Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Carcass and Meat Quality Characteristics of Romney, 7/8 and 15/16 Wiltshire Lambs

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Science

in

Animal Science

at Massey University, Palmerston North, New Zealand



Emma Kate Yorke

2026

Abstract

There has been increased interest in self-shedding sheep breeds, such as the Wiltshire, as the cost to shear sheep in New Zealand rises and coarse wool prices decrease. Wiltshire are currently judged on a subjective basis where they are often discounted for meat yield due to their long “leggy” frame. There is limited objective data to support this. A previous study looked at the meat quality of Romney and 3/4 Wiltshire lambs and found little difference in carcass and meat quality; however, a larger proportion of Wiltshire genetics will give a better indication of the suitability of the breed in New Zealand production systems. Therefore, the objective of this study was to investigate whether 7/8 and 15/16 Wiltshire lambs have differing carcass and meat quality characteristics to Romney lambs. Two separate studies were carried out with fourteen 7/8 Wiltshire lambs managed together with fourteen Romney lambs in 2024. In 2026 a further fifteen 15/16 Wiltshire lambs were raised with thirteen Romney lambs. In both 2024 and 2026 both breeds were on perennial ryegrass-based pasture, had identical management practices and were slaughtered as one group. The carcass characteristics investigated included the start weight, final live weight, hot carcass weight, dressing out, muscle weight and percentage, femur length, dissectible fat percentage and the muscularity index. The meat quality attributes measured were the pH, colour, water holding capacity and tenderness following standard objective measurement methods. The results revealed that both 7/8 and 15/16 Wiltshire had a heavier final live weight and hot carcass weight, a greater dressing out and muscle percentage and a lesser dissectible fat percentage than Romney lambs ($P<0.05$). The 15/16 Wiltshire had a longer femur length and greater muscularity index ($P<0.05$) which was not found when comparing 7/8 Wiltshire with Romney. There was no difference between 7/8 Wiltshire and Romney for any meat quality measurements ($P>0.05$). The meat from 15/16 Wiltshire had a lower ultimate pH, shear force and a greater chromameter redness compared to Romney ($P<0.05$). The 7/8 and 15/16 Wiltshire lambs can produce equal to or greater amounts of lean meat that is a similar quality to that of Romney lambs. Overall, these two studies show that producing lambs using the Wiltshire breed is unlikely to negatively impact potential meat yield or eating quality.

Acknowledgements

First and foremost, I would like to thank my supervisors Dr Nicola Schreurs, Dr Natalia Martin and Dr Paul Kenyon for their support throughout my master's. I appreciated your willingness to answer all my questions even if I had to check my list to make sure I had asked them all. Thank you for always being available and willing to provide me with any resources or extra encouragement that I needed. Your guidance has been invaluable throughout this process.

I would also like to thank Catriona for giving me the opportunity to go out on lambing beats. I thoroughly enjoyed the chance to see the lambs as newborns and follow them all the way through the process. To Mark and Brian thank you for caring for the ram lambs from weaning onwards and allowing me to help with the weighing even if I had trouble reading the tiny numbers on the tags. Also thank you to Dr Nick Sneddon for providing tech support, general knowledge and advice.

Thank you to my friends for always being there and making sure we attended every university event with free food that we could. Having such a great group of people to laugh and struggle with made this process inexplicably more enjoyable.

I would also like to thank the C. Alma Baker Postgraduate Scholarship, Hudson and McGowan Scholarship, Millar Massey Buchanan Scholarship, Sinclair Cummings Veterinary and Animal Sciences Scholarship, Charles Elgar Scholarship and the Leonard Condell Farming Research Scholarship for providing financial support.

Finally, thank you to my family for their unwavering support. I appreciate that you guys are always there with a listening ear and that you never let me give up. I would not have achieved any of this without you, I am privileged to have you all in my life.

