$	21.1 (1.7)$^{ab}_{B}$	19.3 (4.7)$^{ac}_{A}$	24.4 (2.2)$^{a}_{A}$	20.0 (5.7)$^{ac}_{A}$	14.1 (6.3)$^{cd}_{A}$	19.5 (3.1)$^{ad}_{A}$	18.0 (3.1)$^{bd}_{B}$
Beef trim 85CL	-12		16.8 (8.5)$^{ab}_{A}$	23.5 (1.9)$^{a}_{A}$	12.1 (4.0)$^{b}_{A}$	16.9 (6.1)$^{ab}_{A}$	19.2 (3.9)$^{ab}_{A}$	6.6 (5.7)$^{c}_{A}$	13.9 (7.6)$^{ac}_{A}$	19.1 (10.6)$^{ab}_{A}$
	-18	27.1 (3.0)^{a}	14.4 (4.5)$^{b}_{A}$	14.8 (4.7)$^{b}_{B}$	21.0 (2.6)$^{c}_{B}$	13.6 (4.2)$^{b}_{A}$	22.7 (3.9)$^{ac}_{A}$	10.3 (4.3)$^{b}_{AB}$	22.8 (1.8)$^{ac}_{A}$	21.4 (4.1)$^{c}_{A}$
	-24		17.3 (4.7)$^{ab}_{A}$	20.4 (3.6)$^{b}_{AB}$	14.7 (3.5)$^{ab}_{A}$	19.8 (6.7)$^{ab}_{A}$	18.9 (2.4)$^{ab}_{A}$	15.8 (6.7)$^{ab}_{B}$	14.6 (6.6)$^{ab}_{A}$	13.1 (4.7)$^{a}_{A}$
Beef trim 65CL	-12		7.9 (3.2)$^{a}_{A}$	10.3 (2.9)$^{ab}_{A}$	11.2 (4.3)$^{ab}_{A}$	12.3 (1.8)$^{ab}_{A}$	14.7 (6.5)$^{b}_{A}$	9.0 (2.7)$^{a}_{A}$	16.6 (4.4)$^{b}_{A}$	14.1 (7.6)$^{a}_{A}$
	-18	22.0 (3.8)^{a}	13.3 (2.6)$^{bc}_{A}$	15.9 (2.9)$^{ab}_{B}$	10.5 (4.8)$^{bc}_{A}$	13.0 (7.3)$^{bc}_{A}$	13.0 (4.1)$^{bc}_{A}$	6.7 (4.0)$^{c}_{A}$	10.0 (7.4)$^{bc}_{A}$	9.0 (2.5)$^{bc}_{A}$
	-24		8.5 (5.3)$^{a}_{A}$	10.4 (3.8)$^{a}_{A}$	10.9 (3.3)$^{a}_{A}$	11.2 (2.7)$^{a}_{A}$	12.1 (5.4)$^{a}_{A}$	11.1 (7.4)$^{a}_{A}$	19.0 (3.4)$^{b}_{A}$	13.2 (4.2)$^{a}_{A}$
Lamb loin	-12		22.1 (1.7)$^{a}_{A}$	25.5 (3.2)$^{b}_{A}$	20.9 (1.8)$^{a}_{A}$	27.8 (0.8)$^{b}_{A}$	27.7 (2.9)$^{b}_{A}$	20.3 (2.2)$^{a}_{A}$	21.0 (1.0)$^{a}_{A}$	28.5 (2.1)$^{b}_{A}$
	-18	26.3 (3.0)^{a}	24.2 (1.4)$^{a}_{A}$	15.2 (1.1)$^{b}_{B}$	26.1 (1.2)$^{a}_{B}$	20.6 (2.5)$^{c}_{B}$	17.5 (1.3)$^{bd}_{B}$	26.1 (0.5)$^{a}_{B}$	18.0 (2.9)$^{cd}_{A}$	18.3 (0.8)$^{cd}_{B}$
	-24		28.6 (1.7)$^{a}_{B}$	16.2 (1.6)$^{b}_{B}$	23.2 (2.9)$^{c}_{AB}$	23.6 (1.0)$^{c}_{C}$	20.5 (2.6)$^{c}_{B}$	21.8 (2.3)$^{c}_{AB}$	20.8 (2.9)$^{c}_{A}$	22.3 (2.2)$^{c}_{C}$
Lamb trim 90CL	-12		26.6 (3.9)$^{a}_{A}$	24.7 (2.3)$^{ab}_{A}$	23.7 (2.0)$^{ab}_{A}$	19.7 (2.3)$^{b}_{A}$	24.7 (5.1)$^{ab}_{A}$	17.8 (4.1)$^{c}_{A}$	19.9 (4.3)$^{bc}_{A}$	17.7 (3.0)$^{c}_{A}$
	-18	35.4 (3.5)^{a}	18.5 (4.0)$^{b}_{B}$	25.1 (2.9)$^{c}_{A}$	19.6 (7.2)$^{bc}_{A}$	23.2 (2.9)$^{bc}_{A}$	23.4 (5.3)$^{bc}_{A}$	21.7 (2.7)$^{bc}_{A}$	22.5 (2.0)$^{bc}_{A}$	21.5 (2.2)$^{bc}_{AB}$
	-24		17.5 (1.3)$^{a}_{B}$	18.3 (4.6)$^{ab}_{B}$	24.0 (5.6)$^{c}_{A}$	22.3 (4.8)$^{abc}_{A}$	23.0 (2.9)$^{bc}_{A}$	20.4 (2.6)$^{abc}_{A}$	19.8 (2.3)$^{abc}_{A}$	23.2 (2.0)$^{bc}_{B}$
Lamb trim 85CL	-12		18.2 (4.7)$^{ab}_{A}$	24.3 (2.8)$^{a}_{A}$	22.9 (4.3)$^{a}_{A}$	20.7 (3.3)$^{ab}_{A}$	21.1 (6.3)$^{ab}_{A}$	15.8 (4.1)$^{b}_{A}$	22.9 (3.1)$^{a}_{A}$	18.1 (2.1)$^{ab}_{A}$
	-18	31.1 (6.2)^{a}	23.5 (4.2)$^{b}_{A}$	21.9 (1.6)$^{b}_{AB}$	19.5 (4.7)$^{b}_{A}$	22.3 (2.6)$^{b}_{A}$	24.4 (2.4)$^{b}_{A}$	12.9 (3.7)$^{c}_{A}$	24.4 (5.0)$^{b}_{A}$	21.8 (2.8)$^{b}_{AB}$
	-24		19.4 (2.5)$^{ab}_{A}$	20.1 (2.8)$^{ab}_{B}$	20.4 (3.5)$^{ab}_{A}$	19.5 (4.8)$^{ab}_{A}$	24.5 (2.1)$^{ab}_{A}$	18.8 (4.5)$^{b}_{A}$	19.7 (3.0)$^{ab}_{A}$	24.9 (4.4)$^{a}_{A}$
Lamb trim 65CL	-12		8.0 (3.1)$^{a}_{A}$	10.9 (3.8)$^{a}_{A}$	7.9 (4.3)$^{a}_{A}$	15.4 (2.6)$^{b}_{AB}$	10.0 (4.1)$^{a}_{A}$	12.8 (3.1)$^{ab}_{A}$	11.4 (1.2)$^{ab}_{A}$	15.0 (2.8)$^{b}_{A}$
	-18	21.5 (5.7)^{a}	5.8 (1.6)$^{b}_{A}$	11.3 (2.0)$^{c}_{A}$	11.3 (3.5)$^{c}_{AB}$	14.2 (5.6)$^{c}_{A}$	13.7 (3.2)$^{c}_{A}$	9.3 (2.3)$^{bc}_{A}$	10.5 (1.4)$^{bc}_{AB}$	12.2 (2.1)$^{c}_{A}$
	-24		9.9 (7.8)$^{a}_{A}$	11.4 (1.7)$^{a}_{A}$	14.5 (3.5)$^{a}_{B}$	21.0 (2.2)$^{b}_{B}$	12.5 (2.7)$^{a}_{A}$	11.4 (3.9)$^{a}_{A}$	8.5 (2.0)$^{a}_{B}$	14.5 (4.1)$^{a}_{A}$

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)


Beef loin
% Cooking loss
Frozen storage duration (Months)
Lamb loin
% Cooking loss
Frozen storage duration (Months)
Beef trim 95CL
% Cooking loss
Frozen storage duration (Months)
Lamb trim 90CL
% Cooking loss
Frozen storage duration (Months)

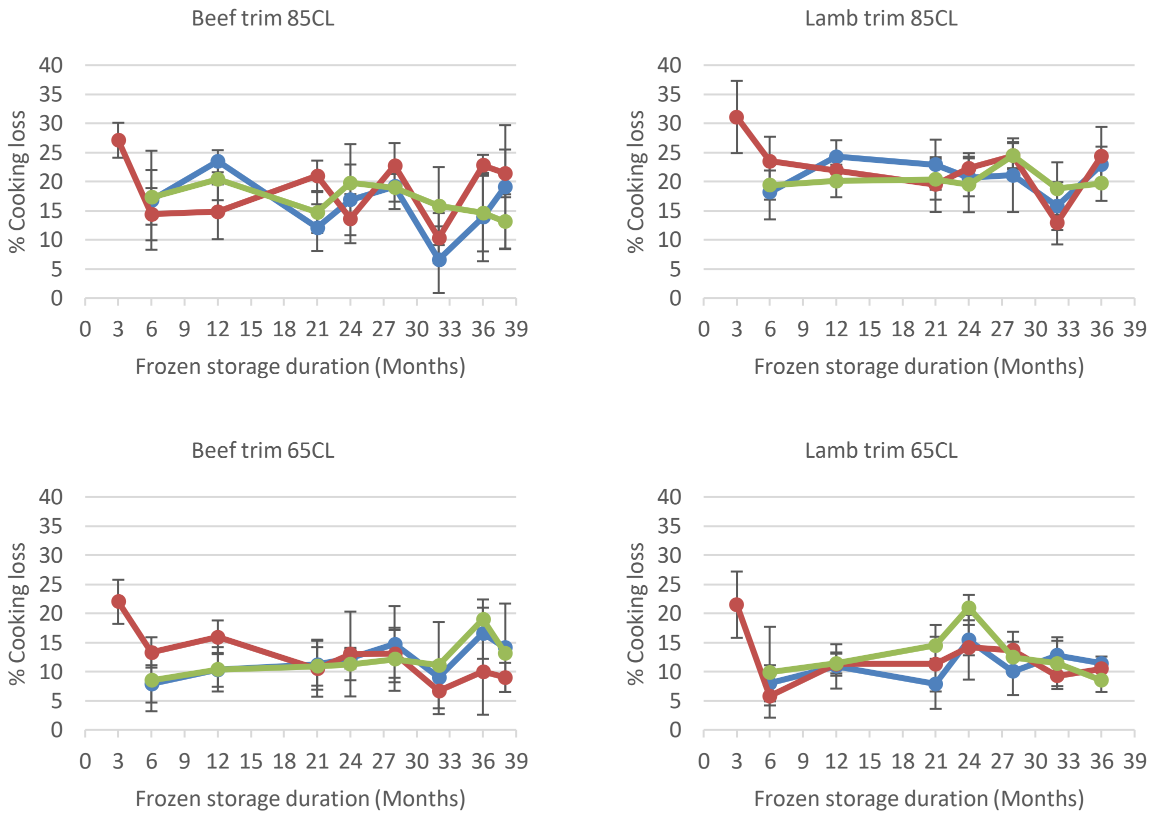


Figure 10. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean cooking loss (%) from beef/lamb loin and trim (Vertical bars: ±1SD)

4.1.5 Instrumental texture (Warner–Bratzler shear force [WBSF])

Beef and lamb 'firmness' (maximum shear force) and 'toughness' (total work of shear) results an arrival, 6, 12, 21, 24, 28, 32, 36, and 38 months are shown in Table 12 and Table 13Table 12. Effect of frozen storage duration and temperature on mean (SD) firmness (N) measured on beef/lamb loin and trim

Sample	Temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	6	12	21	24	28	32	36	38
Beef loin (pattie)	-12		0.7 (0.1)$^{abc}_{A}$	1.1 (0.4)$^{abd}_{A}$	2.3 (0.4)$^{e}_{A}$	1.4 (0.4)$^{d}_{A}$	1.2 (0.3)$^{ad}_{A}$	0.9 (0.1)$^{abc}_{A}$	0.6 (0.2)$^{bc}_{A}$	0.5 (0.2)$^{c}_{A}$
	-18	1.0 (0.4)^{ab}	0.7 (0.2)$^{ac}_{A}$	0.8 (0.2)$^{ade}_{AB}$	2.3 (0.5)$^{f}_{A}$	1.1 (0.2)$^{bdg}_{A}$	0.9 (0.1)$^{ag}_{A}$	0.9 (0.1)$^{ag}_{A}$	0.7 (0.2)$^{ah}_{A}$	0.4 (0.1)$^{ceh}_{A}$
	-24		0.7 (0.2)$^{ab}_{A}$	0.5 (0.2)$^{a}_{B}$	1.4 (0.6)$^{c}_{B}$	1.5 (0.3)$^{c}_{A}$	1.0 (0.2)$^{b}_{A}$	0.7 (0.1)$^{ab}_{A}$	0.6 (0.1)$^{ab}_{A}$	0.4 (0.2)$^{a}_{A}$
Beef trim 95CL (pattie)	-12		0.8 (0.1)$^{ab}_{A}$	0.5 (0.3)$^{ac}_{A}$	0.9 (0.2)$^{b}_{A}$	1.3 (0.3)$^{d}_{A}$	1.0 (0.5)$^{bd}_{A}$	1.1 (0.2)$^{bd}_{A}$	0.3 (0.1)$^{c}_{A}$	0.5 (0.2)$^{ac}_{A}$
	-18	1.1 (0.2)^{a}	0.8 (0.2)$^{abc}_{A}$	0.4 (0.2)$^{d}_{A}$	0.6 (0.2)$^{bcd}_{B}$	1.1 (0.4)$^{a}_{A}$	0.7 (0.2)$^{bcd}_{A}$	0.9 (0.3)$^{ab}_{A}$	0.5 (0.1)$^{cd}_{A}$	0.4 (0.2)$^{d}_{A}$
	-24		0.9 (0.1)$^{a}_{A}$	0.6 (0.2)$^{abc}_{A}$	0.4 (0.2)$^{b}_{B}$	1.6 (0.5)$^{d}_{A}$	0.9 (0.4)$^{ac}_{A}$	1.0 (0.3)$^{ac}_{A}$	0.4 (0.2)$^{b}_{A}$	0.4 (0.2)$^{b}_{A}$
Beef trim 85CL (pattie)	-12		1.3 (0.6)$^{a}_{A}$	0.5 (0.1)$^{b}_{A}$	0.7 (0.1)$^{bc}_{A}$	0.9 (0.2)$^{ac}_{A}$	0.7 (0.3)$^{bc}_{A}$	1.0 (0.1)$^{ac}_{A}$	0.5 (0.2)$^{b}_{A}$	0.4 (0.3)$^{b}_{A}$
	-18	0.4 (0.2)^{a}	0.8 (0.2)$^{bc}_{A}$	0.5 (0.1)$^{ab}_{A}$	0.4 (0.1)$^{a}_{B}$	1.0 (0.2)$^{c}_{A}$	0.8 (0.2)$^{bc}_{A}$	0.7 (0.2)$^{ab}_{B}$	0.6 (0.1)$^{ab}_{A}$	0.5 (0.1)$^{a}_{A}$
	-24		0.8 (0.3)$^{ab}_{A}$	0.9 (0.5)$^{a}_{A}$	0.6 (0.1)$^{ab}_{AB}$	1.6 (0.4)$^{c}_{B}$	0.8 (0.3)$^{ab}_{A}$	0.8 (0.2)$^{ab}_{AB}$	0.5 (0.2)$^{b}_{A}$	0.7 (0.3)$^{ab}_{A}$
Beef trim 65CL (pattie)	-12		1.3 (0.2)$^{a}_{A}$	0.8 (0.2)$^{bcd}_{A}$	1.1 (0.2)$^{ab}_{A}$	1.0 (0.2)$^{abc}_{A}$	0.7 (0.3)$^{cd}_{A}$	0.9 (0.4)$^{abc}_{A}$	0.8 (0.3)$^{bcd}_{A}$	0.5 (0.1)$^{d}_{A}$
	-18	0.5 (0.2)^{a}	1.4 (0.3)$^{b}_{A}$	0.7 (0.2)$^{ac}_{A}$	0.8 (0.1)$^{ac}_{AB}$	0.9 (0.1)$^{c}_{A}$	0.7 (0.5)$^{ac}_{A}$	0.6 (0.1)$^{ac}_{A}$	0.6 (0.2)$^{ac}_{AB}$	0.7 (0.3)$^{ac}_{A}$
	-24		1.4 (0.2)$^{a}_{A}$	0.5 (0.2)$^{b}_{A}$	0.6 (0.3)$^{b}_{B}$	1.2 (0.5)$^{ac}_{A}$	0.8 (0.2)$^{bc}_{A}$	0.5 (0.1)$^{b}_{A}$	0.5 (0.1)$^{b}_{B}$	0.6 (0.4)$^{b}_{A}$
Lamb loin (pattie)	-12		1.1 (0.2)$^{a}_{A}$	0.7 (0.2)$^{a}_{A}$	3.3 (1.6)$^{b}_{A}$	1.4 (0.2)$^{a}_{A}$	0.7 (0.3)$^{a}_{A}$	0.9 (0.1)$^{a}_{A}$	0.9 (0.3)$^{a}_{A}$	0.7 (0.3)$^{a}_{A}$
	-18	0.7 (0.2)^{ab}	0.9 (0.2)$^{a}_{A}$	0.6 (0.1)$^{ab}_{AB}$	0.8 (0.1)$^{ab}_{B}$	1.4 (0.2)$^{c}_{A}$	0.9 (0.5)$^{a}_{A}$	0.7 (0.1)$^{ab}_{B}$	0.5 (0.2)$^{b}_{B}$	0.6 (0.2)$^{ab}_{A}$
	-24		0.9 (0.2)$^{ab}_{A}$	0.4 (0.2)$^{c}_{B}$	1.3 (0.6)$^{d}_{B}$	1.2 (0.2)$^{ad}_{A}$	0.5 (0.1)$^{c}_{A}$	0.8 (0.1)$^{bc}_{AB}$	0.7 (0.2)$^{abc}_{AB}$	0.6 (0.1)$^{abc}_{A}$
Lamb trim 90CL (pattie)	-12		1.2 (0.6)$^{ab}_{A}$	0.4 (0.1)$^{c}_{A}$	1.0 (0.2)$^{abd}_{A}$	1.4 (0.5)$^{b}_{A}$	0.7 (0.2)$^{cd}_{A}$	0.8 (0.1)$^{acd}_{A}$	0.8 (0.2)$^{acd}_{A}$	0.4 (0.1)$^{c}_{A}$
	-18	0.8 (0.2)^{ab}	1.2 (0.6)$^{c}_{A}$	0.4 (0.1)$^{a}_{A}$	0.9 (0.0)$^{bcd}_{A}$	1.3 (0.4)$^{c}_{A}$	0.5 (0.3)$^{ad}_{A}$	0.7 (0.2)$^{ad}_{A}$	0.6 (0.2)$^{ad}_{AB}$	0.5 (0.1)$^{ad}_{A}$
	-24		1.2 (0.2)$^{a}_{A}$	0.6 (0.3)$^{bc}_{A}$	0.9 (0.1)$^{b}_{A}$	1.3 (0.2)$^{a}_{A}$	0.6 (0.1)$^{c}_{A}$	0.6 (0.1)$^{bc}_{A}$	0.4 (0.1)$^{c}_{B}$	0.5 (0.1)$^{c}_{A}$
Lamb trim 85CL (pattie)	-12		1.5 (0.7)$^{a}_{A}$	0.5 (0.1)$^{b}_{A}$	0.5 (0.1)$^{b}_{A}$	1.2 (0.4)$^{ac}_{A}$	0.8 (0.1)$^{bc}_{A}$	1.3 (0.4)$^{ac}_{A}$	0.6 (0.2)$^{b}_{A}$	0.6 (0.3)$^{bc}_{A}$
	-18	1.1 (0.8)^{ab}	1.1 (0.5)$^{ab}_{A}$	0.4 (0.1)$^{c}_{A}$	0.6 (0.1)$^{ac}_{A}$	1.4 (0.3)$^{b}_{A}$	0.9 (0.1)$^{abc}_{A}$	1.2 (0.2)$^{bd}_{A}$	0.8 (0.2)$^{acd}_{A}$	0.5 (0.1)$^{c}_{A}$
	-24		1.1 (0.5)$^{ab}_{A}$	0.5 (0.1)$^{c}_{A}$	0.5 (0.2)$^{c}_{A}$	1.8 (0.6)$^{a}_{A}$	0.7 (0.3)$^{bc}_{A}$	0.9 (0.3)$^{bc}_{A}$	0.6 (0.3)$^{bc}_{A}$	0.6 (0.2)$^{bc}_{A}$
Lamb trim 65CL (pattie)	-12		1.3 (0.2)$^{a}_{A}$	0.7 (0.2)$^{bc}_{A}$	0.8 (0.1)$^{bc}_{A}$	1.2 (0.4)$^{a}_{A}$	0.6 (0.2)$^{bc}_{A}$	0.9 (0.4)$^{ab}_{A}$	0.7 (0.2)$^{bc}_{A}$	0.5 (0.1)$^{c}_{AB}$
	-18	1.0 (0.4)^{ab}	1.4 (0.3)$^{a}_{A}$	0.5 (0.2)$^{c}_{A}$	0.7 (0.2)$^{bc}_{A}$	1.8 (0.4)$^{d}_{A}$	0.7 (0.2)$^{bc}_{A}$	0.6 (0.1)$^{c}_{A}$	0.5 (0.2)$^{c}_{A}$	0.7 (0.1)$^{c}_{A}$
	-24		1.4 (0.2)$^{a}_{A}$	0.5 (0.2)$^{b}_{A}$	0.7 (0.3)$^{b}_{A}$	1.5 (0.5)$^{a}_{A}$	0.8 (0.3)$^{b}_{A}$	0.5 (0.1)$^{b}_{A}$	0.6 (0.1)$^{b}_{A}$	0.4 (0.1)$^{b}_{B}$
Beef loin (steak)	-12		5.9 (1.5)$^{ab}_{AB}$	4.3 (2.1)$^{ac}_{A}$	3.1 (0.7)$^{c}_{A}$	4.9 (0.6)$^{ac}_{A}$	5.3 (2.1)$^{ab}_{A}$	7.2 (1.0)$^{b}_{A}$	5.8 (1.5)$^{ab}_{A}$	6.1 (1.7)$^{ab}_{A}$
	-18	5.9 (0.6)^{ab}	7.7 (1.9)$^{a}_{A}$	7.0 (0.6)$^{ac}_{B}$	4.7 (1.5)$^{bd}_{B}$	5.5 (0.9)$^{bc}_{A}$	5.6 (0.9)$^{bc}_{A}$	4.7 (2.2)$^{bd}_{B}$	2.7 (0.3)$^{e}_{B}$	3.6 (1.2)$^{de}_{B}$
	-24		5.2 (1.2)$^{a}_{B}$	5.1 (0.6)$^{ab}_{AB}$	3.2 (0.5)$^{c}_{AB}$	6.1 (1.4)$^{a}_{A}$	6.2 (1.1)$^{a}_{A}$	3.8 (0.5)$^{bc}_{B}$	5.8 (1.4)$^{a}_{A}$	5.4 (0.6)$^{a}_{AB}$
Lamb loin (steak)	-12		4.8 (1.6)$^{a}_{A}$	1.5 (0.2)$^{b}_{A}$	2.6 (0.3)$^{bc}_{A}$	3.9 (1.6)$^{ac}_{A}$	2.5 (0.3)$^{bc}_{A}$	2.3 (0.5)$^{bd}_{A}$	3.6 (1.3)$^{acd}_{A}$	3.8 (0.7)$^{acd}_{A}$
	-18	3.5 (1.1)^{ab}	4.2 (0.9)$^{a}_{A}$	1.4 (0.1)$^{c}_{A}$	1.8 (0.2)$^{c}_{B}$	4.0 (1.3)$^{a}_{A}$	2.8 (0.7)$^{bd}_{A}$	2.3 (0.5)$^{cd}_{A}$	1.8 (0.4)$^{cd}_{A}$	2.3 (0.5)$^{cd}_{B}$
	-24		3.5 (0.4)$^{a}_{A}$	1.2 (0.3)$^{b}_{A}$	2.2 (0.7)$^{bc}_{AB}$	3.0 (0.4)$^{ac}_{A}$	3.0 (0.9)$^{ac}_{A}$	2.5 (0.2)$^{ac}_{A}$	3.0 (1.5)$^{ac}_{A}$	2.4 (0.4)$^{ac}_{B}$

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)

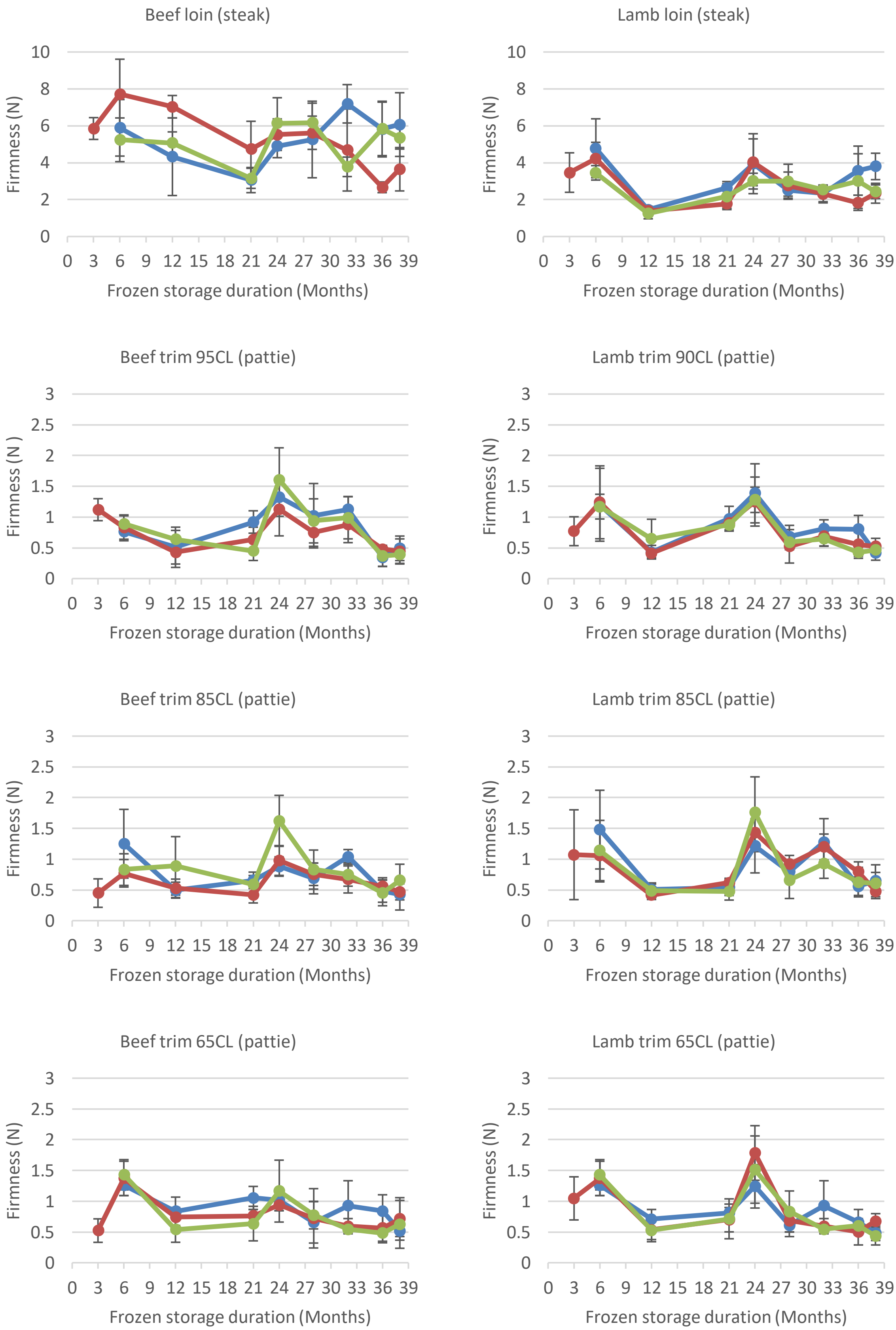


Figure 11. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean firmness (N) of beef/lamb loin and trim (Vertical bars: ±1SD) N.B. beef and lamb loin steak data are presented on different scale to trim

Table 13, respectively. The results are compared graphically in Figure 11 and Figure 12, respectively. Overall, the results showed no repeatable trend for firmness (shear force) or toughness to change with storage duration, with the highest mean values being recorded at different storage durations at all three different storage temperatures in different groups. 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, again, is most likely due to box-to-box variation in the commercially produced meat, particularly differences in the composition of the trim. The high firmness and toughness observed in the samples is likely to be due in part to the relatively short period of time between slaughter and freezing of the meat. Overall beef loin steak samples were firmer and tougher than lamb loin steak samples. This is to be expected as meats from different muscles of different species differ in tenderness due to variation in the calpains activity (Dransfeld, 1994).

