The prevalence of high *rigor mortis* temperature beef carcasses at abattoirs across South Africa

By

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Declaration

I, **Nthabiseng Inocentia Masemola** hereby declare that this thesis, submitted for the MSc (Agric) Animal Science: Physiology and Product Quality (Meat Science) degree at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at any other University.

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The book of Numbers 23 verse 19 says: God is not like men, who lie, He is not a human who changes his mind. Whatever he promises, he fulfils, He speaks, and it is done. This scripture kept me going despite the challenges and I am grateful to God for this blessing and gift.

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Abstract

High *rigor mortis* temperature carcass conditions occur when the pH drops below 6.0 while the temperature is still above 35˚C. The aim of this research was to find out if there is an increase in the prevalence of high *rigor mortis* temperature carcasses in abattoirs across South Africa (SA). With the increase in the production of larger and heavier carcasses in the SA beef industry, it is essential to investigate the factors that might contribute to the increased occurrence of carcass conditions that might affect the supply of beef of consistent quality to consumers. A total of 12 abattoirs, across most of the 9 provinces of SA, were visited. The pH and temperature readings (at 1 hour and 2 hours *post mortem*) were taken on a total of 180 carcasses (90 per day) over a period of 2 days per abattoir. The beef carcasses were from both grain fed and grass-fed cattle, with additional data collected being whether the abattoir makes use of electrical stimulation (ES) or not, the cold and warm carcass weight, the age, and the fat code and the use of beta-agonists. The temperature at pH6 was measured to check for the proportion of carcasses with high *rigor mortis* temperature conditions. The frequency of occurrence of high *rigor* temperature carcasses across the 12 abattoirs was 65.64 %, with most of these carcasses falling under the weight category of 200-300 kg (40.09%). Carcass weight had an effect on the occurrence of *rigor* at a high temperature ($p < 0.001$) with an increase in carcass weight leading to an increase in the occurrence. The carcasses that went into *rigor mortis* at a high temperature, had an average weight of 283kg, while those at risk of going into *rigor* at high temperature had an average weight of 251kg. The group that did not go into *rigor* at high *mortis* temperature, had an average weight of 242kg. In general, it can therefore be said that carcasses that have a weight of over 250kg, are likely to go into *rigor mortis* at high temperatures. There was a significant effect of age and fat code on the incidence of high *rigor* ($p<0.001$ for both). The incidence of occurrence of high *rigor* temperature increased with an increase in fat code and increase in age. It must be noted however that the majority of the carcasses were fat code 2 and A age carcasses (the data was therefore skewed), which is what the majority of the SA abattoirs produce in terms of their carcasses. The use of beta-agonists (leading to an increase in carcass weight) and the use of ES on heavier carcasses, contribute towards the occurrence of high *rigor* temperature. Most abattoirs if not all in SA, make use of ES, hence it will be a requirement to manage the duration and timing of the ES correctly. The chiller rooms will also need to be re-adjusted and updated to accommodate the heavier carcasses produced in today's market so that adequate chilling of the carcasses occurs.

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List of Abbreviations

a	Meat redness
ADP	Adenosine di-phosphate
ADG	Average daily gain
ANOVA	Analysis of variance
ATP	Adenosine Triphosphate
B	Meat Yellowness
Beta-agonist	Beta-adrenergic agonist
˚C	Degrees Celsius
Ca^2	Calcium ions
CP	Creatine Phosphate
CW	Carcass weight
DL	Drip loss
DFD	Dark Firm Dry meat
ES	Electrical Stimulation
GDP	Gross domestic products
GLM	Generalized Linear Model
g	Gram
G-6-P	Glucose-6-phosphate
H	Hydrogen ions
h pm	Hour *post mortem*
HTLP	High temperature low pH
HVES	High Voltage electrical stimulation
Hz	Hertz
Kg	Kilograms
KJ	Kilojoule
L	Meat lightness
LL	*Longissimus dorsi et lumborum*
LVES	Low voltage electrical stimulation

MANOVA	Multiple analysis of variance
MbO_2	Oxymyoglobin
Mg^2	Magnesium ions
MSA	Meat Australia
mRNA	Messenger Ribonucleic Acid
MVES	Medium voltage electrical stimulation
NES	Non electrically stimulated
P	Phosphorus
Pm	*post mortem*
PSE	Pale soft exudative meat
pHu	Ultimate pH (pH 24 hours pm)
SA	South Africa
SD	Standard deviation
SF	Shear force
Sf	Subcutaneous fat
SL	Sarcomere length
SM	*semimembranosus* muscle
USA	United States of America
V	Voltage
WHC	Water holding capacity
µmol	Micro-molar
Zilmax	Zilpaterol Hydrochloride

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Chapter 1

1.1. Introduction

The trends in the weight of beef carcasses has changed since the deregulations in the '90s (Strydom *et al.*, 2015), from lighter to heavier carcass production. Many producers in South Africa (SA) have adopted this trend, as heavier carcasses are favoured by slaughter-house pricing (Agbeniga & Webb, 2018). The improvement in the beef industry in terms of nutrition, health, and genetics, have contributed to the increase in this trend. The Red Meat Abattoirs Association (RMAA) indicated that the market prefers beef that is lean and tender(from A2 carcasses (Vermeulen & Pretorius, 2015). The price and appearance (colour, presentation and fatness) plays an influential role when it comes to the consumer's willingness to pay for a specific cut of beef to mention a few(Strydom *et al.*, 2019; Liu *et al.*, 2022).

The changes since the deregulation (the removal of state regulations and restrictions on the beef industry), have occurred in abattoirs, with regards to how they operate. Meat safety inspection is now privatised, with the abattoir hygiene act (1992) being replaced by the Meat Safety Act (No. 40 of 2000). This Act ensures that the safety and hygiene of meat in both local and international markets are met (Coetzer, 2016a). Abattoirs play a very important role in the conversion of live animals into meat for human consumption. Most of the abattoirs that slaughter more than 100 head of cattle on a daily basis, have a link with commercial feedlots. Feedlots produce the bulk of the beef consumed in SA, that amounts to approximately 80% of the total beef consumed (DAFF, 2018). The majority of larger feedlots are located near big cities with well-established infrastructure and easy access to operating resources.

1.2. Beef production and feedlot practices

The feed from feedlots consists mainly of high energy diets, containing grain and grain by-products. South Africa (SA) is faced with a challenge of fluctuating grain prices such as maize, that pushes farmers towards the feeding of their cattle to a higher liveweight as a compensation route for the higher prices of grains (Agbeniga & Webb, 2018).

The plane of nutrition plays a significant role in the type of carcass produced, in terms of size and quality. The feed that cattle consumes has the ability to modify the quality of beef, due to the variability in the amount of energy each feed type can offer to the body of the cattle (Muir *et al.*, 2010). Grain-based diets (corn, barley, wheat etc.), have higher energy compared to grass or forage-based diets (pasture, hay, or silage). This therefore implies that cattle fed higher energy- based diets are much heavier than grass-fed cattle (Jacob *et al.*, 2014b).

The pH and proteolytic enzyme activity *post mortem* (pm) are influenced by the plane of nutrition(Thomson *et al.*, 2008; Bhat *et al.*, 2018a). Cattle that are grain-fed experience an accelerated rate of protein synthesis compared to grass fed cattle. This subsequently results in these cattle reaching maturity faster due to their elevated potential for a faster growth rate (Muir *et al.*, 2010), hence more economic benefit for producers.

The use of growth enhancers(exogenous growth enhancing molecules) is mostly used in feedlots, consequently contributing towards the accelerated muscle growth in these cattle.

There has been a noticeable increase in the use of growth enhancers popularly known as beta-adrenergic agonist (beta-agonists), since the official approval in 1997 (Strydom & Smith, 2010). One of the beta-agonists that was approved for use in SA is Zilpaterol hydrochloride (Zilmax). The latter channels nutrients to increase the growth rate more towards the production of muscle, and less towards fat accumulation (Jacob *et al.*, 2014b). This consequently results in a more efficient animal, with a higher average daily gain (ADG), hence an increase in the dressing percentage.

Farmers get higher profitability from the higher live weight of cattle, the age and the fat class, as this is the determinant of abattoir prices. The majority of feedlots in SA use growth enhancers to increase the production of beef with a reduced number of cattle heads, through an increased production efficiency. This therefore implies that less land, water, and energy is utilized in this regard, leading to a reduction in the negative impact on the environment through reduced carbon footprint contribution (Terry *et al.*, 2020; Ismail & Al-Ansari, 2023). The cattle are ready to go into the feedlot by at least seven months of age. They then reach slaughter weight at roughly 12 months of age, meaning that they are sold to abattoirs before fat starts to accumulate, therefore their maximum yield would have been reached by then (Agbeniga & Webb, 2018).

Fat accumulation is metabolically expensive as cattle requires a lot more energy for the deposition to occur. This implies that the animal needs to eat more to generate that large amount of energy, therefore costing the producers more money from the purchasing of more feed. Too much fat on a carcass is discriminated against due to reasons that, it weighs less than muscle and the classification system rates lower fat code carcasses as the most desired carcasses in SA. This consequently results in abattoirs trimming off the fat, and therefore the producers getting less profit from their carcass sales. Fat is also associated with fewer health benefits, while others prefer the fat for juiciness and more flavour enhancements (Webb & Erasmus, 2013; Erasmus & Hoffman, 2017).

Improved management practices in terms of nutrition and health plays a significant role in the increased production of heavier carcasses. The feed industries have highly trained formulators and inspectors who make sure that the health of the cattle is not compromised. Most of the farms have highly qualified nutritionists to ensure that the feed consumed by the cattle is safe and within the correct feed ratios required for efficient beef yields. Effective vaccination programmes are implemented and easily accessible to producers, hence better control of diseases within and between herds.

Seed stock producers play an important role of continuous genetic improvement and careful selection of favourable quality traits, such as increase in ADG and dressing percentage. They strive towards introducing the latest and updated genetic materials into the herds that are major suppliers of cattle for bulk slaughter in SA (Molebeledi *et al.*, 2020).

Despite the controversy, that beef is more expensive than other protein sources and that its production is not environmentally friendly, the consumption of beef is increasing gradually, hence an increase in production. This owes to the fact that there is an increase in the proportion of consumers that are able to afford specific cuts of beef (Webb & Erasmus, 2013). The latter is more beneficial because the human population is expected to be double the amount by 2030 (Wicks *et al.*, 2019), so there will be a higher demand than there is at the moment.

The production of heavier carcasses means that there is a higher lean mass, hence more beef produced. Increase in the amount of beef produced means that the farmers get more profit, meaning the business runs and continues to operate at a consistent rate. This implies that more people will be employed while most retain their jobs, and therefore able to alleviate the level of poverty in the country.

1.3. Slaughter and carcass management practices

The production of heavier carcasses in SA has come with its own share of challenges. Careful selection of more efficiently producing cattle, has resulted in the increased susceptibility to stress due to the increased temperament in the cattle, hence making it difficult to control and prevent fighting within the herd(Poveda-Arteaga *et al.*, 2023). This consequently results in the development of meat defects, such as Dark Firm and Dry meat (DFD) and Pale Soft Exudative meat (PSE). The latter in turn affects the quality of beef (Adzitey & Nurul, 2011), with regards to its tenderness, water holding capacity (WHC), ageing ability and therefore its shelf life.

The chiller rooms in the abattoirs countrywide, that were previously designed to accommodate lighter carcasses, are used for the chilling of these heavier carcasses that are currently being produced in larger numbers (Jacob & Hopkins, 2014a; Agbeniga & Webb, 2018). The heavier carcasses take longer to cool because they are closely packed, and therefore interfering with the flow of air between the carcasses. The heavier carcasses pose a challenge to the packing and processing plant that were previously designed with normal cuts from small carcasses in mind. The distribution boxes are now heavier than they were before, hence it is becoming more labour intensive (Bruns *et al.*, 2017)

After slaughter, the pH drops from 7.5 to 6.0 within the first hours, and subsequently the temperature also drops to below 35˚C. This is the point where the onset of *rigor mortis* occurs under normal circumstances, for the conversion of muscle to meat to occur (Greaser, 1986). The drop in pH is caused by the depletion of energy sources required for the synthesis of Adenosine Tri-phosphate (ATP) (Paredi *et al.*, 2012). The process of glycolysis then continues anaerobically to create more hydrogen ions (H^+) in the muscles (Thompson *et al.*, 2006). The latter accumulates in the muscles and creates a more acidic environment due to the depletion of ATP, that causes pH to drop (Pearson, 2012) causing the actomyosin bond to be formed and the muscles to be more inextensible.

When the temperature of the carcasses remain higher than 35˚C whilst the pH drops rapidly below 6.0 (Warner *et al.*, 2014a), this condition is known as high *rigor* temperature carcass conditions. High *rigor* temperature carcasses have an accelerated glycolytic process, which results in the accelerated drop in pH on an abnormal rate within the first hour after slaughter (Pighin *et al.*, 2014). This condition is one of the contributing factors towards the increased variation in the quality of beef, in terms of tenderness and appearance (Strydom *et al.*, 2015). Other factors contributing to high *rigor* temperature conditions include slow chilling rate or a combination of the latter.

Most of the abattoirs in SA make use of Low Voltage ES (LVES) to improve the tenderness of beef (Frylinck *et al.*, 2015). Electrical stimulation (ES) is a technique that uses electrical energy to accelerate the *post mortem* changes, through the accelerated drop in pH of muscle to convert it into meat (Żywica *et al.*, 2018). The latter prevents cold shortening, and over or under stimulation that can lead to heat or cold shortening. The optimum temperature and pH regarded as normal for the conversion of muscle to meat ranges between 15°C and 30°C, and pH 6.0 respectively (Pighin *et al.*, 2014).

The use of ES on heavier carcasses has become a global challenge, even in countries such as SA. When these overstimulated and heavier carcasses are chilled in the chiller rooms, that were previously designed with specifications for small carcasses, the pH rapidly continues to drop lower than 6.0 while the temperature is still above 35°C. The temperature remains higher as it drops slower than with smaller carcasses, due to the cooling rate of the chiller rooms.

The consistent quality of carcasses is dependent on how effective the cooling air from the chillers is in the removal of heat from the surface of the carcass. The heavier carcasses create a smaller surface area for the dissipation of heat compared to its weight ratio (Jacob *et al.*, 2014b). The overpacking of these heavier carcasses, is the reason for the cooling rate and air flow not being very effective in chilling the carcasses. The later results in carcasses being removed from the chilling rooms while the temperature has not dropped sufficiently to maintain a consistent quality of beef from these carcasses. Feedlotting (intensive growing of livestock over a short period time) increases the risks of high *rigor* temperature occurrences as discovered by Jacob *et al*. (2014), because of the high energy diets which increase the core body temperature and therefore increasing the temperature of the carcasses.

The prevalence of high *rigor* temperature in abattoirs across Australia, was discovered to be around 72 % (Warner *et al.*, 2014a). It was further discovered that the abattoirs that had higher prevalence, had a higher proportion of grain-fed cattle. The prevalence of high *rigor* in abattoirs across SA must be frequent because SA as a Southern African Country, it has similar conditions as those of beef production in Australia. It is therefore important to conduct this study to verify if the occurrence is as high as predicted, given the changes in the production to heavier carcass yields in SA.

The major objective of this research was to investigate whether the prevalence of high *rigor* temperature carcasses in abattoirs across SA is frequent or not. This is due to changes that have been observed throughout the past years of increasing the production of heavier carcasses. Major abattoirs that supply the bulk of the beef consumed in the country will be closely assessed. The pH and temperature readings of carcasses from these major abattoirs across all 8 provinces will be recorded to make a conclusion. The major abattoirs were selected on the basis that they supply to major retail stores and major processors in the country and exports to other countries such as Mozambique.

Chapter 2

Literature Review

2.1. Layout of the beef industry

Livestock farming forms part of the agricultural sector, which is of high significance in South Africa (SA). Approximately 70% of the agricultural land available is used for livestock (DAFF, 2018). The beef industry contributes to the overall supply of protein source, and also contribute towards the overall meat value chain, as the second fastest growing commodity in the agricultural sector after the broiler sector (DAFF, 2019a).

The beef industry is divided into the formal (commercial) and informal sector. The informal sector is further sectioned into the small-scale subsistence producers and emerging producers. The similarities between the two is that they produce beef on a small scale, and they seldom reach and meet the standards of the beef commercial sector. Subsistence producers mainly keep their cattle for reasons such as maintaining a social status, for consumption and for performing different religious and cultural rituals. They therefore contribute very little towards the gross value of the beef industry as a whole. The emerging producers on the other note, keep their cattle and generate income from sales through the formal and informal markets (Kalaba *et al.*, 2018). This subsector of the informal sector usually has poor herd management and no accurate measurement of calving rates, and therefore seldom reach the entry level for the formal meat value chain. Other factors that contribute to this are the lack of proper infrastructure, information, health management and a well operating recording system(Soji *et al.*, 2015; Jaja *et al.*, 2020).

The total number of cattle in SA is approximately 13.6 million, with beef cattle contributing approximately 80% of the total number of cattle in South Africa, while 20% of the remaining is dairy cattle and only 60% of the beef cattle originating from the formal sector (DAFF, 2018). Even though there is a smaller proportion of cattle in the informal sector, this sector has a very high production potential. Merging the gap between these two sectors will improve the production of beef in South Africa. This owes to the motivation that states that the beef industry structure is commercially well anchored, with farming units that range between a few hectares consisting of small numbers to large farms with thousands of cattle producing to an optimal level (Spies, 2016). Table 1 below shows an outlay of the livestock statistics across all the provinces in SA. Overall , Eastern Cape was responsible for the highest proportion of cattle in the year 2018/ 2019. Gauteng on the other hand , had the lowest number of cattle in the same period. Even though the number of cattle across all nine provinces vary tremendously, beef production still occurred in all provinces. The amount of beef produced does not however, depend on the number of cattle available in the area, but by the infrastructures available. These includes abattoirs, feedlots and transport infrastructure that enable easy movement of cattle from one area to the next. This scenario is indicated by table 2.1 below, where Eastern Cape accounts for only 7% of the beef cattle slaughtered during 2018/2019, while Gauteng slaughtered 17% of the beef produced in the same year.

Table 2.1: The number of cattle across all nine provinces in the year 2018/2019 in millions (AMT, 2017).