Table of Contents

Abstract i
Acknowledgements iii
Table of Contents v
List of Tables vii
List of Figures viii
List of Abbreviations viii
Chapter 1: General Introduction 1
Chapter 2: Literature Review 3
2.1 Introduction 3
2.1.1 The New Zealand Sheep Industry 3
2.1.2 The Primary Product Produced by New Zealand Sheep Farmers 3
2.1.3 The Interest in Shedding Sheep for New Zealand Farmers 5
2.1.4 Carcass Classification and Meat Quality 6
2.1.4.1 Carcass Classification Objective 6
2.1.4.2 Carcass Classification Criteria 7
2.1.4.3 Meat Quality 7
2.2 The Effect of Different Sheep Breeds on Carcass Characteristics 8
2.2.1 Carcass Weight 8
2.2.2 Dressing Out Percentage 11
2.2.3 Carcass Composition 11
2.2.4 Muscle-to-Bone Ratio 16
2.2.5 Muscularity 19
2.3 The Effect of Different Sheep Breeds on Meat Quality 19
2.3.1 pH 19
2.3.2 Colour 23
2.3.3 Water Holding Capacity 27
2.3.4 Tenderness 30
2.4 Research Objective 33
Chapter 3: Materials and Methods 35
3.1 Carcass Characteristics 36
3.2 Meat Quality 38
3.2.1 Ultimate pH 38

3.2.2 Meat Colour 38
3.2.3 Water Holding Capacity 40
3.2.4 Shear Force 40
3.3 Statistical Analysis 41
Chapter 4: Results 43
4.1 Carcass Characteristics – Romney versus 7/8 Wiltshire 43
4.2 Carcass Characteristics – Romney versus 15/16 Wiltshire 45
4.3 Meat Quality – Romney versus 7/8 Wiltshire 47
4.4 Meat Quality – Romney versus 15/16 Wiltshire 49
Chapter 5: Discussion 51
5.1 Carcass Characteristics 51
5.1.1 Live weight and Carcass Performance 51
5.1.2 Carcass Composition and Shape 52
5.2 Meat Quality 53
5.3 Implications 54
5.4 Limitations 55
5.5 Conclusion 56
Chapter 6: References 57
Chapter 7: Appendices 69
7.1 Appendix: SAS Code for Carcass Characteristics 69
7.2 Appendix: SAS Code for Meat Quality 70

List of Tables

Table 2.1 Lamb and Mutton produced and exported from New Zealand 4

Table 2.2 Beef + Lamb 2023-2024 dollar per farm type analysis for sheep and wool 5

Table 2.3 A summary table of representative studies examining carcass weight and dressing out percentage of offspring of pure and crossbred meat breeds that have a wool fleece 9

Table 2.4 A summary table of representative studies examining carcass weight and dressing out percentage of offspring of pure and crossbred meat breeds with a hair or shedding fleece 10

Table 2.5 A summary table of representative studies examining carcass composition of the offspring of purebred meat breeds with a wool fleece 14

Table 2.6 A summary table of representative studies examining carcass composition of the offspring of pure and crossbred meat breeds with a hair or shedding fleece 15

Table 2.7 A summary table of representative studies examining the muscle-to-bone ratio and muscularity of the offspring of purebred meat breeds with a wool fleece 17

Table 2.8 A summary table of representative studies examining the muscle-to-bone ratio and muscularity of the offspring of pure and crossbred meat breeds with a hair or shedding fleece 18

Table 2.9 A summary table of representative studies examining the pH of the offspring of purebred meat breeds with a wool fleece 21

Table 2.10 A summary table of representative studies examining the pH of the offspring of pure and crossbred meat breeds with a hair or shedding fleece 22

Table 2.11 A summary table of representative studies examining the meat colour of the offspring of purebred meat breeds that have a wool fleece, measured using the International Commission on Illumination system (CIE, L*, a* and b* parameters) 25

Table 2.12 A summary table representative studies examining the meat colour of the offspring of pure and crossbred meat breeds with a hair or shedding fleece, measured using the International Commission on Illumination system (CIE, L*, a*, and b* parameters) 26

Table 2.13 A summary table of representative studies examining the water holding capacity of the offspring of purebred meat breeds with a wool fleece 28

Table 2.14 A summary table of representative studies examining the water holding capacity of the offspring of pure and crossbred meat breeds with a hair or shedding fleece 29

Table 2.15 A summary table of representative studies examining the tenderness of the offspring of purebred meat breeds with a wool fleece 31

Table 2.16 A summary table of representative studies examining the tenderness of the offspring of pure and crossbred meat breeds with a hair or shedding fleece 32

Table 4.1 Live weight and carcass performance (mean ± SEM) of Romney and 7/8 Wiltshire lambs. Hot carcass weight (CW) was fitted as a covariate for carcass composition and shape obtained by physical dissection of the hind leg. 44

Table 4.2 Live weight and carcass performance (mean ± SEM) of Romney and 15/16 Wiltshire lambs. Hot carcass weight (CW) was fitted as a covariate for carcass composition and shape obtained by physical dissection of the hind leg. 46