As noted by Muela *et al.* (2015), there is conflicting evidence in the literature on the effect of freezing and frozen storage on texture (shear force). It has been reported to have no effect, a decrease in toughness, or an increase. This may be due to an effect of differences in initial freezing rates among studies (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, which may be affected by post-mortem proteolysis (Pinheiro *et al.*, 2015).

Pinheiro *et al.* (2015) observed no effect of storage duration on shear force in vacuum-packed lamb (*L. lumborum*) stored up to 12 months at -25°C. A few studies have reported that meat to become more tender with frozen storage duration (Farouk *et al.*, 2003; Lagerstedt *et al.*, 2008; Coombs *et al.*, 2017a). This has been attributed to the breakdown of muscle structure caused by enzyme activity and/or changes to ice crystal formation (Farouk *et al.*, 2003). Fernandes *et al.* (2013) observed a linear increase in shear force over storage duration in vacuum-packed lamb loin stored for up to 12 months at -18°C. They attributed this change to a corresponding increase in cooking loss during storage that they observed in their study (while no change in cooking loss with storage duration was observed in this study). Similarly, Holman *et al.* (2017) also observed an increase in shear force with storage duration in vacuum-packed beef (*M. longissimus lumborum*) stored for up to 12 months at -12°C or -18°C. Muela *et al.* (2015) observed that shear force increased with storage duration for lamb stored at -18°C for up to 21 months, but thawed meat experienced a significant gradual decrease in shear force in subsequent chilled retail display over 6 days. Again, none of these studies stored frozen meat beyond 24 months.

Table 12. Effect of frozen storage duration and temperature on mean (SD) firmness (N) measured on beef/lamb loin and trim

Sample	Temp (°C)	Frozen storage duration (Months) 3 (arrival)	6	12	21	24	28	32	36	38
Beef loin (pattie)	-12		0.7 (0.1)$^{abc}_{A}$	1.1 (0.4)$^{abd}_{A}$	2.3 (0.4)$^{e}_{A}$	1.4 (0.4)$^{d}_{A}$	1.2 (0.3)$^{ad}_{A}$	0.9 (0.1)$^{abc}_{A}$	0.6 (0.2)$^{bc}_{A}$	0.5 (0.2)$^{c}_{A}$
	-18	1.0 (0.4)^{ab}	0.7 (0.2)$^{ac}_{A}$	0.8 (0.2)$^{ade}_{AB}$	2.3 (0.5)$^{f}_{A}$	1.1 (0.2)$^{bdg}_{A}$	0.9 (0.1)$^{ag}_{A}$	0.9 (0.1)$^{ag}_{A}$	0.7 (0.2)$^{ah}_{A}$	0.4 (0.1)$^{ceh}_{A}$
	-24		0.7 (0.2)$^{ab}_{A}$	0.5 (0.2)$^{a}_{B}$	1.4 (0.6)$^{c}_{B}$	1.5 (0.3)$^{c}_{A}$	1.0 (0.2)$^{b}_{A}$	0.7 (0.1)$^{ab}_{A}$	0.6 (0.1)$^{ab}_{A}$	0.4 (0.2)$^{a}_{A}$
Beef trim 95CL (pattie)	-12		0.8 (0.1)$^{ab}_{A}$	0.5 (0.3)$^{ac}_{A}$	0.9 (0.2)$^{b}_{A}$	1.3 (0.3)$^{d}_{A}$	1.0 (0.5)$^{bd}_{A}$	1.1 (0.2)$^{bd}_{A}$	0.3 (0.1)$^{c}_{A}$	0.5 (0.2)$^{ac}_{A}$
	-18	1.1 (0.2)^{a}	0.8 (0.2)$^{abc}_{A}$	0.4 (0.2)$^{d}_{A}$	0.6 (0.2)$^{bcd}_{B}$	1.1 (0.4)$^{a}_{A}$	0.7 (0.2)$^{bcd}_{A}$	0.9 (0.3)$^{ab}_{A}$	0.5 (0.1)$^{cd}_{A}$	0.4 (0.2)$^{d}_{A}$
	-24		0.9 (0.1)$^{a}_{A}$	0.6 (0.2)$^{abc}_{A}$	0.4 (0.2)$^{b}_{B}$	1.6 (0.5)$^{d}_{A}$	0.9 (0.4)$^{ac}_{A}$	1.0 (0.3)$^{ac}_{A}$	0.4 (0.2)$^{b}_{A}$	0.4 (0.2)$^{b}_{A}$
Beef trim 85CL (pattie)	-12		1.3 (0.6)$^{a}_{A}$	0.5 (0.1)$^{b}_{A}$	0.7 (0.1)$^{bc}_{A}$	0.9 (0.2)$^{ac}_{A}$	0.7 (0.3)$^{bc}_{A}$	1.0 (0.1)$^{ac}_{A}$	0.5 (0.2)$^{b}_{A}$	0.4 (0.3)$^{b}_{A}$
	-18	0.4 (0.2)^{a}	0.8 (0.2)$^{bc}_{A}$	0.5 (0.1)$^{ab}_{A}$	0.4 (0.1)$^{a}_{B}$	1.0 (0.2)$^{c}_{A}$	0.8 (0.2)$^{bc}_{A}$	0.7 (0.2)$^{ab}_{B}$	0.6 (0.1)$^{ab}_{A}$	0.5 (0.1)$^{a}_{A}$
	-24		0.8 (0.3)$^{ab}_{A}$	0.9 (0.5)$^{a}_{A}$	0.6 (0.1)$^{ab}_{AB}$	1.6 (0.4)$^{c}_{B}$	0.8 (0.3)$^{ab}_{A}$	0.8 (0.2)$^{ab}_{AB}$	0.5 (0.2)$^{b}_{A}$	0.7 (0.3)$^{ab}_{A}$
Beef trim 65CL (pattie)	-12		1.3 (0.2)$^{a}_{A}$	0.8 (0.2)$^{bcd}_{A}$	1.1 (0.2)$^{ab}_{A}$	1.0 (0.2)$^{abc}_{A}$	0.7 (0.3)$^{cd}_{A}$	0.9 (0.4)$^{abc}_{A}$	0.8 (0.3)$^{bcd}_{A}$	0.5 (0.1)$^{d}_{A}$
	-18	0.5 (0.2)^{a}	1.4 (0.3)$^{b}_{A}$	0.7 (0.2)$^{ac}_{A}$	0.8 (0.1)$^{ac}_{AB}$	0.9 (0.1)$^{c}_{A}$	0.7 (0.5)$^{ac}_{A}$	0.6 (0.1)$^{ac}_{A}$	0.6 (0.2)$^{ac}_{AB}$	0.7 (0.3)$^{ac}_{A}$
	-24		1.4 (0.2)$^{a}_{A}$	0.5 (0.2)$^{b}_{A}$	0.6 (0.3)$^{b}_{B}$	1.2 (0.5)$^{ac}_{A}$	0.8 (0.2)$^{bc}_{A}$	0.5 (0.1)$^{b}_{A}$	0.5 (0.1)$^{b}_{B}$	0.6 (0.4)$^{b}_{A}$
Lamb loin (pattie)	-12		1.1 (0.2)$^{a}_{A}$	0.7 (0.2)$^{a}_{A}$	3.3 (1.6)$^{b}_{A}$	1.4 (0.2)$^{a}_{A}$	0.7 (0.3)$^{a}_{A}$	0.9 (0.1)$^{a}_{A}$	0.9 (0.3)$^{a}_{A}$	0.7 (0.3)$^{a}_{A}$
	-18	0.7 (0.2)^{ab}	0.9 (0.2)$^{a}_{A}$	0.6 (0.1)$^{ab}_{AB}$	0.8 (0.1)$^{ab}_{B}$	1.4 (0.2)$^{c}_{A}$	0.9 (0.5)$^{a}_{A}$	0.7 (0.1)$^{ab}_{B}$	0.5 (0.2)$^{b}_{B}$	0.6 (0.2)$^{ab}_{A}$
	-24		0.9 (0.2)$^{ab}_{A}$	0.4 (0.2)$^{c}_{B}$	1.3 (0.6)$^{d}_{B}$	1.2 (0.2)$^{ad}_{A}$	0.5 (0.1)$^{c}_{A}$	0.8 (0.1)$^{bc}_{AB}$	0.7 (0.2)$^{abc}_{AB}$	0.6 (0.1)$^{abc}_{A}$
Lamb trim 90CL (pattie)	-12		1.2 (0.6)$^{ab}_{A}$	0.4 (0.1)$^{c}_{A}$	1.0 (0.2)$^{abd}_{A}$	1.4 (0.5)$^{b}_{A}$	0.7 (0.2)$^{cd}_{A}$	0.8 (0.1)$^{acd}_{A}$	0.8 (0.2)$^{acd}_{A}$	0.4 (0.1)$^{c}_{A}$
	-18	0.8 (0.2)^{ab}	1.2 (0.6)$^{c}_{A}$	0.4 (0.1)$^{a}_{A}$	0.9 (0.0)$^{bcd}_{A}$	1.3 (0.4)$^{c}_{A}$	0.5 (0.3)$^{ad}_{A}$	0.7 (0.2)$^{ad}_{A}$	0.6 (0.2)$^{ad}_{AB}$	0.5 (0.1)$^{ad}_{A}$
	-24		1.2 (0.2)$^{a}_{A}$	0.6 (0.3)$^{bc}_{A}$	0.9 (0.1)$^{b}_{A}$	1.3 (0.2)$^{a}_{A}$	0.6 (0.1)$^{c}_{A}$	0.6 (0.1)$^{bc}_{A}$	0.4 (0.1)$^{c}_{B}$	0.5 (0.1)$^{c}_{A}$
Lamb trim 85CL (pattie)	-12		1.5 (0.7)$^{a}_{A}$	0.5 (0.1)$^{b}_{A}$	0.5 (0.1)$^{b}_{A}$	1.2 (0.4)$^{ac}_{A}$	0.8 (0.1)$^{bc}_{A}$	1.3 (0.4)$^{ac}_{A}$	0.6 (0.2)$^{b}_{A}$	0.6 (0.3)$^{bc}_{A}$
	-18	1.1 (0.8)^{ab}	1.1 (0.5)$^{ab}_{A}$	0.4 (0.1)$^{c}_{A}$	0.6 (0.1)$^{ac}_{A}$	1.4 (0.3)$^{b}_{A}$	0.9 (0.1)$^{abc}_{A}$	1.2 (0.2)$^{bd}_{A}$	0.8 (0.2)$^{acd}_{A}$	0.5 (0.1)$^{c}_{A}$
	-24		1.1 (0.5)$^{ab}_{A}$	0.5 (0.1)$^{c}_{A}$	0.5 (0.2)$^{c}_{A}$	1.8 (0.6)$^{a}_{A}$	0.7 (0.3)$^{bc}_{A}$	0.9 (0.3)$^{bc}_{A}$	0.6 (0.3)$^{bc}_{A}$	0.6 (0.2)$^{bc}_{A}$
Lamb trim 65CL (pattie)	-12		1.3 (0.2)$^{a}_{A}$	0.7 (0.2)$^{bc}_{A}$	0.8 (0.1)$^{bc}_{A}$	1.2 (0.4)$^{a}_{A}$	0.6 (0.2)$^{bc}_{A}$	0.9 (0.4)$^{ab}_{A}$	0.7 (0.2)$^{bc}_{A}$	0.5 (0.1)$^{c}_{AB}$
	-18	1.0 (0.4)^{ab}	1.4 (0.3)$^{a}_{A}$	0.5 (0.2)$^{c}_{A}$	0.7 (0.2)$^{bc}_{A}$	1.8 (0.4)$^{d}_{A}$	0.7 (0.2)$^{bc}_{A}$	0.6 (0.1)$^{c}_{A}$	0.5 (0.2)$^{c}_{A}$	0.7 (0.1)$^{c}_{A}$
	-24		1.4 (0.2)$^{a}_{A}$	0.5 (0.2)$^{b}_{A}$	0.7 (0.3)$^{b}_{A}$	1.5 (0.5)$^{a}_{A}$	0.8 (0.3)$^{b}_{A}$	0.5 (0.1)$^{b}_{A}$	0.6 (0.1)$^{b}_{A}$	0.4 (0.1)$^{b}_{B}$
Beef loin (steak)	-12		5.9 (1.5)$^{ab}_{AB}$	4.3 (2.1)$^{ac}_{A}$	3.1 (0.7)$^{c}_{A}$	4.9 (0.6)$^{ac}_{A}$	5.3 (2.1)$^{ab}_{A}$	7.2 (1.0)$^{b}_{A}$	5.8 (1.5)$^{ab}_{A}$	6.1 (1.7)$^{ab}_{A}$
	-18	5.9 (0.6)^{ab}	7.7 (1.9)$^{a}_{A}$	7.0 (0.6)$^{ac}_{B}$	4.7 (1.5)$^{bd}_{B}$	5.5 (0.9)$^{bc}_{A}$	5.6 (0.9)$^{bc}_{A}$	4.7 (2.2)$^{bd}_{B}$	2.7 (0.3)$^{e}_{B}$	3.6 (1.2)$^{de}_{B}$
	-24		5.2 (1.2)$^{a}_{B}$	5.1 (0.6)$^{ab}_{AB}$	3.2 (0.5)$^{c}_{AB}$	6.1 (1.4)$^{a}_{A}$	6.2 (1.1)$^{a}_{A}$	3.8 (0.5)$^{bc}_{B}$	5.8 (1.4)$^{a}_{A}$	5.4 (0.6)$^{a}_{AB}$
Lamb loin (steak)	-12		4.8 (1.6)$^{a}_{A}$	1.5 (0.2)$^{b}_{A}$	2.6 (0.3)$^{bc}_{A}$	3.9 (1.6)$^{ac}_{A}$	2.5 (0.3)$^{bc}_{A}$	2.3 (0.5)$^{bd}_{A}$	3.6 (1.3)$^{acd}_{A}$	3.8 (0.7)$^{acd}_{A}$
	-18	3.5 (1.1)^{ab}	4.2 (0.9)$^{a}_{A}$	1.4 (0.1)$^{c}_{A}$	1.8 (0.2)$^{c}_{B}$	4.0 (1.3)$^{a}_{A}$	2.8 (0.7)$^{bd}_{A}$	2.3 (0.5)$^{cd}_{A}$	1.8 (0.4)$^{cd}_{A}$	2.3 (0.5)$^{cd}_{B}$
	-24		3.5 (0.4)$^{a}_{A}$	1.2 (0.3)$^{b}_{A}$	2.2 (0.7)$^{bc}_{AB}$	3.0 (0.4)$^{ac}_{A}$	3.0 (0.9)$^{ac}_{A}$	2.5 (0.2)$^{ac}_{A}$	3.0 (1.5)$^{ac}_{A}$	2.4 (0.4)$^{ac}_{B}$

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 ($P<0.05$)

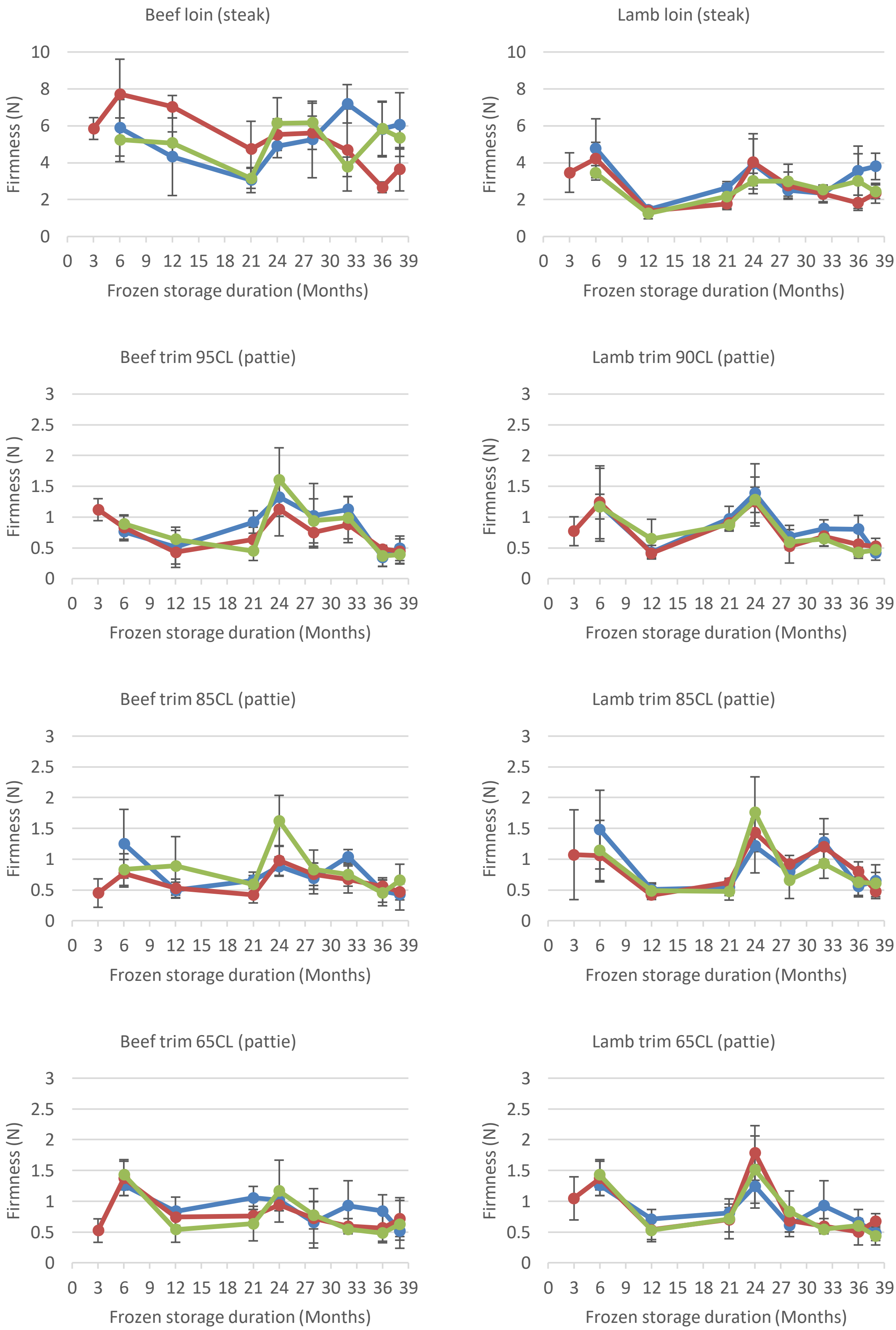


Figure 11. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean firmness (N) of beef/lamb loin and trim (Vertical bars: ±1SD) N.B. beef and lamb loin steak data are presented on different scale to trim

Table 13. Effect of frozen storage duration and temperature on mean (SD) toughness (Ns^{-1}) measured on beef/lamb loin and trim

Sample	Temp (°C)	Frozen storage duration (Months) 3 (arrival)	6	12	21	24	28	32	36	38
Beef loin (pattie)	-12		10.8 (2.8)$^{ab}_{A}$	9.8 (4.8)$^{abc}_{A}$	20.2 (6.6)$^{d}_{AB}$	18.5 (5.1)$^{de}_{A}$	12.9 (7.1)$^{ae}_{A}$	0.9 (0.1)$^{f}_{A}$	5.8 (2.5)$^{bcf}_{A}$	4.5 (1.6)$^{cf}_{A}$
	-18	12.3 (1.7)^{ab}	8.0 (2.6)$^{cd}_{A}$	6.6 (2.4)$^{cd}_{AB}$	22.7 (3.1)$^{e}_{A}$	14.3 (3.2)$^{a}_{A}$	9.5 (5.5)$^{bc}_{A}$	0.9 (0.1)$^{f}_{A}$	4.4 (1.4)$^{df}_{A}$	4.3 (1.8)$^{df}_{A}$
	-24		8.5 (1.2)$^{ab}_{A}$	4.6 (1.6)$^{ac}_{B}$	12.5 (6.6)$^{b}_{B}$	18.9 (2.9)$^{d}_{A}$	9.6 (3.6)$^{b}_{A}$	0.7 (0.1)$^{c}_{A}$	4.5 (0.7)$^{ac}_{A}$	4.0 (2.6)$^{c}_{A}$
Beef trim 95CL (pattie)	-12		9.0 (0.7)$^{a}_{A}$	7.1 (3.2)$^{a}_{A}$	10.1 (2.2)$^{a}_{A}$	17.8 (2.4)$^{b}_{AB}$	11.4 (6.2)$^{ac}_{A}$	12.8 (2.1)$^{bc}_{A}$	2.9 (1.6)$^{d}_{A}$	3.7 (1.5)$^{d}_{A}$
	-18	15.9 (2.8)^{a}	10.3 (4.0)$^{bc}_{AB}$	6.8 (3.0)$^{de}_{A}$	7.7 (2.3)$^{bd}_{AB}$	18.4 (3.4)$^{ac}_{A}$	13.6 (2.9)$^{abc}_{A}$	12.7 (4.1)$^{b}_{A}$	3.0 (1.5)$^{e}_{A}$	3.6 (1.2)$^{de}_{A}$
	-24		13.5 (1.2)$^{a}_{AB}$	7.0 (2.0)$^{bc}_{A}$	7.3 (1.7)$^{b}_{B}$	18.4 (6.9)$^{d}_{B}$	13.8 (6.2)$^{a}_{A}$	12.6 (3.6)$^{ac}_{A}$	3.0 (1.5)$^{b}_{A}$	3.6 (1.0)$^{b}_{A}$
Beef trim 85CL (pattie)	-12		16.8 (7.4)$^{a}_{A}$	5.5 (1.6)$^{b}_{A}$	7.1 (1.8)$^{b}_{A}$	15.5 (2.8)$^{a}_{A}$	7.7 (3.1)$^{bc}_{A}$	12.2 (1.5)$^{ac}_{A}$	4.2 (1.7)$^{b}_{A}$	3.9 (2.2)$^{b}_{A}$
	-18	5.6 (1.7)^{ab}	9.9 (2.7)$^{c}_{A}$	7.2 (3.3)$^{ab}_{A}$	4.8 (1.8)$^{a}_{A}$	14.6 (1.8)$^{d}_{A}$	8.2 (2.1)$^{bc}_{A}$	8.4 (2.3)$^{bc}_{B}$	4.7 (2.0)$^{a}_{A}$	4.8 (1.3)$^{a}_{A}$
	-24		10.6 (4.8)$^{ab}_{A}$	12.0 (6.6)$^{a}_{A}$	6.6 (1.8)$^{ac}_{A}$	22.5 (5.0)$^{d}_{B}$	9.3 (3.9)$^{ae}_{A}$	9.0 (1.3)$^{ae}_{B}$	3.1 (1.9)$^{c}_{A}$	5.8 (2.0)$^{bce}_{A}$
Beef trim 65CL (pattie)	-12		18.0 (7.1)$^{a}_{A}$	10.4 (3.3)$^{bc}_{A}$	10.6 (1.0)$^{b}_{A}$	16.4 (2.8)$^{a}_{A}$	5.9 (2.7)$^{cd}_{A}$	10.5 (2.8)$^{bc}_{A}$	8.0 (2.1)$^{bcd}_{A}$	5.3 (1.3)$^{d}_{A}$
	-18	5.8 (1.1)^{a}	10.6 (5.3)$^{b}_{A}$	9.9 (1.8)$^{b}_{A}$	8.0 (1.1)$^{ab}_{AB}$	15.3 (1.5)$^{c}_{A}$	7.8 (4.1)$^{ab}_{A}$	8.6 (1.9)$^{ab}_{A}$	5.3 (2.0)$^{a}_{AB}$	5.6 (0.9)$^{a}_{A}$
	-24		20.8 (7.9)$^{a}_{A}$	7.8 (3.4)$^{b}_{A}$	7.0 (2.9)$^{b}_{B}$	14.6 (2.8)$^{c}_{A}$	7.2 (1.6)$^{b}_{A}$	7.9 (1.2)$^{b}_{A}$	3.4 (1.1)$^{b}_{B}$	5.9 (3.3)$^{b}_{A}$
Lamb loin (pattie)	-12		13.2 (2.1)$^{a}_{A}$	6.4 (1.6)$^{b}_{A}$	23.1 (3.5)$^{c}_{A}$	16.8 (2.0)$^{c}_{AB}$	7.4 (3.1)$^{b}_{A}$	11.5 (1.6)$^{a}_{A}$	7.9 (2.6)$^{b}_{A}$	5.4 (2.1)$^{b}_{A}$
	-18	7.0 (0.9)^{ab}	11.4 (2.5)$^{c}_{A}$	5.0 (1.2)$^{a}_{A}$	8.3 (1.1)$^{b}_{B}$	19.6 (1.8)$^{d}_{A}$	7.2 (4.1)$^{ab}_{A}$	9.6 (1.5)$^{bc}_{A}$	4.6 (2.1)$^{a}_{B}$	4.7 (1.4)$^{a}_{A}$
	-24		13.2 (4.0)$^{ab}_{A}$	4.0 (2.3)$^{c}_{A}$	13.9 (5.7)$^{ab}_{B}$	16.1 (1.7)$^{b}_{B}$	4.6 (0.9)$^{c}_{A}$	10.7 (1.4)$^{a}_{A}$	6.7 (1.0)$^{c}_{AB}$	5.8 (1.1)$^{c}_{A}$
Lamb trim 90CL (pattie)	-12		15.2 (6.8)$^{ab}_{A}$	3.9 (0.9)$^{c}_{A}$	9.6 (1.9)$^{de}_{A}$	17.4 (5.1)$^{a}_{A}$	6.5 (2.1)$^{cd}_{A}$	12.1 (1.2)$^{be}_{A}$	6.8 (1.8)$^{cd}_{A}$	3.6 (1.6)$^{c}_{A}$
	-18	8.5 (3.3)^{abc}	14.7 (3.1)$^{d}_{A}$	3.9 (0.9)$^{e}_{A}$	9.8 (1.3)$^{ab}_{A}$	15.8 (4.0)$^{d}_{A}$	5.2 (1.9)$^{ce}_{A}$	10.9 (1.8)$^{a}_{AB}$	6.3 (2.9)$^{bce}_{A}$	4.1 (0.7)$^{e}_{A}$
	-24		14.0 (2.1)$^{a}_{A}$	5.8 (3.1)$^{bc}_{A}$	8.0 (0.9)$^{cd}_{A}$	17.6 (2.3)$^{e}_{A}$	6.2 (0.9)$^{bc}_{A}$	9.3 (0.5)$^{d}_{B}$	3.6 (1.3)$^{b}_{A}$	4.8 (0.9)$^{b}_{A}$
Lamb trim 85CL (pattie)	-12		13.9 (0.6)$^{a}_{A}$	4.8 (0.9)$^{bc}_{A}$	5.9 (1.5)$^{bc}_{A}$	15.4 (2.8)$^{a}_{A}$	7.3 (2.2)$^{b}_{A}$	15.1 (2.2)$^{a}_{A}$	4.3 (1.7)$^{c}_{A}$	5.2 (1.9)$^{bc}_{A}$
	-18	6.5 (2.2)^{ab}	10.6 (1.7)$^{cd}_{A}$	3.9 (1.6)$^{a}_{A}$	7.7 (1.2)$^{bc}_{A}$	15.7 (2.9)$^{e}_{A}$	8.6 (2.4)$^{bc}_{A}$	14.0 (3.9)$^{de}_{A}$	6.7 (1.3)$^{ab}_{A}$	4.2 (1.1)$^{a}_{A}$
	-24		12.0 (3.3)$^{a}_{A}$	4.2 (1.1)$^{b}_{A}$	5.5 (1.9)$^{b}_{A}$	20.6 (3.5)$^{c}_{B}$	7.5 (3.8)$^{bd}_{A}$	11.4 (3.4)$^{ad}_{A}$	5.7 (2.3)$^{b}_{A}$	4.4 (0.9)$^{b}_{A}$
Lamb trim 65CL (pattie)	-12		12.4 (2.1)$^{a}_{A}$	6.8 (2.2)$^{b}_{A}$	8.0 (1.6)$^{b}_{A}$	13.0 (2.0)$^{a}_{A}$	5.2 (2.2)$^{b}_{A}$	12.0 (2.6)$^{a}_{A}$	6.8 (3.5)$^{b}_{A}$	4.1 (1.3)$^{b}_{A}$
	-18	14.4 (4.6)^{ab}	18.4 (4.6)$^{a}_{B}$	5.0 (1.5)$^{c}_{A}$	6.2 (1.0)$^{c}_{A}$	17.0 (2.4)$^{ab}_{A}$	6.4 (2.2)$^{c}_{A}$	12.9 (2.0)$^{b}_{A}$	3.7 (2.4)$^{c}_{A}$	6.7 (2.4)$^{c}_{A}$
	-24		16.0 (2.6)$^{a}_{B}$	4.7 (1.9)$^{bc}_{A}$	6.8 (2.9)$^{bc}_{A}$	15.9 (4.4)$^{a}_{A}$	8.7 (3.3)$^{b}_{A}$	13.2 (0.6)$^{a}_{A}$	5.9 (1.6)$^{bc}_{A}$	3.9 (1.5)$^{c}_{A}$
Beef loin (steak)	-12		53.9 (10.9)$^{a}_{A}$	47.1 (21.6)$^{ab}_{A}$	20.0 (4.8)$^{c}_{A}$	39.2 (4.2)$^{ab}_{A}$	38.7 (14.5)$^{ab}_{A}$	52.3 (6.7)$^{a}_{A}$	33.9 (5.6)$^{bc}_{A}$	37.5 (9.4)$^{b}_{A}$
	-18	49.6 (5.8)^{ab}	54.1 (10.4)$^{a}_{A}$	73.8 (9.9)$^{c}_{B}$	31.2 (9.9)$^{de}_{B}$	45.3 (4.8)$^{ab}_{AB}$	43.5 (7.9)$^{abd}_{A}$	38.7 (15.4)$^{bd}_{AB}$	17.9 (1.5)$^{f}_{B}$	22.5 (5.0)$^{ef}_{B}$
	-24		41.8 (11.1)$^{ab}_{A}$	56.3 (5.4)$^{c}_{AB}$	22.0 (3.6)$^{d}_{AB}$	49.1 (7.8)$^{ac}_{B}$	45.6 (7.5)$^{a}_{A}$	30.9 (4.7)$^{de}_{B}$	39.5 (11.0)$^{abe}_{A}$	34.3 (3.3)$^{be}_{A}$
Lamb loin (steak)	-12		56.8 (15.4)$^{a}_{A}$	12.3 (1.0)$^{b}_{A}$	20.8 (2.3)$^{bc}_{A}$	44.9 (11.1)$^{d}_{A}$	33.3 (2.9)$^{e}_{A}$	23.9 (3.5)$^{ce}_{A}$	29.4 (7.1)$^{ce}_{A}$	33.0 (3.3)$^{e}_{A}$
	-18	35.2 (8.3)^{a}	43.1 (13.1)$^{a}_{AB}$	11.9 (0.9)$^{b}_{AB}$	16.2 (2.8)$^{bc}_{A}$	44.5 (9.8)$^{a}_{A}$	35.5 (7.4)$^{a}_{A}$	24.2 (4.7)$^{c}_{A}$	24.0 (2.6)$^{c}_{A}$	23.0 (3.4)$^{c}_{B}$
	-24		34.8 (7.4)$^{ab}_{AB}$	10.2 (1.8)$^{c}_{B}$	17.4 (5.8)$^{cd}_{A}$	39.6 (4.4)$^{a}_{A}$	35.0 (9.8)$^{ab}_{A}$	25.2 (1.1)$^{bd}_{A}$	32.1 (11.2)$^{abe}_{A}$	23.9 (5.3)$^{de}_{B}$