PROVINCE	CATTLE	
	Aug-18	**Nov-18**
Western Cape	507	504
Northern Cape	442	437
Free State	2178	2150
Eastern Cape	3145	3133
KwaZulu-Natal	2481	2453
Mpumalanga	1279	1265
Limpopo	936	932
Gauteng	246	246
North West	1574	1564
TOTAL	**12788**	**12684**

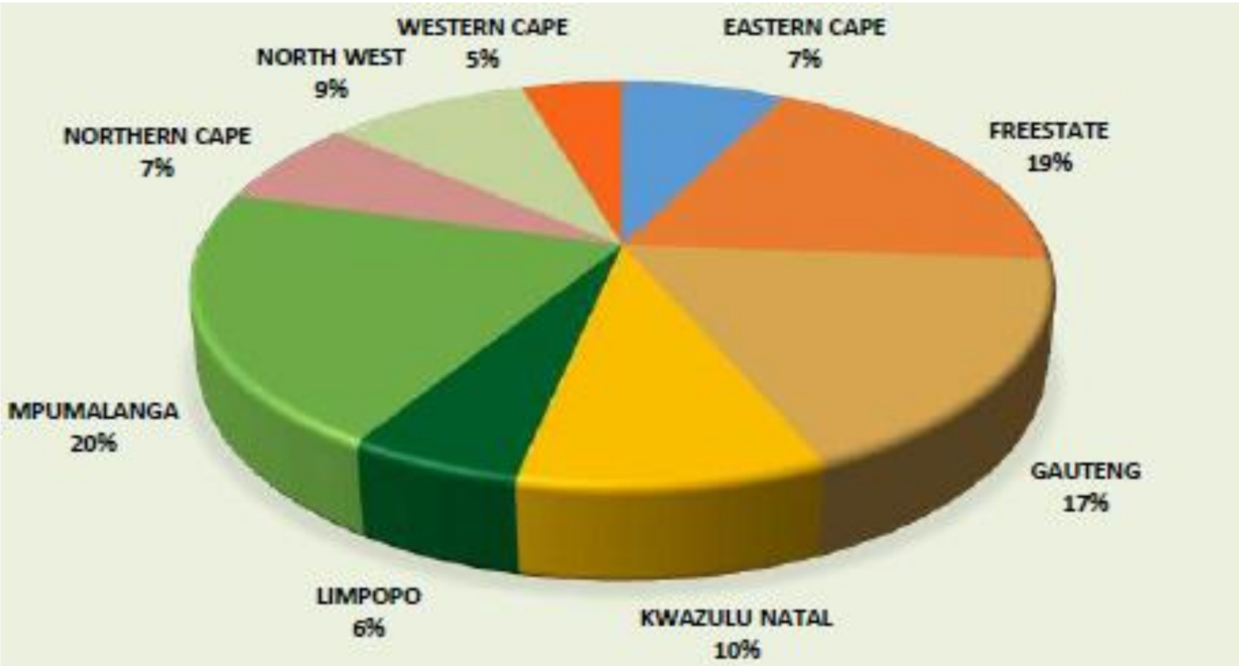

Figure 2.1.: Beef slaughtering per province in percentages (DAFF, 2019a)

Mpumalanga, Gauteng and Free State were the lead producers of beef in the country in the years 2017/2018 (AMT, 2017). Figure 2.1 above indicates that Mpumalanga still produced the highest amount of beef in the year 2019/2020 followed by Free State and Gauteng, respectively.
The red meat value chain in SA as indicated by the flow diagram in figure 2.2, comprises of many divisions namely, traders, producers (feedlots and grazing), abattoirs, wholesalers and retailers (Kalaba *et al.*, 2018).

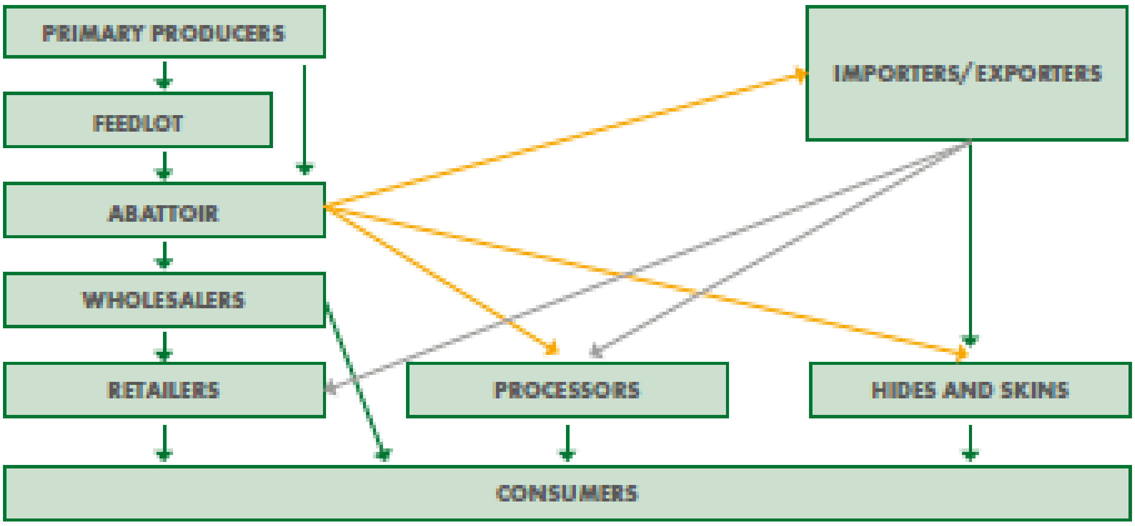

Figure 1.2.: The red meat industry value chain (AgriSETA, 2021)

The beef industry has undergone many changes in all parts of the value chain since the deregulation in the 90s (Strydom *et al.*, 2015). These changes also took place in abattoirs, with regards to how they operated and their policies. The agricultural marketing act (1968), which stated that producers were allowed to market their livestock in one of the metropolitan areas around Abakor abattoirs was later revised. This was after Abakor lost all its legal metropolitan status, and was no longer under the control of the state (Spies, 2016). These changes resulted in the emergence of small abattoir operations and meat safety inspections being privatized. The abattoir hygiene act (1992) was replaced by the Meat Safety Act (No. 40 of 2000), which ensures that the safety and hygiene of meat in both domestic and international markets are met and the standards are adhered to (Coetzer, 2016b).

Abattoirs form a very important part of the meat value chain, as their main role is to convert live animals from producers into meat. The total number of abattoirs responsible for slaughtering cattle, pigs, and sheep in SA, was approximately 495 in the years 2017/2018. The Agri SETA (2021) has reported that the red meat subsector industry comprises of approximately 420 abattoirs in 2019/2020. The decline has occurred due to the current changes in the economy due to factors such as the COVID-19 outbreak. The distribution of the abattoirs across all the nine provinces in SA, is indicated in Table 2.2 below.

Table2.2.: The number of red meat abattoirs per province across SA (From Agri SETA, 2021)

Province	Total abattoirs per Province
Gauteng	40
Limpopo	34
North West	35
Free State	80
KZN	50
Eastern Cape	67
Western Cape	46
Mpumalanga	33
Northern Cape	38

Free State has the highest number of abattoirs. This is due to the easy access to the market and the fact that it has the second highest number of cattle in the country.

Red Meat Abattoirs are divided into 5 classes, which ranges from A to E, depending on the number of cattle slaughtered daily (Soji *et al.*, 2015). The classes that slaughter more than 100 head of cattle per day are classed into the category of A and B, and usually have a link with the commercial feedlots. The feedlots across all nine provinces in SA, account for approximately 80% of the total amount of beef consumed on an annual basis (DAFF, 2018).The feedlots in SA have distinguishable sizes, which range from small to over 100 000 animals per herd. The majority of these larger feedlots are located closer to the big cities, which have well established infrastructure and advanced access to operating resources. Farmer feeders, seasonal feeders and commercial feeders collectively fall under the categories of feedlots in SA (Spies, 2016).
There are a number of economic and non-economic factors that impact the profitability of feedlots. The economic factors are those that the feedlots do not have control over such as, the prices of maize. Other non-economic factors include average daily gain (ADG) and efficiency which largely depends on the weight of the cattle. The weight is influenced by factors such as the genetic performance, nutritional background and the overall health status of the cattle breed (Spies, 2016; Webb *et al.*, 2019). Feedlots are important due to their predominant weaner production system. Most of the commercial feedlots have shifted towards vertically integrated systems consisting of a backgrounding unit. The latter system means that the weaner calves are being introduced to the

feedlot diets gradually before they are fattened. These weaner calves are introduced into the feedlot where they are fattened at 7 months of age and remain there for a period of 120-150 days, which is approximately 4-5 full months. They are thereafter ready to be marketed or sold to abattoirs as cattle that will yield a live weight of 380 – 400kg depending on the breed type and maturing types. The feedlots will usually employ agents to help with the purchasing of their product, depending on the criteria set by individual feedlots such as weights. Management practices namely, herd, pasture, nutritional and health management as well as breed selection is of high importance in the success of the feedlot and industry as a whole (Kalaba *et al.*, 2018). The changes in the carcass weight trends have emerged noticeably throughout the past decades. Producers have shifted more towards the production of heavier and leaner carcasses (Lawrie, 1985; Jacob *et al.*, 2014b). There has been an increase in the vertical integration, which has led to more intensified feeding systems that consists mainly of grains and grain by-products (Muir *et al.*, 2010). The genetic selection mainly focuses on the increased ADG and dressing percentage, with less fat accumulation. Abattoirs which had equipment and chiller rooms that were designed for lighter carcasses are now faced with a growing challenge of having to keep up with the drastic changes in carcass weights. These aforementioned changes have resulted in an increase in the inconsistency of the quality of beef, as stated by Strydom *et al*. (2015).

The other challenge that has emerged, is the occurrence of high *rigor* temperature carcasses in abattoirs locally and internationally. Australia is one of the countries that has conducted a study to identify whether the high *rigor* temperature conditions are a common problem in most of the abattoirs supplying the bulk of their beef (Warner *et al.*, 2014a). Warner *et al*. (2014) found that increasing days in the feedlot and heavier carcass weights, were highly correlated and are both the reason behind the occurrence of High Temperatures Low pH (HTLP) as indicated by Table 2.3.

Table 2.3: Effect of increasing days of feeding grain on the occurrence of high *rigor mortis* temperatures (From Warner *et al*., 2014a)

Days of grain feeding						
	0	**60-70**	**700-110**	**141-190**	**200-250**	**270-350**
Number	409	211	222	224	84	162
Temp@pH6 (˚C)	32.7±0.02	34.4±0.02	36.9±0.01	37.2±0.01	37.7±0.04	38.4±0.01
% High *rigor* temperature	51.8	46.0	83.8	81.3	82.0	95.0

SA on the other hand has not done much research on the occurrence of high *rigor* temperature in abattoirs across the country, unlike other countries with similar conditions and production systems. The sudden research on the occurrence of high *rigor* in SA owes to the fact that the variation in the quality and supply of beef is a rising problem that is a concern to most consumers and a threat to the profitability of producers in the beef industry. Carcass weight is the primary determinant of carcass characteristics such as dressing percentage (DP), which influences the profit of the farmer (Nour & Thonney, 1983).

This condition occurs when there is a faster pH decline due to a higher than normal glycolytic rate and the temperature is still higher than the normal temperature for the conversion of muscle to meat (Webb & Agbeniga, 2020). The carcasses are said to have high *rigor* temperature conditions when the pH is below 6.0 and the temperature is above 35˚C (Warner *et al.*, 2014a). This condition occurs more frequently in carcasses that are heavier, as they take time to cool down and the air flow between the closely packed carcasses in the cooling rooms is inhibited. Carcasses with a thick fat cover are also susceptible to high *rigor* temperature conditions. The prevalence of high *rigor mortis* temperature conditions in beef carcasses cost producers their profitability. This owes to factors such as the loss in the weight of the carcass due to a reduced water retainment from the PSE-like conditions caused by the latter.

The cattle from grain-based feeding system produce heavier carcasses that pasture-based system cattle of the same age after slaughter(Poveda-Arteaga *et al.*, 2023).The latter is caused by the high calories found in the grain based diets, which in turn reduces the degradation rate of glycogen until the animal is slaughtered. This consequently results in the heavier carcasses yielding more darker and lean muscle, due to an increased L^* ,a^*, and b^* attributes than lighter carcasses. The high caloric diets with high energy, promote the deposition of fat due to the slower glycolytic depletion, hence more lactic acid formation in the muscles. The chiller room temperatures that are higher than they are supposed to be for the optimal conversion of muscle to meat, result in the decrease in the moisture content and the pH drops slower, due to the accumulated fat . The latter negatively affects the tenderness of the meat(Zhang & Hopkins, 2018).

2.2. The consumption of beef in South Africa

The human population is expected to increase by twice the current population by 2030 (Wicks *et al.*, 2019). Thus, the production of food, meat and animal products need to increase to meet the demand of the rapidly growing population.

The amount of beef produced depends on the distance to the nearest abattoir and the number of feedlots and the number of cattle in that area(Polkinghorne *et al.*, 2018b). The total amount of beef produced for the previous ten years amounts to 9.5 million tons(DAFF, 2021).

Per capita consumption of beef in South Africa has decreased from 26kg in 1970s to 19kg in 2018 (DAFF, 2018). The production of beef between 2014 and 2016, however exceeded the consumption. Hence making the country self-sufficient enough during that period. The A2/A3 carcasses are the most popular classes of beef in South Africa. The input of weaner and feed prices affect the output yield of these popular carcasses, consequently influencing profitability of the industry. The farm to retail price spreads of A2/A3 class beef increased by 12.49% from November 2018 to January 2019 and reached R42.20/kg in January 2019 (SA feedlots, 2019). Due to the changes in climate that led to drought, the number of cattle slaughtered decreased in 2018. The estimated number of head of cattle slaughtered in July 2018, was 212060, which is 0.6% less cattle slaughtered compared to the same time years ago (Agri Trends & Agribusiness, 2018). The consequences arising from this problem are, an increase in beef prices and the shift of consumers from beef to other cheaper sources of protein such as poultry and pork (Kalaba *et al.*, 2018). The current outbreak of foot and mouth disease in Limpopo , has led to a drastic decrease in the number of cattle slaughtered (DAFF, 2019b). This consequently affects the price of beef, hence the loss of producers' profitability. Protein availability from is projected to increase by 5.9% by 2030(OECD-FAO, 2021). The greatest increase in consumption is seen in developing countries such as SA. The amount of consumption is still expected to increase during the next decade and double by 2050 (Kalaba *et al.*, 2018).This owes to the increase in the number of people in the middle-class income bracket, which gives them a more flexible preference when it comes to meat based on their affordability (Webb & Erasmus, 2013). Beef production is expected to increase by 60% in order to meet the increasing demands.

The balance between the amount of beef exported and imported, with less amounts of exports is questioned. This is due to reasons that the increase in the demand for beef exceeds the supply in SA, and this has resulted in an increase in the net import (DAFF, 2012). The latter thus made SA a net importer, as a result of attempting to compensate for the deficit. This puts pressure on the economy as a whole because the beef industry does not only have to compete on a local level with other protein sources, but also on a global level. SA exports close to 150 000 kg of beef per annum to countries such as Mozambique, which receives approximately 73% of the total beef exported.

The formal and informal sectors are accountable for up to 85% of the beef supply in SA, with15% of the supply being from imports (DAFF, 2018). Figure 2.3 indicates the imports and exports in SA from 2016 to 2019 (Mare, 2020). The latter indicates that amount of beef exported outweighs the amounts imported. The beef quantities include chilled, frozen, whole and half carcasses, bone in and deboned cuts. SA has imported 1257 tons of beef and exported 2620 tons on average monthly (AMIE-SA, 2020).

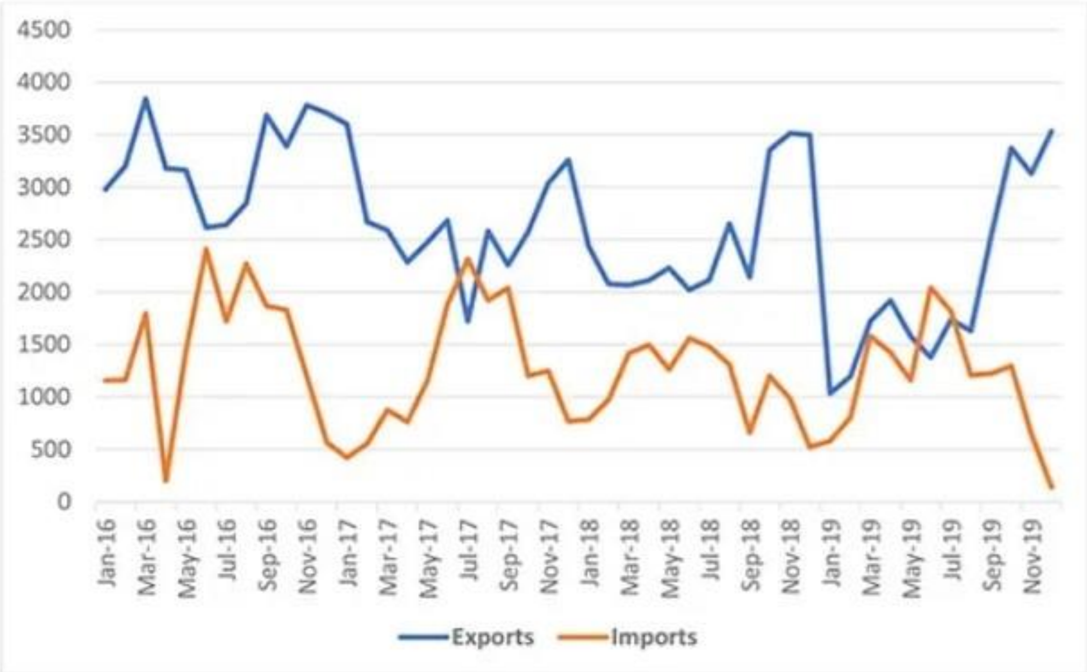

Figure 2.3.: Beef imports and exports from 2016- 2019*(from AMIE-SA, 2020)*

The supply chain of beef in SA is complicated by increased competition with other protein sources available in the market and land reform issues. The number of cattle slaughtered is the main driver of the beef supply chain in the country (Kalaba *et al.*, 2018). All the challenges that influence the functioning of the beef industry need to be studied in much more detail and understanding. This will therefore help the industry to succeed in supplying beef consistently on a regional and international level.