Table 4.3 Meat quality characteristics (mean ± SEM) from Longissimus lumborum muscle samples of Romney and 7/8 Wiltshire lambs. Ultimate pH was fitted as a covariate for colour, water holding and tenderness characteristics. 48

Table 4.4 Meat quality characteristics (mean ± SEM) from Longissimus lumborum muscle samples of Romney and 15/16 Wiltshire lambs. Ultimate pH was fitted as a covariate for colour, water holding and tenderness characteristics. 50

List of Figures

Figure 2.1 Carcass composition of the offspring of pure and crossbred meat breeds with a wool versus hair or shedding fleece.....13

Figure 3.1 A schematic diagram showing the partitioning of the lamb Longissimus lumborum muscle for meat quality assessment. Adapted from Rawidech (2024) 39

List of Abbreviations

CW	Carcass weight
DO%	Dressing out percentage
IMF	Intramuscular fat percentage
kgF	Kilogram-force
M:B	Muscle-to-bone ratio
PCRU	Pasture and Crop Research Unit
SF	Shear Force

Chapter 1: General Introduction

The primary breed farmed in New Zealand are Romney which are a dual-purpose breed that produce both meat and strong wool (Beef + Lamb New Zealand, 2023, n.d.-a). However strong wool has seen considerable competition from alternative products made from synthetic materials which has reduced its value (Ministry for Primary Industries, 2019). Along with this there has been an increase in shearing costs, meaning shearing strong wool breeds is no longer profitable (Beef + Lamb New Zealand, 2025b; Johnson et al., 2021). This has led to changes within the majority of the New Zealand sheep industry with a shift in the primary production focus from wool to meat (Beef + Lamb New Zealand, 2023). As a result there has been increased interest in the viability of self-shedding sheep breeds such as the Wiltshire (Beef + Lamb New Zealand, 2023, 2024b).

Carcass characteristics and meat quality traits have been found to vary between different breeds of sheep (Schreurs & Kenyon, 2017a, 2017b). The performance of Wiltshire lambs in terms of carcass and meat quality characteristics is not well known and is often based on subjective observations rather than objective measurements (Farrell et al., 2020; Johnson et al., 2021; Sneddon et al., 2024). Subjectively Wiltshire lambs have been assessed to have a longer "leggy" frame (S. Morris, personal communication, September 24, 2025) which is assumed to result in a less valuable carcass compared to those of popular New Zealand meat breeds (Kirton et al., 1985; Nsoso et al., 2000; Schreurs & Kenyon, 2017b). However, the observable shape of the live animal has been shown to have minimal correlation to the value of the carcass (Kirton & Pickering, 1967; Nsoso et al., 2000).

The objective of this study was to investigate whether 7/8 and 15/16 Wiltshire lambs have differing carcass and meat quality characteristics to Romney lambs. The result of this research will allow a better understanding of the meat production and yield potential of Wiltshire lambs which can then be used to infer the carcass value and expected returns for those that utilise the breed.

Note

The experimental component of this thesis has been submitted in part elsewhere. It has been reformatted and presented here with permission:

Yorke, E., Martín, N., Kenyon, P., Morris, S., & Schreurs, N. (under review). BRIEF COMMUNICATION: Carcass and meat quality characteristics of Wiltshire compared to Romney lambs. *New Zealand Society of Animal Production 86*

Chapter 2: Literature Review

2.1 Introduction

2.1.1 The New Zealand Sheep Industry

Sheep farming is a major sector of New Zealand's agriculture industry. Globally, New Zealand is the fifth biggest exporter of sheep meat and the third largest exporter of wool (Beef + Lamb New Zealand, 2023; FAOSTAT, 2023). Differing consumer demands, land use competition, changing climatic conditions and the increasing popularity of alternative products has resulted in a 56% decrease in sheep numbers since 1991-92 (Beef + Lamb New Zealand, 2023; Journeaux et al., 2017; McRae et al., 2018; Ministry for Primary Industries, 2019; Montossi et al., 2013). Despite this, the number of lambs produced has only fallen 13% (Beef + Lamb New Zealand, 2023) . Producers have been able to remain profitable by enhancing farm systems and making substantial investments to improve the genetics of their flocks (Beef + Lamb New Zealand, n.d.-b). These changes include the increased use of terminal sires, which contributed to a 37% increase in the live weight of lambs and increased lambing percentages which increased the lambing performance per ewe by 24% since 1990 (Beef + Lamb New Zealand, 2023; Johnson et al., 2021; Morris, 2013). Another notable improvement within the industry is the 114% increase in the kilograms of lamb meat produced per ewe annually (Beef + Lamb New Zealand, 2023). Along with improved production, specialised marketing has allowed access to new markets and established New Zealand meat and wool as premium products.