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 ($P<0.05$)

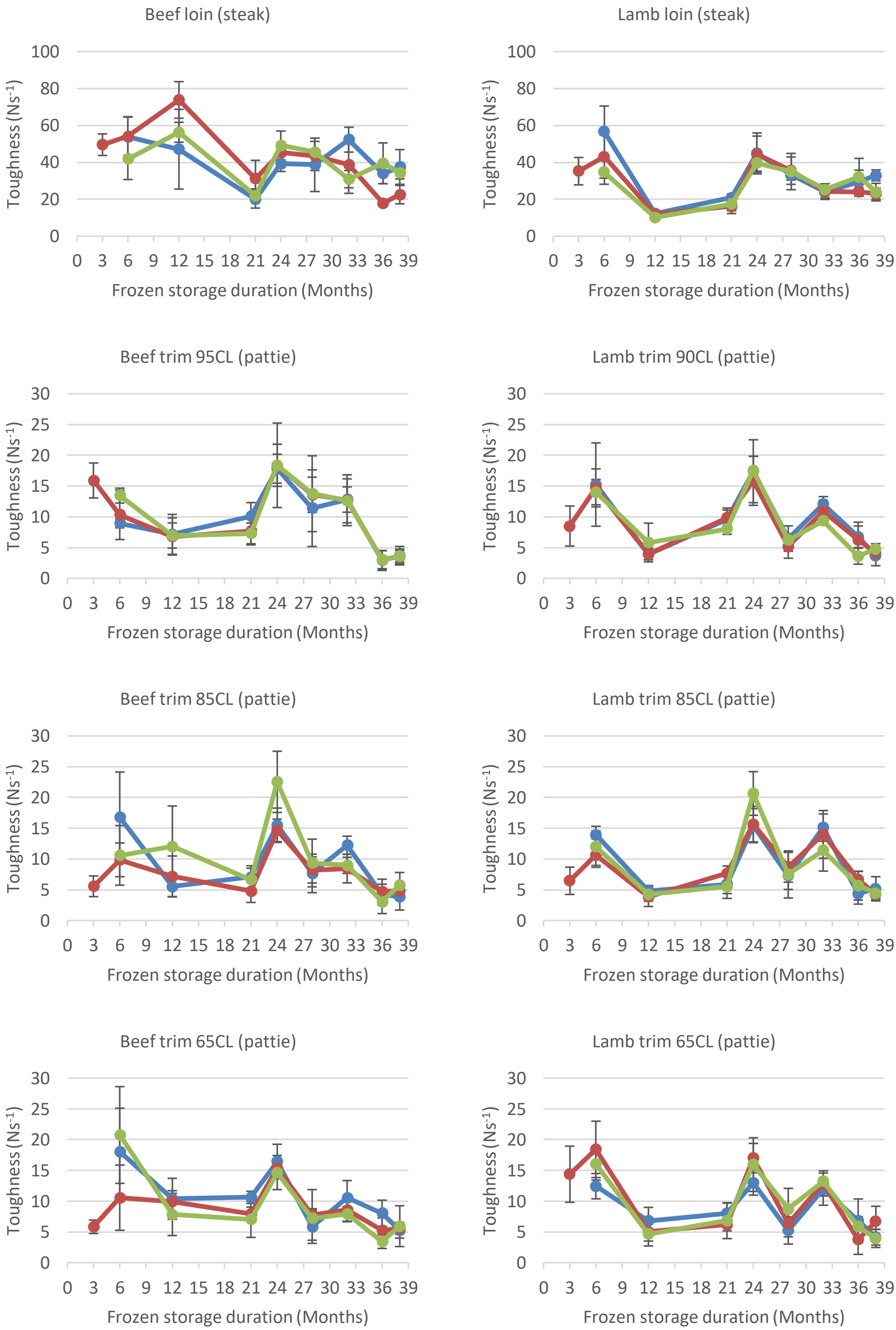


Figure 12. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean toughness (Ns^{-1}) of beef/lamb loin and trim (Vertical bars: ±1SD) N.B. beef and lamb loin data are presented on a different scale to trim

4.1.6 Microbial loading

Mean aerobic colony counts (ACCs) measured in samples on arrival and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage are shown in Table 14. The data is compared graphically in Figure 13. In common with the results of the University of Melbourne (Ha & Warner, 2018), the microbiological testing results show that the meat samples were all within acceptability threshold, although counts were generally a little higher than they reported (Ha & Warner, 2018). ACC counts of frozen beef and lamb boneless trim were generally a little higher than the mean of 2.22 and 2.80 $\log_{10}$ cfu g^{-1} of reported in the Australian industry's fourth national abattoir study, but below the maximums of 5.53 and 5.51 $\log_{10}$ cfu g^{-1}, respectively, reported by that survey (MLA, 2012).

As also found by the University of Melbourne (Ha & Warner, 2018) a few subsamples during the study had particularly high microbiological counts. Samples of 95CL beef trim stored at -18°C and sampled at 36 months, and samples stored at -24°C sampled at 38 months, exceeded 4 $\log_{10}$ cfu g^{-1}. While samples of 65CL beef trim stored at -24°C and sampled at 24 months, stored at -18°C and sampled at 36 months, and samples stored at -12°C and sampled at 38 months, exceeded 4 $\log_{10}$ cfu g^{-1}. Lamb loin samples stored at -12°C and -18°C analysed at month 12 exceeded 4 $\log_{10}$ cfu g^{-1}. While 85CL lamb trim samples stored at -12°C and -18°C exceeded 4 $\log_{10}$ cfu g^{-1} when sampled at month 6, and month 12 and 36, respectively. Samples of 65CL lamb trim stored at all temperatures exceeded 4 $\log_{10}$ cfu g^{-1} when sampled at month 6, and in a sample stored at -24°C when analysed at month 38. Since bacteria do not grow at frozen temperatures (pathogens will not grow below -1.5°C and no microorganisms below -10°C [James & James, 2014]), these variations are likely due to box-to-box variations in the commercially produced meat.

A detailed microbial analysis of the counts ($\log_{10}$ CFU g^{-1}) of *Enterobacteriaceae* (EB), Coliforms (CF), *Staphylococcus aureus* (SA) and *Escherichia coli* (EC), and the detection of *Salmonella* (SAL) in the samples were carried out at month 24 and is shown in Table 15. The overall microbial quality was found to be acceptable. No *Salmonella* was detected in the samples.

Overall, there was no consistent effect of frozen storage temperature on microbial counts, confirming that the -12°C storage temperature used in this study was sufficient to prevent the growth of bacteria and that any temperature rise or fluctuation during the regular defrosts at this temperature (as is standard practice) had no impact on microbial quality. It should be noted that frozen meat carcasses, sides, and quarters from Australia to the UK were for many years (prior to the 1970s) transported to and stored in the UK at -10°C to -9°C (Cutting & Malton, 1974). This was believed sufficient at the time to prevent any microbial growth and spoilage and maintain the quality of the frozen meat. Similarly, recent studies by Coombs *et al.* (2017b) and Holman *et al.* (2017) found that long term storage of lamb and beef, respectively, at -12°C for up to a year provided comparable safe frozen storage to that at -18°C.

Table 14. 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 (arrival)	6	12	21	24	28	32	36	38
	-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)$^{cf}_{A}$
Beef loin	-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)$^{ac}_{A}$
	-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)$^{ac}_{A}$
Beef trim 95CL	-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)$^{e}_{B}$
	-12		3.28 (0.36)$^{a}_{A}$	2.65 (0.11)$^{b}_{A}$	1.70 (0.00)$^{c}_{A}$	2.32 (0.75)$^{bd}_{A}$	2.58 (0.82)$^{b}_{A}$	1.82 (0.27)$^{cd}_{A}$	3.81 (0.07)$^{a}_{A}$	3.28 (0.08)$^{a}_{A}$
Beef trim 85CL	-18	3.35 (0.09)^{ab}	3.19 (0.29)$^{ab}_{A}$	2.91 (0.32)$^{ac}_{A}$	2.15 (0.38)$^{def}_{B}$	2.60 (0.22)$^{cd}_{A}$	1.88 (0.27)$^{e}_{A}$	2.53 (0.18)$^{cf}_{B}$	4.51 (0.08)$^{g}_{B}$	3.59 (0.58)$^{b}_{AB}$
	-24		2.79 (0.35)$^{a}_{A}$	2.85 (0.19)$^{a}_{A}$	1.82 (0.16)$^{b}_{AB}$	3.37 (0.28)$^{c}_{B}$	2.24 (0.74)$^{bd}_{A}$	1.94 (0.25)$^{b}_{A}$	2.58 (0.41)$^{ad}_{C}$	3.93 (0.22)$^{e}_{B}$
	-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)$^{e}_{A}$
Beef trim 65CL	-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)$^{e}_{B}$
	-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)$^{cd}_{A}$
Lamb loin	-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	-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)$^{b}_{A}$
trim	-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)$^{ae}_{A}$
90CL	-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	-12		4.94 (0.49)$^{a}_{A}$	2.64 (0.15)$^{b}_{A}$	2.45 (0.25)$^{b}_{A}$	2.65 (0.50)$^{b}_{A}$	2.74 (0.62)$^{b}_{A}$	1.76 (0.13)$^{c}_{A}$	3.83 (0.06)$^{d}_{A}$	2.48 (0.54)$^{b}_{A}$
trim	-18	2.93 (0.32)^{a}	3.85 (0.19)$^{b}_{B}$	4.20 (0.39)$^{b}_{B}$	3.36 (0.41)$^{a}_{B}$	3.02 (0.13)$^{a}_{A}$	2.33 (0.47)$^{c}_{A}$	1.94 (0.25)$^{c}_{A}$	4.20 (0.07)$^{b}_{B}$	3.04 (0.32)$^{a}_{AB}$
85CL	-24		3.64 (0.11)$^{a}_{B}$	2.88 (0.09)$^{a}_{A}$	3.33 (0.30)$^{a}_{B}$	3.65 (1.06)$^{a}_{A}$	2.87 (1.44)$^{a}_{A}$	2.79 (0.74)$^{a}_{B}$	3.65 (0.14)$^{a}_{C}$	3.24 (0.22)$^{a}_{B}$
Lamb	-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)$^{b}_{A}$
trim	-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)$^{ad}_{B}$
65CL	-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)

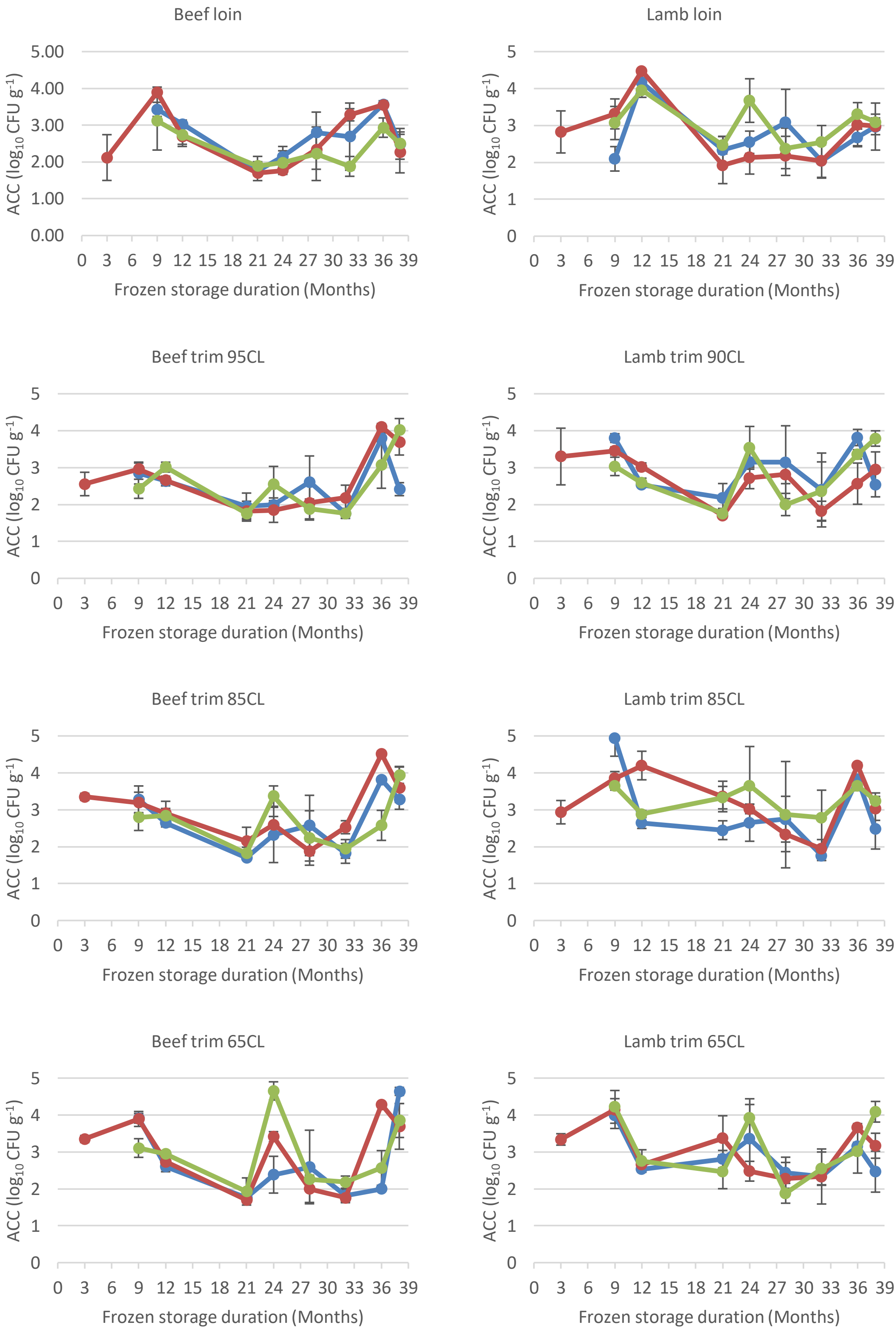


Figure 13. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean aerobic colony counts (ACC; $\log_{10}$ CFU g^{-1}) of beef/lamb loin and trim (Vertical bars: ±1SD)

Table 15. Mean (SD) Enterobacteriaceae (EB), Coliforms (CF), Staphylococcus aureus (SA), Escherichia coli counts (EC); Salmonella (SAL) counts (log_{10} CFU g^{-1}) from samples measured after 24 months of frozen storage

Sample	Temp (°C)	EB	CF	SA	EC	SAL*
Beef loin	-12	1.70 (0.00)	1.70 (0.00)	1.76 (0.13)	1.70 (0.00)	ND
	-18	2.19 (0.51)	1.79 (0.14)	1.70 (0.00)	1.73 (0.08)	ND
	-24	1.73 (0.08)	1.70 (0.00)	2.00 (0.21)	1.70 (0.00)	ND
Beef trim 95CL	-12	2.01 (0.20)	1.94 (0.35)	1.80 (0.10)	1.70 (0.00)	ND
	-18	1.70 (0.00)	1.70 (0.00)	1.76 (0.13)	1.70 (0.00)	ND
	-24	1.86 (0.20)	1.70 (0.00)	1.70 (0.00)	1.70 (0.00)	ND
Beef trim 85CL	-12	1.70 (0.00)	1.73 (0.08)	2.31 (0.96)	1.70 (0.00)	ND
	-18	1.70 (0.00)	1.95 (0.30)	1.70 (0.00)	1.80 (0.10)	ND
	-24	2.61 (0.53)	1.70 (0.00)	2.82 (0.43)	1.70 (0.00)	ND
Beef trim 65CL	-12	1.70 (0.00)	1.70 (0.00)	2.13 (0.42)	1.85 (0.33)	ND
	-18	2.69 (0.20)	3.04 (0.20)	1.73 (0.08)	2.04 (0.40)	ND
	-24	1.85 (0.16)	3.19 (0.81)	4.39 (0.50)	1.70 (0.00)	ND
Lamb loin	-12	1.70 (0.00)	1.70 (0.00)	2.09 (0.52)	1.70 (0.00)	ND
	-18	1.88 (0.14)	1.79 (0.14)	2.44 (0.58)	1.70 (0.00)	ND
	-24	3.60 (0.24)	3.67 (0.14)	2.13 (0.50)	1.70 (0.00)	ND
Lamb trim 90CL	-12	1.70 (0.00)	3.06 (0.32)	1.73 (0.08)	1.70 (0.00)	ND
	-18	2.34 (0.41)	2.46 (0.23)	1.80 (0.10)	1.70 (0.00)	ND
	-24	2.11 (0.16)	2.13 (0.26)	1.77 (0.10)	1.70 (0.00)	ND
Lamb trim 85CL	-12	1.70 (0.00)	3.05 (0.51)	1.88 (0.14)	1.70 (0.00)	ND
	-18	2.22 (0.33)	2.23 (0.25)	1.90 (0.23)	1.70 (0.00)	ND
	-24	2.74 (0.36)	2.44 (0.21)	1.90 (0.28)	1.70 (0.00)	ND
Lamb trim 65CL	-12	1.70 (0.00)	2.97 (0.14)	1.95 (0.17)	1.70 (0.00)	ND
	-18	1.91 (0.13)	1.85 (0.15)	2.00 (0.35)	1.70 (0.00)	ND
	-24	2.61 (0.20)	2.51 (0.49)	2.86 (0.98)	1.90 (0.28)	ND

N=5; * ND: None detected (i.e., below the level of detection)

4.1.7 Lipid oxidation

It is well known that unsaturated fatty acids and oxygen are the components that react during the lipid oxidation process (St Angelo *et al.*, 1996; James & James, 2002; Amaral *et al.*, 2018; Domínguez *et al.*, 2019). This is a complex process and is generally considered to consist of 3 phases: 1) an initiation phase, which involves the formation of free lipid radicals and hydroperoxides as primary reaction products; 2) a propagation phase where hydroperoxides formed are decomposed into secondary peroxidation products, such as aldehydes, ketones, alcohols, and acids; and 3) a termination phase involving the formation of tertiary peroxidation products. Lipid oxidation was assessed by measuring peroxide value (PV) as indicative of primary oxidation; and thiobarbituric acid reactive substances (TBARS), mainly malondialdehyde (MDA), as indicative of secondary oxidation. 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).

PV measured in samples on arrival and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage are shown in Table 16. The data is compared graphically in Figure 14. The beef and lamb results showed very clear relationships in PV levels and fat content (CL), storage temperature, duration, and method of packing (whether vacuum-packed or over-wrapped). Low PV levels 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 recorded for beef loins stored at -12°C where PV peaked at 24 months then decreased. PV values in beef trims 95CL 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 and 85CL beef trims showed a similar trend of no considerable changes up to 21 months, after which a progressive increase PV levels was observed in 85CL samples stored at -12°C until end of storage. In the 65CL trim spikes were observed in PV levels in trim stored at -12°C and -24°C at 24 and 28 months, respectively. Although all beef samples stored at the three temperatures showed a rise in PV levels after 21months, samples stored at -18°C and -24°C (with some exceptions) were the most stable throughout the whole storage period.

All boxed beef and the lamb loin samples were vacuum-packed, whereas the boxed lamb trim was simply over-wrapped. PV levels 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. PV levels showed a gradual rise during the storage period in loins stored at -18°C and -24°C, with levels being lower in the meat stored at -24°C. PV levels 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. As also may be expected, the level of oxidation was highest in the lamb 65CL trim which had the highest fat content. There was a clear effect of storage temperature, with the lowest mean PV levels being consistently measured in the samples stored at -24°C and the highest levels in the trim stored at -12°C. Mean PV levels of 65CL lamb trim stored at -12°C were at a level of 2.62 meq kg^{-1} at 6 months (approximately 3 months after having been stored at -12°C on arrival in the UK), showing a further significant (P<0.05) increase up to month 24 and then significantly decreased over the rest of the storage period. The samples stored at -18°C and -24°C showed a rise in PV levels after month 6 in the trim stored at -18°C and after month 12 in the trim stored at -24°C after which PV levels significantly (P<0.05) increased up to month 24 and then appeared to stabilise or slightly decreased over the remaining storage duration. Similar behaviour was observed in the 85CL and 90CL lamb trims.

Coombs *et al.* (2018a) observed that while peroxide activity increased in frozen vacuum-packed lamb stored for up to a year at -12°C or -18°C, unlike this study they found no significant effect of storage temperature. Although they did observe a peak in peroxide activity at 8 weeks in frozen vacuum-packed lamb held at -12°C. This mean peak at 8 weeks (3.55) was similar to that observed in this study in vacuum-packed loin held at -12°C at 21 months (3.03). Peroxide activity levels in the vacuum-packed lamb in this study were similar to those reported by Coombs *et al.* (2018a), generally less than 2. Conversely a parallel study of frozen vacuum-packed beef by Holman *et al.* (2018a) observed a significant drop in peroxide activity measured between 4 and 8 weeks of storage then little change in peroxide activity over time up to 52 weeks. No significant effect of storage temperature was observed.

TBARS measure the secondary lipid-peroxidation products (aldehydes, ketones, alcohols, others) represented by malondialdehyde [MDA] (Vetrovoy *et al.*, 2017; Domínguez *et al.*, 2019). As has previously been highlighted while PV levels are indicative of the start of lipid oxidation, since peroxides are tasteless and odourless compounds, TBARS are better suit comparisons to the sensory assessment and consumer thresholds. As also observed in many other studies, a general rise in TBARS was observed in all meat samples over the storage period, with that rise being higher in the lamb samples than the beef samples, especially in the lamb trim, and that TBARS levels were generally higher in samples with a higher fat content (lower CL). TBARS were also generally lower in samples held at -24°C than -12°C or -18°C, and highest, and showed a greater rise, in meat stored at -12°C. 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 levels remained constant. Alonso *et al.* (2016) observed a rise, decrease, and then stability in TBARS measured in frozen vacuum-packed pork over 2 years of storage at -20°C. A decrease in TBARS concentration 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.

Parallel studies by Coombs *et al.* (2018a) and Holman *et al.* (2018a) observed that TBARS levels in vacuum-packed lamb and beef, respectively, increased with frozen storage duration (of up to a year) but was not significantly influenced by storage temperature (-12°C or -18°C). As noted by Coombs *et al.* (2018a) TBARS levels 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. They also noted that thawing may have an influence on measurements. Pinheiro *et al.* (2015) observed TBARS levels to gradually increase in vacuum-packed lamb (*L. lumborum*) stored up to 12 months at -25°C. TBARS exceeded 1.06 mg MDA kg^{-1} after 12 months. While Muela *et al.* (2015) observed a rise in TBARS with storage duration in vacuum-packed lamb stored at -18°C for up to 21 months they remained below 0.2 mg MDA kg^{-1} during this time. In contrast, Fernandes *et al.* (2013) reported an initial reduction in TBARs in vacuum-packed lamb (*L. dorsi*) during frozen storage for up to 12 months at -18°C, before a rise by the end of the storage period. The authors observed that levels after 12 months were slightly lower than those at the start of the storage period. The authors attributed this unexpected behaviour to variation among samples. TBARS were approximately 0.2 mg MDA kg^{-1}. Although Daszkiewicz *et al.* (2018) observed TBARS levels to be higher in vacuum-packed lamb (*Longissimus thoracis et lumborum*) after 12 months storage at -26°C, this rise was not significant.

There appears no clear agreement in the published literature on the threshold TBARS levels at which consumers may begin to detect a rancid off-flavour in beef and lamb. Various levels have been proposed by several researchers. As discussed by Campo *et al.* (2006) early work by Greene & Cumuze (1981) found that oxidized flavour in beef was detected over a broad range of TBARS from 0.6 to 2.0 mg MDA kg^{-1} indicating a big variation in the threshold of the panellists. The panellists represented untrained ordinary consumers, and the correlations between TBARS and consumers taste were low. Campo *et al.* (2006) reported TBARS levels of 2.28 mg MDA kg^{-1} of beef meat as threshold levels. Campo *et al.* (2006) considered that a TBARS value of 1.0 was 'too low for the rejection of beef'. This threshold of 2.0 mg MDA kg^{-1} has been used by other studies such as Coombs *et al.* (2018). Other researchers (Igene *et al.*, 1979; Ripoll *et al.*, 2011; McKenna *et al.*, 2005) used a lower 'arbitrary' TBARS threshold of 1.0 mg MDA kg^{-1}. It must be noted that consumer thresholds are not infallible, a study by Hughes *et al.* (2015) found when beef TBARS levels reached 2.6 after 20 weeks of chilled storage, the meat still had an acceptable eating quality when assessed using a consumer sensory panel, but not when assessed using a trained sensory panel. As has been highlighted by many studies further investigation is needed to establish why there is this discrepancy and whether clear TBARS thresholds can be established, particularly for frozen meats.

Even if the lowest rancidity threshold of 1.0 mg MDA kg^{-1} is used, the TBARS results in the present study show that at 24 months the concentration of the secondary oxidation products in all beef and lamb samples were within acceptable limits. All the beef and most of the lamb samples remained acceptable throughout the storage period. The only exceptions being some of the 65CL Lamb trim samples stored at -18°C. The 65CL Lamb trim samples stored at -18°C exceeded 1.0 mg MDA kg^{-1} when analysed at 21 months, which appeared to be a peak observed in this sample only. Peaks were also observed in the 65CL lamb trim stored at -12°C at 12 and 21 months, though they did not exceed the threshold of 1.0 mg MDA kg^{-1}. 90CL lamb trim samples stored at -12°C also showed higher TBARS levels at 21 and 28 months, though again they did not exceed the threshold of 1.0 mg MDA kg^{-1}. If the higher threshold of 2.0 mg MDA kg^{-1} is used, then TBARS levels in all samples stored at all storage temperatures remained well below the rancidity threshold regardless of storage period.