More emphasis has been placed on the consumer's side of the value chain. This is through the adjustment of the existing beef product quality into the form that is desired by consumers. This is aimed at satisfying the demands and preferences with regards to the factors that are economic and non-economic (Polkinghorne *et al.*, 2018a). The palatability, tenderness, traceability, and ethical factors are some of the few examples of non-economic factors that provide the producers with pointers to focus on in order to add value to their products and encourage the consumer's willingness to purchase their products and also consider repurchasing consistency. The consumer's preference and willingness to pay for a specific cut of beef serves a purpose of being a tracker for producers to rank their product's position in a specified market (Strydom *et al.*, 2019). The factors that influence the consumer's decision at the point of purchase is the colour, fat colour and drip. Price plays a huge role for most South Africans, especially in rural areas, so the preference is also based on the affordability of individuals and groups (Erasmus & Hoffman, 2017). Factors such as flavour, tenderness and juiciness determine whether the consumer will come back for the same product or not.

Many consumers are interested in the traceability of the product they are buying, which involves the management and care that is invested in making the product and whether the correct procedures were followed regarding the handling of animals from the farm/ producers to the retailers. This has made producers shift towards a more sustainable and environmentally friendly production, that takes the welfare of the animal into consideration (Sonoda *et al.*, 2017). There has been an increase in awareness and education with regards to health hazards related to meat consumption and animal products. These includes issues such as zoonotic diseases and the use of growth promoters to mention a few. In this regard, the control check and validation between farm and fork operations, has become even more strict to give consumers assurance (Soji *et al.*, 2015).

This research is essentially significant in the provision of base information regarding the problems arising with occurrence of high *rigor* that might jeopardise the consistent supply of high-quality beef and beef products. The producers will use the information internally and practically to better equip themselves with skills and techniques to help them increase their profitability and competitive level in each segment of the industry. In turn adding to the value chain, and therefore the country's economy.

The beef industry is important as it adds value to the country's revenue through its exports and trades. There are a lot of jobs that are created by every operating beef production system, from feedlots and abattoirs to retailers and wholesalers who distribute the beef and process it. The consumer's need for a supply of high-quality beef and beef products is met through the hard work and effort put in by all the contributors in the beef industry on a primary and tertiary level despite the criticism that beef production contributes to the negative environmental effect and the non-proven speculations that hormones used such as Zilmax are harmful to human health (Johnson *et al.*, 2014). The society is provided with a source of protein that is high in quality nutrients, in a form that is desirable for people to want to consume it. This is because the cattle converts the low quality proteins provided to them, through their feed into beef of high quality protein (Wickersham & Sawyer, 2016)

2.3. The conversion of muscle to meat

There is a distinguished difference between muscle and meat. Muscle is defined as a band of fibrous tissues that serve a role of locomotion and maintenance of the positioning of the different parts of the body of animals (Greaser, 1986). The animal tissue serves as an important source of food for human consumption and nourishment. The metabolic, physical, and structural alterations are critical in the process of converting muscle to meat. All the factors that influence these aspects, influences the final or end product quality.

Meat is defined as the flesh of animals that is utilized by consumers as a food source (Lawrie, 1979).It largely reflects on the chemical and structural changes occurring in muscles *post mortem*. The conversion of muscle to meat of a high eating quality involves a series of physiological and biochemical processes (Ferguson & Gerrard, 2014). The latter is fully dependant on the storage of meat at lower temperatures (Ouali *et al.*, 2006). The conversion of muscle to meat occurs in three major steps, namely pre *rigor*, *rigor*, and tenderising step.

2.3.1. Pre *rigor*

The last stage of slaughter which is bleeding, is very crucial for the development of a desirable eating quality of meat (Lawrie, 1979). The removal of as much blood as possible is a requirement to enable the process to start and to reduce the risks of microbial growth, that can cause spoilage of the meat and result in an unpleasant appearance. A normal functioning body will try as much as possible to maintain its processes of oxidative energy production optimally (Puolanne, 2004). The muscle's metabolic activity lasts for several days post slaughter, however with oxygenated blood circulation being depleted. This subsequently causes the metabolic end products that increase the Adenosine Tri-phosphate (ATP) synthesis, to form carbohydrates for the separation of the two contractile proteins, actin and myosin (Paredi *et al.*, 2012). This consequently results in the demand for ATP exceeding the aerobic metabolic capacity to supply it, hence the production occurs anaerobically. Even through the oxygen is used up in the body, the generation of ATP continues anaerobically through glycolysis to supply the energy required for muscle contraction (Ferguson & Gerrard, 2014) using the glycogen reserves available *post mortem* (Frylinck *et al.*, 2015).

The latter results in the formation and accumulation of lactic acid and consequently results in increased build-up of H^+ (Kuffi *et al.*, 2018; ZHANG *et al.*, 2018). The latter phase is called the rapid phase. Pyruvate which is the major junction point in the metabolism of carbohydrates, is reduced into lactate in the muscle cells. The accumulation of lactate in the muscles results in the acidification *post mortem* of the muscle, the latter together with a drop in temperature disturbs the optimal uptake and release of calcium from the sarcoplasmic reticulum (SR).

During the delay phase of *rigor mortis*, the muscles are still extensible because the ATP is still present but in small amounts. This then allows the binding of Mg^{2+} to the remaining ATP to form forces that will prevent the formation of the actomyosin cross bridge. The force for shortening of the sarcomere develops as a result of the cyclic interaction between the myosin head and the actin in the thin filament (Puolanne, 2004). This phase will continue until a pH is reached when the enzymes affecting the breakdown becomes inactivated and ATP is completely depleted.

2.3.2. Onset *Rigor*

Onset *rigor* occurs when the ATP in the muscle is depleted for a duration of close to 12 hours. The basic contractile unit of muscle called the sarcomere, will contract as the muscles enter *rigor post mortem* (Ertbjerg & Puolanne, 2017).

Muscles begin the process of *rigor mortis*, which is a permanent cross-bridge formed at pH values of 5.7-5.8. The creatine phosphate depleted, consequently inhibits the phosphorylation of Adenosine Diphosphate (ATP) into ATP. The inextensibility of muscles follows, due to the locking of pyruvate into the muscles.

The actomyosin bond is formed permanently when the actin binds to the myosin post the removal of blood from the carcass, following the release of calcium into the sarcomere.

The interaction of pH and temperature decline in pre *rigor* muscles has a major role in meat tenderization (Balan *et al.*, 2019). The contraction of muscle is dependent on the rate of pH and temperature decline during the conversion of muscle to meat post slaughter, owing to the variations in the cooling rate of muscles.

2.3.3. The tenderising process

This is the step that includes all the process involved in extending the lifespan of the meat during storage. This is also referred to as conditioning or ageing, which has been associated with an increase in tenderness and flavour. The process of conditioning detaches the actin filament from the Z-line with which their union, via tropomyosin is weaker than with myosin. this results in the collapsing of the actin filament onto the myosin due to the release of Ca^{2+} from the sarcoplasmic reticulum. The proteins of the myofibril and of the sarcoplasmic reticulum denature in varying degrees during *post mortem* conditioning. The breakdown of fat and protein during conditioning also contributes to the development of flavour in meat. This is through the production of hydrogen sulphide, ammonia, acetaldehyde, acetone, and diacetyl.

2.3.4. Factors influencing the conversion of muscle to meat

There are a number of factors pre and post slaughter that influence the conversion of muscle to meat. These include, the sex, the plane of nutrition, the pre-slaughter handling, and chilling rate post slaughter. The level of nutrition affects the growth of meat, through the influence it has on the composition of individual muscles. Ferguson and Gerrard (2014) stated that there is little that can be concluded about the differences in glycolytic rate between sexes, due to lack of comparative studies. There is a difference in carcass weight, fatness ,cooling rate and potentially glycolytic rate (Jacob & Hopkins, 2014b). Cattle fed high grain diets appeared to have elevated core body temperature when compared to grass-fed cattle, consequently resulting in accelerated glycolytic rate post slaughter. Improper handling of cattle pre-slaughter can result in high levels of stress, consequently reducing the glycogen concentration required for the conversion of muscle to meat, below the critical threshold of 45-55 mmol/g and therefore a rise in ultimate pH (5.3-5.7) (Ferguson & Gerrard, 2014). The latter results in the pH being elevated above the normal level above 6.0, hence the condition called Dark Firm Dry meat (DFD). This condition is characterised by a darker colour, with increased Water-holding capacity (WHC) and possibly increased toughness.

Pale Soft Exudative meat (PSE) is another condition arising from the above-mentioned factors. PSE meat on the other hand occurs when the cattle is stressed ante mortem, and results in the pH dropping faster than normal pHu as indicated in Figure 2.4 at 45 minutes after slaughter (Adzitey & Nurul, 2011).

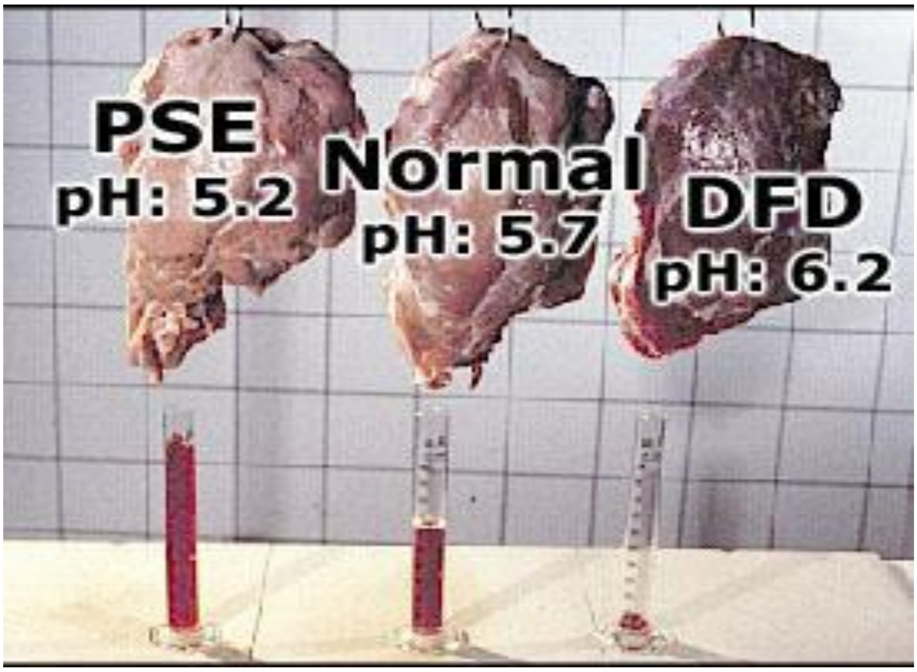

Figure 2.4.: Normal and abnormal glycolysis in beef muscles, http://ae.imcode.com

Cattle which are fed high grain diets pre slaughter have a rapid growth rate with increased turnover rates of protein, which may affect collagen. The breakdown of proteins through proteolysis in these cattle, is accelerated. The latter effect results in disruption of calpain system by calpastatin enzymes that acts as an inhibitor for calpain activity, therefore causing the muscle cells to lose their stability and integrity, hence causing poor quality in meat in terms of tenderness and also increases drip loss resulting from a reduced WHC.

The biochemical processes occur immediately post slaughter, which creates a suitable environment for the growth of microbes that can spoil meat and result in the carcass water loss. This happens if the carcass is not chilled immediately post slaughter (Viljoen, 2000). The Meat Safety Act (Act 40 of 2000), prohibits the slaughter of animals at any other place than the abattoirs for the purpose of obtaining the highest possible hygiene that is safely accommodative of the health of human and animal consumption (Zhang *et al.*, 2019b). The further assessments at the chiller stage, with regards to the level of quality attributes such as meat colour and fat thickness to mention a few, is very limited in SA. This owes to reasons that unlike the Canadian, Japanese and Australian system, SA has its carcasses subjected to classification at slaughter that excludes quality indication at slaughter floors (Soji *et al.*, 2015).

2.4. pH and temperature ratios

Temperatures at which muscles enter *rigor* ranges between 15˚C and 30˚C (Pighin *et al.*, 2014). However, this was later revised by Warner *et al*. (2014), to be between 15˚C and 35˚C. The pH of any living muscle is strongly buffered structurally and metabolically to enable functionality within the metabolic range (Puolanne, 2004). At slaughter, the pH is generally around 7.2 to 7.5 and then decreases until the ultimate pH of approximately 5.3-5.7 is acquired. Subsequently, this is required for the conversion of muscle to meat and to sustain high quality meat traits such as tenderness. An optimum temperature to pH ratio (pH>6.0 at temperatures>35˚C and pH<6.0 at temperatures<12˚C) is required during the conversion of muscles to meat to ensure the quality of meat (Thompson, 2002). A difference in seconds between the ultimate pH or rates in temperature or pH fall, can result in a great variation in the properties of meat (Puolanne, 2004; Ertbjerg & Puolanne, 2017).

Shortening occurs when muscles contract and the sarcomere length is reduced (Ertbjerg & Puolanne, 2017), hence the toughening of meat. Consequently, resulting in two conditions that occur owing to the changes in pH and temperature during the conversion of muscle to meat *post mortem*. These conditions are cold shortening and heat shortening which is also known as high *rigor mortis* temperatures. The shortening progresses until muscles reach onset *rigor*. Cold shortening occurs when muscles are exposed to temperatures below 10 ˚ C pre-*rigor* (Lawrie, 1985). The meats response to a cold exposure decreases as the period post slaughter increases.

The cold shortening occurrence is ATP dependant pre-*rigor* because ATP prevents the binding of actin to myosin head, therefore reduction of contraction. Beef has red muscles, which are more susceptible to cold shortening. When the temperature in the muscles decline rapidly to approximately 15˚C when the pH is above 6.0, prior to onset *rigor*, cold shortening occurs. This owes to the fact that at lower temperatures, the SR together with mitochondria, has a low capacity to bind to the Calcium ions (Ca^{2+}) and thus export it into the intracellular space where shortening or toughening is stimulated (Lawrie, 1985; Pearson & Young, 1990). The red muscles have a smaller number of mitochondria as compared to white muscles, consequently standing a high risk of cold shortening. Very rapid chilling that causes an accelerated drop in temperatures, causes the increased occurrence of cold shortening. Since the production of large carcasses has increased in SA, and the chiller rooms are packed with carcasses closer to each other, the latter is less likely to occur as the drop in temperature is not as rapid as in carcasses with less weight.

Heat rigor, occurs when the muscles are exposed to elevated temperatures pre *rigor* (Ertbjerg & Puolanne, 2017). The muscles then pass into *rigor* at very high temperatures above 35˚C, while the pH has dropped to below 6.0. This condition is also referred to as high *rigor* temperatures. The thicker layered muscles are more susceptible to this condition. The rapid drop in pH while the temperature is still high, can be due to a number of factors. These includes, the use of electrical stimulation, feeding high energy diets, such as feedlot diets and the use of growth enhancers and inadequate chilling rate of these larger carcass that are heavier. Heavier carcasses that are mostly from feedlots, have an accelerated glycolytic rate especially when electrically stimulated, due to the high calorie diet that results on post *mortem* caloricity (Warner *et al.*, 2014a).

Figure 2.5 indicates that cold shortening occurs when muscle pH is greater than 6.0 while the ATP is still available for muscles to contract and when muscle temperature is below 10 ˚C. Heat Shortening then occurs when the temperature of muscles is higher than 35˚C while the pH is just below 6.0, resulting in accelerated rate of proteolysis. The pH and temperature of muscles interact continuously during the development of *rigor*, owing to their impact on the proteolytic enzyme activity (Hwang & Thompson, 2001).

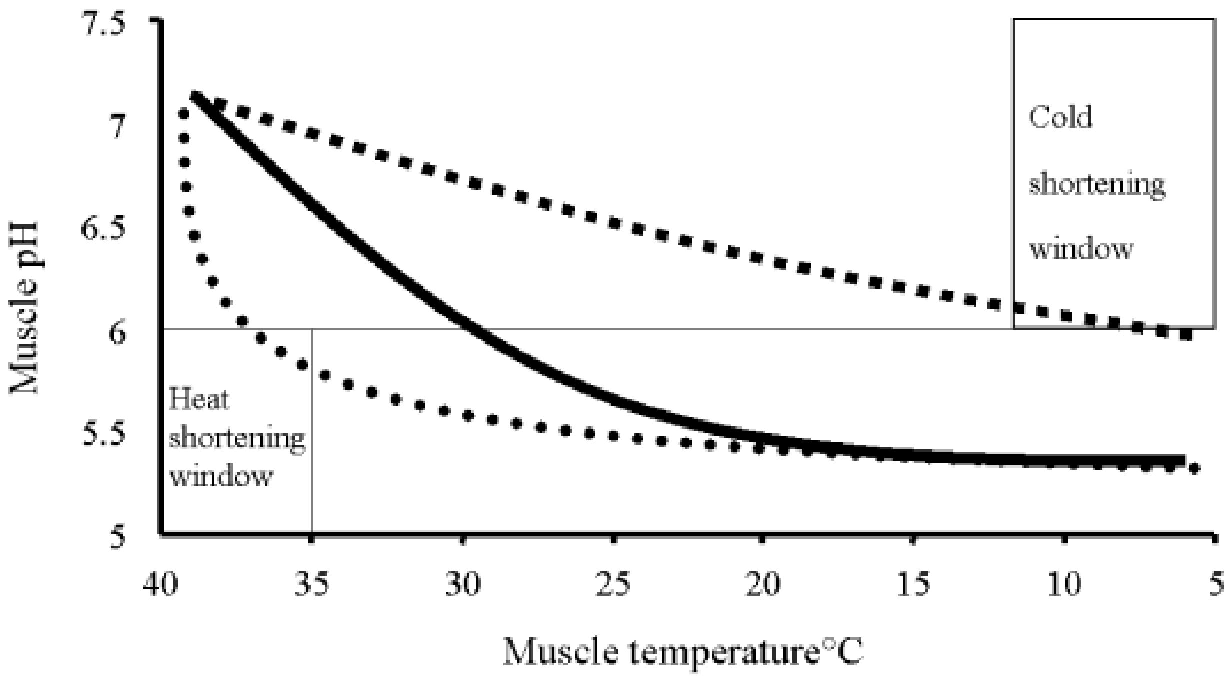

Figure 2.5.: The pH/temperature window used by MSA to optimise the decline in pH relative to the temperature of the muscle. (from Thompson, 2002)

2.5. Factors affecting the prevalence of high *rigor mortis* temperatures.

Beef production trends have evolved drastically throughout the years (Strydom *et al.*, 2015).The increase in the production of cattle which yield higher carcass weight, the use of Electrical stimulation (ES) and the chilling regime all makeup the number of factors that contribute to the increased prevalence of high *rigor mortis* temperature carcasses in SA. These changes have occurred because of the beef industry's aim to consistently produce high quality meat, which will ensure continued consumption (Warner *et al.*, 2010). The factors are explained in detail in the following sub section.