2.1.2 The Primary Product Produced by New Zealand Sheep Farmers

One of the largest changes in the sheep industry has been the shift in primary production focus from wool to meat (Beef + Lamb New Zealand, 2023). In the 2023/2024 season, over 95% of all meat produced was exported to 98 countries (Meat Industry Association of New Zealand, 2024a). In total, this was 389,509 tonnes of sheep meat valued at $3.6 billion (Meat Industry Association of New Zealand, 2024a). These exports are predominantly high value lamb meat and lower value mutton, as seen in Table 2.1. Information gathered by the Meat Industry Association of New Zealand (2024b) shows that the main New Zealand export market for sheep meat was China, with 48% of the export volume at 187,970 tonnes for the 12 months up to June 2024. This was followed by the United Kingdom who imported 38,787 tonnes from New Zealand, which made up 10% of the market share, and then the United States with 9% of the

market at 34,092 tonnes (Meat Industry Association of New Zealand, 2024b). Sheep meat revenue is now a significantly higher percentage than wool revenue of the total gross farm revenue (GFR) on all classes of farms, except the South Island High Country as seen in Table 2.2 (Beef + Lamb New Zealand, 2024a). This is due to a breed difference, with the South Island High Country predominantly farming fine wooled Merinos compared to the strong wool breeds above 30 microns that are dominant in the rest of the country (Beef + Lamb New Zealand, 2025a; Corner-Thomas et al., 2013; Mao, 2025). Fine wool is in higher demand and more valuable as its low micron diameter makes it softer and minimises the occurrence of the itchy texture that can be associated with strong wool (Aryal et al., 2009; Doyle et al., 2021). Therefore, fine wool maintains a high-value textile market share (Doyle et al., 2021). In comparison, strong wool has seen considerable competition from alternative products made from synthetic materials which have reduced its value (Ministry for Primary Industries, 2019). This lower value per kilogram in addition to increased shearing costs, means that the cost of shearing is now greater than the revenue made from selling wool on most classes of farms (Beef + Lamb New Zealand, 2025b; Johnson et al., 2021). Despite this deficit, strong wool breeds of sheep must continue to be shorn to maintain the animal's health and comfort so producers are unable to avoid the cost of shearing (Fisher & Roadknight, 2024).

Table 2.1 Lamb and Mutton produced and exported from New Zealand

	Lamb			Mutton		
	2021-22	**2022-23**	**2023-24**	**2021-22**	**2022-23**	**2023-24**
Numbers (millions)	22.0	21.0	21.1	16.3	15.4	14.8
Slaughtered (millions)	17.8	17.7	18.2	3.6	3.3	3.1
Carcase Weight (kg)	19.0	19.4	19.2	25.6	26.1	25.9
Production	338.3	343.6	348.6	93.6	87.7	82.0
Exports	292	288	301	87	81	77
$/tonne	12,970	11,097	10,323	8,159	6,373	5,211
$million FOB	3782	3197	3110	711	517	400

- Production = thousand tonne bone-in
- Exports = thousand tonnes
- $m FOB = Million Dollars Free on Board value per tonne

Note. Adapted from Beef + Lamb New Zealand (2025b)

Table 2.2 Beef + Lamb 2023-2024 dollar per farm type analysis for sheep and wool

Location	Class	GFR	% of GFR		Wool Profit ($)
			Sheep	Wool	
North Island	Hard Hill Country	661,815	52.5	4.8	-20,558
North Island	Hill Country	502,106	40.7	3.1	-9,351
North Island	Finishing	530,995	25.9	1.4	-4,145
South Island	High Country	1,322,750	35.2	32.5	298,343
South Island	Hill Country	715,383	58.6	8.7	9,258
South Island	Finishing-Breeding	625,910	53.5	4.4	-4,293
South Island	Finishing	421,370	64.5	4.9	-7,086

- GFR = Gross Farm Revenue
- % of GFR = (Revenue/GFR) * 100
- Wool Profit = Wool Revenue (Net return after deductions on invoice for testing charges, broker charges and freight) - Shearing Expenditure