Since lipid oxidation starts by the formation of hydroperoxides as primary oxidation products (measured by PV), which are then decomposed into secondary oxidation products such as aldehydes, ketones, and alcohols (measured by TBARS), one can categorise the meat samples based on their oxidative stability during frozen storage. The samples examined in this study have shown four different degrees of oxidative rancidity over the storage duration which are: (1) **slightly oxidised**; these include all beef loins and lamb loins stored at low temperature (-18°C and -24°C) and beef trim 95CL. In these samples low PV and TBARS levels were observed throughout the 38 months of frozen storage with no noticeable increase in levels. (2) **moderately oxidised**; these include lamb trims 85CL stored at all temperatures and all lamb trims stored at -24°C. In these samples, although higher PV levels were observed, all showed low TBARS levels, indicating that oxidation may not have progressed from primary to secondary oxidation. (3) **oxidised**; these include beef trims 65CL and 85CL which showed lower PV levels, except for some spikes, during the storage period and an increase in levels in samples stored at -12°C but a rise in TBARS levels with storage duration, especially in the beef 65CL trim samples. These samples showed a progression from primary to secondary oxidation during storage. Although, these samples did not hit the threshold of the rancid flavour. (4) **highly oxidised**; these include the lamb trims 65CL and 90CL stored at -12°C and -18°C in which a higher level of both PV and TBARS were observed during the storage period, indicating a higher oxidation rate and degree of oxidation than in the other frozen samples. Nevertheless, except for the lamb trim 65CL at 21 months, TBARS did not exceed a threshold that may be detected in sensory analysis.

Overall, the TBARS levels measured in this study on this type of commercially produced meat were below the threshold where rancidity would be likely to be detected by sensory analysis over all frozen storage durations and temperatures, up to and including 38 months, for the majority of the samples. Some high fat content (65CL) lamb trim samples that were stored in non-vacuum packaging for the storage duration showed signs of chemical rancidity during the storage period but there is no clear evidence that this was detected by the taste panel (see sensory results).

Table 16. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) Peroxide value (PV) (meq kg^{-1}) of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months) 3 (arrival)	6	12	21	24	28	32	36	38
Beef loin	-12	0.34 (0.17)^{a}	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		0.23 (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	0.17 (0.03)^{a}	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		0.63 (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 85CL	-12	0.32 (0.04)^{a}	0.88 (0.11)$^{a}_{A}$	0.22 (0.04)$^{b}_{A}$	0.50 (0.09)$^{c}_{A}$	1.44 (0.23)$^{d}_{A}$	0.84 (0.10)$^{a}_{A}$	1.48 (0.52)$^{d}_{A}$	1.17 (0.07)$^{e}_{A}$	3.60 (0.23)$^{f}_{A}$
	-18		0.34 (0.04)$^{ac}_{B}$	0.46 (0.31)$^{bc}_{BC}$	0.34 (0.05)$^{a}_{B}$	0.51 (0.18)$^{b}_{BC}$	0.30 (0.12)$^{a}_{B}$	0.66 (0.07)$^{d}_{B}$	0.29 (0.05)$^{a}_{B}$	0.94 (0.11)$^{e}_{B}$
	-24		1.05 (0.30)$^{a}_{AC}$	0.58 (0.21)$^{b}_{C}$	0.19 (0.04)$^{c}_{C}$	0.54 (0.11)$^{bd}_{C}$	0.57 (0.10)$^{bd}_{C}$	1.47 (0.18)$^{d}_{AC}$	0.41 (0.03)$^{e}_{C}$	1.35 (0.43)$^{de}_{C}$
Beef trim 65CL	-12	0.12 (0.04)^{a}	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		0.30 (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	0.31 (0.03)^{a}	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		0.66 (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	0.97 (0.03)^{a}	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		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 85CL	-12	0.58 (0.08)^{a}	1.30 (0.31)$^{a}_{A}$	2.62 (0.23)$^{b}_{A}$	2.72 (0.14)$^{b}_{A}$	2.99 (0.11)$^{c}_{A}$	2.95 (0.05)$^{c}_{A}$	2.73 (0.22)$^{b}_{A}$	2.39 (0.23)$^{d}_{A}$	2.10 (0.16)$^{e}_{A}$
	-18		0.68 (0.05)$^{a}_{B}$	2.33 (0.22)$^{b}_{B}$	2.32 (0.11)$^{b}_{B}$	2.14 (0.09)$^{b}_{B}$	2.35 (0.27)$^{b}_{B}$	2.11 (0.08)$^{c}_{B}$	2.23 (0.21)$^{bc}_{A}$	3.78 (0.39)$^{d}_{B}$
	-24		0.50 (0.07)$^{a}_{B}$	1.30 (0.10)$^{b}_{C}$	2.02 (0.31)$^{c}_{C}$	1.70 (0.15)$^{d}_{C}$	2.27 (0.25)$^{e}_{B}$	1.57 (0.07)$^{d}_{C}$	0.85 (0.06)$^{f}_{B}$	3.37 (0.07)$^{g}_{C}$
Lamb trim 65CL	-12	0.94 (0.38)^{a}	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		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)

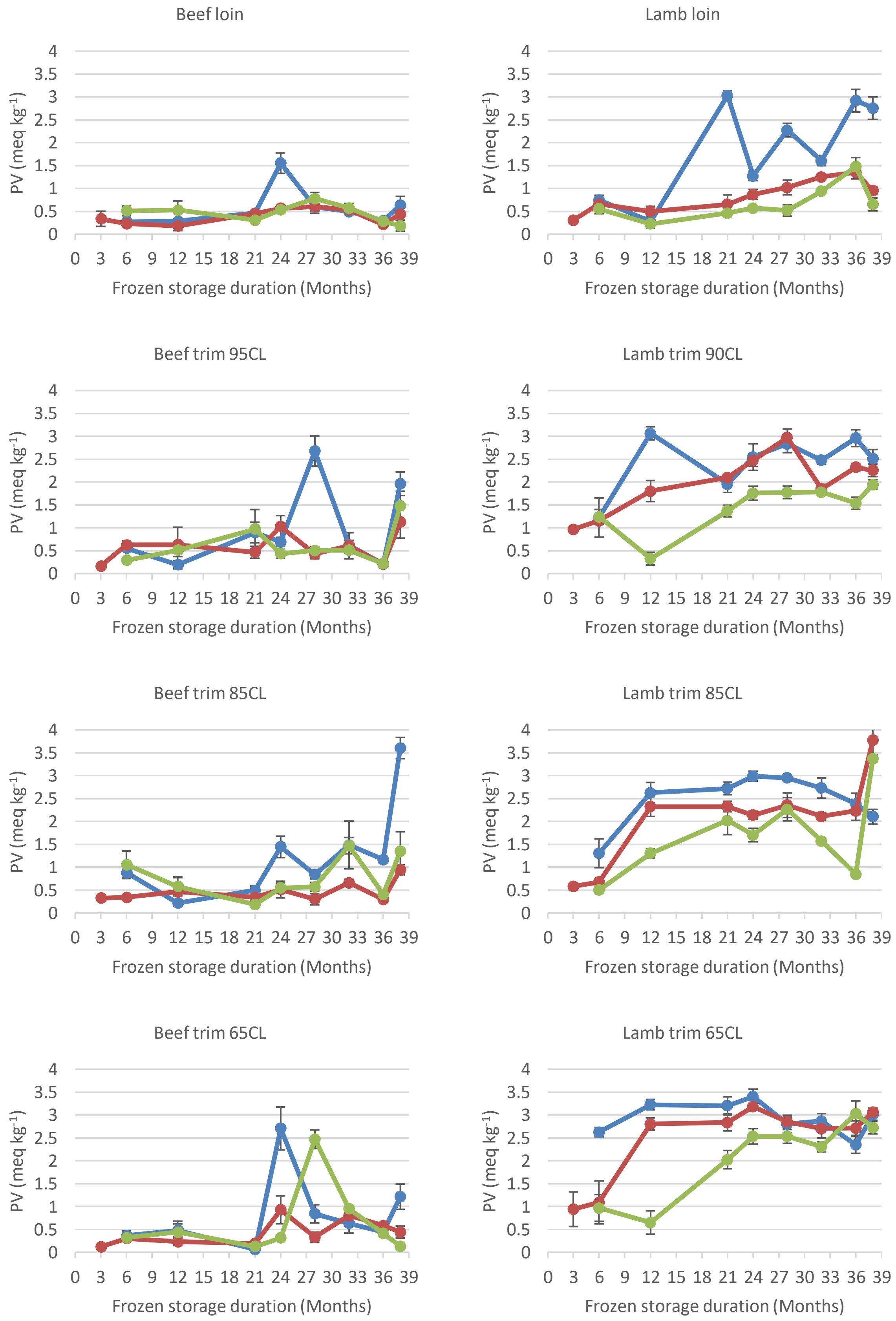


Figure 14. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean PV (Milliequivalent/kg of fat) of beef/lamb loin and trim (Vertical bars: ±1SD)

Table 17. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) TBARS (mg malondialdehyde (MDA) kg^{-1}) of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	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 85CL	-12		0.05 (0.00)$^{a}_{A}$	0.05 (0.00)$^{a}_{A}$	0.11 (0.01)$^{b}_{A}$	0.08 (0.01)$^{c}_{A}$	0.10 (0.02)$^{bc}_{A}$	0.14 (0.03)$^{d}_{A}$	0.12 (0.02)$^{bd}_{A}$	0.11 (0.03)$^{b}_{A}$
	-18	0.06 (0.01)^{a}	0.03 (0.00)$^{b}_{B}$	0.04 (0.00)$^{b}_{B}$	0.07 (0.00)$^{b}_{B}$	0.08 (0.00)$^{a}_{A}$	0.11 (0.01)$^{ac}_{A}$	0.10 (0.02)$^{d}_{B}$	0.11 (0.03)$^{d}_{A}$	0.10 (0.02)$^{d}_{A}$
	-24		0.05 (0.00)$^{a}_{AC}$	0.05 (0.01)$^{a}_{B}$	0.06 (0.01)$^{b}_{C}$	0.07 (0.01)$^{b}_{B}$	0.06 (0.01)$^{b}_{B}$	0.09 (0.01)$^{c}_{B}$	0.10 (0.03)$^{d}_{A}$	0.07 (0.01)$^{b}_{B}$
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 85CL	-12		0.03 (0.00)$^{a}_{A}$	0.26 (0.03)$^{b}_{A}$	0.25 (0.03)$^{bc}_{A}$	0.19 (0.02)$^{d}_{A}$	0.31 (0.03)$^{e}_{A}$	0.19 (0.01)$^{d}_{A}$	0.25 (0.01)$^{bc}_{A}$	0.31 (0.02)$^{f}_{A}$
	-18	0.12 (0.01)^{a}	0.05 (0.00)$^{b}_{B}$	0.09 (0.00)$^{c}_{B}$	0.32 (0.02)$^{d}_{B}$	0.13 (0.01)$^{a}_{B}$	0.36 (0.02)$^{e}_{B}$	0.21 (0.01)$^{f}_{B}$	0.27 (0.02)$^{g}_{A}$	0.16 (0.01)$^{h}_{B}$
	-24		0.06 (0.01)$^{a}_{C}$	0.06 (0.01)$^{a}_{C}$	0.21 (0.02)$^{b}_{C}$	0.17 (0.01)$^{c}_{C}$	0.17 (0.01)$^{c}_{C}$	0.14 (0.01)$^{d}_{C}$	0.16 (0.02)$^{c}_{B}$	0.21 (0.02)$^{b}_{C}$
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 ($P<0.05$)

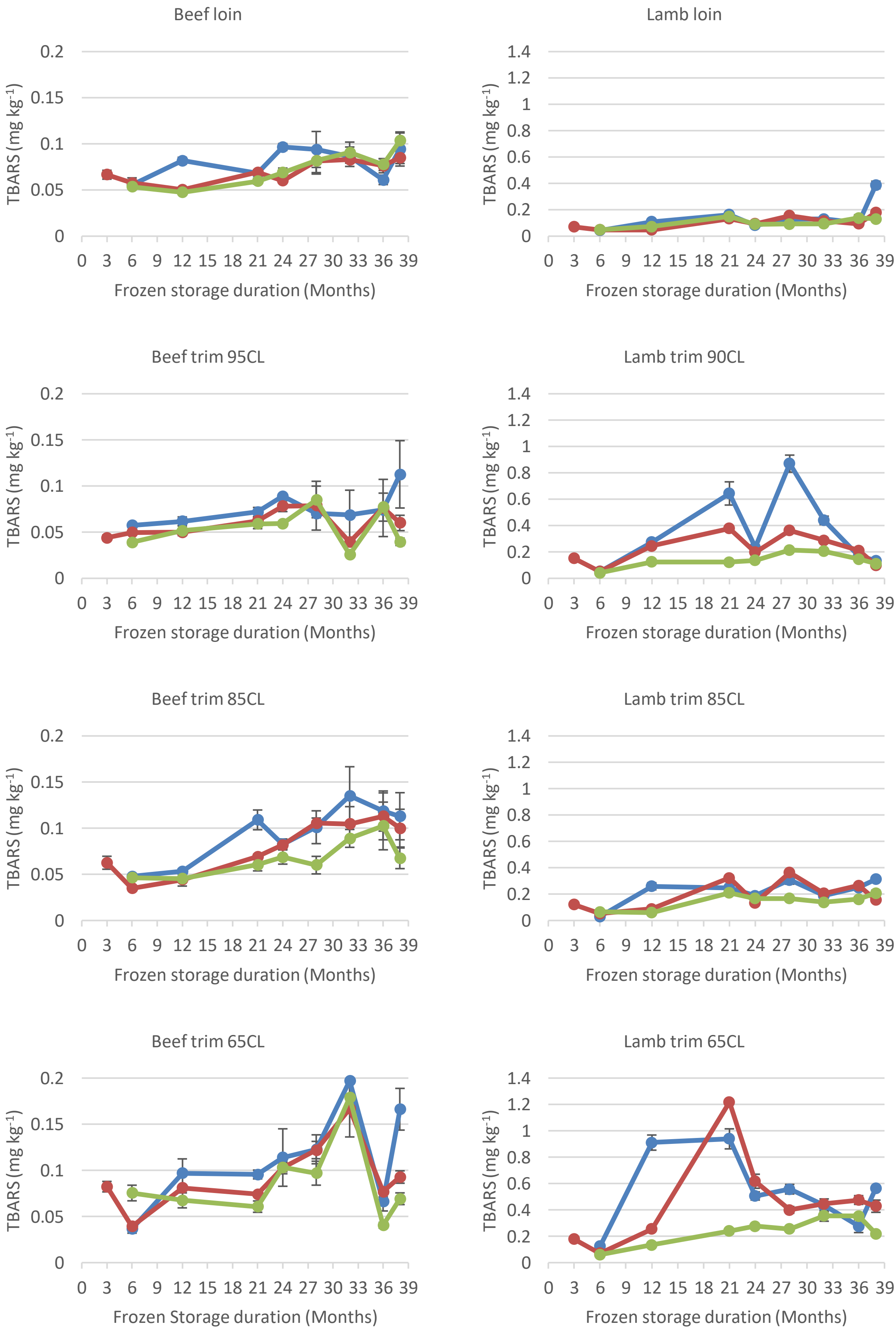


Figure 15. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean TBARS (mg MDA kg^{-1}) of beef/lamb loin and trim (Vertical bars: ±1SD) N.B. beef data are presented on a different scale to lamb data

4.1.8 Ratio of hexanal to nonanal by GCMS

Primary oxidation products (peroxide) were measured using the PV test. Secondary oxidation products (malondialdehyde) were measured using the TBARS test. Hexanal and nonanal have been shown to be of the most abundant aldehydes formed during the secondary oxidation in meat (Akcan *et al.*, 2017). Hexanal is linked to a fatty, grassy odour and a lack of consumer acceptability (Coombs *et al.*, 2017a). Hexanal and the ratio of hexanal to nonanal have been used as an indicator of lipid oxidation in meat, with studies showing a correlation between these and TBARS levels (Shadidi & Pegg, 1994; Ahn *et al.*, 2008; Karabagias, 2018). A comparison of mean ratio of hexanal to nonanal measured in samples using GC-MS on arrival, and after 6, 12, 21, 24, 28, 32, 36, and 38 months of storage is shown in Table 18 and a graphical comparison with TBARS in beef and lamb shown in Figure 16 and Figure 17, respectively.

A statistical analysis to establish whether there was a statistical correlation between the TBARS and the ratio of hexanal to nonanal measured in the beef and lamb samples has not been carried out. But, a comparison of the results as shown in Figure 16 and Figure 17,, do show that, with a few exceptions, changes in levels of TBARS were reflected in similar changes in the ratio of hexanal to nonanal in beef and lamb samples, particularly in the lamb. As with TBARS the ratio of hexanal to nonanal was lower in beef samples than lamb samples, confirming that there was more lipid oxidation in the lamb over the storage period than in the beef. As previously discussed, this is unsurprising as the beef samples were vacuum-packed and the lamb, except for the lamb loins, was over-wrapped. Except for the 65CL beef trim samples (where a clear effect of temperature was apparent), there was less effect of storage temperature on the ratio of hexanal to nonanal in beef samples, though ratios were consistently low over time in samples stored at -24°C. Whilst the TBARS showed little change in TBARS levels in the lamb loin over the storage period, the ratio of hexanal to nonanal in lamb showed significant ($P<0.05$) peaks in the ratio of hexanal to nonanal at 21 months in the lamb loin stored at -12°C and at 32 months in the loin stored at -18°C indicating that some oxidation has taken place in this meat over the storage duration that was not reflected in the TBARS. Significant ($P<0.05$) peaks in the ratio of hexanal to nonanal measured at different storage durations generally matched those measured in the TBARS (with some exceptions). In common with the TBARS higher ratios of hexanal to nonanal were observed in samples stored at -12°C, than those at -18°C, with the lowest ratios generally being measured in the samples stored at -24°C (which remained low and did not significantly ($P<0.05$) change over the storage duration).

A rise then decline in hexanal, similar to that observed in some samples in this study, has been observed in other studies, though over a much shorter storage duration and shorter analysis periods. Utrera *et al.* (2014) observed a significant increase of hexanal in frozen beef patties during the first 8 weeks of frozen storage followed by a marked decline after 12 weeks. The authors attributed this decline to the reaction of hexanal with other meat components, or its further oxidation to hexanoic acid with extended storage periods (Shahidi & Pegg, 1994). No recent studies on meat of the type used in this study appear to have measured the evolution of hexanal or the ratio of hexanal to nonanal for such long frozen storage periods. Bueno *et al.* (2013) studied the effect of freezing method on a wide range of odour active compounds (including hexanal and nonanal) in lamb that was subsequently stored for 10 months at -18°C, but the samples were only analysed at month 1 and 10. Storage duration had no significant effect on hexanal or nonanal levels over this duration.

Table 18. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) Hexanal to Nonanal ratio of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	6	12	21	24	28	32	36	38
Beef loin	-12		0.06 (0.11)$^{ab}_{A}$	0.00 (0.00)$^{a}_{A}$	0.17 (0.18)$^{b}_{A}$	0.08 (0.04)$^{ab}_{A}$	0.05 (0.03)$^{ab}_{AB}$	0.03 (0.03)$^{ab}_{A}$	0.04 (0.04)$^{ab}_{A}$	0.14 (0.13)$^{ab}_{A}$
	-18	0.04 (0.06)^{a}	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.07 (0.12)$^{a}_{A}$	0.09 (0.15)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.19 (0.32)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.07 (0.08)$^{a}_{A}$
	-24		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.01 (0.01)$^{a}_{A}$	0.14 (0.08)$^{b}_{B}$	0.00 (0.00)$^{a}_{B}$	0.26 (0.11)$^{c}_{A}$	0.00 (0.00)$^{a}_{A}$
Beef trim 95CL	-12		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.06 (0.10)$^{ab}_{A}$	0.08 (0.01)$^{b}_{A}$	0.05 (0.03)$^{ab}_{A}$	0.08 (0.03)$^{b}_{A}$	0.04 (0.03)$^{ab}_{A}$	0.01 (0.01)$^{ab}_{A}$
	-18	0.00 (0.00)^{a}	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.15 (0.16)$^{b}_{A}$	0.14 (0.08)$^{bc}_{A}$	0.13 (0.02)$^{b}_{A}$	0.03 (0.06)$^{abcd}_{A}$	0.02 (0.03)$^{ac}_{A}$	0.01 (0.00)$^{ad}_{A}$
	-24		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.08 (0.14)$^{a}_{A}$	0.08 (0.13)$^{a}_{A}$	0.01 (0.01)$^{a}_{A}$	0.07 (0.06)$^{a}_{A}$	0.03 (0.02)$^{a}_{A}$	0.01 (0.01)$^{a}_{A}$
Beef trim 85CL	-12		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.16 (0.05)$^{bc}_{A}$	0.26 (0.16)$^{b}_{A}$	0.13 (0.05)$^{ab}_{A}$	0.06 (0.04)$^{ac}_{A}$	0.10 (0.09)$^{ac}_{A}$	0.12 (0.02)$^{ac}_{A}$
	-18	0.00 (0.00)^{a}	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.15 (0.08)$^{a}_{A}$	0.05 (0.05)$^{a}_{AB}$	0.25 (0.21)$^{b}_{B}$	0.24 (0.21)$^{b}_{A}$	0.00 (0.00)$^{a}_{A}$	0.03 (0.02)$^{a}_{B}$
	-24		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{B}$	0.00 (0.00)$^{a}_{B}$	0.02 (0.02)$^{b}_{C}$	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.01 (0.01)$^{ab}_{B}$
Beef trim 65CL	-12		0.00 (0.00)$^{a}_{A}$	0.13 (0.22)$^{ab}_{A}$	0.78 (0.20)$^{c}_{A}$	0.34 (0.09)$^{b}_{A}$	0.14 (0.06)$^{ab}_{A}$	0.09 (0.03)$^{a}_{A}$	0.16 (0.11)$^{ab}_{A}$	0.16 (0.13)$^{ab}_{A}$
	-18	0.00 (0.00)^{a}	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.16 (0.15)$^{ab}_{A}$	0.02 (0.04)$^{a}_{B}$	0.33 (0.42)$^{b}_{A}$	0.14 (0.12)$^{ab}_{A}$	0.09 (0.05)$^{ab}_{A}$	0.01 (0.02)$^{a}_{A}$
	-24		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.62 (0.63)$^{b}_{A}$	0.00 (0.00)$^{a}_{B}$	0.19 (0.17)$^{ab}_{A}$	0.33 (0.32)$^{ab}_{A}$	0.08 (0.10)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$
Lamb loin	-12		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	3.50 (5.23)$^{a}_{A}$	0.43 (0.12)$^{a}_{A}$	1.40 (1.29)$^{a}_{A}$	0.04 (0.08)$^{a}_{A}$	0.83 (0.54)$^{a}_{A}$	0.31 (0.50)$^{a}_{A}$
	-18	0.26 (0.45)^{a}	0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.44 (0.53)$^{a}_{A}$	0.00 (0.00)$^{a}_{B}$	0.40 (0.20)$^{a}_{A}$	5.95 (6.32)$^{b}_{A}$	2.03 (2.00)$^{ab}_{A}$	0.64 (0.67)$^{a}_{A}$
	-24		0.03 (0.06)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.76 (0.83)$^{ab}_{A}$	0.00 (0.00)$^{a}_{B}$	2.39 (2.19)$^{b}_{A}$	0.82 (0.46)$^{ab}_{A}$	1.05 (0.30)$^{ab}_{A}$	0.38 (0.29)$^{a}_{A}$
Lamb trim 90CL	-12		0.04 (0.08)$^{a}_{A}$	0.29 (0.50)$^{a}_{A}$	3.80 (0.53)$^{bc}_{A}$	0.32 (0.02)$^{a}_{A}$	0.66 (0.11)$^{ad}_{A}$	2.62 (2.39)$^{b}_{A}$	5.21 (1.34)$^{c}_{A}$	1.61 (0.40)$^{ad}_{A}$
	-18	0.00 (0.00)^{a}	0.47 (0.09)$^{ab}_{B}$	0.00 (0.00)$^{a}_{A}$	1.50 (0.99)$^{bc}_{B}$	0.51 (0.06)$^{ab}_{B}$	0.33 (0.13)$^{a}_{B}$	0.64 (0.23)$^{ab}_{A}$	1.85 (1.39)$^{c}_{B}$	1.36 (0.25)$^{b}_{A}$
	-24		0.00 (0.00)$^{a}_{A}$	0.00 (0.00)$^{a}_{A}$	0.36 (0.11)$^{a}_{B}$	0.00 (0.00)$^{a}_{C}$	0.24 (0.16)$^{a}_{B}$	1.50 (0.75)$^{b}_{A}$	1.41 (0.59)$^{b}_{B}$	0.61 (0.12)$^{a}_{B}$
Lamb trim 85CL	-12		0.00 (0.00)$^{a}_{A}$	2.56 (0.26)$^{b}_{A}$	1.80 (0.81)$^{cd}_{A}$	2.20 (0.07)$^{bc}_{A}$	0.24 (0.05)$^{a}_{A}$	0.72 (0.20)$^{ae}_{A}$	2.69 (0.39)$^{b}_{A}$	1.35 (0.38)$^{de}_{A}$
	-18	0.36 (0.34)^{ab}	0.16 (0.14)$^{a}_{A}$	0.00 (0.00)$^{a}_{B}$	1.28 (0.49)$^{cd}_{AB}$	1.69 (0.17)$^{c}_{B}$	0.83 (0.12)$^{bd}_{B}$	1.66 (0.32)$^{c}_{A}$	2.57 (0.20)$^{e}_{A}$	0.85 (0.36)$^{bd}_{A}$
	-24		0.27 (0.16)$^{ab}_{A}$	0.00 (0.00)$^{a}_{B}$	0.40 (0.11)$^{ab}_{B}$	0.00 (0.00)$^{a}_{C}$	0.20 (0.10)$^{ab}_{A}$	0.90 (0.78)$^{b}_{A}$	1.40 (1.08)$^{c}_{A}$	0.62 (0.10)$^{abc}_{A}$
Lamb trim 65CL	-12		1.11 (0.47)$^{a}_{A}$	13.15 (6.18)$^{b}_{A}$	11.50 (1.23)$^{b}_{A}$	2.61 (1.65)$^{a}_{A}$	3.34 (3.41)$^{a}_{A}$	1.53 (0.42)$^{a}_{A}$	4.39 (0.32)$^{a}_{A}$	3.28 (0.13)$^{a}_{A}$
	-18	0.93 (1.02)^{ab}	0.00 (0.00)$^{a}_{B}$	1.19 (0.50)$^{ab}_{B}$	6.98 (5.23)$^{c}_{AB}$	2.46 (1.83)$^{ab}_{A}$	4.10 (0.92)$^{bc}_{A}$	3.41 (0.51)$^{abc}_{B}$	4.75 (0.18)$^{bc}_{A}$	1.93 (0.26)$^{ab}_{B}$
	-24		0.00 (0.00)$^{a}_{B}$	1.52 (1.36)$^{ab}_{B}$	0.84 (0.43)$^{ab}_{B}$	2.88 (2.47)$^{b}_{A}$	0.63 (0.24)$^{a}_{A}$	1.42 (0.11)$^{ab}_{A}$	2.85 (0.20)$^{b}_{B}$	2.51 (0.94)$^{ab}_{AB}$

N=3; 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 ($P<0.05$); Zero values mean the sample was analysed but no peaks were identified