2.5.1. The effect of carcass weight on the prevalence of high *rigor mortis* temperatures

There has been an increase in the selection of increased muscle yield by many producers. The mass of the carcasses has increased by 20% in the past 30 years, with the mass close to 422kg in 2015 (Bruns *et al.*, 2017). Increased carcass yields are important in the beef industry, as it is the main determinant of profitability for producers. There are several factors that contribute to the drastic changes that has occurred in the beef industry, with regards to the production of beef with heavier carcasses. These factors include, improved genetics, management, and growth promotants (Zhang *et al.*, 2019a). The use of growth enhancers, the diets of feedlots and the duration for feeding cattle are standardised in SA, and about 60% of all carcasses slaughtered are A class, produced in feedlots.

The feeding of cattle to a higher weight for a prolonged period has been adopted by most feedlots in SA, to compensate for the grain price fluctuations and the fact that animals are sold by weight and favoured by the slaughterhouse prices (Agbeniga & Webb, 2018). The main reason why the United States Of America (USA) has increased the production of beef with larger carcass weights, was to increase the production of meat per carcass (Grayson *et al.*, 2013) and for the same reasons, SA is also following the same trend. The muscle layer over the bones of the larger carcasses is much thicker. Therefore, larger carcasses have more lean yield because muscle weighs more than fat, thus more money. This means that there are less animals and less land utilized to produce the same amount of beef required but with a smaller number of cattle. The heavier carcasses appear to be more susceptible to the occurrence of high *rigor* temperature conditions, due to a faster decline in pH after being exposed to electrical stimulation *post mortem* (Agbeniga & Webb, 2018).

The rate of pH decline may be slightly slower in the *Bos Indicus* breed compared to the *Bos Taurus* breed. This owes to reasons that include the growth rate which is much faster in Bos Taurus breeds. This remains important because the breed difference and maturity gives an indication of the variation in carcass weight and fatness, subsequently carcass cooling rate and the influence on the rate of glycolysis.

2.5.2. Growth enhancers

The use of growth enhancers has increased drastically since 2000. They are supplements of slow releasing hormones that occur naturally in animals and most plants (Viljoen, 2000). The two beta-agonist that occur naturally are epinephrine and norepinephrine, which benefits animal growth. They also play a role in the regulations of the body's metabolic and physiological functions (Manni *et al.*, 2018). Most of the feedlots have adopted the utilization of these beta-adrenergic agonists (beta-agonists) and South Africa is one of those countries that has most of its feedlots using the approved zilpaterol hydrochloride (Zilmax®). It is used in more than 80% of all the feedlots in South Africa. Zilmax® is a synthetic beta-agonist ,and is one of the 2 beta agonist that have been approved for utilization in SA (Agbeniga & Webb, 2018). The latter use is believed to increase the accumulation of muscles through the increased synthesis of protein, subsequently blocking the degradation of protein. Strydom (2009) reported an increase in carcass weight by 14kg when Zilmax® was used.

The dressing percentage is defined as the amount of lean yield that is obtained from the carcass per kilogram of cold carcass weight. The higher the amount of lean yield, the higher the dressing percentage. This therefore results in more profit for the producer, as they are paid per kg of cold carcass weight. Beta agonists help with the increase in lean carcass production and yield, as they channel nutrients away from the production of fat. The accumulation of fat in the carcass is a very expensive process as the producers will invest more in feed costs, which will result in a waste, and is metabolically expensive for animal to produce and pack in more fat.

The point where the body of the cattle should start accumulating or depositing fat, it results in the production of lean meat before the body reaches that point. Beta-agonists increase muscle mass through the increase in the Deoxyribonucleic Acid (DNA) to protein ratio (Johnson *et al.*, 2014). They have a response and a mechanism that is similar to that of muscle hypertrophy and therefor increase the redirection of nutrients towards increased growth and lean build-up. The beta agonists bind to the beta-adrenergic receptors that is in the cellular membrane. These receptors stimulate the actions that are responsible for increasing synthesis and storage of fats. They also increase the feed efficacy, and therefore a gain in liveweight by increasing the average daily gain (ADG) by 15% and 30% respectively (Packer *et al.*, 2018). ADG is what the cattle gains every day in weight per amount of feed in kilograms (Kg). This determines the final weight of the cattle, as it has to gain efficiently in relation to what it is fed. Growth promotants are administered orally towards the end of the finishing period, that is 28-42 days before harvest (Strydom & Smith, 2010). This results in an expected improvement of daily weight gain by 15-25%.

The use of these growth enhancers saves up to 2.3 million tons of feedstuff and 265000 hectare (ha) of land reserved for production of beef in the USA (Strydom, 2016). Feeding can be used as a strategy to manipulate the quality of the end product or carcass. This can be done through the compensatory growth, whereby the rate at which the cattle growth is accelerated following a period of restricted growth. This consequently influences rate of protein degradation and synthesis (Manni *et al.*, 2018).

Growth enhancers have economic benefits which are significantly recognized by most feedlot producers since they reduce the deposition of fat, which is highly energy expensive, thus saving on the cost of feed. The cattle still eat less, but however still able to maintain the required carcass weight. The application of ES on the carcasses of cattle that have been administered with beta agonists, can reduce the negative effect on the beef quality (Strydom *et al.*, 2011). ES and ageing are used to counteract the negative effect of beta-agonists on meat tenderness(Hope-jones & Strydom, 2010).

This however is not as effective in the heavier carcasses with high *rigor* temperature conditions, owing to the issue that these carcasses have a reduced ageing potential compared to normal lighter carcasses. The reduced ageing potential is a result of the accelerated tenderization , due to a higher initial temperature(Webb & Agbeniga, 2020).This has resulted in a decrease in the eating quality of beef due to the increased expression of mRNA which contributes to decreased tenderness of meat (Agbeniga & Webb, 2018). The growth promotants form a large part of the family of protein receptors .There is a negative relationship that occurs between the calpastatin activity and proteolysis in muscles, which contributes to reduced tenderness of the meat (Strydom *et al.*, 2011). Growth enhancers increase the calpastatin activity, hence reducing the calpain enzyme activity that occurs during the process of proteolysis (Ertbjerg & Puolanne, 2017).

2.5.3. Genetics

Genetics is defined as the unit of hereditary that occupies a specific locus on a chromosome (Warner *et al.*, 2010).The altering of muscle morphology of cattle towards increased yields have the potential of increasing the value of beef at slaughter (Judge *et al.*, 2019). The number of farmers in SA was estimated to be approximately 35000 in 2011, with 2500 of the number being seedstock or stud producers (DAFF, 2012). The stud producers play a very important role of providing the beef industry with updated genetic breeding materials that helps many producers to increase their production efficiency (SA feedlots, 2019). The selection of multiple traits of economic importance is the objective of seedstock producers. They aim at providing the producers with bulls that have a higher ability to transmit superior genetic merit, updated genetic breeding material , that will serve the objective of higher production efficiency and subsequently their profitability (Thompson *et al.*, 2006).

The main principle focus was on the values of the carcass that have an influence on the carcass weight and back fat thickness to mention a few (Mcneill *et al.*, 2012). Due to reasons that feed comprises the highest percentage of feedlot expenditures, genetic selection of more efficient cattle is essential. A commonly used measure of efficiency is Feed Conversion Ratio (FCR), which is feed intake (FI) per estimated weight gain. Robinson and Oddy (2004), indicated that FI had higher genetic correlation with feedlot gain and metabolic rate, with a slightly lower environmental effect. FCR has a low heritability and strong negative genetic correlation with weight gain, metabolic weight and FI. Direct selection of increased weight would imply that there will be a reduction in the FCR. FI and fat measurement indicated a low heritability, meaning that heavier animals tend to eat more, and excessive feed intake can lead to fat deposition. The most efficient feedlot selection would be the selection for low Relative FI , which will result in the reduction of subcutaneous fat or selection for reduced FCR by selecting for weight gain. The interaction that occurs between the breed type and the diet composition, is very crucial in determining the level and rate of fat deposition, subcutaneous type to be specific as observed in grass-fed cattle. Genetic manipulation contributes to the environmental effect positively. This is through the reduced emission of methane indirectly. The selection of residual feed intake reduces maintenance requirements by stimulating the latter reduced emissions(Strydom, 2016).

The increase in animal productivity is through continued genetic selection, by using breeding programmes (Ouali *et al.*, 2006).Genetics is used to increase the muscling, carcass yield, and coupling with the use of growth promotants. The environmental influence which in most cases is nutrition, can have an effect on multiple generations. Intra and inter muscle variation that occurs will depend on muscle and the location within the muscle. Muscle responds to their type of environment (in this case the plane of nutrition) and the sum of their genetic variation (GXE) throughout their development and growth. The latter determines the measure of trait of interest outcomes such as tenderness (Warner *et al.*, 2010). Gene markers have been used to identify cattle with better performance for commercial traits. The longissimus muscle (LM) and carcass size are highly correlated, with a correlation that is approximately 0.97. this implies that because carcass has increased in size throughout the years, so has the size of the cuts from these muscles (Maples *et al.*, 2018)

The intense selection comes with its own side effects, example can be seen with animals that are selected for more lean yield, these breeds are more susceptible to stress and consequently develop defects that affect the quality of meat (Adzitey & Nurul, 2011). These conditions include the DFD and PSE meat to mention a few. The PSE-like signs are also observed in cattle with high *rigor* temperature conditions, which influences the colour, the drip loss and the pH of meat which are characteristics of meat that are important for consumers. Consumers regard the safety of meat based on its appearance on the shelves. The more exudates on the meat poses questions and concerns to a lot of consumers, meaning no purchase, no profit for the producers.

2.5.4. Diet

Nutrition is one of the most critical environmental factors that influences the quality of beef and the carcass characteristics (Webb, 2014). Genetic improvement, nutrition and better management techniques (Agbeniga & Webb, 2018), explains the reason behind the steady increase in carcass weights in these recent times. All the feedlot producers in SA, which are intensive, have increased the utilization of finishing diets. These diets comprise mostly of grains and grain by products (Jacob *et al.*, 2014b). The densities of the energy form the diet is the main determinant of carcass yield (Nour & Thonney, 1983).

Feed makes up the major proportion of costs in the production of beef cattle. This therefore implies that the utilization of feed in the most cost-effective way must be the top prioritised technique. Feeding duration and type influence the conditioning, conformation and composition of the carcass, consequently the yield of carcass and its fat content (Webb, 2014). Jacob *et. al.* (2014) has concluded that feedlotting can increase the likelihood of high *rigor* temperature conditions, after he found that the core body temperature of steers from feedlot treatments was ranging from 0.3-0.4˚C. The latter was more than core temperature of grass-fed cattle at a time of slaughter.

The environmental conditions such as climate change, are contributors to the increased incidences of high *rigor* temperature occurrences in beef carcasses. This therefore calls for a need for farmers and abattoirs to come up with ways to adapt to these drastic changes. The high core body temperatures is elevated ,due to an increased susceptibility of grain fed cattle to stress during transportation for long distances and handling pre slaughter, which also contributes to the increased core body temperature (Jacob *et al.*, 2014b). The increased core body temperature causes the cattle to be hyper thermic. The core body temperature increase, caused by stress, can have an effect that can last for days, weeks , months and even years depending on the severity and duration of exposure (DiGiacomo *et al.*, 2014).

Grain feeding increases fat accumulation, which then results in the response of the cattle to the stressor resembling those that are observed in humans who are insulin resistent (DiGiacomo *et al.*, 2014). This consequently causes an elevation in the insulin and glucose circulation, subsequently inducing insulin resistance, which is the body's inability to respond to the effect of insulin in its body. This occurs when the cattle are introduced to high energy diets, which increases the amount of glucose and insulin circulating in the blood(Warner *et al.*, 2014a). Leptin is another hormone that is produced by adipocytes due to increased fat deposition the grain fed cattle. This hormone interaction with glucose and insulin in the plasma concentration, will result in the reduced ability of the cattle to cope with stressors, hence the increased susceptibility to high *rigor* conditions(Boito *et al.*, 2017).

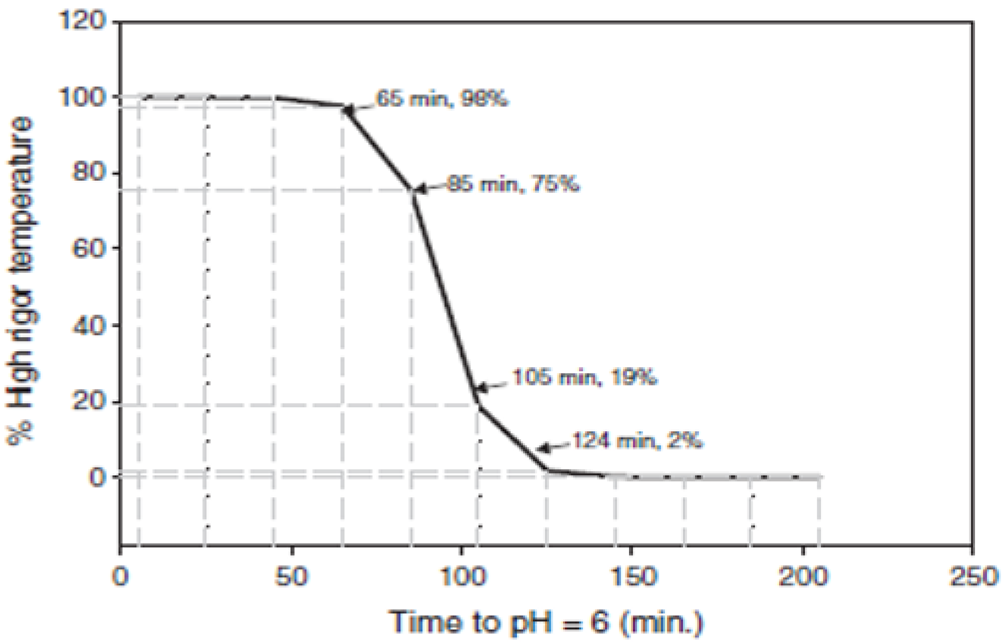

Figure 2.6.: % high rigor temperature, time to pH 6 of grain fed carcasses.(Warner et al., 2014a)

Figure 2.6 indicates the relationship between the proportion of high *rigor* temperature occurrence at a time to pH of 6 for grain and grass-fed cattle. It predicts that when the time to pH at 6 is at 65 minutes or less, the proportion of occurrence of high *rigor* temperature incidences in grain fed cattle increases by 98% compared to grass fed that increases by 93% at the same given time.

Most abattoirs use ES, which reduces the time taken for the pH to drop to 6. From this figure we can estimate that the prevalence of high *rigor mortis* temperature carcasses is higher in grain fed cattle. This can be as a result of the contributing factors that are mentioned above.

2.5.5. Electrical stimulation

Electrical stimulation (ES) is a method of running electrical current through the carcass , as a way of inducing contraction of muscles, consequently accelerating the use of energy required for glycolysis, hence a decline in pH that is accelerated (Matarneh *et al.*, 2017). ES has been introduced in the 70s and 80s as one of the technical methods of increasing the tenderness of meat (George *et al.*, 1980). It also reduces the variations in tenderness that is observed in the carcasses of beef (Frylinck *et al.*, 2015). ES has now become a criterion method of technological processing in commercial abattoirs for beef and lamb. There are two popular methods of ES application namely, low voltage and high voltage stimulation with voltages of 50-120 Voltage (V) and 300-1000V respectively (Lopez-Campos *et al.*, 2017). South African abattoirs mostly use Low Voltage ES(LVES). This is because the low voltage ES reduces the capital costs and is easy to install and use and preserves the safety of the workers in the abattoirs. The LVES is used in cases of reduced delay in time between the slaughter and stimulation (approximately 10minutes) after the bleeding process is completed.

The High Voltage ES (HVES) has more extended time between bleeding and stimulation (approximately 60 minutes). It is however not preferred because it is easier to overstimulate carcasses using HVES, due to its vigorously high voltage power. This can reduce the safety of workers in the abattoirs and is very much high costing with regards to maintenance. The duration of the stimulation is critical to ensure that overstimulation is avoided. The optimum duration should be between 20 and 120 seconds and not more than that. The effectiveness of ES was higher back then when the production of lighter carcasses was dominating. Recently however, the latter has become an issue of concerns, due to many countries worldwide including SA, switching to increased carcass weights, which have a reduced cooling rate, hence requiring less stimulation (Thompson *et al.*, 2006).

A study conducted by Warner et al (2014) , has reported that heavier carcasses , that are specially from feedlots, showed a faster decline in pH while the temperature is still higher than 35˚C when electrically stimulated. ES increases the calpain activity in muscles that have a rapid glycolysis by a factor of 6 compared to unstimulated muscles (Hope-Jones & Strydom, 2010). ES uses up all the ATP energy stores before *rigor* onset, resulting in an accelerated pH decline, hence a reduction in the incidences of cold shortening.

These heavier carcasses, that are currently produced, have a higher susceptibility to overstimulation. Because most of the cattle producing these carcass types , are fed high carbohydrate diets. Therefore, their muscle thickness is higher, due to them being larger. This is, as a result of many contributing factors such as the use of growth promoters and genotype, which might interact with the ES effectiveness.

Juárez et.al., (2016) has shown that the lighter carcasses benefit more from the utilization of ES (to prevent cold shortening), than heavier carcasses, as they cool quicker. The ES reduces this susceptibility to cold shortening by increasing the drop in pH to avoid the scenario of a high pH at low carcass temperatures. Hope-Jones and Strydom (2010) reported that animals supplemented with beta- agonist produce tougher meat, as it increases the calpastatin activity which increases the toughness of meat. The use of ES on the carcasses from animals supplemented with beta-agonists, will counter act the increased activity of calpastatin by increasing the activity of calpain enzyme for early onset *rigor* and ageing which improves the tenderness of meat as indicated in Table 2.4. Stimulated lighter carcasses show a higher L*, a*, b* value, thus improved red bright colour in the initial period of display of the meat that is desired by consumers. This is not the case however, with heavier and larger carcasses, because as the meat ages, the lightness increases, making the meat look more pale and less appealing (Kim *et al.*, 2013).