Note. Adapted from Beef + Lamb New Zealand (2024a)

2.1.3 The Interest in Shedding Sheep for New Zealand Farmers

Romney make up around 50% of the New Zealand sheep population, contributing to the over 60% of the flock that produce strong wool (Beef + Lamb New Zealand, 2023, n.d.-a). Breeds with a medium wool type account for around 10% and those that produce fine wool such as Merinos make up around 5% of the flock (Beef + Lamb New Zealand, 2023, n.d.-a). The remaining breeds are categorised as composites and other breeds (including non-wool) that each make up around 13% of the national flock (Beef + Lamb New Zealand, 2023, n.d.-a). As the profitability of strong wool falls and the cost of shearing increases, some producers are looking to move away from the current strong wool breeds to alternatives that produce meat but do not require shearing (Beef + Lamb New Zealand, 2023, 2024b). Farmers are looking to compare the profitability of their current wool flock to hair or shedding breeds (Beef + Lamb New Zealand, 2025c; Morris, 2017). Shedding was defined by Slee (1959) as “the absolute loss of fleece, as observed macroscopically, over the whole or any significant part of the body area”. Some of the haired and shedding breeds currently present in New Zealand include the Dorper, Australian White, Damara, Exlana, EasyCare, Meatmaster and the Wiltshire (Beef + Lamb New Zealand, n.d.-a; Johnson et al., 2021; New Zealand Sheep Breeders Association, n.d.; Rare Breeds, n.d.). Limited research is available regarding production data (including carcass characteristics and meat quality) for hair and shedding breeds under New Zealand

conditions (Farrell et al., 2020; Johnson et al., 2021; Sneddon et al., 2024). The generation of such data has begun with a large scale "Grading up to a Wiltshire flock of shedding sheep" trial being run at Massey University (Duffin, 2022). As a part of this larger study, Rawidech (2024) examined the carcass characteristics and meat quality attributes of 3/4 Wiltshire versus Romney lambs, however, many breed societies consider 15/16 as the minimum an animal must be to be considered of that breed. Along with this, 3/4 Wiltshire lambs cannot be considered 100% shedding so do not fulfil the goal of collecting data on shedding sheep. Thus, research is required to fill this gap.

Different breeds of sheep have been found to have different carcass characteristics and meat quality traits (Schreurs & Kenyon, 2017a, 2017b). Due to a lack of New Zealand objective measurement data, Wiltshire are currently judged on a subjective basis. A common opinion amongst sheep breeders and meat processors is that the breeds with a higher value carcass can be selected based on their visible conformation when alive (Kirton et al., 1985; Nsoso et al., 2000; Schreurs & Kenyon, 2017b). However, the observable shape of the live animal has been shown to have minimal correlation to the value (Kirton & Pickering, 1967; Nsoso et al., 2000). It was found that sheep with a blocky carcass had little effect on the weight of the cut and had no higher muscle content than those with a leggy carcass (Kirton & Pickering, 1967; Scales et al., 2000). Wiltshire lambs have been discounted for meat yield, particularly when they are sold in the store market due to their long "leggy" frame (S. Morris, personal communication, September 24, 2025). Therefore, it is important to assess whether the opinion on Wiltshire is supported by objective data to ensure farmers are being paid accurately.

2.1.4 Carcass Classification and Meat Quality

2.1.4.1 Carcass Classification Objective

When farmers in New Zealand sell lambs to a processor, they are paid according to the classification of the animal (New Zealand Meat Classification Authority, 2004). The objective of the carcass classification system in New Zealand is to organise carcasses into distinct groups based on carcass weight (CW) and fat depth (New Zealand Meat Classification Authority, 2004). This allows the carcasses with a greater saleable meat yield to be identified and processed together (Price, 1995). In order to ensure a consistent classification of meat destined for export, New Zealand meat processing companies use the New Zealand Meat Classification guide (New Zealand Meat Classification Authority, 2004).

2.1.4.2 Carcass Classification Criteria

A carcass is classified according to the maturity of the animal and its level of fat cover (New Zealand Meat Classification Authority, 2004). When it comes to maturity, lambs are characterised as females or males that do not have any permanent incisor teeth(New Zealand Meat Classification Authority, 2004). Mutton is categorized as females or castrated males that have more than two permanent incisors (New Zealand Meat Classification Authority, 2004). There is also a classification for rams, which are males that are uncastrated that have two or more permanent incisors (New Zealand Meat Classification Authority, 2004). All rams are processed as a set weight and fat classification (New Zealand Meat Classification Authority, 2004).