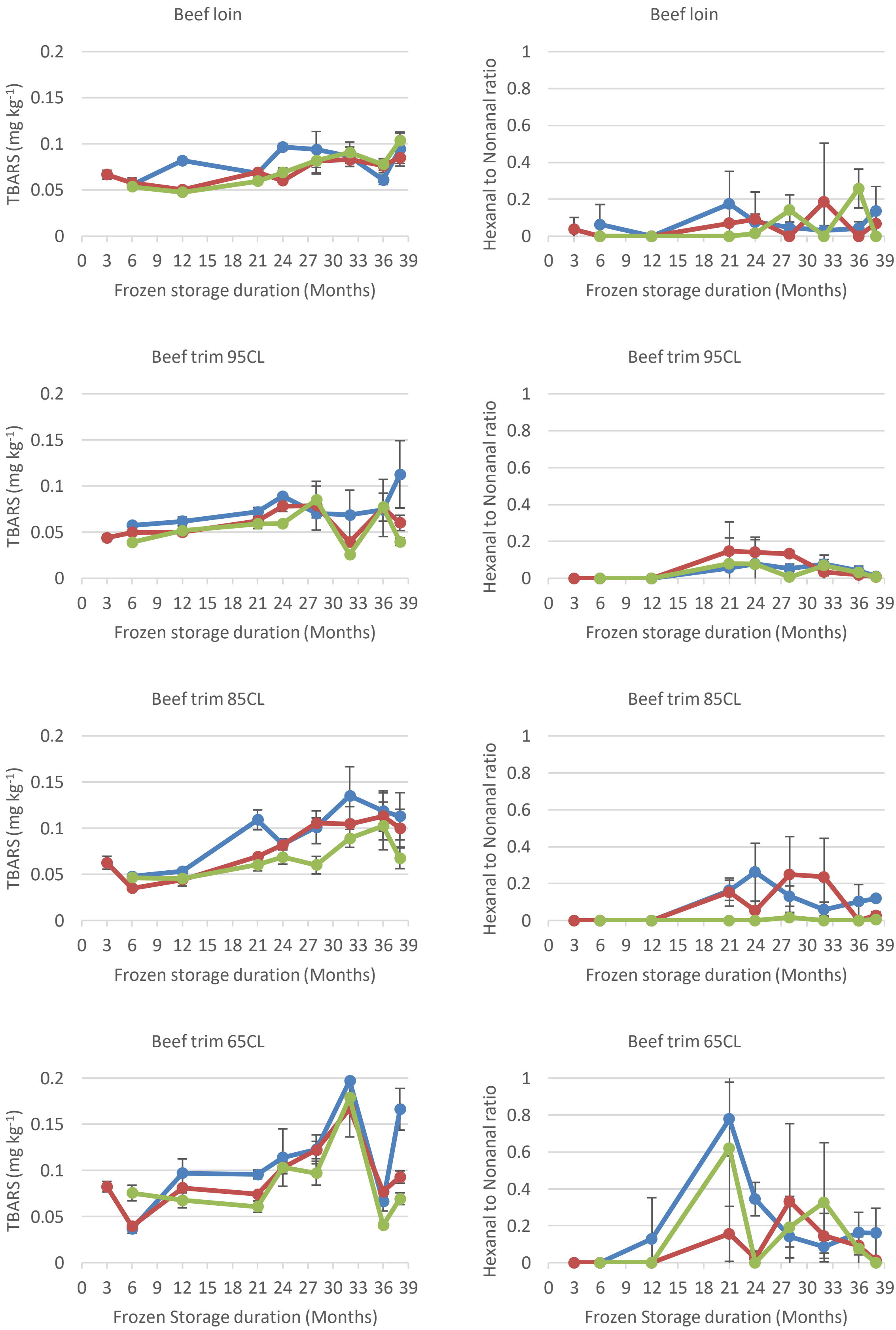


Figure 16. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean TBARS (left) and Hexanal to Nonanal ratio (right) of beef loin and trim (Vertical bars: ±1SD)

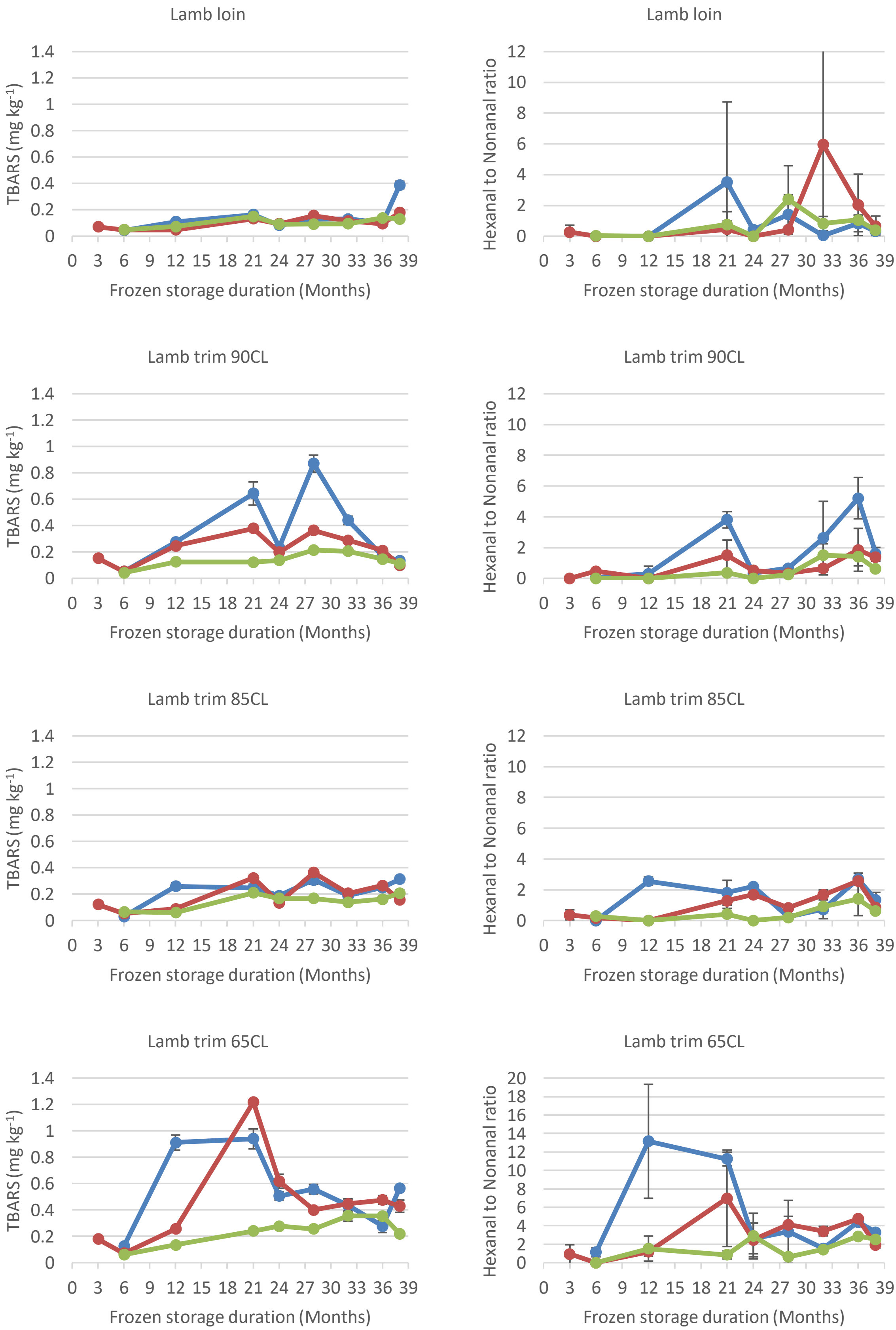


Figure 17. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean TBARS (left) and Hexanal to Nonanal ratio (right) of lamb loin and trim (Vertical bars: ±1SD)

4.1.9 Sensory testing

The results of the sensory analysis of the samples assessed on arrival, and after 6, 12, 21, 24, 28, 32, 36, and 38 months storage duration are compared in Table 19 to Table 25. The results are compared graphically in Figure 18 to Figure 24. The sensory analysis scores of the different samples are shown graphically in Figure 25 to Figure 32.

Unfortunately, a few practical problems occurred with preparation of the 65CL beef and lamb trim samples assessed at 6 months and 24 months leading to no assessment of these samples at 6 months and only a partial assessment (of appearance and odour) at 24 months. Due to Covid restrictions and time constraints, these assessments could not be repeated with new samples.

In addition, initial data indicated that -18°C 95CL beef trim samples assessed at 24 months scored significantly lower than all other samples. This assessment did not appear to relate to the PV or TBARS data or any of the other measured parameters. After careful re-examination of the results, we now believe this was due to an error with the Red Jade sensory software and the data has been omitted.

Beef

A detailed analysis of the sensory results showed the following changes in the characteristics assessed.

Beef overall appearance

Loin – The mean overall cooked appearance score of beef loin samples that had been stored at -24°C showed a trend for means to steadily decrease from 6.2 to 4 over the storage period. With the 3 and 6 month means being significantly different (P<0.05) to most of the mean scores after month 24. With samples that had been stored at -18°C mean scores were >5.5 up to month 12 and approximately 4.5 from month 28 to 38. The mean score at 3 months were significantly different (P<0.05) to all mean scores from 28 months onward. However, the month 6 mean score was not significantly different to any later mean scores. In the samples stored at -12°C considerable variability was seen in mean scores up to month 12. All mean scores after month 21 were in the 4 to 4.7 range and were not significantly different (P>0.05).

95CL trim – In cooked beef patties made from 95CL beef trim stored at -24°C the mean appearance scores remained below 5.1 until month 21 then rose to 5.9 at month 24 before declining. The month 38 mean was only significantly different (P<0.05) to month 3. In cooked beef patties made from trim stored at -18°C after month 12 means settled in the 4.75 to 5.7 range with one outlier at 24 months. The month 6 mean score was only significantly different (P<0.05) to mean scores at months 12 and 36. In cooked beef patties made from trim stored at -12°C mean scores declined erratically to month 21 then rose before declining steadily. The month 6 mean score was only significantly different (P<0.05) to month 24.

85CL trim – In cooked beef patties made from 85CL beef trim stored at -24°C there was no significant difference (P>0.05) between the 3 month mean score and those at any other storage time. In cooked beef patties made from trim stored at -18°C the 6 month mean score was higher than all other mean scores and significantly different to month 12, 21 and 32 scores but not the 36 and 38 month mean score. In cooked beef patties made from trim stored at -12°C appearance scores remained at or above 5 up to and including storage month 32 then declined to 4 at months 36 and 38. The month 6 mean score was significantly different (P<0.05) to month 36 and 38 scores.

65CL trim – In cooked beef patties made from 65CL beef trim stored at all temperatures the mean overall appearance scores dropped at 36 or 38 months**.** In cooked beef patties made from trim stored at -24°C only the 38 month mean score was significantly different (P<0.05) to that on month 3. In cooked beef patties made from trim stored at -18°C the pattern was similar with only the 38 - month mean score being significantly different (P<0.05) to that on month 3. In cooked beef patties made from trim stored at -12°C the 24, 38 and 38 month mean scores were all significantly different to the month 3 mean score.

Beef odour intensity

Loin – In loin made stored at -24°C the mean beef odour intensity scores rose over the first 21 months the declined. The month 12 mean score was significantly different (P<0.05) to mean scores at month 32 and 36 while the month 21 mean score was significantly different (P<0.05) to month 32. In loin stored at -18°C no month mean scores were significantly different (P>0.05) to any others. In loin stored at -12°C the mean score for month 12 was significantly higher that all other months. No other mean scores were significantly different (P<0.05) from each other.

95CL trim – In cooked beef patties made from 95CL beef trim stored at all three temperatures no significant differences (P>0.05) between mean scores of beef odour intensity was found.

85CL trim – In cooked beef patties made from 85CL beef trim stored at -24°C and -18°C no significant differences (P>0.05) between mean beef odour intensity score were found. In cooked beef patties made from 85CL beef trim stored at -12°C mean scores rose from 4 at 6 months to 5.4 at month 21 before declining to 4.1 at month 38. Only the mean score for month 21 was significantly different and only to month 6 and 38.

Beef fat odour intensity

Loin – Mean fat odour intensity score tended to reduce with storage duration at all temperatures. No mean scores were significantly different (P>0.05) in loin stored at either -24°C or -12°C. In loin stored at -18°C the month 12 mean score was significantly different (P<0.05) to 6, 28, 32 and 38 month mean scores and the month 3 score was significantly different (P<0.05) to month 38.

95CL trim – No significant differences were found in the mean scores of cooked beef patties made from 95CL beef trim stored at -24°C and -18°C. In cooked beef patties made from trim stored at -12°C the mean score tended to rise to a peak at month 32 then fall. The mean score at 32 months was significantly different to 3, 6 and 21 month mean scores.

85CL trim – No significant differences (P>0.05) were found in the mean scores in cooked beef patties made from 85CL beef trim stored at -24°C and -12°C. In cooked beef patties made from trim stored at -18°C the peak mean score at 32 months was significantly different (P<0.05) to mean scores at 6, 12, 21 and 28 months.

65CL trim – No significant differences in mean scores in cooked beef patties made from 65CL beef trim stored at all three temperatures were found after month 21.

Beef meat flavour

Loin – No overall statistically different changes (P>0.05) in mean scores of cooked beef meat flavour were found between storage duration or storage temperatures.

95CL trim – There appeared to be a trend for slight rise in mean meat flavour scores in cooked beef patties made from 95CL beef trim stored at all temperatures with storage duration. Though no significant differences (P>0.05) were found between mean scores for cooked beef patties made from 85CL beef trim stored at the 3 temperatures after different storage durations.

85CL trim – No overall statistically different changes (P>0.05) in mean scores of cooked beef meat flavour were found between storage duration or storage temperatures.

65CL trim – The only significant difference (P<0.05) found were between the peak mean score at 21 month and mean scores at 12 and 38 months.

Beef meat fat flavour

Loin – No significant differences (P>0.05) in mean scores were found in cooked loin that had been stored at -24°C and -12°C. In loin that had been stored at -24°C all mean scores were within 5±0.5. In loin that had been stored at -18°C the 12 month and 38 month mean scores were the only scores outside the 5±0.5 range.

95CL trim – No significant differences (P>0.05) were found between mean scores for cooked beef patties made from 95CL beef trim stored at -24°C and -18°C at different storage durations. For cooked beef patties made from trim stored at -12°C mean scores rose to a peak of 6 at month 32 before falling to 3.3 at month 38. Significant differences (P<0.05) were found between month 32 and month 3, 6, 21, and 32 mean scores.

85CL trim – No significant differences (P>0.05) were found between mean scores for cooked beef patties made from 85CL beef trim stored at -24°C and -12°C for different storage durations. For cooked beef patties made from trim stored at -18°C mean scores rose to a peak of 6 at month 32 before falling to 4.75 at month 36. Significant differences (P<0.05) were found between month 32 and month 6, 12, 21, and 28 scores.

65CL trim – No significant differences (P>0.05) were found between mean scores for cooked beef patties made from 65CL beef trim stored at -24°C and -12°C for different storage durations. For cooked beef patties made from trim stored at -18°C mean scores remained above 4 until month 38 and the mean at this duration was statistically different (P<0.05) to mean scores at 3 and 32 months.

Beef overall juiciness

Loin – Mean scores tended to rise to a peak at month 24 before falling. No significant differences (P<0.05) were found between mean scores for the loin stored at -18°C and -12°C temperatures at different storage times. At -24°C there were significant differences (P<0.05) between month 24 mean score and month 6, 12, 21 and 36 scores. There was also a difference between month 6 and 28 scores.

95CL trim - The variability in the mean scores for overall juiciness in cooked beef patties made from 95CL beef trim were higher than for other types of sample. For cooked beef patties made from trim stored at -24°C mean scores rose steadily from 2.6 at month 6 to 4.6 at month 38 with an odd drop at month 36. The month 38 mean was significantly different (P<0.05) to months. For cooked beef patties made from trim stored at -18°C mean scores rose steadily from 2.5 at month 6 to 4.7 at month 38. The month 38 mean score was significantly different (P<0.05) to scores at months 6, 12, 24 and 36. For cooked beef patties made from trim stored at -12°C mean scores remained below 4 from month 3 to 21 then rose above 4 from 24 to 36 months before dropping below 3 at month 38. Several comparisons were significantly different (P<0.05) including month 6 vs months 24, 28, 32 and 38.

85CL trim - There was a similar pattern with mean scores in cooked beef patties made from 85CL beef trim stored at all three temperatures, mean scores rising to peak at 21 months then decreasing before rising again at 32 months. There were no significant differences (P>0.05) in mean scores in patties made from trim stored at -18°C and only one from patties made from trim that had been stored at -24°C (month 21 versa 28). There was more scatter in mean scores for cooked beef patties made from trim stored at -12°C with significant differences (P<0.05) including month 21 vs 6, 12, 28 and 36 months.

65CL trim - There were no significant differences in mean scores for cooked beef patties made from 65CL beef trim stored at -12°C with all means between 4 and 4.6. There was more variability for cooked beef patties made from trim stored at -18°C with a peak of 6.1 at 32 months and low mean scores <3.6 at months 28 and 36. Month 36 was significantly different differences (P<0.05) to months 21 and 32. The mean score at 3 months was not significantly different (P>0.05) to any other month.

Beef overall tenderness

Loin - There was an overall trend for a slight rise in mean tenderness score with storage duration. For loin stored at -24°C there were no significant differences (P>0.05) found between mean scores at different storage durations. For loin stored at -18°C the only statistical differences (P<0.05) were found between mean scores at month 12 and 28 and 36. For loin stored at -12°C the only statistical differences (P<0.05) in mean scores were found between month 36 and 12 and 21.

95CL trim - Again there was an overall trend for a slight rise in mean tenderness scores with storage duration. In cooked beef patties made from 95CL trim stored at-24°C and -18°C no significant differences (P>0.05) were found between mean scores. In cooked beef patties made from trim stored at -12°C the only statistical difference (P<0.05) was between month 6 and 24 mean scores.

85CL trim - Again for cooked beef patties made from 85CL beef trim stored at all temperatures there was an overall trend for a slight rise in mean tenderness score with storage duration. For cooked beef patties made from trim stored at -24°C no significant differences (P>0.05) were found between mean scores. For cooked beef patties made from trim stored at -18°C the only statistical difference

($P<0.05$) was between mean scores at month 28 and 38, and for cooked beef patties made from trim stored at -12°C there was a significant difference between mean scores at month 21 and 28.

65CL trim – Again for cooked beef patties made from 65CL beef trim stored at all temperatures there was an overall trend for a slight rise in mean tenderness score with storage duration. For cooked beef patties made from 65CL beef trim stored at -12°C and -18°C no significant differences ($P>0.05$) were found between mean scores at different storage durations. For cooked beef patties made from trim stored at -24°C the only statistical difference ($P<0.05$) was between mean scores at month 28 and 32.

Beef overall

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, fat odour intensity, meat flavour intensity, or overall tenderness scores for all types of beef sample stored at all temperatures over the full storage duration. There was more variation in overall juiciness scores than the other characteristics for the different beef samples over the assessment period, but again no clear overall change in mean overall 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 box-to-box variation in the samples supplied. Although some slight elevations in PV and TBARS were measured in some beef samples during the storage duration the literature suggests that these levels would be too low to be detected in a sensory assessment, which appears to be supported by the sensory analysis.

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Lamb

A detailed analysis of the sensory results showed the following changes in the characteristics assessed.

Lamb overall appearance

Loin - Overall no significant difference ($P>0.05$) was found in the cooked appearance of the lamb loin between the first (month 3) and last (month 38) determinations or any systematic difference between different storage temperatures. However, some small trends and changes were found at individual storage temperatures. In samples stored at -12°C a change occurred at month 12 with a mean aggregated score of 5.9 before month 12 and a mean of 4.8 after. With no further change after 21 months. There were statistical differences ($P<0.05$) between pre and post 12 month scores, except 6 months vs 38months. In cooked samples stored at -18°C again a change occurred at month 12 with a mean aggregated score of 6.1 before month 12 and a mean of 5 after however there was no significant difference in the change ($P>0.05$). Scores at 12 months were significantly ($P<0.05$)

higher than post 12 month scores. In cooked samples stored at -24°C except for a low mean score at 24 months there was no significant change during storage.

90CL trim - Overall a statistically significant difference (P<0.05) was found in the cooked appearance of patties made of 90CL lamb trim between the first (month 3) and last (month 38) determinations stored at -12°C, but not in patties made from samples stored at -18°C or -24°C. No systematic difference was found between different storage temperatures. In samples made from 90CL trim stored -12°C a change occurred at month 12 with a mean aggregated score of 5.4 before month 12 and a mean of 3.5 after. Mean scores at 6 months were significantly higher (P<0.05) than all later determinations. In samples made from 90CL trim stored -18°C the drop in overall appearance scores was not significantly different (P>0.05). In cooked samples made from 85CL trim stored -24°C a change occurred at month 12 with a mean aggregated score of 5.1 before month 12 and a mean of 3.7 after. No further changes occurred after month 12.

85CL trim - Overall a statistically significant difference (P<0.05) was found in the cooked appearance of patties made of 85CL lamb trim between the first (month 3) and last (month 38) at all three temperatures. The change tending to occur after month 12. No significantly significant (P>0.05) changes occurred at -12°C after month 6. In samples made from 85CL trim stored at -18°C a change occurred at month 12 with a mean aggregated score of 5.5 before month 12 and a mean of 3.8 after. No statistical differences were found between month 6 vs 36 and 12 vs 36. In samples made from 85CL trim stored -24°C a change occurred at month 21 with a mean aggregated score of 5.1 before month 21 and a mean of 3.9 after. No changes occurred after month 24.

65CL trim - There was more variability in the scores of the cooked appearance of patties made from 65CL trim over the storage duration but no statistical overall change with storage duration at any temperature.

Lamb meat odour

Loin – In cooked loin from samples stored at -24°C there were no changes in meat odour with storage duration, while from samples stored at -12°C there were some statistical differences results but no overall change. In cooked loin from samples stored at -18°C a change occurred at month 21 with a mean aggregated score of 5.3 before month 21 and a mean of 4.2 after. But this was not a statistical (P>0.05) difference except between 6 vs 38, 12 vs 38. No changes in mean scores occurred after month 24.

90CL trim - No overall statistically different changes (P>0.05) in cooked meat odour were found between storage duration or storage temperatures.

85CL trim - In cooked patties made from 85CL lamb trim samples stored at -18°C and -24°C, no overall statistically different changes (P>0.05) in cooked meat odour were found. In cooked patties made from 85CL lamb trim samples stored at -12°C there was a slight drop after 24 months. No statistical differences (P>0.05) were found except between month 21 vs 28 and month 21 vs 38.

65CL trim - In cooked patties made from 65CL lamb trim samples stored at -24°C lamb odour scores reduced consistently with storage duration and a similar but not as consistent trend occurred in samples made from samples stored at -18°C. But these changes were generally not statistically significant (P>0.05). Little overall trend was observed in cooked patties made from 65CL trim stored at -12°C

Lamb fat odour

There was an overall trend with all cuts for slight but steady drop off in cooked lamb fat odour intensity with storage duration.

Loin - No statistically different changes (P>0.05) in cooked fat odour were found between storage duration or storage temperatures. In cooked loin from samples stored at -18°C the mean aggregated score reduced from 5.6 prior to month 21 to 4.3 after month 24 but the change was not statistically significant (P>0.05).

90CL trim - There were clear trends for a reduction in cooked fat odour intensity score between 6 and 21 months and after 24 months in cooked patties made from 90CL trim stored at all temperatures. In cooked patties made from 90CL lamb trim stored at -12°C there was a drop between pre 28 month and 32 months (mean aggregated score 4.6 before vs mean aggregated score 3.7 after). In cooked patties from 90CL lamb trim stored at -24°C there was a drop in mean scores post 28 months (mean aggregated score 4.6 before vs mean aggregated score 3.6 after).

85CL trim - There was very little change in cooked fat odour intensity in patties made from 85CL trim stored for the first 21 months, then small but not significantly different (P>0.05) reductions in mean scores in cooked patties made from 85CL lamb trim stored at all storage temperatures between month 21 and month 38.

65CL trim - Although there were gaps in this assessment, there appeared to be a reduction in cooked fat odour intensity with storage duration, with significantly different differences (P<0.05) between 3 and 38 months, than scored in patties made from other trim levels or loin, and more variable results. This may reflect oxidative changes that were detected instrumentally. Nether-the-less while changes were detected in the cooked samples, they remained palatable and were not considered to be excessively 'rancid' by the panellists. While the instrumental analysis clearly showed a big difference between samples stored at -12°C and those stored at -18°C and -24°C the sensory scores did not show a big difference between samples made from trim stored at these different temperatures, just a general reduction in scores with frozen storage duration.

Lamb meat flavour

Loin - There was no overall statistical change in mean cooked lamb meat flavour scores in cooked loin from samples stored at -18°C and -24°C with storage duration between 3 and 38 months storage times, but there was a slight drop (though not generally statistical) in mean scores of cooked loin from samples stored at -12°C. Overall, there was little sign of any changes in mean scores in meat stored at any temperature for up to month 21 then a small reduction in cooked meat flavour intensity in samples from meat stored at -18°C and -12°C.

90CL trim - The only statistically significant changes (P<0.05) in mean cooked meat flavour scores occurred in cooked patties made from 90CL trim stored at -12°C assessed at month 6 and assessed at months 32 and 38.

85CL trim - The only statistically significant changes ($P<0.05$) in mean cooked meat flavour scores occurred in cooked patties made from 85CL trim stored at -18°C between months 3 vs 38, 12 vs 38, 24 vs 38.

65CL trim – Greater reductions in mean cooked meat flavour intensity scores occurred in patties made from 65CL trim assessed between month 3 and 38 than in patties made from other CL levels and lamb loin. There were no statistically significant differences ($P>0.05$) in mean scores of patties made from 65CL trim stored at -24°C and only a small number of cases in differences between scores in patties made from trim stored at -18°C and -12°C.

Lamb fat flavour

Loin – Mean cooked fat flavour intensity scores for lamb loin stored at all temperatures tended to be consistent or rising, up to storage month 21 and peaking at 21 or 24 months, before a slight drop at all temperatures.

90CL trim – There were no statistically different changes ($P>0.05$) in mean cooked fat flavour intensity scores in cooked patties made from 90CL trim stored at all storage temperatures for the storage duration.

85CL trim – There were no statistically different changes ($P>0.05$) in mean cooked fat flavour intensity scores in cooked patties made from 85CL trim stored at all storage temperatures for the storage duration

65CL trim – Although there were gaps in this assessment, there was a large variation in mean scores of cooked fat flavour intensity for cooked patties made from 65CL lamb trim than in that of cooked patties made from trim other fat levels or in cooked lamb loins. Mean cooked fat flavour intensity scores in cooked patties made from trim stored at all three temperatures tended to fall after month 21. Mean aggregate scores were above 7 from samples stored at -12°C and -18°C up to month 21 then dropped to 4.7 after. This change was not as apparent in scores of cooked patties made from 65CL trim stored at -24°C. Again, while changes were detected in the cooked samples, they remained palatable and were not considered to be excessively 'rancid' by the panellists. Also again, while the instrumental analysis clearly showed a big difference between samples stored at -12°C and those stored at -18°C and -24°C the sensory scores did not show as big difference between samples, though there was a difference between samples stored at -24°C.

Lamb juiciness

There was a possible overall trend for mean cooked juiciness scores in the cooked samples to rise over the first 21 months of frozen storage.

Loin - There were no statistically different changes ($P>0.05$) in mean cooked juiciness score in samples stored at all storage temperatures. There appeared to be a trend in higher scores with storage duration in the samples held at -12°C and -18°C.

90CL trim - Apart from a peak in mean juiciness score in cooked patties made from 90CL trim stored at -24°C assessed at 21 months, there were generally no statistically different changes ($P>0.05$) in mean cooked juiciness score of cooked patties made from 90CL trim stored at all storage temperatures over the storage duration.

85CL trim - Overall mean juiciness scores of cooked patties made from 85CL trim stored at all temperatures tended to peak at 21 or 24 months of storage then all decline to month 32 then rise slightly.

65CL trim - Although there were gaps in this assessment, overall mean juiciness scores of cooked patties made from 65CL trim stored at all temperatures tended to peak at month 21. There appeared to be less change in scores of patties made from trim stored at 24°C.

Lamb tenderness

Overall, there was little change or a small reduction in mean tenderness score with storage duration. There was no clear relationship with frozen storage temperature.

Loin - Mean scores in cooked loin tenderness from samples stored -12°C decreased from 6 to 12 months then remained almost constant, with no significant differences, up to 38 months. Mean scores for samples stored at -18°C showed no significant change (P>0.05) in tenderness with storage duration. While scores for samples stored at -24°C showed a rise in mean tenderness score, reaching a highest mean score at month 21, then a decrease in mean score. Changes were not generally significant.

90CL trim - There appeared to be no significant change (P>0.05) in mean tenderness score in cooked patties made from 90CL lamb trim that had been stored at any of the temperatures with storage duration.

85CL trim - All mean tenderness scores stayed approximately constant until peaking at month 21. Then mean tenderness scores in cooked patties made from 85CL trim stored at -12°C showed a step drop (mean 5.6 to 4.1) between pre 21 month (inclusive) and post 24 month (inclusive). Similarly, mean tenderness scores in cooked patties made from 85CL trim stored at -18°C showed a drop (mean 5.2 to 3.5) between pre 28 month (inclusive) and post 28 month (inclusive). Though this was only significant for 21vs32 and 21vs36 results. Again, with mean tenderness scores in cooked patties made from 85CL trim stored at -24°C there was a drop (mean 5.2 to 3.9) between pre 28 month (inclusive) and post 28 month (inclusive). But only a few mean results were statistically different, 21vs32 and 21vs38.