Table 2.4.: The effect of ES on carcasses from animals that were supplemented with Zilmax and those that were not supplemented(Kim *et al.*, 2013)

Treatment	**β-agonist treatment**		**SEM***	***P* value**
	Control	**Zilpaterol**		
WBSF(kg)(aged 14days)	3.53	4.75	0.1922	<0.001
Calpastatin activity	2.15	2.61	0.0525	<0.001
µ-calpain activity	0.64	0.80	0.0344	<0.021
Stimulation				
	ES	**NES**	**SEM***	***P* value**
WBSF(kg)(aged 14days)	3.81	4.47	0.1205	<0.001
Calpastatin activity	2.21	2.55	0.0377	<0.001

µ-calpain activity	0.53	0.91	0.0306	<0.001

The muscle fiber type influences the effectiveness of the ES on the carcasses. Muscles throughout the carcass have different rates of muscle metabolism, temperature decline and drop in pH. This occurs because of the differences in muscle densities and size (Jacob & Hopkins, 2014a). The rate of temperature and pH decline during *rigor* and the interaction that occurs continuously and co dependently, is an important factor affecting meat quality attributes post slaughter (Cadavez *et al.*, 2019). This interaction is of importance because it affects both physical shortening and proteolytic enzyme activity of the muscles involved. The deeper muscles of the heavier carcasses coupled with overstimulation of ES and higher subcutaneous fat thickness, result in high *rigor* temperature conditions that were previously known as heat shortening (Bhat *et al.*, 2018a). The muscles in the body have different types and amounts of fibres, therefore respond differently to the effectiveness of the application of ES (Hope-Jones & Strydom, 2010). This is seen in the semimembranosus muscle (SM) and the *longissimus Dorsi* muscles. There was an accelerated drop in pH of the LD muscle which were stimulated compared to the Non ES(NES) muscles, this however was not the same in the SM muscles, as both of the SM that were stimulated and non-stimulated were both the same with regards to the drop in pH, which in the case didn't change with regards to its rate(Kim *et al.*, 2013). Figure 2.7 indicates the decline in pH of the LD muscles post slaughter in the stimulated and non-stimulated LD muscles. The figure indicates that at the same time post slaughter, the ES muscles have a lower pH value than the NES muscles. Hence the effectiveness of the ES on the carcasses post slaughter is indicated to be stronger.

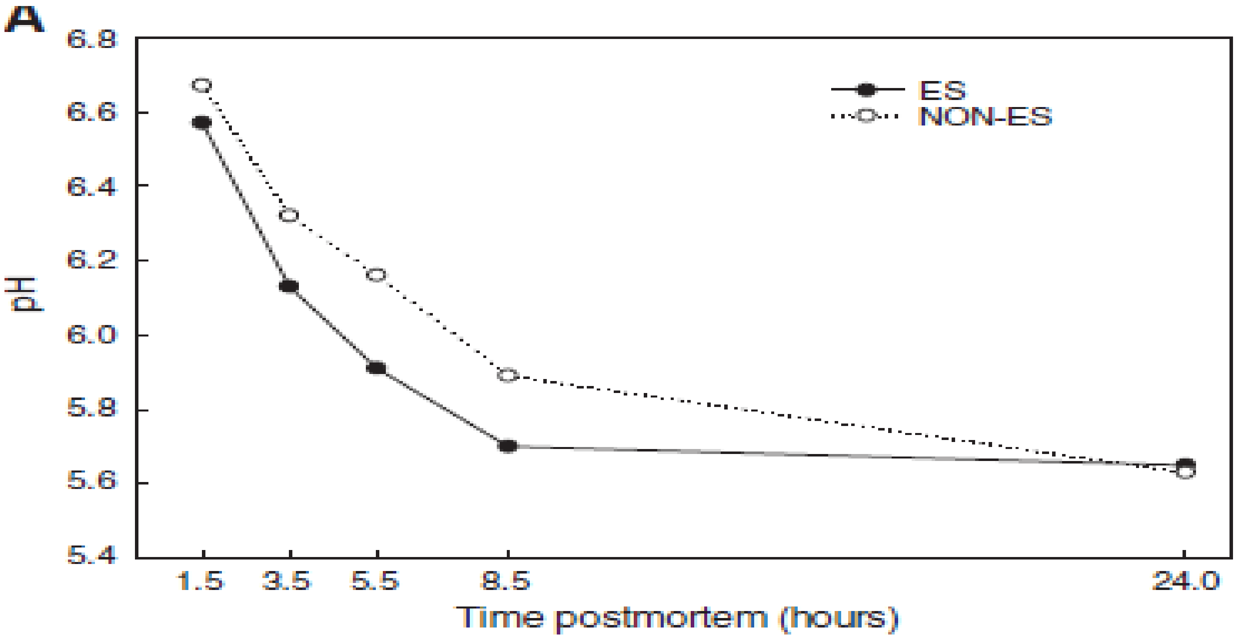

Figure 2.7 : The decline in pH over time in ES and NES longissimus Dorsi muscles of beef carcasses. (Kim et al., 2013)

2.5.6. Chilling of carcasses

The development of major eating qualities is fully dependant on the storage of meat at low temperature (Ouali *et al.*, 2006)**.** Previously, our forefathers used to slaughter animals during cooler seasons of the year. This was done as a preservative measure, to prevent the biochemical process that results in meat wasting away. Today, technology has introduced chillers, which are mostly used in all abattoirs and processing plant facilities. The chilling regimes were designed to accommodate the variety that is there in the animal species, processing systems and the end product usage (Zhang *et al.*, 2019b).

There are challenges arising due to the increase in the production of larger carcasses. This is because the chiller rooms were designed with the smaller and lighter carcasses in mind, therefore the heavier carcasses are not chilled as effectively as the small carcasses. These larger and heavier carcasses are more predisposed to high *rigor* temperature effects ,as they have more thicker layers of muscle above the surface of the bone (Jacob *et al.*, 2014a) The heavier carcasses that are closer to each other in the cooling facility interfere with the normal airflow, as the air is inhibited by the depth of the muscles and the reduced space between the carcasses. Due to the high demand for beef, the chillers end up being over packed, thereby leaving very little space between carcasses for the cold air to move efficiently. The more thick layered muscles of heavier carcasses generate more heat , hence more heat production that exceeds the amount of heat diffused towards the surface through the conductive route of heat loss (Kuffi *et al.*, 2016)

The latter intensifies the inability to dissipate heat, and consequently can cause an increased susceptibility of the carcass to high *rigor* temperature conditions (Kuffi *et al.*, 2016). The grass-fed carcasses have a smaller carcass, therefore cool much quicker and are more susceptible to cold shortening. This is no longer a problem however, due to the use of ES to prevent cold shortening.

The variation in the distribution of temperature within the muscle in the carcass is caused by the maintenance of the balance between heat loss and heat production. The uniformity of the carcasses with regards to their quality, depends on the movement and effectiveness of the cooling air in the chiller rooms to remove as much heat as possible from the surface of the carcass. This has to happen until the temperature drops to the optimum level required for normal *rigor* to take place. The heterogenous flow of air over these carcasses can result in lowering the cooling rate. The heat transfer happens between the floor and surrounding environment of the chiller rooms and the surface of the carcass. The direction of the flow of the air in the cooling facility goes down vertically towards the carcass from above. This is followed by a low air velocity which flows horizontally over the carcass. The two resistance which are within the carcass and between the carcasses and the air , are influenced by the direction of the flow of air (Tablada De La Torre *et al.*, 2009)The heat from the surface of the carcass is removed through three routes namely, convection, conduction and radiation (Bhat *et al.*, 2018a). The cooling rate is determined by the convective heat and mass transfer at the surface of the carcass.

The carcass geometry such as the size, shape, fatness and temperature are the contributors towards the heat loss effectiveness (Kuffi *et al.*, 2016). The carcasses with a larger size have a more reduced surface area available for dissipation of heat compared to its weight ratio (Jacob *et al.*, 2014b). With the note that these days carcasses are larger because of the use of beta-agonists. The fat layer of the smaller carcasses of grass-fed cattle is much thicker than that of grain-fed cattle, owing to the effect of the promotants.

The cooling rate of the carcass, has an influence on the pH and temperature ratio of carcasses, during the conversion of muscle to meat post slaughter (Warner, 2016). Thus, it affects the quality attributes of meat such as tenderness, colour, and ageing potential. There is a gradient that exists between the surface and the inner area of carcass in terms of temperature drop during the cooling process *post mortem*. This indicates that even though it is within the same carcass, the muscles do not have a uniform rate of cooling as indicated in Figure 2.8. We can presume that the muscles with a larger distance between the surface have a slower cooling rate, hence their temperature is still higher by the time the pH drops to 6.0. The overall quality of beef is dependent on the chemical composition, physical status and the structure of the muscles and tissues. These are predicted based on the ultimate value of the pH, which is determined by the origin of the meat in terms of its overall nutritional and herd management. This pH is measured within 48 hours post slaughter, and therefore influences the final product quality and shelf life as it drives the conversion of muscle to meat together with the drop in temperature (Żywica *et al.*, 2018).

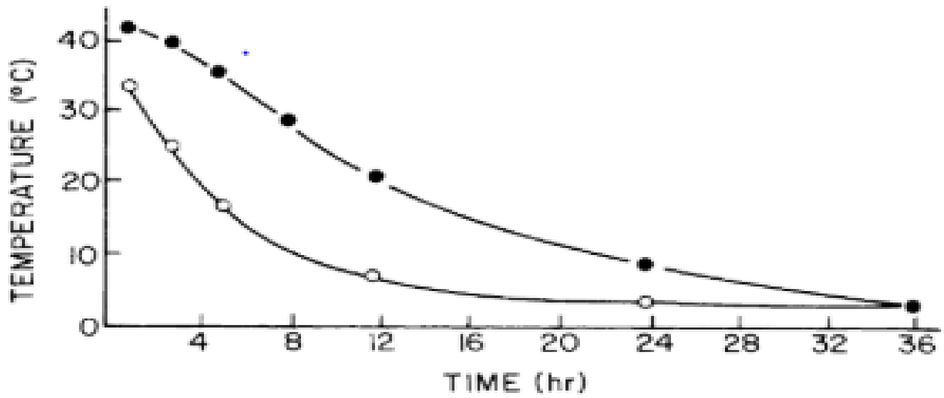

Figure 2.8 : The temperature gradients effect for a surface distance of 2cm and 8 cm on cooling rates in beef semimembranosus muscles of beef carcasses placed in a 2-3˚C chiller an hour pm (Warner, 2016)

Key: ○-2cm;●- 8cm

Slaughterhouse operators are more focused on the capacity of production than other factors that can endanger the quality of beef. The temperature increases continuously even after the carcass has entered the chilling room, due to the sustained activity of the glycolytic enzyme in the deeper muscles. This consequently adds up to the temperature being higher at a pH below 6.0. Because the focus is to produce more meat to meet the demands that exceed the supply, abattoirs focus more on the number of cattle slaughtered daily for more profit. Hence the time or duration that the carcasses remain in the chilling rooms is very strictly kept consistent. A shorter cooling time increases the rate of production turnover, which is an economic benefit for most commercial abattoirs (Aalhus *et al.*, 2011).

2.6. The prevalence of high *rigor mortis* temperature carcasses globally

The problem of high *rigor mortis* temperature carcasses is exaggerated by the changes that the beef industry has undergone throughout the years as discussed above. A study by Warner *et.al.* (2014), has investigated the incidences of the prevalence of high *rigor mortis* temperatures across the beef industry in Australia. The study discovered that there has been an unacceptably high incidence of high *rigor mortis* temperature in beef carcasses (72%). Most beef cattle produced in Australia are situated in the tropical and subtropical parts of the country, which have similar conditions to Southern Africa. It is therefore warranted to look at the situation in our country, as no recent research has been done in SA with regards to the high

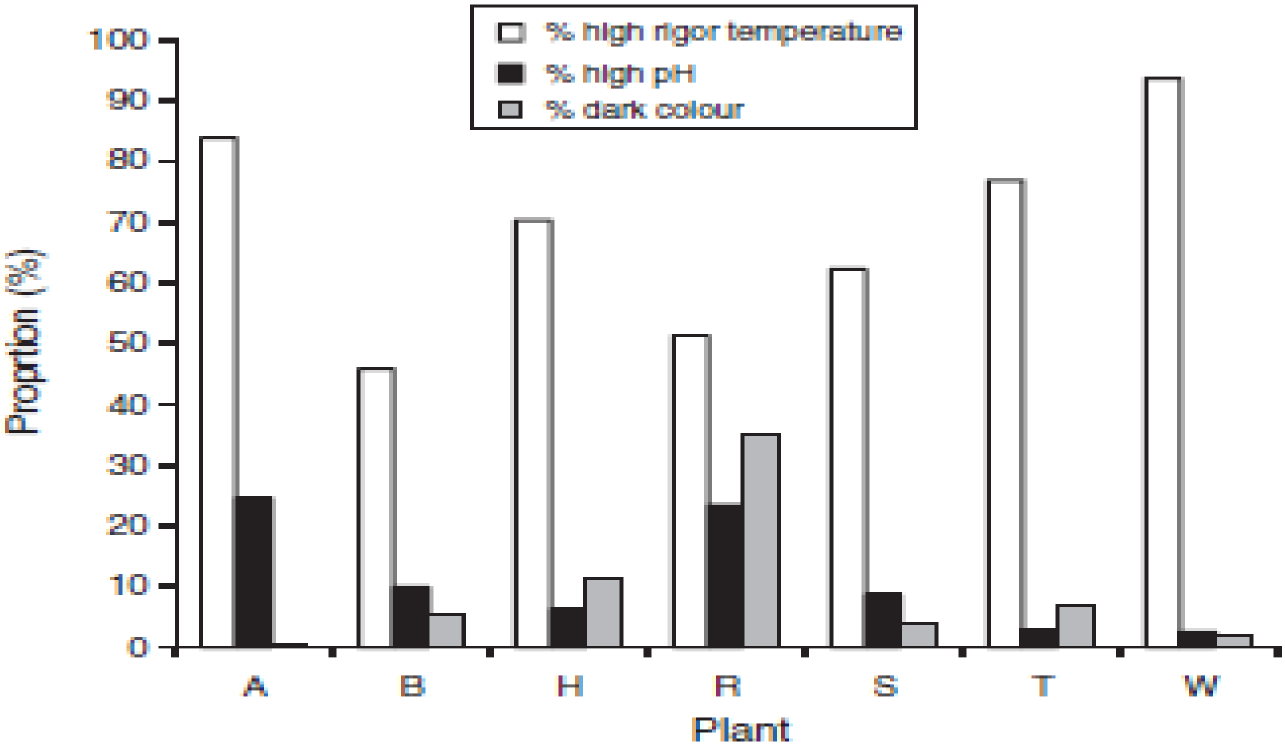

Figure 2.9 : Proportion of high *rigor mortis* temperatures (%), pH and dark colour (Warner *et al.*, 2014a)

rigor temperatures. Figure 2.9 shows the prevalence of high *rigor mortis* temperature conditions (%) in processing plants across Australia. This figure also indicates that the higher prevalence result in the colour of the carcasses being less dark and rather much paler. There is an inverse relation observed between the proportion of pH and high *rigor* temperatures. The higher the temperature conditions, the lower the pH, therefore the reduced proportion of darker coloured carcasses in most if not all plants. The plants with higher pH have higher proportions of darker colour.

Predictions show that the global population is expected to grow to 9.5 billion people in the year 2050 (Capper, 2011). This suggests that the production of food will have to undergo an increase that is approximately 70% more than what they are producing. This, however, will be a challenge because there will be a shortage of land that is available to accommodate the required production increase. The latter need can be achieved by using alternative production techniques such as the increase in the production of animals with higher carcass weights (HCW), this is done through the use of growth enhancers, and careful genetic selection for traits of economic importance such as efficiency. Genetic selection of specialized beef cattle has been directed in France to favor the growth of muscle with the aim of increasing the production of lean carcasses.(Hocquette *et al.*, 2012). Muscle yields more weight than adipose tissue, hence increased profitability. The United States Department of Agriculture has reported that there has been a continued increase in beef carcass weights in the past 30 years (Lancaster *et al.*, 2020). The latter increase has shown to increase the occurrence colour variations and discoloration throughout the beef across the country. Table 2.5. below, indicates that there has been a selection for increased calf birthweight, between 1977 and 2007. The average number of days on feed has increased, due to reasons that most producers feed their cattle for longer to a higher body weight so they can make up for the higher costs of feed. The growth rate has also shown an increase through the 10 years duration, consequently an improved productivity upon population size and time at slaughter. The table also indicates that there has been an increase in the number of cattle within a feedlot finishing system, hence reduced concerns about overgrazing issues. The beef industry worldwide has one thing in common, which is that there has been a steady increase in the production of cattle that yield (HCW). This implies that the prevalence of high *rigor* temperatures conditions must be present, looking at the effects that are mentioned above. The Canadian food inspection agency as indicated in Table 6, shows that there has been an increase in the production of HCW between 1999 and 2015.

Table 2.5.: Characteristics of the 1977 and 2007 beef production systems (from Capper, 2011)

Variable	1977	2007
Predominant beef breeds	Angus, Hereford	AngusxHereford
Calf birth BW, kg	33	42
Average slaughter BW,kg	468	607
Average beef yield per animal, kg	274	351
Average age at slaughter, d	609	485
Overall growth rate (birth to slaughter), kg/d	0.75	1.08
Average days on feed	164	183
Proportion of yearling-fed beef breed in feedlot, %	100.0	72.7
Proportion of calf-fed beef breeds in feedlot, %	-	14.4
Proportion of calf-fed dairy breeds in feedlot, %	-	12.9
Proportion of cull beef/dairy animals in slaughter population, %	25.7	18.5

Table 2.6: Source: Canadian Food Inspection Agency, as compiled by AAFC, AID: Average warm carcass weights for federally inspected plants between the year 1999 and 2015

		West	Ontario	Quebec - Atlantic	TOTAL
TOTAL	2015	839.3	866.8	787.1	844.6
	2014	809.7	848.6	748.4	817.2
	2013	811.4	828.6	768.8	814.5
	2012	808.9	822.3	686.5	807.6
	2011	793.2	833.7	667.1	793.6

		British Columbia - Saskatchewan - Manitoba	Alberta	Ontario	Quebec - Atlantic	TOTAL
TOTAL	2010	612.1	807.3	849.8	607.8	802.3
	2009	811.4	785.5	839.3	617.4	786.8
	2008	818.5	801.5	835.1	633.5	799.0
	2007	841.6	801.2	819.2	662.6	798.1
	2006	836.5	796.3	809.5	650.0	791.4

		British Columbia - Saskatchewan - Manitoba	Alberta	Ontario	Quebec - Atlantic	TOTAL
TOTAL	2005	802.6	798.0	801.9	652.6	788.3
	2004	791.3	799.1	833.4	662.1	795.1
	2003	794.0	805.9	833.0	670.8	801.9
	2002	768.4	801.4	832.1	663.5	795.4
	2001	768.6	796.0	812.0	648.0	786.9

		British Columbia - Saskatchewan - Manitoba	Alberta	Ontario	Quebec - Atlantic	TOTAL
TOTAL	2000	758.7	782.1	791.4	656.3	773.6
	1999	723.9	744.0	766.6	652.3	739.6
	1998					
	1997					
	1996					

The average carcass weights (kg) for steers, heifers , young bulls, and all prime beef in Great Britain (GB), has increased for over the past decade (2005-2015) as indicated in Table 2.7.