65CL trim - Although there were gaps in this assessment, there appeared to be no significant change (P>0.05) in tenderness scores with storage duration or temperature.

Lamb overall

While the lipid oxidation analysis (the PV, TBARS, and GCMS analyses) showed clear signs of the development of lipid oxidation over this time in some samples, particularly in the overwrapped frozen boxed lamb trim stored at -12°C, this did not appear to have been picked up as clearly in the corresponding taste panel scores. Although there was a decline in mean scores for certain characteristics in lamb trim with storage duration at all storage temperatures. Despite freezer burn being observed in the lamb trim stored at -12°C, but not in lamb trim stored at the other storage temperatures, mean scores did not show clear differences with storage temperature. This likely because 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 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).

As previously discussed at the start of this report few studies published in the last 25 years on the frozen storage of beef or lamb have assessed what effect frozen storage duration or temperature has on final eating quality. Studies published by Muela *et al.* (2010, 2015, 2016) on the frozen storage life of lamb were one of the few studies that evaluated the quality of the frozen samples with a trained sensory panel and a consumer panel. Overall, their studies indicate that panels cannot pick up differences between freezing methods, that frozen meat is often preferred over unfrozen meat. They observed that a difference could be detected by the untrained sensory panel in frozen lamb between storage periods of 15 and 21 months, but not by the trained sensory panel. The untrained panel still considered the samples to be acceptable. 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. These studies were all on lamb, we are unaware of any similar sensory studies on long term stored frozen beef. Also, again none of these studies stored frozen meat beyond 24 months.

Table 19. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) sensory analysis scores of overall appearance of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months) 3 (arrival)	6	12	21	24	28	32	36	38
Beef loin	-12		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	6.2 (1.5)^{a}	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		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	6.7 (1.5)^{a}	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 85CL	-12		5.9 (1.5)$^{a}_{A}$	5.7 (1.2)$^{a}_{A}$	5.3 (1.6)$^{ab}_{A}$	6.4 (2.1)$^{a}_{A}$	6.2 (1.9)$^{a}_{A}$	5.4 (1.8)$^{ab}_{A}$	3.9 (1.2)$^{b}_{A}$	4.0 (0.9)$^{b}_{A}$
	-18	4.9 (1.2)^{abc}	6.7 (1.4)$^{d}_{A}$	5.0 (1.0)$^{b}_{A}$	4.2 (1.7)$^{b}_{A}$	5.8 (1.5)$^{cd}_{A}$	6.0 (1.4)$^{cd}_{A}$	4.9 (1.5)$^{ac}_{A}$	5.5 (0.8)$^{acd}_{B}$	5.4 (0.9)$^{acd}_{B}$
	-24		6.4 (1.4)$^{a}_{A}$	5.7 (1.0)$^{ab}_{A}$	4.9 (1.9)$^{bc}_{A}$	4.9 (1.8)$^{bc}_{A}$	5.5 (1.7)$^{abc}_{A}$	4.6 (0.7)$^{bc}_{A}$	4.6 (0.5)$^{bc}_{AB}$	4.1 (0.9)$^{c}_{A}$
Beef trim 65CL	-12		-	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	6.6 (1.8)^{ab}	-	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		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	5.7 (1.0)^{ab}	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		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	5.3 (1.1)^{a}	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 85CL	-12		4.7 (1.0)$^{a}_{A}$	4.8 (0.9)$^{a}_{A}$	4.8 (1.5)$^{a}_{A}$	4.6 (1.5)$^{ab}_{A}$	3.9 (1.1)$^{ab}_{A}$	3.4 (1.4)$^{b}_{A}$	4.4 (0.8)$^{ab}_{A}$	4.3 (1.2)$^{ab}_{A}$
	-18	5.5 (1.5)^{a}	5.4 (1.2)$^{ab}_{A}$	5.7 (0.8)$^{a}_{B}$	4.0 (2.1)$^{bc}_{A}$	4.0 (2.2)$^{bc}_{A}$	3.8 (0.9)$^{c}_{A}$	3.1 (1.5)$^{c}_{A}$	4.1 (1.5)$^{abc}_{A}$	3.6 (1.1)$^{c}_{A}$
	-24		4.9 (1.4)$^{a}_{A}$	5.1 (0.8)$^{a}_{AB}$	4.9 (1.6)$^{a}_{A}$	3.8 (1.6)$^{ab}_{A}$	3.2 (1.4)$^{b}_{A}$	3.9 (1.0)$^{ab}_{A}$	4.6 (1.0)$^{ab}_{A}$	4.0 (0.9)$^{ab}_{A}$
Lamb trim 65CL	-12		-	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	5.6 (0.5)^{a}	-	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 20. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) sensory analysis scores of meat odour intensity of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage time (Months)								
		3 (arrival)	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 85CL	-12		4.0 (0.9)$^{a}_{A}$	5.3 (1.1)$^{ab}_{A}$	5.7 (1.7)$^{b}_{A}$	5.4 (1.2)$^{ab}_{A}$	4.8 (1.9)$^{ab}_{A}$	4.8 (2.0)$^{ab}_{A}$	4.6 (1.5)$^{ab}_{A}$	4.1 (1.2)$^{a}_{A}$
	-18	4.8 (1.3)^{a}	4.5 (1.4)$^{a}_{A}$	5.0 (1.3)$^{a}_{A}$	5.0 (1.2)$^{a}_{A}$	4.9 (1.8)$^{a}_{A}$	4.5 (1.3)$^{a}_{A}$	4.4 (1.4)$^{a}_{A}$	5.1 (2.0)$^{a}_{A}$	5.0 (1.3)$^{a}_{A}$
	-24		4.3 (1.2)$^{a}_{A}$	4.7 (1.2)$^{a}_{A}$	4.7 (1.7)$^{a}_{A}$	4.7 (2.0)$^{a}_{A}$	4.8 (1.8)$^{a}_{A}$	4.4 (1.3)$^{a}_{A}$	5.0 (1.3)$^{a}_{A}$	4.1 (1.8)$^{a}_{A}$
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 85CL	-12		4.7 (1.6)$^{ab}_{A}$	5.0 (1.1)$^{ab}_{A}$	6.0 (1.9)$^{a}_{A}$	5.4 (1.7)$^{ab}_{A}$	4.3 (1.7)$^{b}_{A}$	4.9 (1.5)$^{ab}_{A}$	4.4 (2.2)$^{ab}_{A}$	3.8 (1.6)$^{b}_{A}$
	-18	4.8 (1.8)$^{a}_{A}$	5.3 (1.6)$^{a}_{A}$	5.2 (1.2)$^{a}_{A}$	5.1 (1.8)$^{a}_{A}$	4.8 (1.9)$^{a}_{A}$	4.5 (1.4)$^{a}_{A}$	5.1 (2.0)$^{a}_{A}$	4.9 (2.1)$^{a}_{A}$	4.1 (1.7)$^{a}_{A}$
	-24		4.8 (1.2)$^{a}_{A}$	5.1 (1.4)$^{a}_{A}$	5.2 (2.1)$^{a}_{A}$	4.9 (1.7)$^{a}_{A}$	4.2 (1.6)$^{a}_{A}$	5.5 (2.0)$^{a}_{A}$	4.6 (0.8)$^{a}_{A}$	4.0 (1.9)$^{a}_{A}$
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 21. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) sensory analysis scores of fat odour intensity of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months) 3 (arrival)	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	-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)$^{a}_{A}$
trim	-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)$^{a}_{A}$
95CL	-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	-12		4.3 (0.9)$^{a}_{A}$	4.8 (1.1)$^{a}_{A}$	5.0 (1.6)$^{a}_{A}$	4.6 (1.6)$^{a}_{A}$	4.3 (1.6)$^{a}_{A}$	4.6 (2.1)$^{a}_{A}$	4.3 (1.0)$^{a}_{A}$	3.8 (1.4)$^{a}_{A}$
trim	-18	4.8 (1.5)$^{a}_{A}$	4.5 (1.8)$^{a}_{A}$	4.5 (0.9)$^{a}_{A}$	4.4 (1.6)$^{a}_{A}$	4.2 (1.7)$^{a}_{A}$	3.9 (1.4)$^{a}_{A}$	4.3 (1.5)$^{a}_{A}$	4.6 (1.8)$^{a}_{A}$	4.4 (1.7)$^{a}_{A}$
85CL	-24		4.7 (1.3)$^{ab}_{A}$	5.1 (1.5)$^{a}_{A}$	4.3 (1.3)$^{ab}_{A}$	4.2 (1.1)$^{ab}_{A}$	4.0 (1.9)$^{ab}_{A}$	4.1 (1.2)$^{ab}_{A}$	4.6 (1.5)$^{ab}_{A}$	3.4 (1.5)$^{b}_{A}$
Beef	-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)$^{a}_{A}$
trim	-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)$^{a}_{A}$
65CL	-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	-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)$^{b}_{A}$
trim	-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)$^{a}_{A}$
90CL	-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	-12		5.2 (0.9)$^{a}_{A}$	4.9 (1.1)$^{a}_{A}$	4.9 (1.9)$^{a}_{A}$	4.7 (1.7)$^{a}_{A}$	3.9 (2.0)$^{a}_{A}$	4.3 (1.8)$^{a}_{A}$	3.6 (1.1)$^{a}_{A}$	3.6 (1.3)$^{a}_{A}$
trim	-18	4.6 (1.7)$^{a}_{A}$	4.9 (1.6)$^{a}_{A}$	5.1 (1.4)$^{a}_{A}$	4.2 (1.8)$^{a}_{A}$	4.1 (2.0)$^{a}_{A}$	4.1 (1.3)$^{a}_{A}$	4.5 (2.1)$^{a}_{A}$	3.4 (1.4)$^{a}_{A}$	3.6 (1.7)$^{a}_{A}$
85CL	-24		4.8 (0.9)$^{a}_{A}$	4.6 (1.3)$^{a}_{A}$	4.5 (1.7)$^{a}_{A}$	4.2 (2.0)$^{a}_{A}$	3.6 (1.4)$^{a}_{A}$	4.1 (2.2)$^{a}_{A}$	4.0 (1.2)$^{a}_{A}$	3.6 (1.5)$^{a}_{A}$
Lamb	-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)$^{b}_{A}$
trim	-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)$^{c}_{A}$
65CL	-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 22. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) sensory analysis scores of meat flavour intensity of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	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 85CL	-12		5.0 (1.8)$^{a}_{A}$	4.1 (1.4)$^{a}_{A}$	5.3 (1.5)$^{a}_{A}$	5.2 (1.1)$^{a}_{A}$	4.4 (1.1)$^{a}_{A}$	5.0 (0.8)$^{a}_{A}$	4.8 (1.0)$^{a}_{A}$	4.1 (1.4)$^{a}_{A}$
	-18	4.9 (1.6)$^{a}_{A}$	3.9 (2.1)$^{a}_{A}$	4.6 (1.9)$^{a}_{A}$	4.5 (0.8)$^{a}_{A}$	4.3 (1.3)$^{a}_{A}$	4.7 (1.4)$^{a}_{A}$	4.9 (0.6)$^{a}_{A}$	4.5 (1.2)$^{a}_{A}$	5.0 (1.8)$^{a}_{A}$
	-24		4.8 (1.7)$^{a}_{A}$	4.3 (1.6)$^{a}_{A}$	5.4 (2.1)$^{a}_{A}$	3.9 (1.2)$^{a}_{A}$	4.7 (1.6)$^{a}_{A}$	4.5 (0.9)$^{a}_{A}$	5.1 (1.2)$^{a}_{A}$	4.0 (1.4)$^{a}_{A}$
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 85CL	-12		4.5 (1.6)$^{a}_{A}$	5.0 (1.0)$^{a}_{A}$	4.6 (1.4)$^{a}_{A}$	4.7 (1.3)$^{a}_{A}$	4.6 (1.6)$^{a}_{A}$	3.9 (2.0)$^{a}_{A}$	4.7 (1.4)$^{a}_{A}$	3.8 (1.8)$^{a}_{A}$
	-18	5.3 (1.8)$^{a}_{A}$	4.1 (1.9)$^{ab}_{A}$	5.0 (1.0)$^{a}_{A}$	4.4 (2.0)$^{ab}_{A}$	5.2 (1.6)$^{a}_{A}$	4.9 (1.7)$^{ab}_{A}$	3.8 (2.1)$^{ab}_{A}$	5.0 (1.9)$^{ab}_{A}$	3.1 (1.6)$^{b}_{A}$
	-24		4.6 (1.4)$^{a}_{A}$	4.9 (1.5)$^{a}_{A}$	5.6 (2.5)$^{a}_{A}$	5.3 (1.3)$^{a}_{A}$	4.5 (1.5)$^{a}_{A}$	4.1 (2.3)$^{a}_{A}$	5.1 (0.7)$^{a}_{A}$	4.1 (1.6)$^{a}_{A}$
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 23. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) sensory analysis scores of fat flavour intensity appearance of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	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 85CL	-12		5.0 (1.8)$^{a}_{A}$	4.6 (1.5)$^{a}_{A}$	5.2 (1.4)$^{a}_{A}$	5.4 (1.0)$^{a}_{A}$	4.5 (1.0)$^{a}_{A}$	5.5 (1.6)$^{a}_{A}$	4.8 (1.0)$^{a}_{A}$	4.2 (1.2)$^{a}_{A}$
	-18	4.9 (2.0)$^{ab}_{A}$	4.1 (1.8)$^{a}_{A}$	4.3 (1.4)$^{a}_{A}$	3.6 (1.3)$^{a}_{A}$	4.9 (0.9)$^{ab}_{AB}$	4.3 (1.4)$^{a}_{A}$	6.3 (1.8)$^{b}_{A}$	4.8 (1.3)$^{ab}_{A}$	5.0 (1.4)$^{ab}_{A}$
	-24		4.9 (1.7)$^{a}_{A}$	5.1 (1.7)$^{a}_{A}$	4.5 (2.1)$^{a}_{A}$	4.3 (1.0)$^{a}_{B}$	4.8 (1.6)$^{a}_{A}$	5.6 (1.8)$^{a}_{A}$	4.9 (1.0)$^{a}_{A}$	3.9 (1.6)$^{a}_{A}$
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 85CL	-12		5.1 (1.8)$^{a}_{A}$	5.5 (1.6)$^{a}_{A}$	4.8 (1.6)$^{a}_{A}$	4.6 (1.1)$^{a}_{A}$	4.4 (2.0)$^{a}_{A}$	5.0 (1.7)$^{a}_{A}$	5.1 (1.8)$^{a}_{A}$	4.3 (2.3)$^{a}_{A}$
	-18	4.8 (2.3)$^{a}_{A}$	4.3 (2.2)$^{a}_{A}$	4.7 (1.3)$^{a}_{A}$	4.3 (1.8)$^{a}_{A}$	5.1 (1.3)$^{a}_{A}$	4.4 (1.7)$^{a}_{A}$	4.5 (2.6)$^{a}_{A}$	5.4 (2.5)$^{a}_{A}$	4.1 (2.2)$^{a}_{A}$
	-24		5.2 (1.6)$^{a}_{A}$	4.6 (1.4)$^{a}_{A}$	4.4 (2.0)$^{a}_{A}$	5.6 (1.2)$^{a}_{A}$	4.3 (2.1)$^{a}_{A}$	5.4 (2.1)$^{a}_{A}$	5.7 (2.1)$^{a}_{A}$	3.8 (1.7)$^{a}_{A}$
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 24. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) sensory analysis scores of overall juiciness of beef/lamb loin and trim stored for up to 38 months

Sample	Temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	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 85CL	-12		3.6 (2.0)$^{ab}_{A}$	4.0 (1.3)$^{ab}_{A}$	5.8 (1.6)$^{c}_{A}$	4.8 (1.9)$^{ac}_{A}$	3.2 (1.0)$^{b}_{A}$	5.3 (0.9)$^{c}_{A}$	3.5 (1.3)$^{ab}_{A}$	4.4 (1.3)$^{abc}_{A}$
	-18	4.5 (1.6)$^{a}_{A}$	3.6 (1.6)$^{a}_{A}$	4.3 (1.7)$^{a}_{A}$	4.8 (1.5)$^{a}_{A}$	3.8 (1.8)$^{a}_{A}$	3.5 (1.1)$^{a}_{A}$	4.9 (0.6)$^{a}_{AB}$	3.5 (1.8)$^{a}_{A}$	4.8 (1.3)$^{a}_{A}$
	-24		4.4 (2.0)$^{ab}_{A}$	4.5 (1.7)$^{ab}_{A}$	5.3 (2.4)$^{a}_{A}$	4.8 (1.1)$^{ab}_{A}$	3.5 (1.5)$^{b}_{A}$	4.4 (0.5)$^{ab}_{B}$	4.1 (2.1)$^{ab}_{A}$	3.7 (1.6)$^{ab}_{A}$
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 85CL	-12		4.5 (2.1)$^{ab}_{A}$	4.5 (1.3)$^{ab}_{A}$	5.7 (1.9)$^{a}_{A}$	4.3 (1.7)$^{ab}_{A}$	3.0 (1.1)$^{b}_{A}$	2.4 (1.5)$^{c}_{A}$	3.0 (1.2)$^{b}_{A}$	2.9 (1.2)$^{b}_{A}$
	-18	4.8 (1.9)$^{ab}_{A}$	3.8 (1.7)$^{abc}_{A}$	3.5 (1.7)$^{ac}_{A}$	4.8 (2.3)$^{abc}_{A}$	5.2 (1.9)$^{b}_{A}$	3.2 (0.8)$^{ad}_{A}$	2.0 (1.4)$^{d}_{A}$	3.0 (1.3)$^{acd}_{A}$	3.0 (1.3)$^{cd}_{A}$
	-24		4.1 (1.7)$^{ab}_{A}$	3.5 (1.4)$^{ab}_{A}$	5.1 (2.7)$^{a}_{A}$	4.6 (2.2)$^{ac}_{A}$	3.2 (0.9)$^{bc}_{A}$	2.5 (2.0)$^{b}_{A}$	3.3 (1.3)$^{ab}_{A}$	3.6 (1.3)$^{ab}_{A}$
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 25. Effect of frozen storage duration and temperature (-12°C, -18°C, and -24°C) on mean (SD) sensory analysis scores of overall tenderness of beef/lamb loin and trim stored for up to 38 months

Sample	Storage temp (°C)	Frozen storage duration (Months)								
		3 (arrival)	**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 85CL	-12		4.9 (2.2)$^{ab}_{A}$	5.2 (2.1)$^{ab}_{A}$	6.1 (1.9)$^{b}_{A}$	4.9 (1.4)$^{ab}_{A}$	4.1 (1.1)$^{a}_{A}$	5.4 (1.3)$^{ab}_{A}$	5.0 (0.8)$^{ab}_{A}$	4.9 (1.5)$^{ab}_{A}$
	-18	5.2 (1.4)$^{ab}_{A}$	5.1 (2.0)$^{ab}_{A}$	5.4 (1.6)$^{ab}_{A}$	5.4 (1.6)$^{ab}_{A}$	4.6 (0.9)$^{ab}_{A}$	4.1 (0.9)$^{a}_{A}$	5.3 (0.9)$^{ab}_{A}$	5.5 (1.1)$^{ab}_{A}$	6.0 (1.6)$^{b}_{A}$
	-24		5.7 (2.5)$^{a}_{A}$	5.4 (1.4)$^{a}_{A}$	5.8 (2.3)$^{a}_{A}$	5.6 (1.7)$^{a}_{A}$	5.0 (1.4)$^{a}_{A}$	5.0 (0.8)$^{a}_{A}$	5.9 (1.9)$^{a}_{A}$	4.8 (1.8)$^{a}_{A}$
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 85CL	-12		5.8 (1.6)$^{a}_{A}$	5.5 (1.2)$^{ab}_{A}$	5.5 (1.4)$^{ab}_{A}$	4.6 (1.7)$^{ac}_{A}$	3.9 (1.2)$^{c}_{A}$	4.0 (1.5)$^{bc}_{A}$	3.9 (1.2)$^{bc}_{A}$	4.4 (1.7)$^{ac}_{A}$
	-18	5.5 (1.8)$^{a}_{A}$	5.4 (1.7)$^{ab}_{A}$	4.8 (1.8)$^{abc}_{A}$	5.8 (1.8)$^{a}_{A}$	5.2 (1.6)$^{abd}_{A}$	4.6 (1.1)$^{a}_{A}$	3.4 (1.6)$^{c}_{A}$	3.6 (1.5)$^{bc}_{A}$	3.6 (1.5)$^{cd}_{A}$
	-24		5.1 (1.5)$^{ab}_{A}$	4.9 (1.7)$^{ab}_{A}$	5.9 (1.9)$^{b}_{A}$	5.0 (2.2)$^{ab}_{A}$	4.6 (1.3)$^{ab}_{A}$	3.8 (1.8)$^{a}_{A}$	4.0 (1.3)$^{ab}_{A}$	4.0 (1.4)$^{a}_{A}$
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 ($P<0.05$)

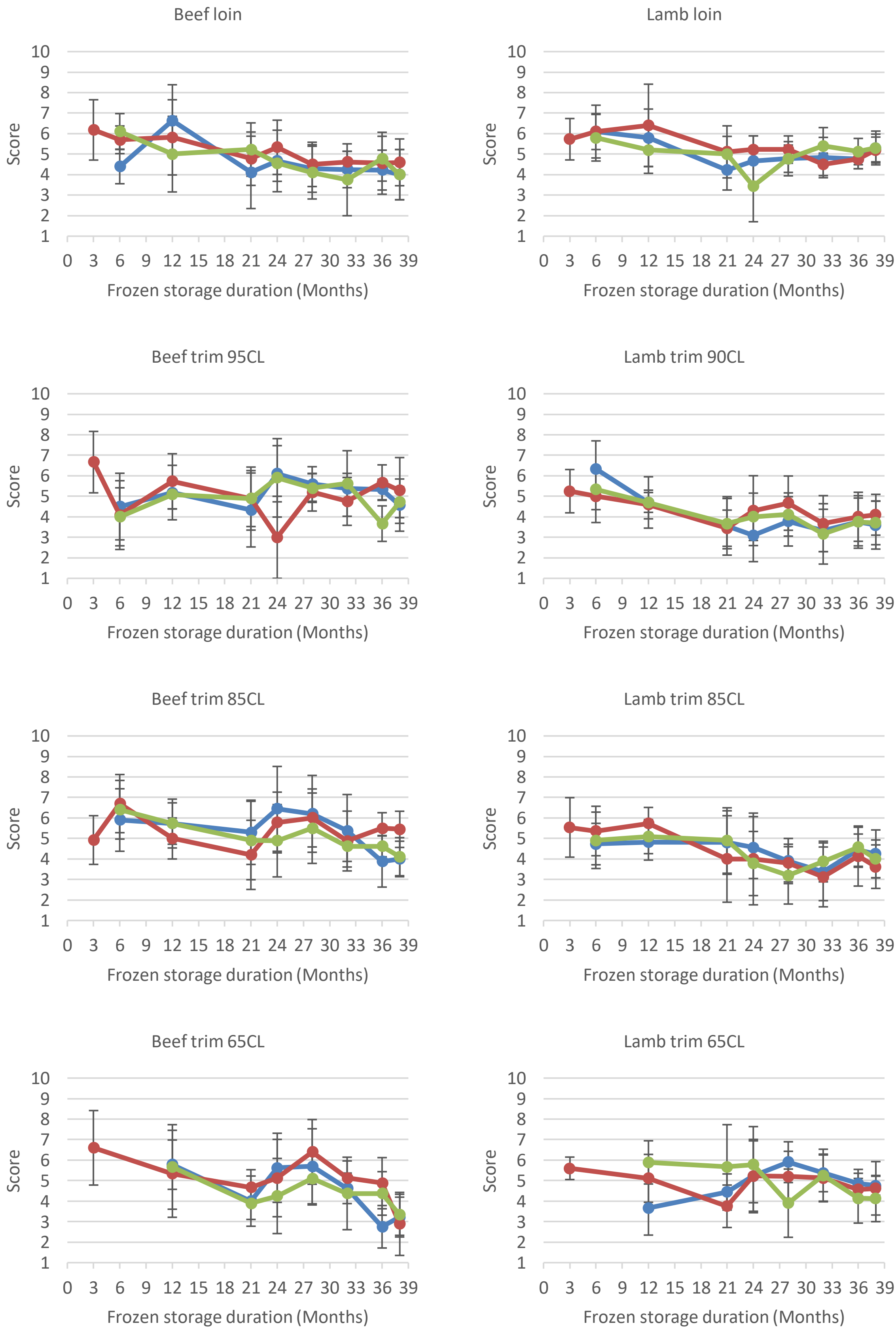

Figure 18. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean overall appearance sensory scores of beef/lamb loin and trim (Vertical bars: ±1SD)

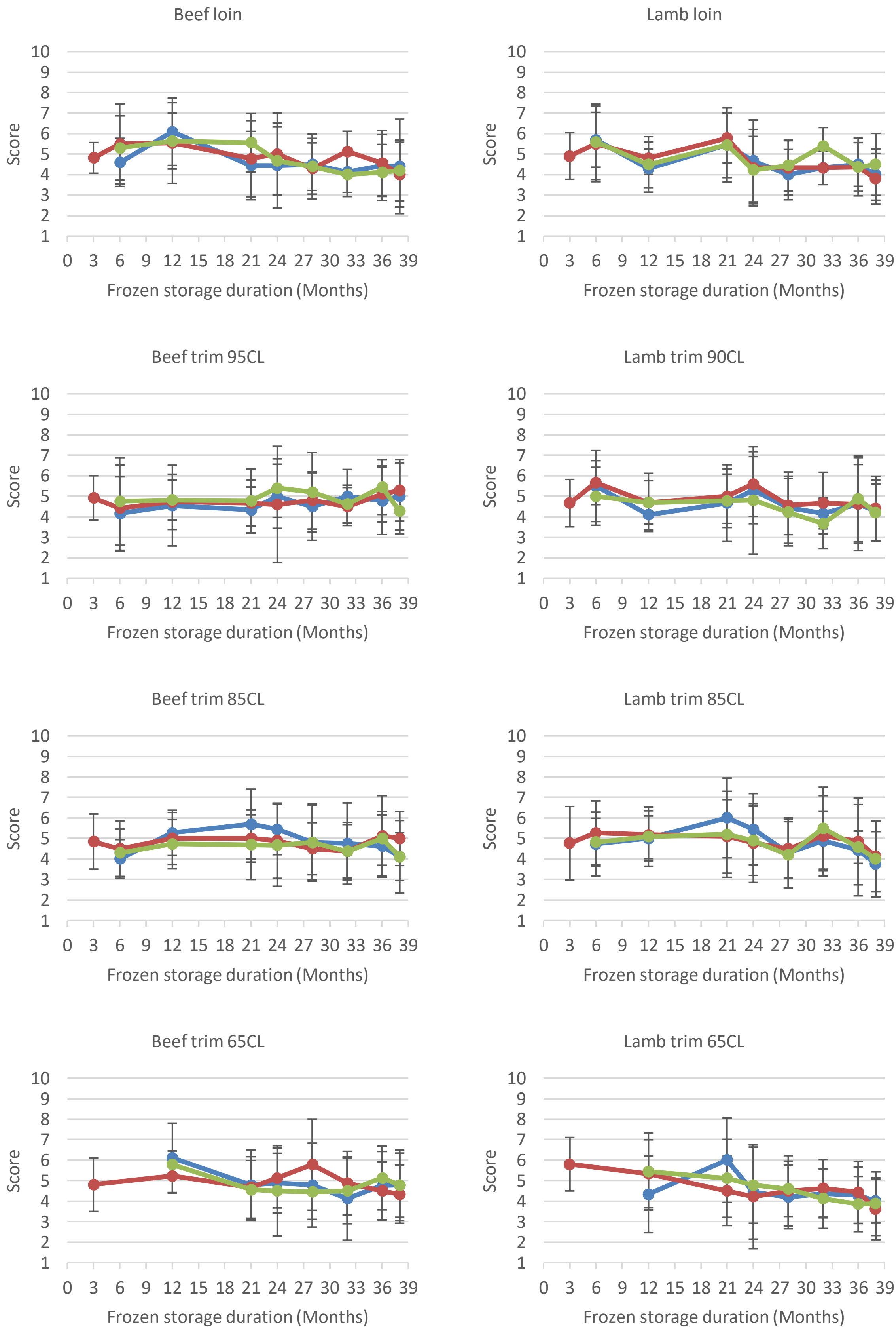

Figure 19. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean meat odour intensity sensory scores of beef/lamb loin and trim (Vertical bars: ±1SD)

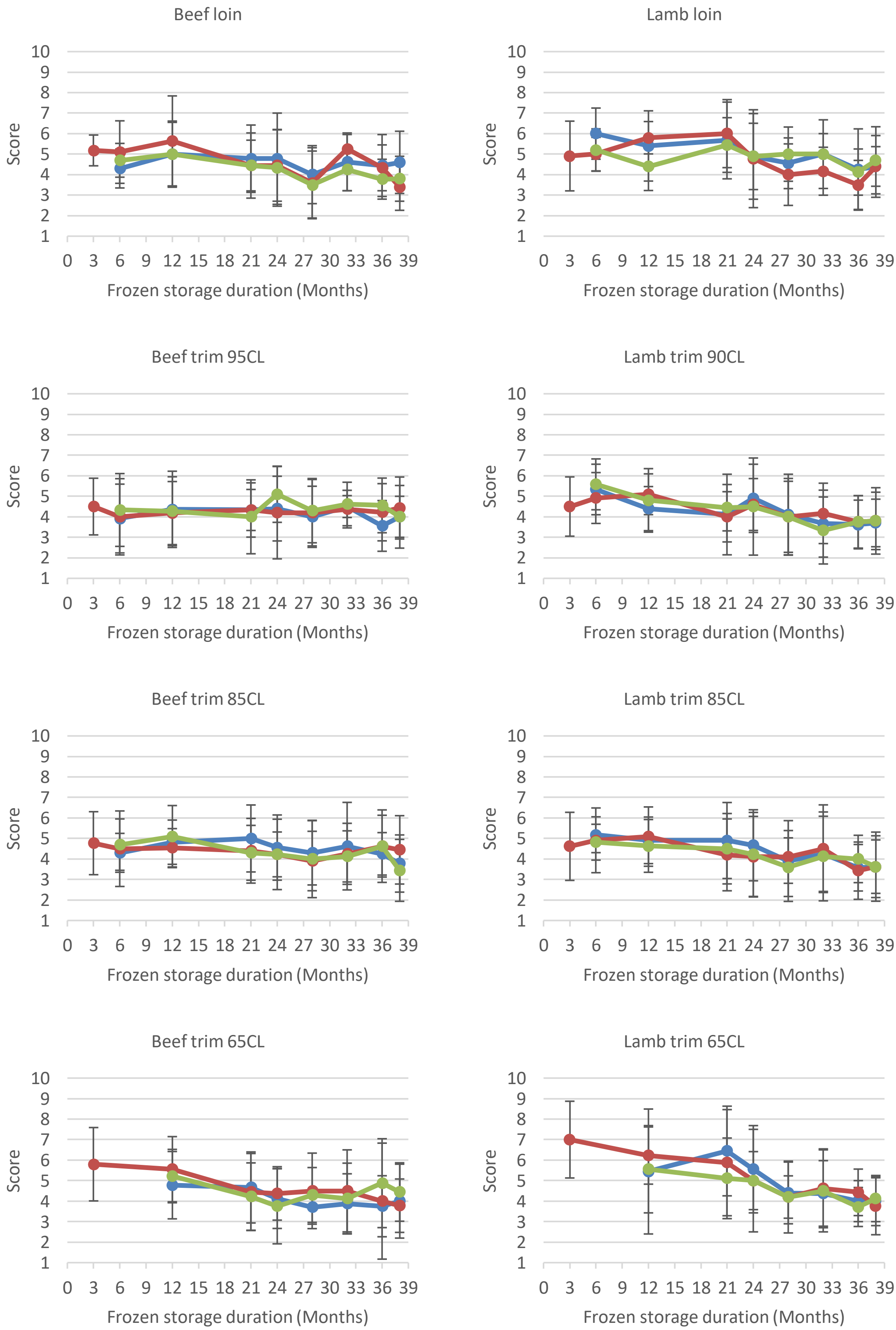

Figure 20. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean fat odour intensity sensory scores of beef/lamb loin and trim (Vertical bars: ±1SD)

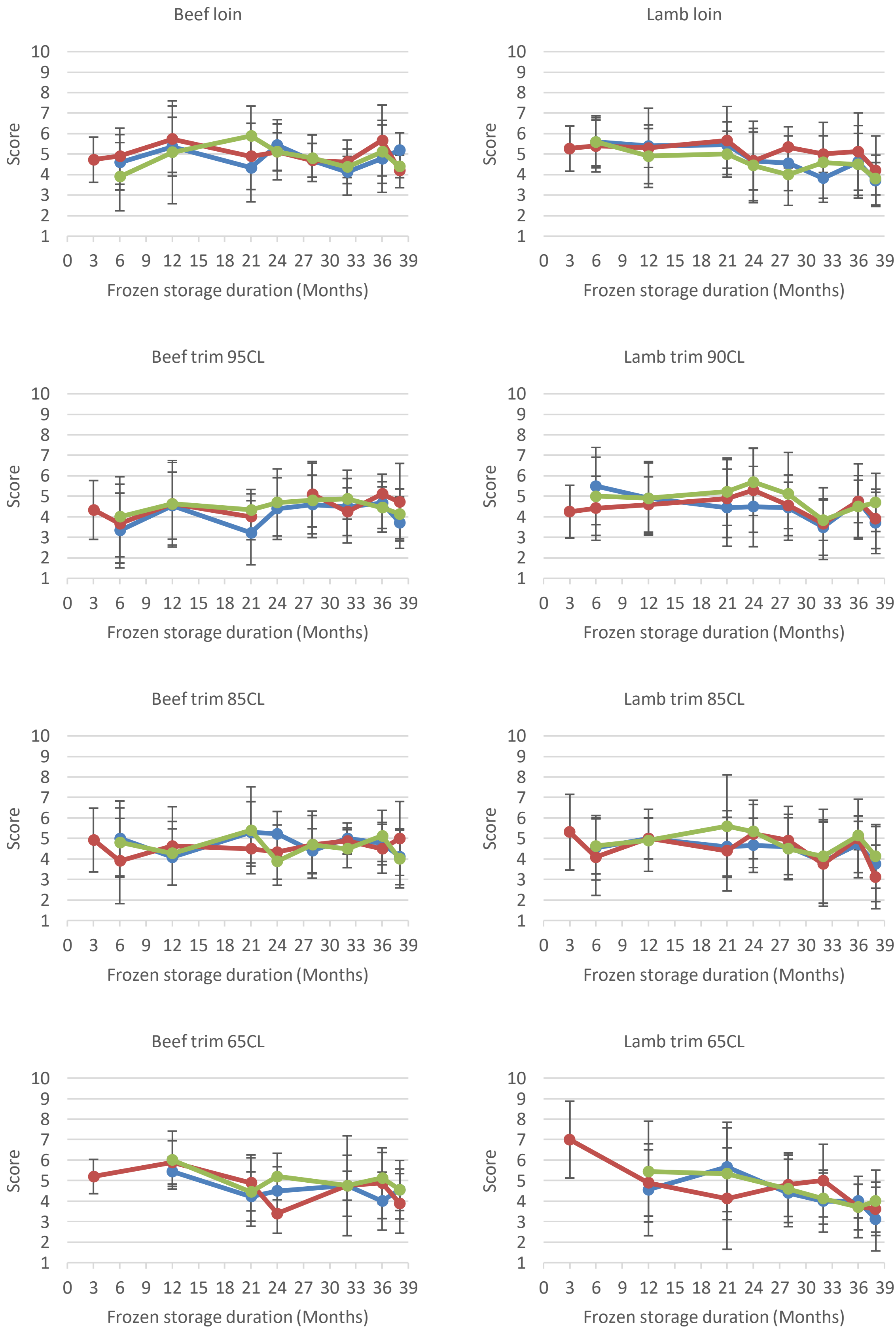

Figure 21. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean meat flavour intensity sensory scores of beef/lamb loin and trim (Vertical bars: ±1SD)

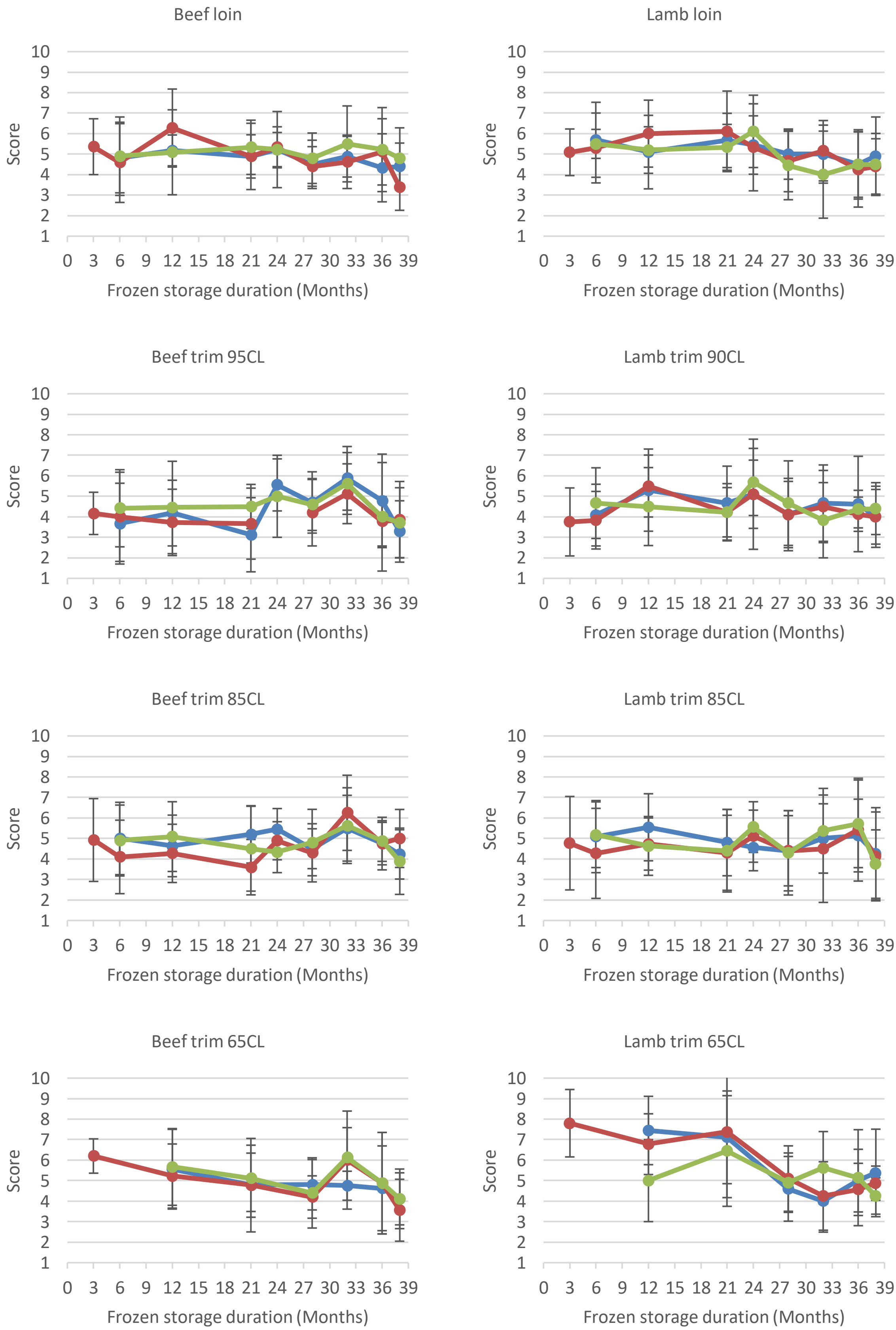

Figure 22. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean fat flavour intensity sensory scores of beef/lamb loin and trim (Vertical bars: ±1SD)

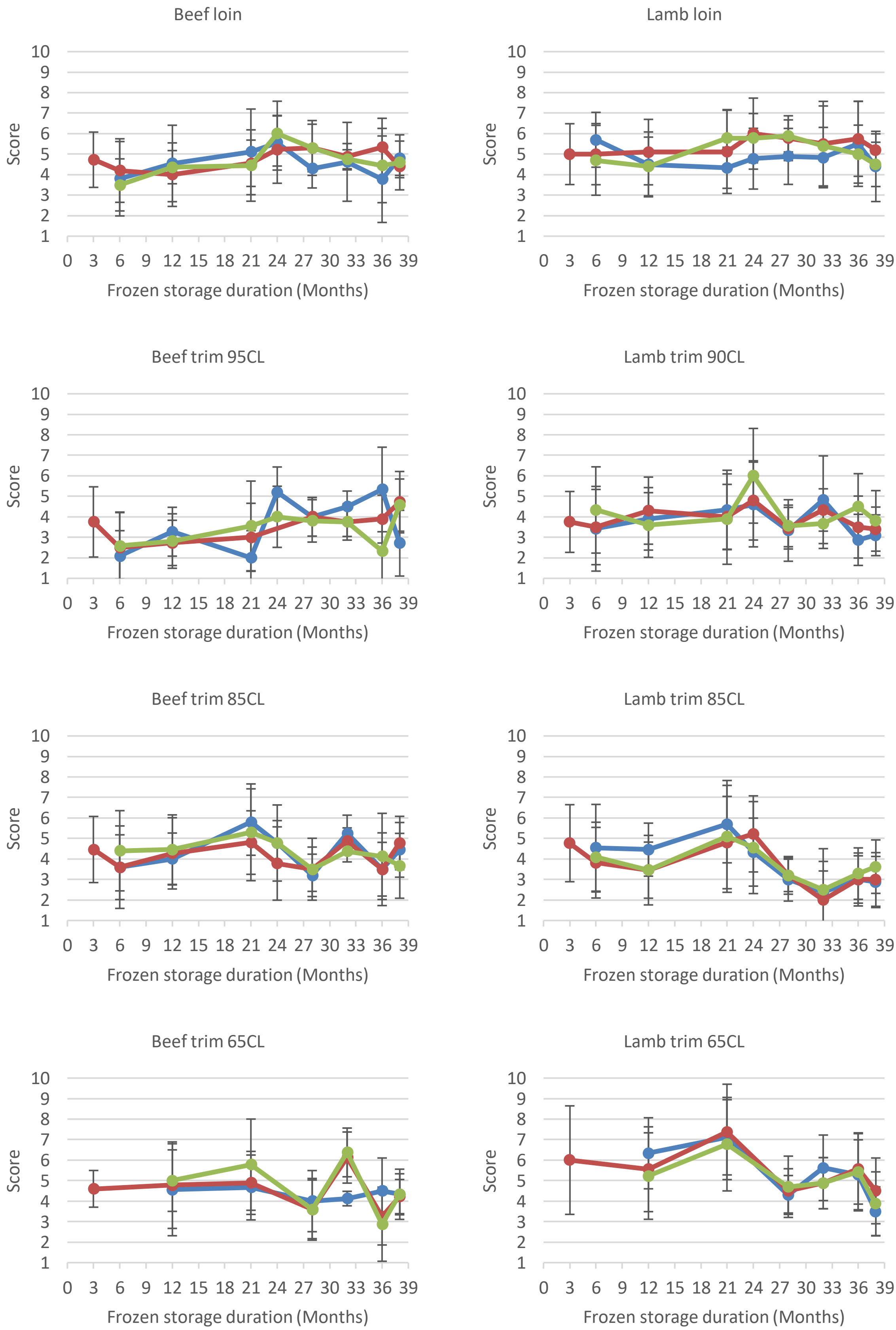

Figure 23. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean overall juiciness sensory scores of beef/lamb loin and trim (Vertical bars: ±1SD)

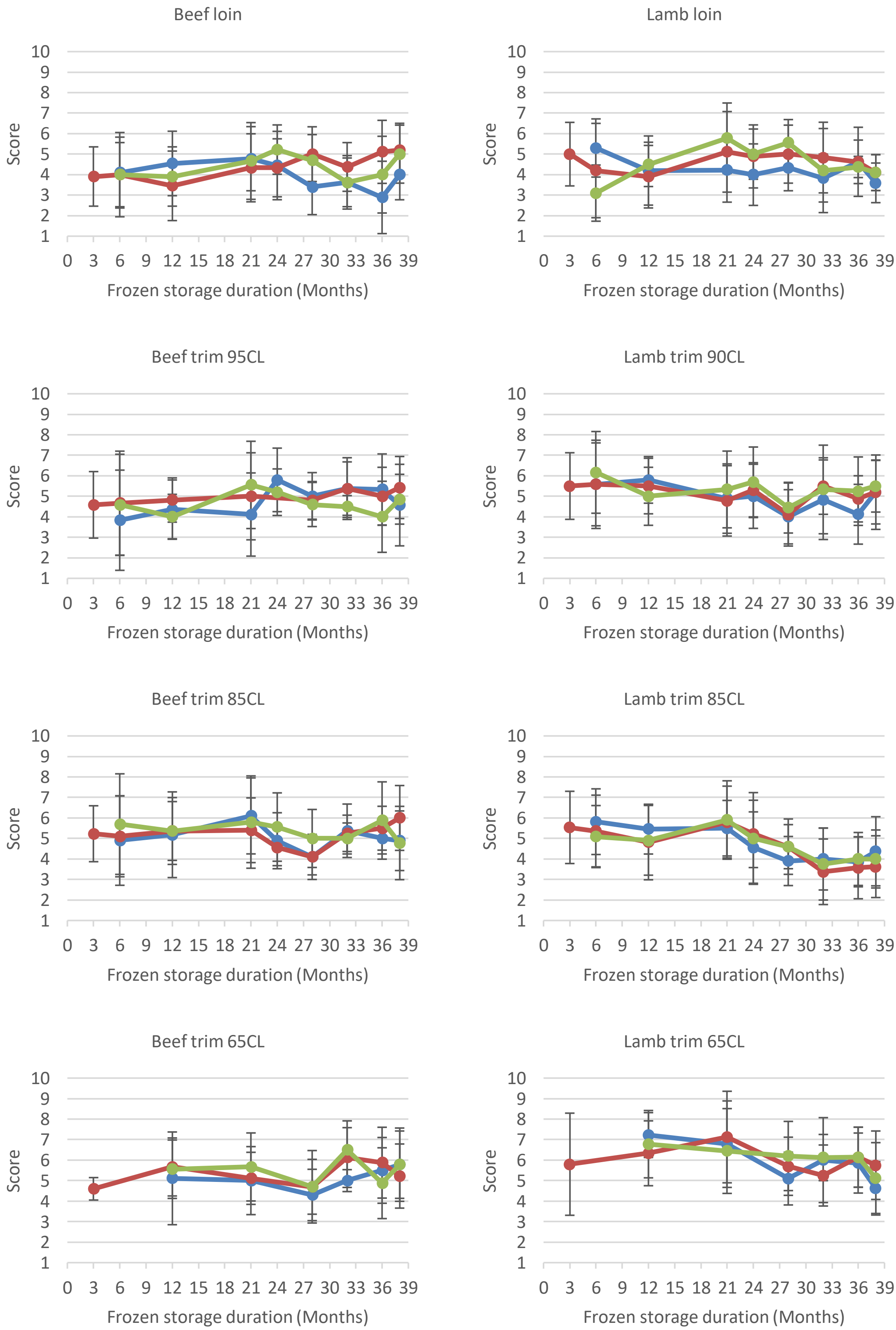

Figure 24. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean overall tenderness sensory scores of beef/lamb loin and trim (Vertical bars: ±1SD)

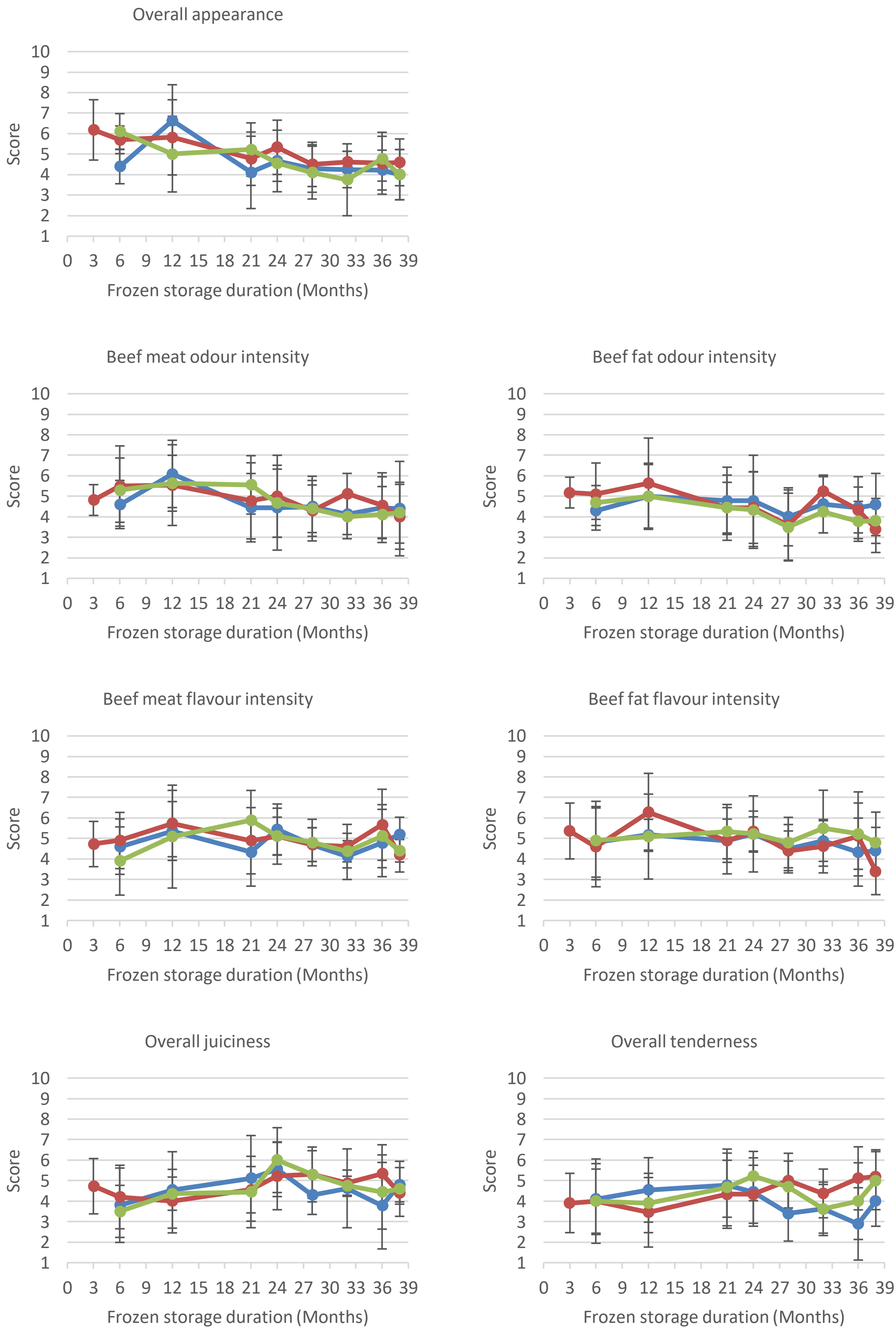

Figure 25. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of beef loin (Vertical bars: ±1SD)

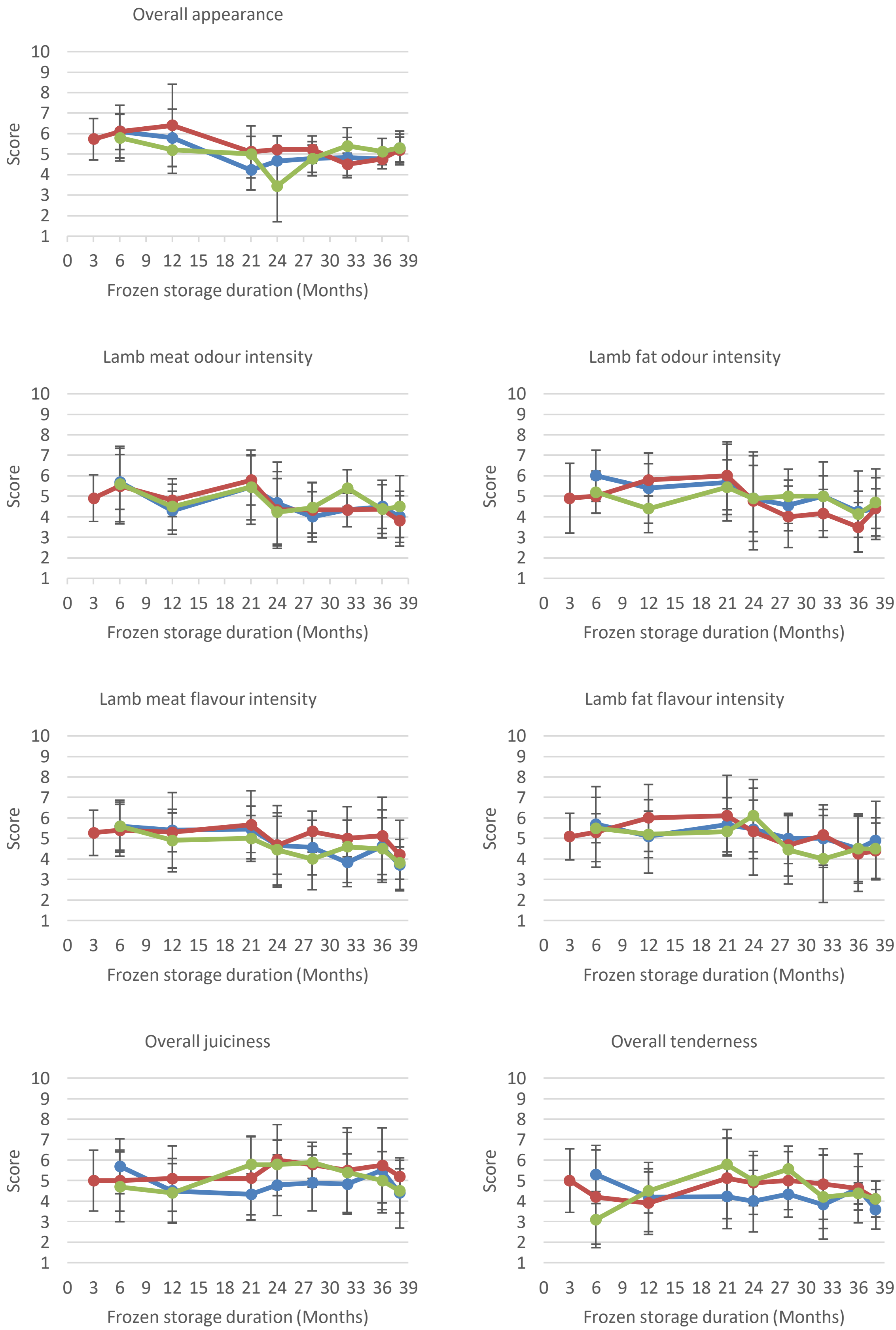

Figure 26. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of lamb loin (Vertical bars: ±1SD)

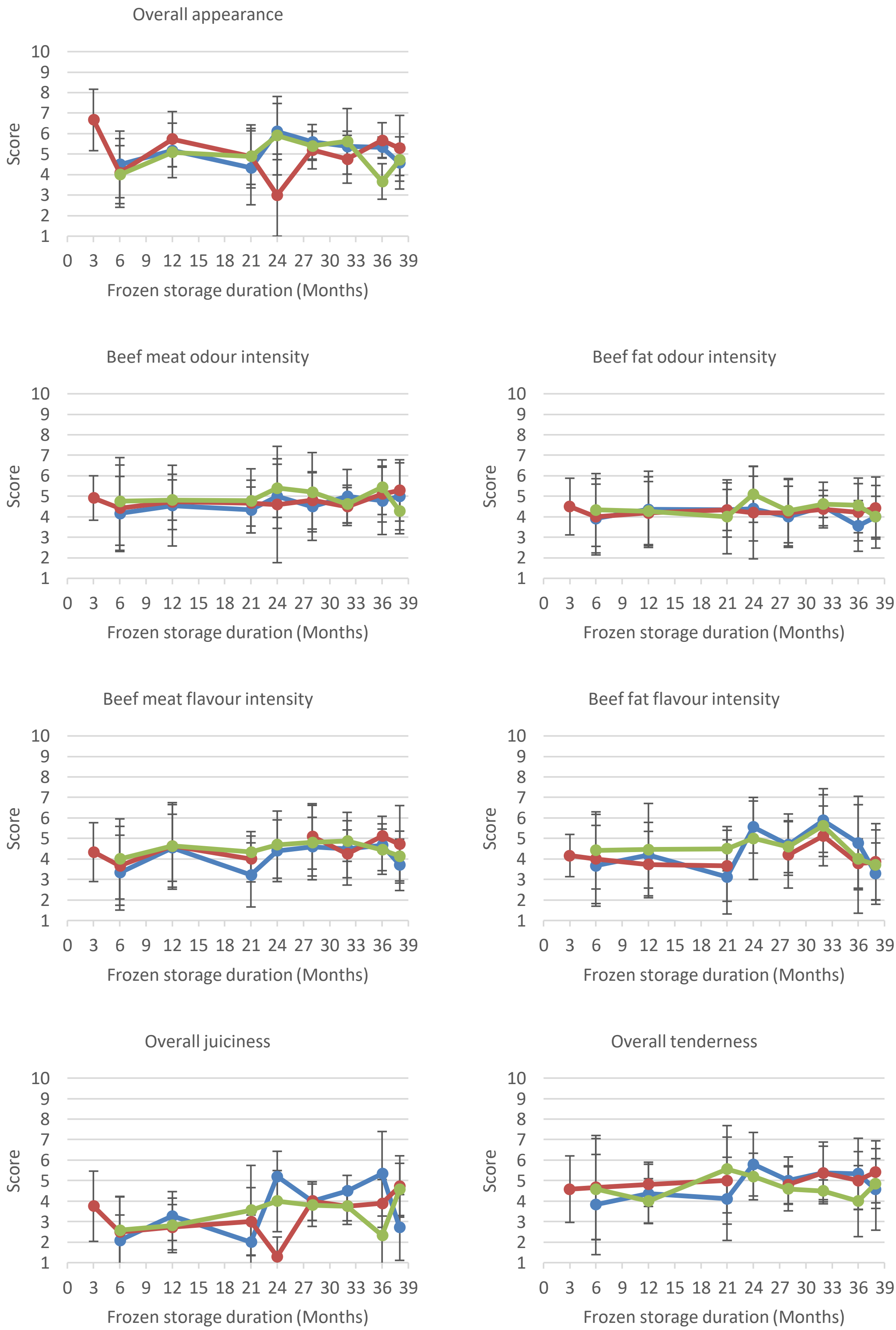

Figure 27. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of beef trim 95CL (Vertical bars: ±1SD)