Table 2.7: Average carcass weight for steers, heifers, young bulls and prime beef in Great Britain between 2005 and 2015.

	Steers	Heifers	Young bulls	Prime beef
2005	350	299	323	329
2006	344	300	327	327
2007	348	303	330	331
2008	343	299	328	326
2009	345	307	335	329
2010	351	310	327	335
2011	344	305	325	329
2012	353	311	333	337
2013	352	310	328	335
2014	359	318	335	342

2015	362	322	342	347

The above table indicates that heavier carcass production increases by 5kg in average per year. The increase indicated poses a problem with regards to the size of beef cuttings being bigger, hence making the inconsistency much more difficult to maintain.

2.7. Effects of high *rigor mortis* temperature conditions on beef quality traits

The variations in meat eating quality has been a growing concern for several years (Warner *et al.*, 2014a) .Consequently meat yield from carcasses with unfavourable meat quality, can sustain economic penalties thus producers and processors loss within the beef industry (Hughes *et al.*, 2018). Considering the effects that high *rigor* temperature has on consumer meat eating quality attributes, the evaluation of the factors which contribute to the occurrence of this problem in abattoirs across SA is of high significance. All the pre and post slaughter factors that increases the prevalence of high temperature *rigor* in abattoirs, need to be considered when studying meat quality attributes. These quality attributes include tenderness, colour, water-holding capacity (WHC) and fat content.

High temperature *rigor mortis* effect on the quality of beef such as colour, tenderness and WHC has previously been studied on the *longissimus* muscles (Warner *et al.*, 2014b). Jacob *et al*.(2014a) has stated that, targeting these muscles rather than the entire body will assist with the provision of solutions for high *rigor* temperatures under commercial conditions. The variability of beef eating quality attributes is the most important factor that determines consumer satisfaction (Kilgannon *et al.*, 2019).

Consumers demand meat of high quality, that will complement their health and dietary requirements. The visual and sensory traits of beef determine the consumers level of satisfaction, when the meat is raw or cooked.

2.7.1. Tenderness

Tenderness is the single most important attribute influencing the acceptability of beef by consumers (Listrat *et al.*, 2016). The inconsistency of beef is a growing problem particularly in beef (Frylinck *et al.*, 2015). Muscles go through a series of bio physio- chemical processes that helps it convert to meat (Bhat *et al.*, 2018a). There are three important factors that influence the overall tenderization of meat, these include, the collagen content and solubility which is also referred to as background toughness, the extent to which the muscle shorten and ageing. Ageing is the most important of the three because most of the tenderization occurs during the ageing process. High *rigor* temperatures have a negative influence on the tenderness of meat. The latter affects the sarcomere length, by reducing it and increasing the shortening, consequently increasing the toughness of meat.

Kim *et al*. (2014) has stated that there was improved tenderness in early *post mortem*(pm) when ES is being applied on heavier carcasses that have been fed Zilmax in feedlots, but the latter effect decreased with ageing. The musculature tenderising effect is accelerated immediately after death when ES is applied, under slow cooling rates (Sikes *et al.*, 2010). The effect is mostly observed in the *Longissimus Dorsi* (LD) muscles, by reducing the shear force and releasing the catheptic enzymes during dynamic contractions of the muscle (George *et al.*, 1980).

2.7.2. Colour

Colour plays a very huge role in the choice of the consumers, because they use the visual appearance of beef as a tool to evaluate its freshness. The latter however has very little or no correlation with the eating quality of beef (Manni *et al.*, 2018). The bright red colour of beef is highly favoured by consumers , as they perceive it to be fresher and appealing to the eye (Kilgannon *et al.*, 2019). The chemical state of the myoglobin pigment is the most important determinant of meat colour (Hughes *et al.*, 2017). The myoglobin and haemoglobin absorb a series of light wavelength to give rise to the red colour of the meat (Hughes *et al.*, 2019).

This quality is threatened by the prevalence of high *rigor mortis* temperature, as it causes beef carcasses to have a more pale colour resulting from increased drip losses (Aalhus *et al.*, 2011) and reduced mitochondrial activity. This consequently reduce the rate of consumption of oxygen, and therefore more light is reflected from the surface of the meat (Jacob & Hopkins, 2014a). The net charges on the myofilament surface and lactate, are reduced due to accelerated pH drop, acts as an anionic chaotropic. The latter results in the malfunctioning of the water and protein interaction, thus a reduction in the WHC (Kim *et al.*, 2014a). The shrinkage of the lateral space follows as the pH drops drastically, owing to the denaturation of the myosin head (Strydom *et al.*, 2016).The accelerated rate of glycolysis that uses up all the ATP in the muscle, results in the inactivation of the hydrolysing enzyme ATPase. This consequently reduces the contractile forces , hence the decreased electrostatic repulsion between the filaments (Liu *et al.*, 2018).

The changes in flavour of meat is manifested by the lipid oxidation mechanism, which results in the formation of toxic compounds such as aldehydes and ketones, hence a reduced shelf life (Mungure *et al.*, 2016). The reduction in the oxygen of the myoglobin, leads to a slower transition of oxymyoglobin to metmyoglobin (Aroeira *et al.*, 2016).

2.7.3. Water holding capacity (WHC)

The binding of water by muscles refers to WHC (Lawrie, 1985).The water holding capacity has an inverse relationship with the temperature drop. Muscles that have a higher intramuscular fat content, tend to have a more elevated WHC. The fat allows for more water to be retained through the booming of its channels as they open up (Aalhus *et al.*, 2011). As the pH drops, the WHC drops, owing to the equilibrium formed by the attraction of positive and negative charges (Kim *et al.*, 2014b). This consequently results in the holding of the filaments together preventing water from getting in (Santos *et al.*, 2016).

The appearance of the meat on the shelves influences the consumer's preference on a specific cut of meat (Strydom *et al.*, 2016). The reduced WHC results in the meat having a PSE-like appearance. High *rigor* temperature muscles have conditions that are similar to the characteristics of PSE meat that is seen in pigs. Liu *et al*. (2018), has reported in a study, that there are clear PSE-like conditions with shrinkage of muscles under conditions of 38˚C and a pH of 5.5.

Given the benefits that genetics can bring to most producers with regards to increased production of more efficient animals, it can increase the susceptibility of cattle to PSE and DFD meat conditions owing to the increased stress susceptibility in these animals. After the cattle is slaughtered, the importance shifts more towards the quality than quantity characteristics of meat (Thompson *et al.*, 2006). The latter conditions result in heavy financial losses, as they are both associated with the drop on pH at a specific time of slaughter. PSE is known to be more problematic in pigs and poultry, due to the higher proportion of white muscle. This is however a growing problem in beef carcasses, owing to the occurrence of high *rigor* temperature conditions in carcasses. The rate of acidification is accelerated in these carcasses than normal, at lower pH values and higher temperatures. This consequently reduces the water holding capacity of meat.

2.7.4. Ageing

Ageing is the process of improving the palatability that occurs as meat is held *post mortem*. It is largely a function of the calpain system (Hwang & Thompson, 2001). The reduction in the calpain as a result of accelerated glycolysis, results in the reduced ageing of the meat which in turn affects the tenderness of meat (Hwang & Thompson, 2001). Ageing acts as an agent to stimulate the repurchasing of beef by consumers. This is because ageing increases the shelf life. The latter however does not ensure the consistency in the tenderness of meat as it is influenced by genetics and environmental factors.

Heavier carcasses produced from feedlots that use beta-agonists, have a reduced ageing potential which affects the colour and appearance of the meat and its shelf-life. This consequently results in a reduced beef product safety ,which is not good for the health of consumers and the retail potential of the meat (Kilgannon *et al.*, 2019). This can be related to the early exhaustion of proteolytic activity at a higher temperature and a rapid pH decline, caused by an increased insulation from higher subcutaneous fat thickness (Bhat *et al.*, 2018b). Another reason behind reduced ageing potential is the increased release of lysosomal enzymes, especially cysteine after a disruption in the membrane layer of the lysosomes by ATP depletion. During ageing, there is a higher drip loss owing to the degradation of the cytoskeleton protein as the proteolysis progresses (Santos *et al.*, 2016). Shear force has a linear relationship with drip losses, therefore its dependence on tenderisation of the meat that follows post the pH and temperature decline *post mortem*.

2.8. Implications of the prevalence of high *rigor mortis* temperature carcasses

The increase in the production of heavier beef carcasses as discussed, is a challenge. It must therefore be noted that the plants that are designed for processing and distributors, find it challenging to handle the carcasses with the extra muscle weight and the heavier boxes for storage. The other growing concern is that the abattoirs and these plants where the carcasses are chilled and processed, have not changed over the last few decades(Agbeniga & Webb, 2018). This owes to reasons such as high costs for reconstruction and installation of these facilities with a design suitable for accommodating heavier and larger carcasses.

The rapid increase in population sizes has caused the demand for beef to increase, hence more diversion towards the production of more beef with larger carcass sizes. This has raised issues of over packing of chiller rooms beyond their carrying capacity.

The heavier carcasses have deeper muscles, which have a greater mass and are less oxidative(Kim *et al.*, 2015). The muscles have variant growth rates, volume, function, and metabolism of energy. The less oxidative muscles accelerate the rate of pH decline, due to the increased energy metabolism through accelerated glycolysis, hence the elevation of temperature of carcasses. This consequently result in a condition known as high *rigor* temperatures. whereby the pH drops below 6,0 while the carcass temperature is still excessively higher than 35˚C(Warner *et al.*, 2014a). This condition causes an abnormally higher rate of protein denaturation through proteolysis. The latter results in more losses of carcass mass during chilling.

Chapter 3

Materials and methods

3.1. Survey of abattoirs: Materials

Major abattoirs were visited across as many of the provinces as possible (Northern Cape, Gauteng, Limpopo, Northwest, Free State and Mpumalanga). The initial plan was to visit a total of 14 abattoirs, but due to the COVID-19 pandemic, most abattoirs were skeptical about giving access to the carcasses for the collection of data. The two provinces that were excluded from the data collection owing to the mentioned reasons were Kwa-Zulu Natal and the Eastern Cape. The Western Cape was also excluded due to very low slaughter numbers (the area is characterized by predominantly sheep production). The number of the abattoirs that were visited, amounted to a total of 12.

The following 12 abattoirs were visited:

3.1.1. Northern Cape: 1 abattoir

3.1.2. Gauteng: 6 abattoirs

3.1.3. Limpopo:1 abattoir

3.1.4. Northwest: 1 abattoir

3.1.5. Mpumalanga: 1 abattoir

3.1.6. Free State: 2 abattoirs.

These abattoirs were randomly selected after meeting with the industry role players, with the aim of getting direction towards the selection of abattoirs that are major suppliers of the beef that is consumed in the country. The majority of these abattoirs selected supply bulk beef to retailers, restaurants, and processing companies, and for this reason it was essential to investigate whether the occurrence of high *rigor* temperatures was high in these selected abattoirs. The majority of these abattoirs are located close to big cities, which comprise a large part of the major distributors of beef. These selected abattoirs also influence the country's overall value chain, as they contribute a high percentage of the agricultural Gross Domestic Product (GDP).

The conditions and procedures of these big abattoirs had a major influence on the final product quality. This implies that the prevalence of high *rigor mortis* temperature carcasses, was dependent on the conditions of the cattle that were slaughtered in these abattoirs. These on farm factors ranged from the measures taken to reduce stress during transportation to abattoirs before and at slaughter, the carcass weight, the use of beta-agonists, feeding regime , to the hygiene and the voltage and duration of the electrical stimulation in the abattoir. The conditions of the chillers also played a role as a contributing factor, with regards to the rate of air flow, the number of carcasses per chiller room and how close they were to each other. All these details were observed and taken note of upon every visit, as a contribution towards the analysis and the final conclusions of the prevalence of high *rigor mortis* temperature carcass conditions.

3.2. Methodology

As much information as possible was randomly collected from 12 abattoirs across South Africa. The data was collected between January 2019 and April 2021. An application was submitted to the Animal Ethics Committee (AEC) prior to the beginning of the collection of data from the abovementioned abattoirs. The approval certificate with conditions of submitting a permission letter upon every visit was granted, with a protocol number: NAS227/2019. The AEC conditions stated that a consent or permission letter must be uploaded on the ethics portal upon every visit and that was done. This research, however, did not include the use of live animals, but rather the use of *post mortem* measurements of sampling of beef carcasses. In that regard, there were minimal or no risks or harm to the researcher who collected the data and to the animals. Safety and precautionary measures were taken by the contact person who was appointed to supervise us namely, clean overalls, gumboots, hairnets, and helmets before entering the abattoir.

The study focused on two weight groups namely > 250kg and <230kg. An abattoir which does not use beta-adrenergic agonists was included. A full carcass specification (carcass weight, fat code and conformation), electrical stimulation procedures (voltage: high or low; duration, mechanism: rubbing bar, clamps, etc.), use of beta-adrenergic agonists, grain vs grass fed as well as chiller specs (temperature and capacity) were all included and considered. The above-mentioned information was provided by each abattoir upon every visit. This additional information will be useful in answering the question of why the high *rigor mortis* temperature frequency is higher or lower based on the findings.

The method that was used in collecting the above-mentioned data was qualitative as well as quantitative variables, as all these measures determined and explained how much the above-mentioned factors contribute to the variations in the high *rigor* beef carcasses. Quantitative methods were used to determine the prevalence of high *rigor mortis* temperatures and help with answering the primary research question or validating the hypothesis. All these factors influence the overall quality output of beef.

3.2.2. pH and temperature measurements

The pH and temperature reading of 90 carcasses (taken from the left side on the 12th rib of each carcass) per day was measured at 1 hour and 2 hours after slaughter for two days at each abattoir (n=180 at each abattoir). The pH meter that was used for reading is Portable SyberScan pH 11 pH meters (Eutech instruments Pte Ltd, Singapore) fitted with a glass body, gel filled spear tipped pH electrode (Eutech instruments Pte Ltd, Singapore) and Oakton temperature probe (Eutech instruments Pte Ltd, Singapore).

The first measurements were mostly taken just before the carcass entered the chiller rooms, followed by a second measurement that occurred after the placement of carcasses in the chiller rooms. The two pH, temperature and time measurements were recorded with a random selection of the 90 carcasses. The second measurement was timed to ensure that the drop in muscle pH was below 6.0 where the conversion of muscle to meat occurs. All the carcasses were hung by the Achilles tendon to allow more stretching by gravitational force, and chilled conventionally.

Taking readings 1 hour and 2 hours *post mortem* respectively, were to enable the observation of the pattern of how fast or slow the pH drops with reference to the drop in temperature (pH to temperature ratio). By 2 hours, the temperature should've have dropped to 35 ˚C or below that, and the pH dropped to 6.0 for the onset of *rigor*. This then gave a clear indication of whether high *rigor* temperature conditions have occurred or not.

Temperature and pH readings was taken from the *Longissimus lumborum* (LL) muscle, on third last thoracic rib. The reason for taking the readings on the left side of the carcass is because of the intention aimed at purpose of consistency, and to decrease any kind of variations. Care was taken to insert the pH meter in the same incision where it was previously inserted during the first reading. A new incision was used only if the previous incision was not located due to the carcasses drying out due to the air in the chiller rooms. This was to avoid errors and getting inaccurate readings and to increase the level of consistency, regarding the measurements. The pH/temperature probe was calibrated at ambient temperature using buffers of 4.00 and 7.00 and checked regularly for calibration. The knife that was used to make incisions together with the pH/temperature probe was washed and sterilized in hot water after measurements on a few carcasses.

H_0: There is a high prevalence of high *rigor mortis* temperatures in abattoirs across SA

H_0 : Increase in the carcass weight increases the prevalence of high *rigor mortis* temperatures

H$_1$: There is a low prevalence of high *rigor mortis* temperatures in abattoirs across SA

H$_1$: Increase in carcass weight does not increase the prevalence of high *rigor mortis* temperatures

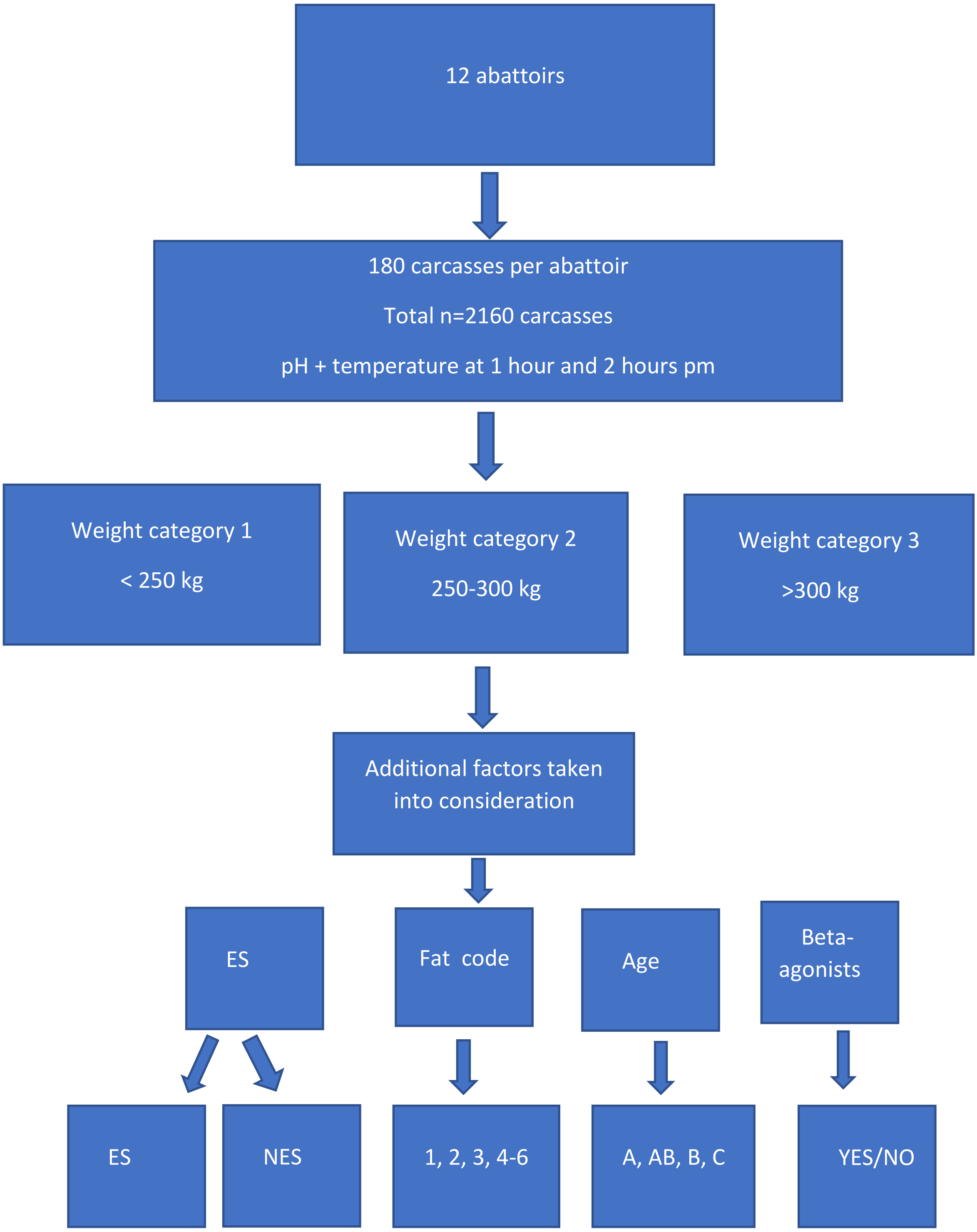

Diagram 3.2.1.1: experimental design

3.3. Statistical analyses

3.3.1 Recording and categorization of data for statistical analyses

The Chi-square option of the Frequency Procedure of SAS (2015) was used to compare frequencies of *rigor* temperature category (high *rigor mortis* temperature, no high *rigor mortis* temperature and risk of high *rigor mortis* temperature) per abattoir, per fat code (1 to 6), per carcass weight category (1: <250kg, 2: 250-300kg, 3: >300kg) and per age class (A, AB, B and C).