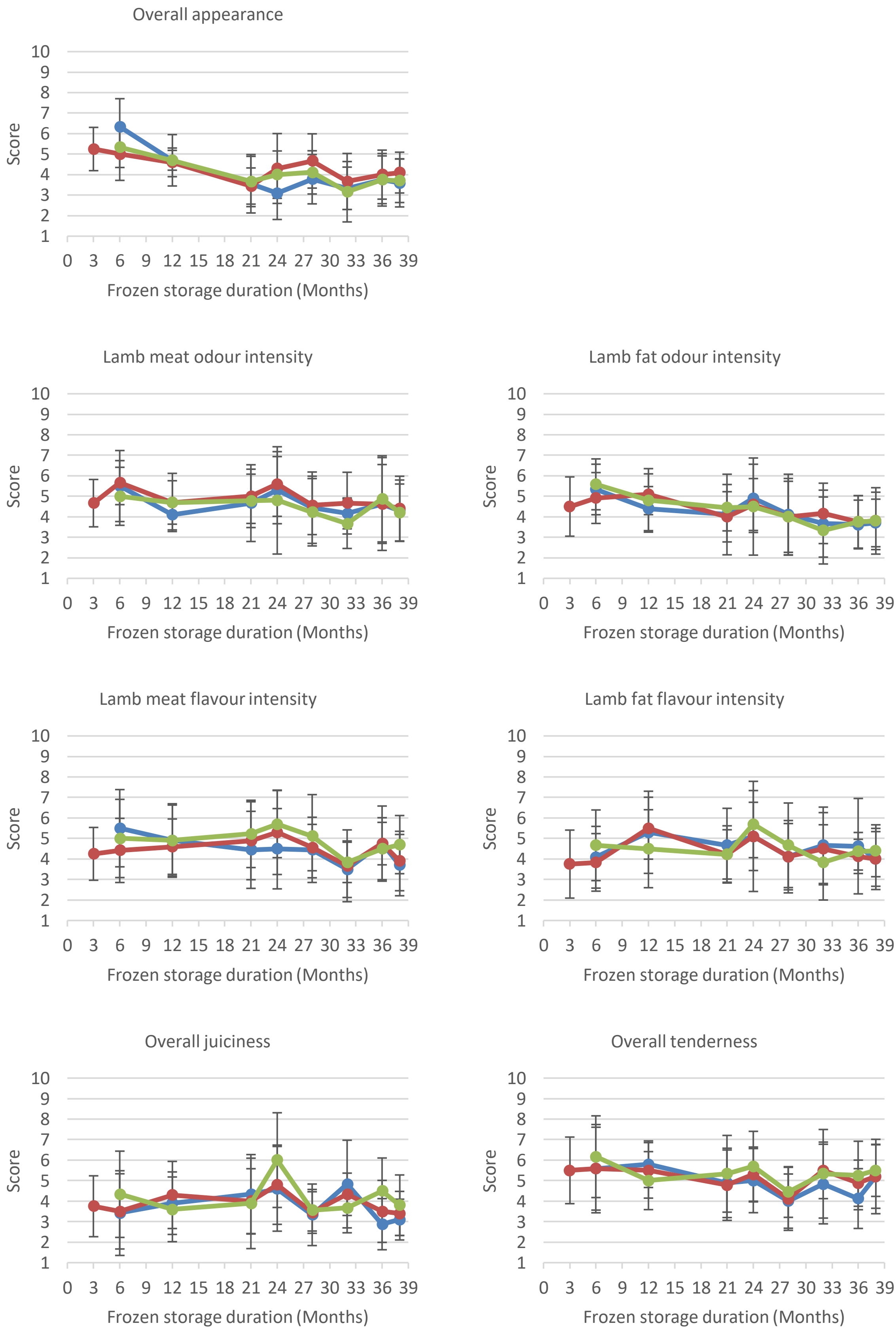

Figure 28. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of lamb trim 90CL (Vertical bars: ±1SD)

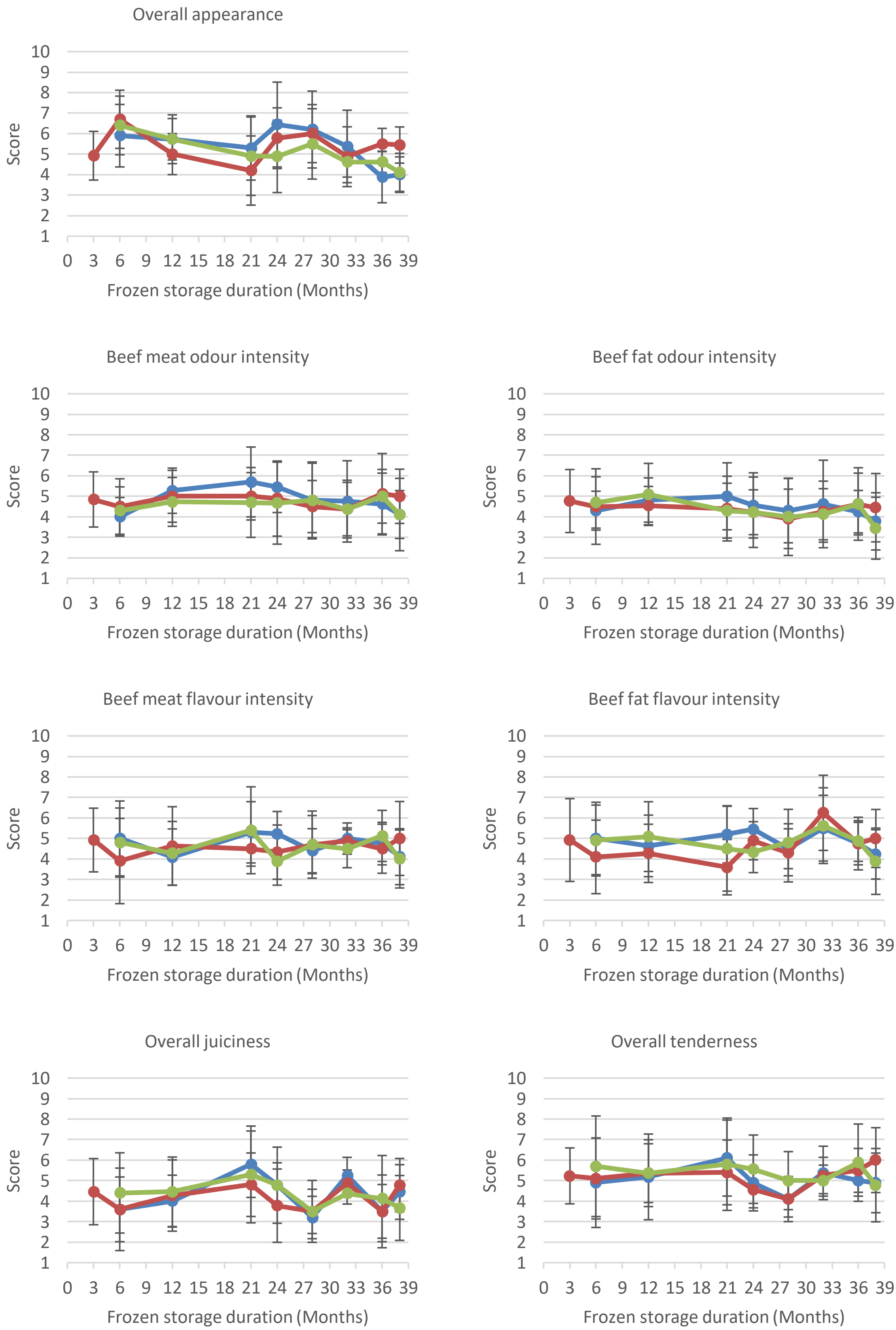

Figure 29. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of beef trim 85CL (Vertical bars: ±1SD)

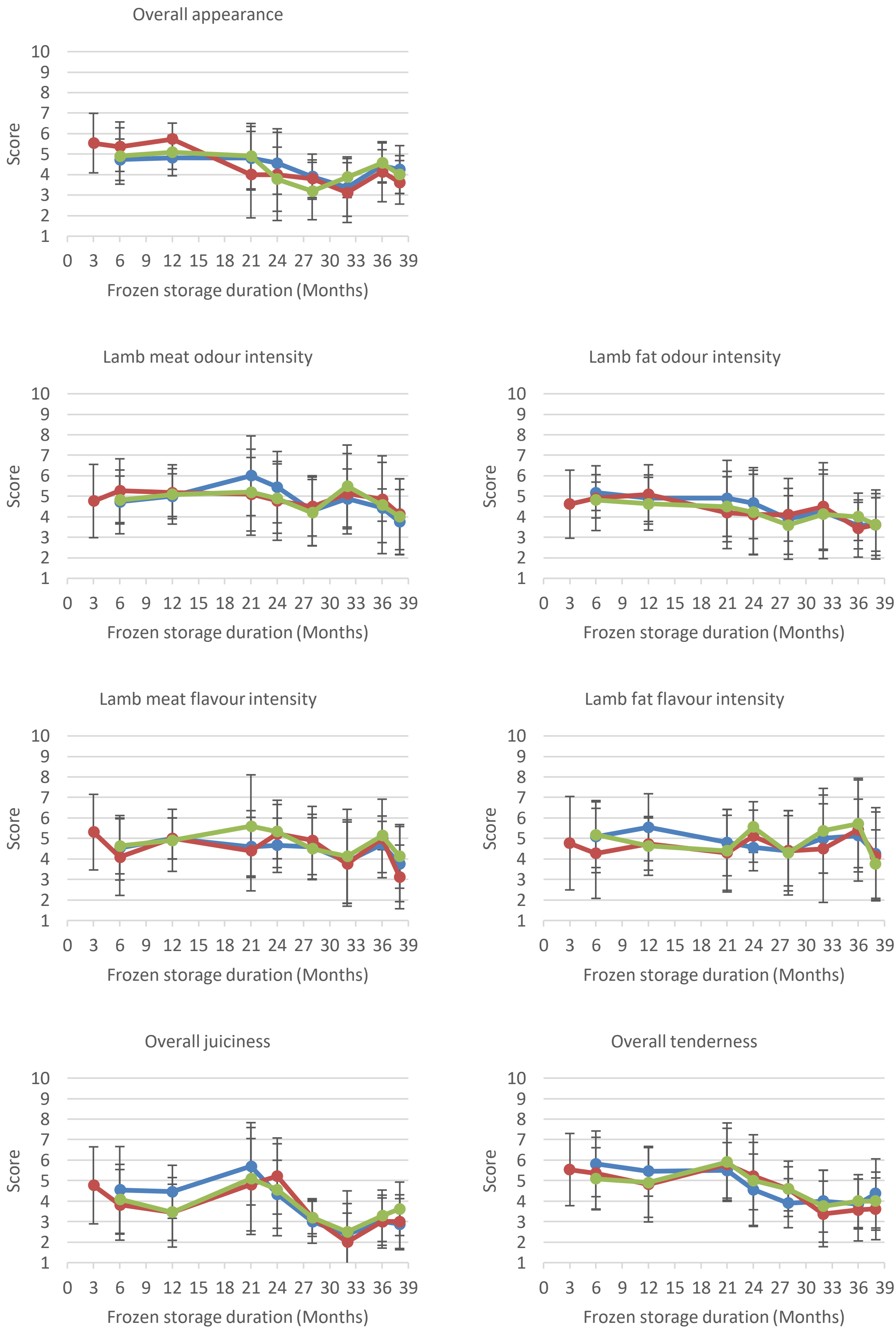

Figure 30. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of lamb trim 85CL (Vertical bars: ±1SD)

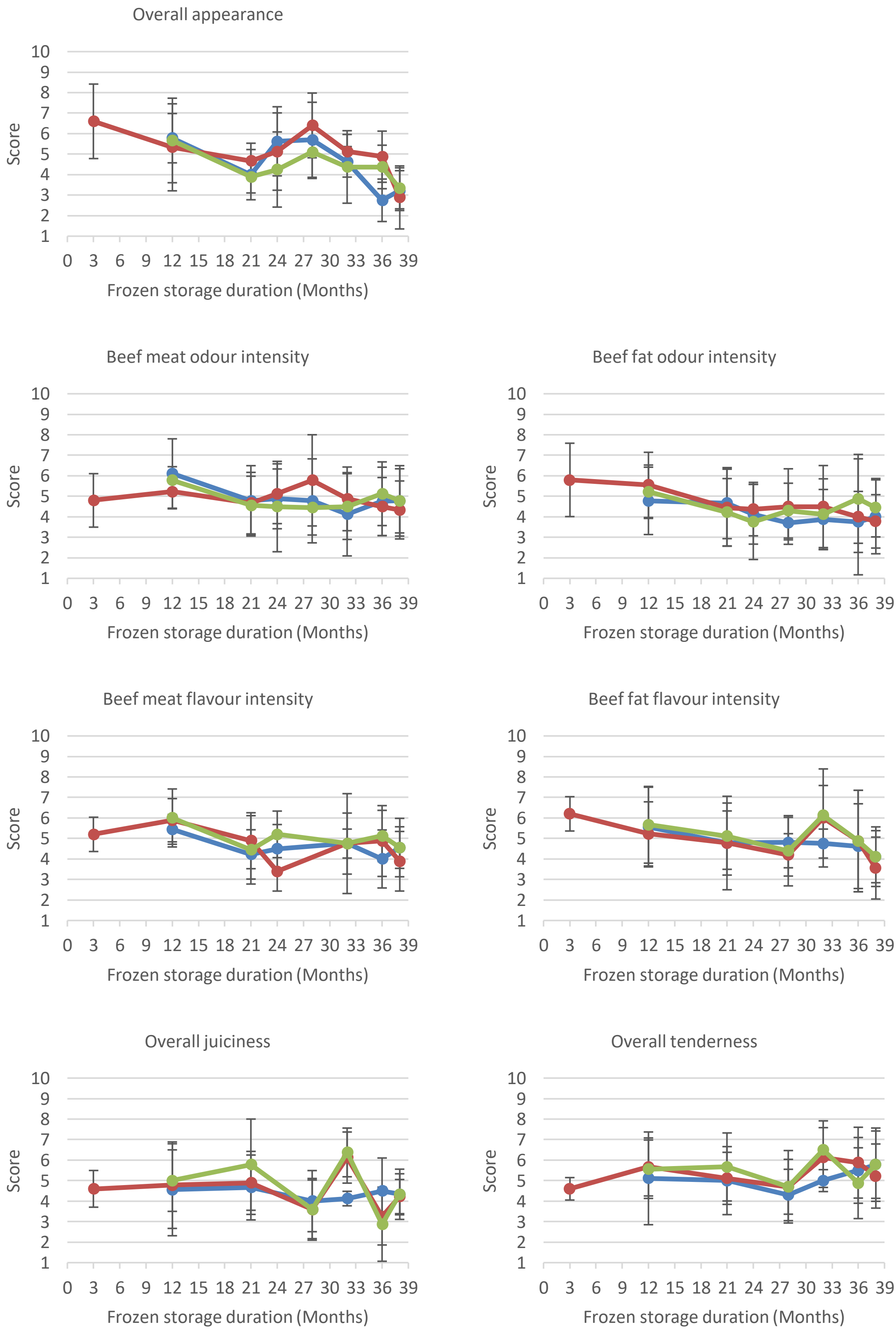

Figure 31. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of beef trim 65CL (Vertical bars: ±1SD)

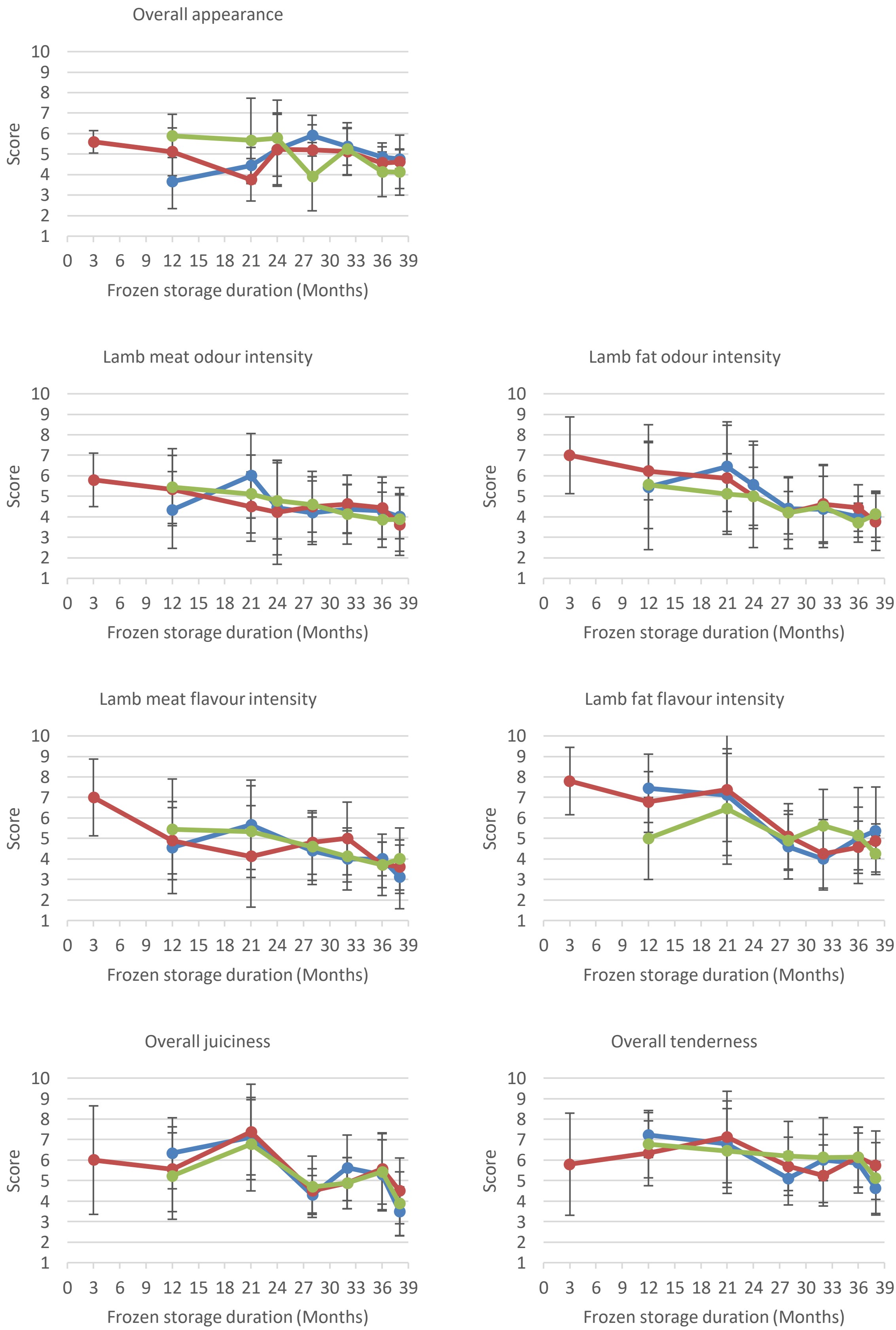

Figure 32. Effect of frozen storage duration and temperature (-12°C: blue; -18°C: red; -24°C: green) on mean sensory scores of lamb trim 90CL (Vertical bars: ±1SD)

5 Overall discussion

As noted in the initial assessment of product quality by the University of Melbourne (Ha & Warner, 2018), there was considerable variation in the trim samples in both the fat and muscle type content in different cartons of a given trim grade, and even at different locations within a carton. Variation in fat content in relation to locations within some cartons of the trims was so significant that little lean was available. Thus, as also reported by the University of Melbourne, varying the sample size/cutting position during the initial cutting of the meat trims was required to obtain a meat block that was representative of the whole carton.

As would be expected, and as highlighted by the initial assessment of product quality by the University of Melbourne, the trim cartons contained a mixture of many muscles with varying content and these muscles are known to differ in sensory attributes including colour, tenderness and water holding capacity (Klont *et al.*, 1998). The contribution of muscle types to variation in the results were significant for all of the parameters measured, especially in the trims with higher CL grades.

In this study no clear relationships/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. While some published studies have shown some of these characteristics to change with time, not all have. 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. This study used commercially produced bulk product, in standard commercial packaging which was stored in bulk in cold rooms. The sample were stored as entire loins or blocks of trim and samples for analysis and 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 many of the recent published previous studies have stored relatively small, prepared meat samples under laboratory conditions in chest freezers.

In common with the literature. The results from the initial analysis of samples on arrival, and after 6, 12, 21, 24, 28, and 32 months storage show a clear trend in lipid oxidation (rise in PV and TBARS) with storage duration and temperature, particularly in the boxed lamb trim samples. The boxed lamb trim was simply overwrapped prior to freezing. Unlike the boxed 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. Freezer burn was also observed in the overwrapped lamb trim stored at -12°C. 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. In common with the literature, the instrumental results show 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, levels were generally lower in all of the types of trim samples but did increase over time. A similar trend was observed in the beef samples, but levels were lower. Overall, the observations of this study reinforce the importance of vacuum-packaging of frozen meat and that storage temperature is important for long term storage.

There appeared to be no clear correlation between the rise in instrumentally measured PV and TBARS levels measured in the samples and sensory panel scores for the beef and lamb samples. The PV, TBARS, and GC-MS assessments clearly showed there to have been more lipid oxidation over time in the samples stored at -12°C than those stored at -18°C and -24°C, particularly in the lamb trim samples. However, this did not appear to be clearly reflected in the mean sensory scores of the samples stored at different temperatures over the same period. Though there was a decline in some mean scores in sensory characteristics with time that may be related to the lipid oxidation that was measured instrumentally, such as odour intensity, fat odour intensity, and flavour intensity. However, the same decline over storage duration was observed for samples held at all storage temperatures.

There were three overall objectives for this research project:

1. To determine the shelf-life of frozen Australian beef and lamb loin (strip loin and eye of loin, respectively), beef trim of 65CL, 85CL, and 95CL, and lamb trim of 65CL, 85CL, and 90CL (Chemical Lean).

While some sensory degradation occurred over time all samples remained palatable after 38 months storage at all temperatures. Excessive freezer burn was apparent in the boxed over-wrapped lamb trim stored at stored at -12°C, but not in vacuum-packed meat. Changes were measured in some of the physical and chemical parameters with time, and these tended to be more pronounced in samples stored at -12°C storage and in over-wrapped samples. These results show, in our opinion, that frozen Australian beef and lamb cuts and trim of the type examined can have a shelf-life of 36 months and longer, even when stored at -12°C.

2. To determine the correlation of frozen end of shelf-life (determined by taste panel) to any measurable parameters, such as oxidative rancidity (PV and TBARS).

Clear changes were found in chemical measures of lipid oxidation (PV and TBARS) that can be related to meat composition, packaging, and storage temperature and duration. These changes are associated with the development of adverse flavours and odours in meat. However, these changes did not appear to correlate clearly with the taste panel results in this study. Whereas the PV and TBARS levels showed a clear relationship with storage temperature over time, this did not appear to be reflected as clearly in the mean taste panel results. The sensory assessment showed a gradual degradation in some sensory characteristics of storage duration, but this did not appear to be influenced by storage temperature. This is not unexpected since the TBARS levels measured in the samples in this study do not appear to have reached a threshold value that other researchers consider detectable by taste panels.

3. To determine the rate of oxidation or development of rancidity in frozen Australian beef and lamb meat stored at -12°C, -18°C (Control), and -24°C.

In common with other published studies, the results of this study showed that PV and TBARS levels rise in the frozen meat over time, particularly in the overwrapped boxed lamb trims, and at warmer storage temperatures, such as -12°C. These results show a clear relationship between fat content, storage temperature and time, and form of packaging, and lipid oxidation. Overall, the results of this study, clearly show the importance of vacuum-packaging of frozen meat and that low storage temperature is important if the meat is intended to be stored for a long time, i.e., the lower the better. However, if meat of the type examined is to be stored for less than 24 months, storage temperature would appear to be less important.

Overall, from the results of this study, we can observe that as an 'objective' instrumental measurement TBARS and PV levels are useful indicators of the onset and development of lipid rancidity in frozen beef and lamb and a subsequent potential loss of 'quality' and show the effect of different storage temperatures and packaging.

This study, along with previous studies on lamb (Coombs *et al.*, 2017b, 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 could be used for the distribution and storage of frozen meat of the type examined without having a significant impact on quality or safety.

6 Conclusions

Commercially produced Australian frozen beef and lamb samples were stored at -12°C, -18°C, and -24°C and instrumental, chemical, microbiological, and sensorial analyses conducted over a 38 calendar month period. Clear changes over time were found in chemical measures of rancidity 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 appear to correlate clearly with any of the taste panel results in this study. Whereas the PV, TBARS, and GC-MS results show a clear relationship with storage temperature over time, this does not appear clearly reflected in the mean taste panel results, which showed a general change in some sensory characteristics over time 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 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. Based on the general lack of undesirable scores shown in the sensory analysis, this supports other published evidence that the frozen storage of beef and lamb could potentially be extended to 2 years or greater.

It would be beneficial if future studies investigated how such meat may be subsequently utilised and consumed by different markets (such as processing, food service, and retail) and its suitability and acceptability for such markets.

7 Recommendations

7.1.1 Storage temperature

While -18°C has become the standard temperature for the storage of most frozen foods, red meat of the type examined appears to be able to be stored successfully for many months or years at a temperature warmer than this threshold. Providing the meat is of sufficient hygienic quality when frozen and handled under controlled hygienic conditions, no food safety hazards exist with 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.

7.1.2 Shelf life at -18°C

This study demonstrated that if held at, or around, -18°C, frozen beef and lamb of the type examined can be stored without significant sensory degradation for a period of over 36 months. Providing the meat is of sufficient hygienic quality when frozen, no food safety hazards arise from long term storage of meat at this temperature. Mandated shorter frozen shelf-life requirements (such as 12 months) should be reviewed to reflect this evidence.

7.1.3 Packaging for frozen

For long frozen shelf-life, vacuumed-packaging is recommended to reduce lipid oxidation and the risk of freezer burn during storage, especially if product is stored at warmer temperatures than -18°C, such as -12°C.

If over-wrap is used for boxed trim, it is recommended to ensure all exposed surfaces are covered and not exposed within the carton. For long frozen shelf-life of such meat a storage temperature of -18°C is appropriate to avoid the risk of freezer burn during storage.

8 Key messages

This study has shown that frozen beef and lamb loin and trim of the type examined can potentially be stored for up to 36 months and longer at -12°C, -18°C, or -24°C.

A -12°C storage temperature is sufficient to prevent the growth of bacteria and that any temperature rise or fluctuation during the regular defrosts at this temperature (as is standard practice) has no impact on microbial quality or safety over the 36 months of storage.

No clear relationships/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.

No clear correlation between the rise in instrumentally measured PV and TBARS levels in the samples and sensory panel scores was observed for the beef and lamb samples examined.

The PV, TBARS, and GC-MS assessments showed increased lipid oxidation over time in the samples stored at -12°C compared to -18°C and -24°C, particularly in the over-wrapped lamb trim samples. However, this did not appear to be clearly reflected in the mean sensory scores of the samples stored at different temperatures over the same period.

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