The data for *rigor mortis* temperature category was subjected to analyses of variance (ANOVA) with abattoir and weight category (1: <250kg, 2: 250-300kg, 3: >300kg) as whole plots. Means for the interaction abattoir x weight category were separated using Fisher's protected t–least significant difference (LSD) (Snedecor & Cochran, 1980). A probability level of 5% was considered significant for all significance tests.

3.3.2 Statistical analysis of the recorded data

All of the statistical analyses were performed using the pro logistic function in Genstat 2015 A mixed model procedure was used owing to reasons that this research used numerical (quantitative) data such as pH and temperature readings and categorical (qualitative) data. This mixed model included the use of analysis of variance (ANOVA), logistical regression model (logit model) and Chi-square to analyze numerical and categorical data.

In the logistical regression model, the pass or failure of high *rigor* temperatures were used as dependent variables and then carcass weights, carcass conformation, age, and fatness as independent variables.

Data of pH and temperature were subjected to analysis of variance (ANOVA), with the three carcass weight groups used as the main effect. Means separation was achieved by Fisher's protected t-test least significant difference (LSD) at the 5% level. Co-variables were included namely fatness, conformation, and electrical stimulation. This was aimed at working out the frequency of high *rigor* temperature occurrences and determining which variables had an effect on the occurrence. This was done using the proc frequency function of SAS, to determine the ratio of pass and failure for all the data recorded including data included on an abattoir basis.

Chapter 4

RESULTS AND DISCUSSION

4.1. Introduction

The aim of this research was to determine whether prevalence of high *rigor mortis* temperature carcasses in abattoirs across SA was high or not. The incidence of high *rigor* temperature occurs when the pH of the carcass drops below 6.0 while the temperature is still higher than 35 ˚C. This occurs due to a number of contributing factors, such as the feed type or the type of diet, the use of beta- agonists, electrical stimulation of carcasses (ES) and / or the chiller room temperature and cooling rates. There is little research in South Africa about the prevalence of high *rigor mortis* temperature beef carcasses at abattoirs. The prevalence of the different categories of high *rigor mortis* temperature beef carcasses assessed in the abattoirs across South Africa is presented in figure 4.1.

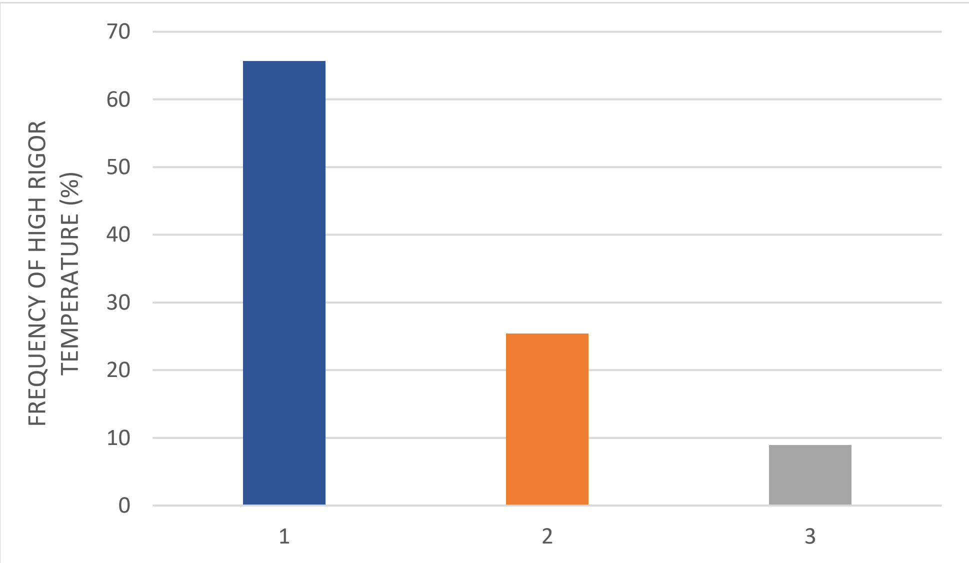

Figure 4.1.: Prevalence of high *rigor mortis* temperature beef carcasses assessed at 11 abattoirs across South Africa. Chi-square P value <0.0001(1= High *rigor* temperature, 2= Risk of high *rigor* temperature, 3= No high *rigor* temperature)

Temperature and pH measurements of a total of 1624 carcasses were recorded for this research based on a random sample of the major abattoirs in SA. 65.64% of carcasses in abattoirs that were visited went into *rigor* at a high temperature (>35°C), while 24.5% of the carcasses went into *rigor* at temperatures below 35°C and approximately 8.92% were at high risk of going into *rigor* at a high temperature (Figure 4.1). The carcasses that were at high risk were those that had a pH close to 6.0

at the 2 hours measurements but not yet below 6, while the temperature was above 35 ˚C. The assumption was therefore made in these cases that the pH would decline below 6 before the muscles chilled to below 35˚C. Figure 4.1 indicates that the prevalence of high *rigor mortis* temperature carcasses is a problem that needs to be given attention to in the beef industry, as it affects the final eating quality of beef (Strydom *et al.*, 2015). These results were similar to a survey done at seven Australian beef processing plants where overall the occurrence of high *rigor* temperature was 74.6%. Increasing days in the feedlot and heavier carcass weights were highly correlated and both caused an increase in the predicted temperature at pH 6 and in the percent high *rigor* temperature (Warner et al., 2014a).

4.2.1. Carcass Weight

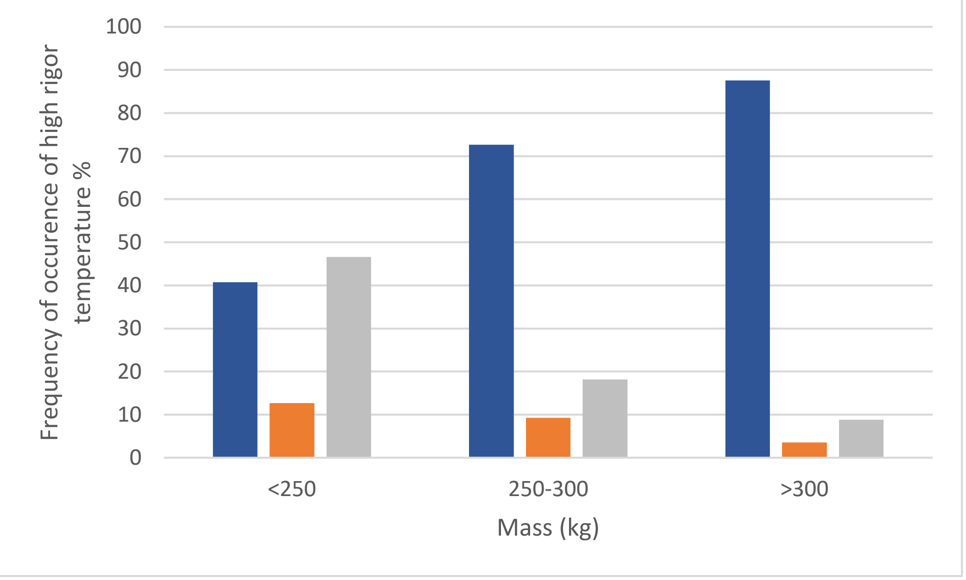

Figure 4.2: Prevalence of high *rigor mortis* temperature over three different carcass weight categories. Chi-square P value< 0.0001 (Blue= High *rigor mortis* temperature, Orange= Risk of high *rigor mortis* temperature, Grey= No high *rigor mortis* temperature)

The shift towards an increase in the production of lean and heavier carcasses, has proven to result in the increase in the prevalence of high *rigor mortis* temperature carcasses across SA. Figure 4.2 above clearly proves that to be true. The latter clearly indicates that the carcasses that weighed less than 250 kg, had a frequency of occurrence of high *rigor mortis* temperature of 40.76% as compared to those that weighed between 250-300kg and above 300kg with a frequency of occurrence of 72.62% and 87.59% respectively. As the carcass weight increases, the prevalence of high *rigor mortis* temperature conditions increases (P<0.001).

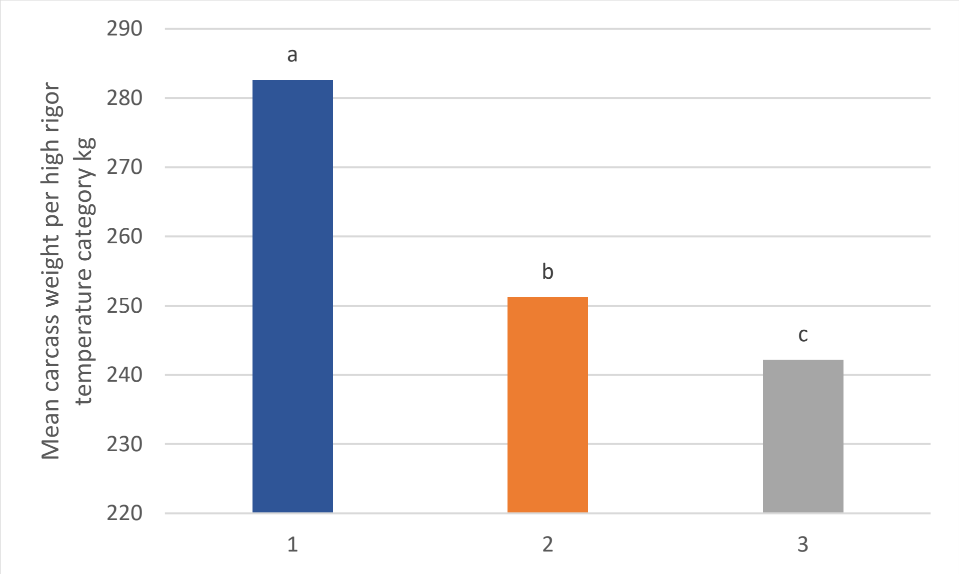

Figure 4.3. The mean carcass weight per high *rigor* category in kg. P <0.001(1= High *rigor mortis* temperature, 2= Risk of high *rigor mortis* temperature, 3= No high *rigor mortis* temperature [a,b,c] Values on the bars with different letters differ significantly

The graph (Figure 4.3) above clearly indicates that more than half of the carcasses measured across most of the abattoirs visited, were bigger and heavier carcasses with high *rigor mortis* temperature conditions. The mean weight for carcasses that fell under the high *rigor* group is 282.62kg, and for the no high *rigor* group is 242.17kg and for the high risk of high *rigor mortis* temperature is 251.24 kg. It can therefore be said, that in general, carcasses over 250kg are likely to go into *rigor* at high temperatures. This means that the main cause of *rigor* at high temperatures is carcass weight. This is an issue that should be focused on as the prevalence has been proven to be higher than normal, and this leads to increased variation in the quality of meat produced for the South African consumers. There is a significant effect (P<0.01) of carcass weight on the prevalence of high *rigor mortis* temperature conditions.

The feed consumed by cattle has the ability to modify the final quality of the beef and beef products, through the plane of nutrition and the feed type (Muir *et al.*, 2010). The bulk of the beef production in SA is through feedlots, which feed high energy diets. The use of beta-agonists simultaneously with the feeding of high grain diets, has resulted in the increased weight of the carcasses produced from those cattle. Warner et al., (2014), predicted with a model that for an increase in carcass weight from 200kg to 400kg ,the Temp@pH6 increased by 1.6˚ C and the percentage of high *rigor* *mortis* temperature occurrence increased from 56 to 81%. Beta-adrenergic agonist also lead to leaner carcasses but with more muscle mass, which results in a smaller surface area to volume ratio leading to a slower chilling process. Large cattle have a reduced surface area to weight ratio hence a relatively smaller surface area from which to disperse heat, than smaller cattle (Sjaastad et al. 2003). The cooling rate of these carcasses is influenced by the body's ability to dissipate heat after slaughter. This implies that the heavier carcasses (above 250kg) will cool slower than the lighter carcasses(<250kg), as they have higher temperatures.

The core body temperature of these heavier and larger carcasses emerging from the grain fed cattle, was discovered to be higher due the high heat increment from the high energy grains in the feedlot diets (Jacob et al., 2014b). Jacob et al. (2014), also suggested that the rate of *post mortem* metabolism was higher in carcasses from feedlot cattle as compared to those from grass-fed cattle. It was further stated that the loin muscle from the feedlot steers went into *rigor* faster than normal after slaughter. Steers from feedlots have an increased risk of high *rigor mortis* temperature because of an increase in core body temperature, a reduction in rate of cooling and an increase in the rate of pH decline post-slaughter. These effects are likely due to a combination of effects on body metabolism and size (Jacob et al., 2014).

Carcass weight plays a role in this research as the main effect contributing towards the increase in the prevalence of high *rigor mortis* temperature conditions, with an increase in carcass weight leading to an increase in the prevalence of high *rigor mortis* temperature conditions. This is proven as a fact because the weights are equally represented enough for a conclusion to be made that the heavier the carcass, the higher the prevalence of high *rigor* temperature conditions in carcasses.

4.2.2. Fat Code

The South African beef industry has been producing leaner beef carcasses, as compared other country such as the USA. The increased fat content in the carcasses has an effect more on the chilling rate after slaughter. The fat layer acts as an insulator that prevents the effective dissipation of heat from the surface of the carcass, consequently resulting in a slower chilling rate of the carcasses. This is, however, not an issue in the carcasses produced in most of the abattoirs across SA, as most of the carcasses produced are that of fat code 2. Most of the consumers in SA , prefer meat that has less fat content, as it is regarded as the most fitting red meat that fits their healthy lifestyle and diets(Erasmus & Hoffman, 2017).

Table 4.1: The frequency and cumulative frequency of prevalence of high *rigor* per fat class/ category in %

Fat Code	Frequency	% Frequency
1	43	3
2	1392	86
3	155	10
4	16	0.1
5	11	0.7
6	3	0.2

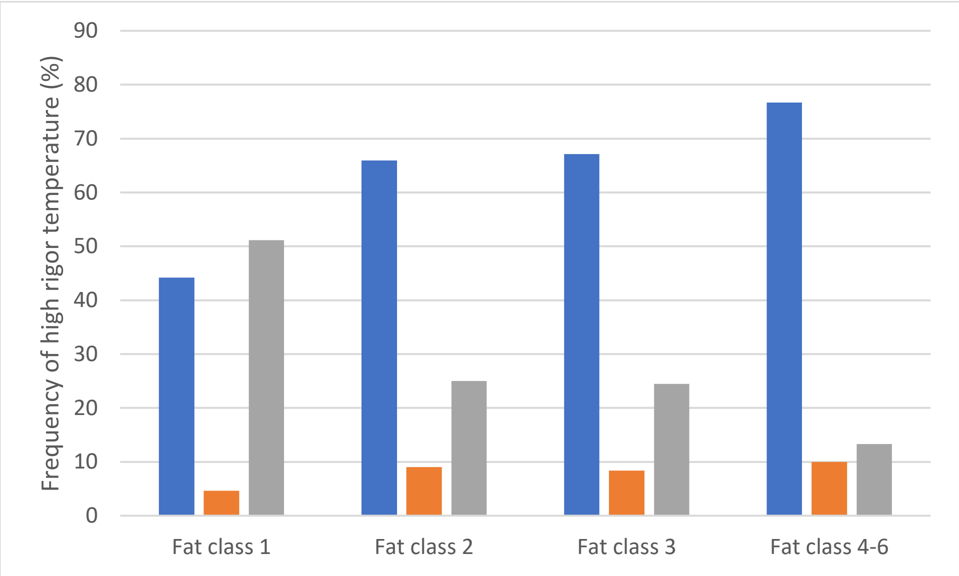

Figure 4.4: The prevalence of high *rigor mortis* temperature carcass conditions in different fat classes/codes (Chi-square P=0.0070) (Blue= High *rigor mortis* temperatures, Orange= Risk of high *rigor mortis* temperatures, Grey= No high *rigor mortis* temperatures)

Table 4.1 above indicates that most of the carcasses that were assessed in this research were in fat code 2 (86% frequency). This is because South African beef production is geared towards producing beef from lean animals. These are carcasses that are still young, and the fat has not yet accumulated. Therefore, the carcasses are those that were in feedlots and fed high concentrate diets with growth promoters such a beta-agonists to level out the effect of maturity on carcasses. Beta-agonists channels the body more towards the increase in the synthesis of protein and less towards the synthesis of fat and its accumulation (Strydom & Smith, 2010; Parr *et al.*, 2016). This situation therefore implies that a strong conclusion cannot be made based on this research data collected, as further research would be required on the other fat codes before a conclusion can be made. Certain patterns can however be seen.

Even with the skewed data, it is observed that there is an increase in the prevalence of high *rigor mortis* temperatures with an increase in the fat code. This is as observed in Figure 4.4, were the prevalence in fat code 4-6 was as high as 76.67%, and the fat code 1 and 2 with a lower prevalence of high *rigor* at 44.19% and 65.95% respectively compared to the latter. In the LL muscles, the thicker backfat corresponds with slower temperature decline and faster pH decline(Aalhus *et al.*, 2011). The faster pH decline and slower cooling rate in fatter carcasses, results in the variation in the colour of the carcasses, ranging from light to more pale colour(Poveda-Arteaga *et al.*, 2023). Increase in the accumulation of fat increases the insulation of the carcass, thus preventing the effective dissipation of heat. The latter affects the cooling rate of these carcasses with high fat content as the temperatures are still high while the pH has dropped to below 6.0. Research has shown that an increase in fat (subcutaneous and intramuscular) can lead to both insulin resistance and an increase in the production of the hormone leptin(Warner *et al.*, 2014a). Both these factors can lead to an increase in core body temperature, which could become exacerbated with the resultant stress and the associated catecholamine-induced heat production around transport and slaughter. It is highly likely that even a small increase in body temperature as the animal enters the kill-chain could be enough to ensure that a carcass becomes classed as high *rigor mortis* temperature (DiGiacomo *et al.*, 2014). This is however an unlikely scenario in South African feedlot cattle as the use of beta-adrenergic agonists results in a leaner carcass with very little intramuscular fat.

This leads to the conclusion that fat code has a very little effect on the prevalence of high *rigor mortis* temperature carcass conditions in abattoirs across SA. The latter is a preference for most of the beef consumers in SA, and producers make more money on the higher lean mass than fat as they are paid by the mass overall.

4.2.3. Age

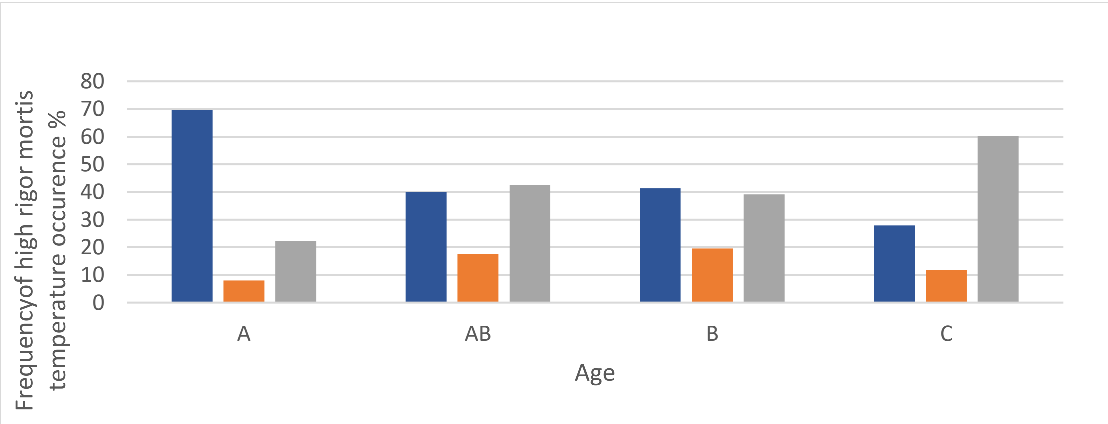

Figure 4.5: The effect of age class on the prevalence of high *rigor* per *rigor* category. Chi-square P<0.0001(Blue= High *rigor mortis* temperatures, Orange= Risk of high *rigor mortis* temperatures, Grey= No high *rigor mortis* temperatures)

The age of an animal is determined by counting the number of permanent incisors (Moholisa *et al.*, 2017). Most of the A and AB carcasses produced in SA, are produced in the feedlot with a high grain/concentrated diet. Grain feeding and the use of beta-agonists in feedlots results in the production of cattle that yield larger carcasses, which tend to be more difficult to chill effectively as they have a higher core body temperature and therefore a reduced surface area for the dissipation of heat during chilling. The latter results in the rapid pH decline and a slower temperature decline. Figure 4.5 indicates that there is an effect of age on the prevalence of high *rigor mortis* temperature carcass conditions, with a chi square P value of P<0.0001.

The graph above (figure 4.5) shows that with an increase in age, there is less chance of the carcass going into *rigor* at high temperatures, meaning that there is an inverse relationship existing between age and the prevalence of high *rigor mortis* temperatures. The carcasses in the C age group, have a high percentage of 60.9% of the carcasses that have no prevalence of high *rigor mortis* temperatures and 11.76% of the carcasses at minimal risks of high *rigor* occurrence, with a 27.94% occurrence of high *rigor* temperature carcasses. The latter percentage of high *rigor* temperature occurrence in the age category C is the lowest compared to that of A, AB, and B , with a frequency of 69.66%, 40.00% and 41,31% respectively. It must however be mentioned that even though there is an age effect according to the graph, it is still difficult to make a conclusion as most of the carcasses were A age carcasses (1427 carcasses in this category). This is because most of the carcasses produced in SA abattoirs and the abattoirs that were visited are A and AB class, and therefore from younger animals. They are consequently susceptible to getting into high *rigor* at higher temperatures. Most C class carcases are finished on the veld,hence the cattle have a most likely chance of having lower metabolic rates compared to those cattle finished on feedlots and threated with growth promotants.

With fat code and age, a conclusion can’t be made that they are both definitely an issue when it comes to the prevalence of high *rigor mortis* temperatures as the data is a bit skewed. This is due to the fact that there will be a need to conduct further tests to prove that both are an issue in the prevalence of high *rigor mortis* temperature conditions in abattoirs across SA.

4.2.4. The prevalence of high *rigor mortis* temperature carcasses per abattoir

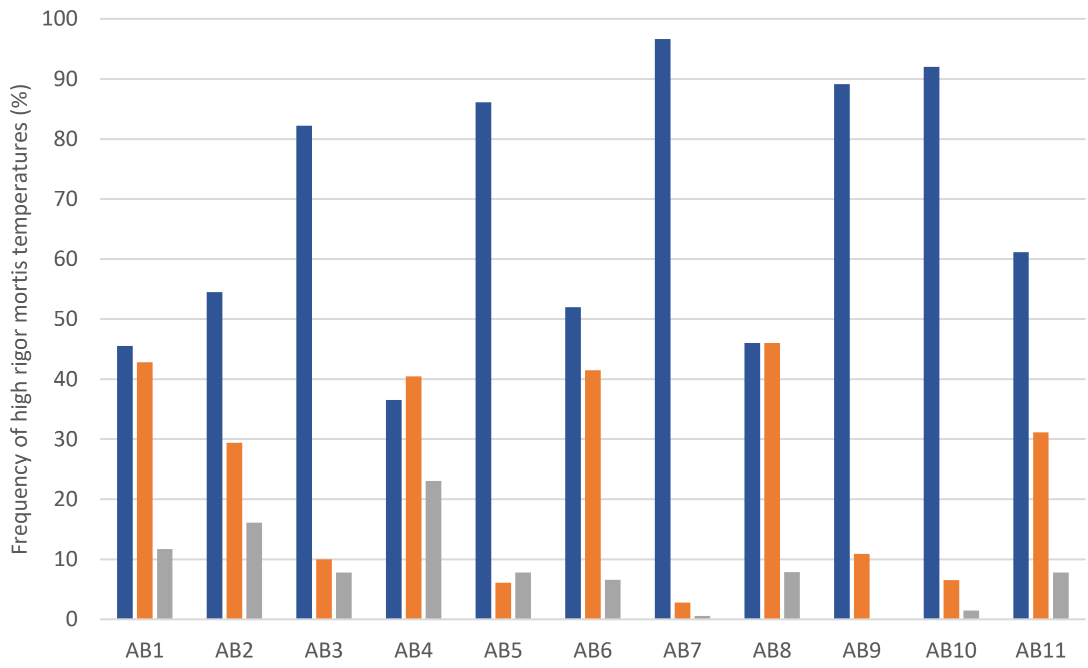

Figure 4.6: The prevalence of high *rigor mortis* temperature per abattoir (chi-square p<0.0001) (Blue= High *rigor mortis* temperatures, orange= Risk of high *rigor mortis* temperatures, grey= No high *rigor mortis* temperatures)

A total of 12 abattoirs across SA were visited. Temperature and pH readings were taken on a total of 180 carcasses per abattoir over a period of 2 days (90 carcasses per day).The graph above clearly indicates that high *rigor mortis* temperature carcass conditions are definitely a problem in most if not all the abattoirs across SA, that slaughter beef. There are abattoirs that have a very high frequency compared to others. The frequency of the prevalence of high *rigor mortis* temperature carcasses ranged from as low as 36.52% (AB4) to as high as 96.65% (AB7). AB9, AB10 and AB7 have the highest occurrence of high *rigor mortis* temperature carcasses, with frequencies of 89.13%, 92.03% and 96.65% respectively. 5.62% of the carcasses in the AB7 abattoir fell under the weight category 1 (less than 250 kg), while 30.33% of the carcasses were in the weight category 2 (250-300kg) and 64.05% of the carcasses fell under the weight category 3 (>300kg). This implies that the bulk of the carcasses produced in this abattoir weighed over 300kg.The same can be said about the other abattoirs like AB9 and AB10, with regards to majority of the carcasses falling under the weight category 2 and 3. AB10 had 34.06% of the carcasses weighing between 250 and 300kg, while 65.94% of the carcasses weighed above 300kg. The carcasses from the above-mentioned abattoirs were heavier, and this implied that they did not cool down fast enough, because some of them where packed tightly together and their sizes were too big for the sizes that the chillers were designed to accommodate. These carcasses were packed closer together as they are bigger than the normal sized carcasses that the chiller rooms are designed to accommodate. This consequently results in the interruption of the effective flow of air in the chiller to cool the carcasses down at an optimum level, hence the carcasses take longer to cool down.

AB9 is the abattoir that had other factors that contributed to the higher frequency of high *rigor* temperature carcass occurrence as seen in figure 4.6 above. These included the fact that the carcasses took longer on the line to get into the chiller rooms, and the staff did not clear the lines before tea and lunch breaks, so the carcasses hung for those times. So, the pH had already dropped significantly by the time the carcasses got into the chiller rooms. The latter abattoir had 57% of its carcasses falling under the weight category of 2, and only 28% in weight category 1. These carcasses were also heavier, and they were also left to hang on the line for long before they could go into the chilling rooms. AB3 also had the bulk of all carcasses in weight categories two and three as well as having 25% of all carcasses being classed as fat class 3, which is higher than the average fat class of two (in this study). Fat insulates the heat and makes the cooling rate to decrease, hence the increase in the prevalence of high *rigor mortis* temperatures

Abattoirs such as AB1, AB4 and AB8 which had 45.56%, 36.52% and 46.06% of their carcasses with high *rigor* temperatures respectively, had the lowest prevalence of high *rigor mortis* temperatures compared to other abattoirs that were also visited. These abattoirs had majority of their carcasses falling under the weight category of 1 which is <250kg (56.43%, 54.49% and 72.12% respectively) and the remaining carcasses fell under the weight category 2, with almost no carcasses falling under the weight category of 3. This proves that mass is one of the major effects contributing towards the prevalence of high *rigor mortis* temperatures and that there is a directly proportional relationship existing between carcass weight and the prevalence of high *rigor mortis* temperatures. AB1 abattoir had about half of its carcasses falling under the B and C age group (38% in C age group). This implies that these carcasses were from older cattle (therefore grass fed), hence a lower core body temperature and lower insulin resistance, making the dissipation of heat much more effective (DiGiacomo *et al.*, 2014). Abattoir AB2 did not make use of any beta-agonists and they had more advanced and more updated chiller rooms that are more effective at chilling the carcasses properly. The latter abattoir also did not have its carcasses packed closer to each other in the chillers as the majority was lighter carcasses. All these factors mentioned, has resulted in the incidence of occurrence of high *rigor* being lower (54.44%) as compared to other abattoirs visited.

4.2.5. The effect of no electrical stimulation

During the collection of data, two abattoirs had issues with their electrical stimulator on the line. One of the abattoirs' electrical stimulators was not working on either of the days the abattoir was visited, while one did not have a working electrical stimulator on the first day it was visited. Even though this was not a reflection of what actually occurs at the abattoir (where ES of carcasses occurs under normal conditions), it was decided that the data be recorded and analysed separately from the main group to get the idea of what the situation will be like should ES be removed from the abattoir line. These results will still shed some light on the potential of effective management of ES usage, even though it may not be completely accurate due to the sample groups being smaller than the main group.

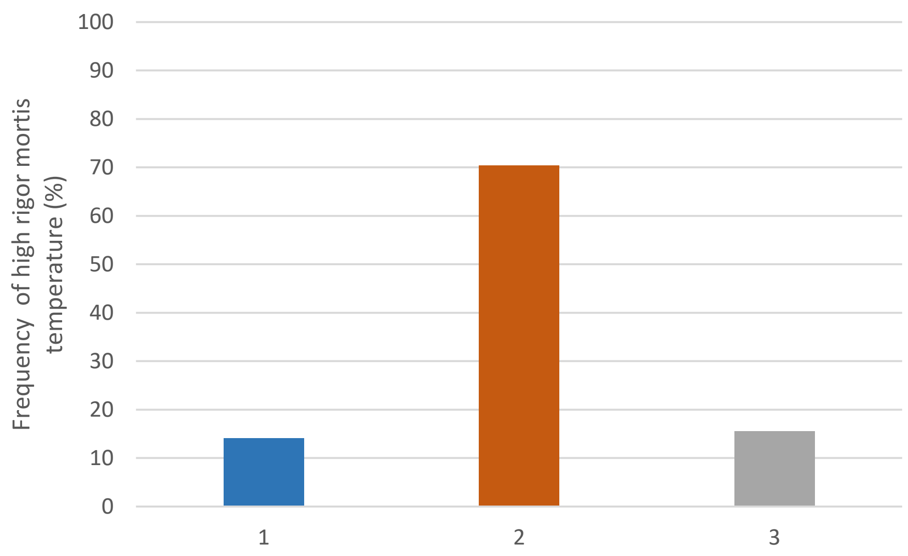

Figure 4.7: The prevalence of high *rigor mortis* temperature in NES abattoirs Chi-square P<0.0001 (1= High *rigor mortis* temperature, 2= Risk of high *rigor mortis* temperature, 3= No High *rigor mortis* temperature)

Figure 4.7 above indicates that even though some of the abattoirs did not use ES, *rigor* at high temperature still occurred. For the two abattoirs that did not make use of ES, there was 14.07% of the carcasses with high *rigor mortis* temperatures, 15.56% did not have high *rigor mortis* temperatures and 70.37% of the carcasses were at the risk of getting high *rigor mortis* temperatures.

This first abattoir had lower prevalence of high *rigor mortis* temperature carcass conditions compared to the abattoirs where ES was used. Most of the carcasses from this abattoir had carcass weights of less than 250 kg and the abattoir made use of huge chillers so the carcasses chilled much more effectively than at the other abattoir that had no ES on the one day of the visit and had it on the other day. The space that was in the chillers made it easier for the carcasses to be packed properly with enough space in between for effective flow of air. ES , as a contributing factor, might have also played a contributing role with regards to its timing and its duration of application not being managed right in most of these abattoirs that high *rigor* temperature carcass condition problems. The duration and the timing of ES play a role in the quality of meat. Thompson (2001) emphasized that early stimulation (3 minutes pm), can cause more harm than late application in terms of beef eating qualities like tenderness (40 minutes pm). This would in turn affect the decline in pH, enzyme activity and the shear force of meat, and therefore the colour and tenderness of meat. The ES levels out the effect of beta agonists by reducing the toughness in meat. Even though ES might come with its advantages especially in SA ,where most carcasses slaughtered are from feedlot beef that has beta-agonists used on them, there is a need to create a balance in the effective application of ES to optimise meat quality through the creation and implementation of protocol regarding the use of ES (Webb & Agbeniga, 2020). This is more important due to the increase in the production of heavier carcasses, which has increased the variability in the quality of meat sold to consumers (Strydom *et al.*, 2019).

The results above insinuate that ES contributes to the prevalence of high *rigor mortis* temperatures, even though it is not the only contributing factor. The latter is in no way saying that the use of ES must be removed completely from abattoirs, as it aids positively towards reducing the variation in the quality of meat. It should however be managed more effectively to avoid under or overstimulation of these carcasses.

Chapter 5

Conclusions

The prevalence of high *rigor mortis* temperature carcasses in abattoirs across SA, is as high as 65.64%, due to a combination of factors, of which carcass weights exceeding 250kg is the most important causative factor. Only 8.92% off the carcasses across all the abattoirs visited were at risk of going into high *rigor mortis* temperatures, while 24.5% of the carcasses did not have high *rigor mortis* temperatures.

The carcasses that had high *rigor mortis* temperature conditions had an average weight of 283kg, those at risk had an average weight of 251kg and those with no high *rigor* temperatures had an average weight of just over 250kg.The fact that most of the beef consumed in SA is produced from feedlots, and are fed high grain diets, coupled with the use of beta-agonists, the carcasses are going to be heavier, with more lean mass. The abattoirs that were visited, are equipped with chillers which were previously designed with a lighter carcass specification and requirements in mind, and due to the fact that the carcasses are now heavier, it now becomes a challenge for the chiller rooms to cool down these heavier carcasses efficiently and effectively. Even though there is a noticeable effect of age and fat code on the frequency of high *rigor* temperature occurrence, a conclusion cannot be made based only on the findings of this research. This is because the data is much more skewed as most of the carcasses produced in SA abattoirs are A and AB age, with a fat code of 2. ES also contributes to the incidence of occurrence of high *rigor* in the heavier carcasses (by causing a rapid drop in pH), and it is therefore required that it is managed more effectively (no overstimulation) as it has a positive effect on meat tenderness (especially on carcasses produced from animals supplemented with beta-agonists). New measures need to be put in place in the abattoirs to accommodate the heavier carcasses produced. These can include reducing or adjusting the number of carcasses entering the chiller rooms per time and adjusting the timing and the duration of the ES. It is well understood however, that adjusting the number of carcasses will probably not be practical because, it would result in a decrease in the production of beef. The time the carcasses take on the line to get into the chiller room must also be monitored closely.

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