Carcasses are categorised into fat classes using a GR measure, which is when the total tissue depth over the 12^{th} rib is measured at a point 11 cm from the middle of the carcass (New Zealand Meat Classification Authority, 2004). Fat classes within this classification system for lamb carcasses include: “A” which is described as when a carcass is lightweight and almost devoid of external fat, “Y” which represents a low fat content between 1 and 6 mm, and “P” which is a medium fat content between 6 and 12 mm (New Zealand Meat Classification Authority, 2004). “T” which has a high fat content between 12 and 15 mm, “F” excessive fat content greater than 15 mm, “C” not eligible for export due to trimming or mutilation, and “M” for manufacturing (New Zealand Meat Classification Authority, 2004). Carcasses are classified as M when they do not meet cutter criteria or if they do not have a high enough fat class to be exported as a carcass (New Zealand Meat Classification Authority, 2004).

Along with this there are weight classes such as A which is less than 9kg, L which is between 9 and 13.2 kg, M which is between 13.3 and 17 kg, X which is between 17.1 and 21.3 kg and H which is greater than 21 kg. (New Zealand Meat Classification Authority, 2004).

2.1.4.3 Meat Quality

A person’s culture, country or eating habits can highly influence the attributes they favour when purchasing meat (Gehring, 2023; Schreurs et al., 2008). The appearance and eating quality of meat is categorised using measures of meat quality (Schreurs & Kenyon, 2017a). Some of the important measures of meat quality include the colour, tenderness, and water holding capacity. Meat quality can be identified using subjective testing, however, due to limitations such as cost

and the limited availability of taster's, objective tests are often used to identify the quality of meat. While these are important measures, meat quality does not typically influence how much a farmer is paid for a carcass in New Zealand.

2.2 The Effect of Different Sheep Breeds on Carcass Characteristics

2.2.1 Carcass Weight

The value of the carcass is linked with carcass weight (CW) so a key goal for producers is to maximise the weight of the lambs that they produce (Muir, 2008). A common measure of CW is the hot CW which is the weight of the animal after the head, skin, feet and digestive tract have been removed and before it is placed in the chiller (Muir, 2008). Terminal breeds can reach saleable live weights faster than maternal breeds which often results in terminal breeds having heavier CWs at a younger age (McEwan et al., 1995).

Table 2.3 shows that the average CW of meat breeds with a wool fleece was 18.6 kgs, and it ranged from 14.8 to 23.8 kilograms. The average CW of meat breeds that shed or had a hair fleece was 18.4 and the range was 14.1 to 21.8 kilograms as seen in Table 2.4. The range for wool sheep was 1.3 kgs greater than the range for hair or shedding sheep. The CW for the Romney breed in Table 2.3 ranged from 16.7 to 21.4 compared to the 3/4 Wiltshire lambs in Table 2.4 that had a CW of 21.8. The representative studies on wool sheep that were carried out in New Zealand were done by Kirton et al. (1985), Wong (2019), Fourie et al. (1970), Sobrinho et al. (2003) and Rawidech (2024). The only New Zealand study for hair and shedding sheep was done by Rawidech (2024); within this study Rawidech (2024) found that the 3/4 Wiltshire had a greater CW at 21.8 kg than the Romney lambs at 17 kg.

Table 2.3 A summary table of representative studies examining carcass weight and dressing out percentage of offspring of pure and crossbred meat breeds that have a wool fleece

Sire Breed	Dam Breed	CW[1]	DO%[2]	Location	Reference
Cheviot	Cheviot	20.7	48.8	New Zealand	(Kirton et al., 1985)
Poll Dorset x Romney	Poll Dorset x Romney	19.6	47.5	New Zealand	(Kirton et al., 1985)
Romney	Romney	17.8	50.0	New Zealand	(Fourie et al., 1970)
Romney	Romney	21.4	48.2	New Zealand	(Kirton et al., 1985)
Romney	Romney	17.0	37.6	New Zealand	(Rawidech, 2024)
Romney	Romney	17.9	44.2	New Zealand	(Sobrinho et al., 2003)
Romney	Romney	16.7	43.2	New Zealand	(Wong, 2019)
Southdown	Southdown	16.6	56.3	New Zealand	(Fourie et al., 1970)
Suffolk	Suffolk	23.8	52.7	United States	(Burke & Apple, 2007)
Texel	Texel	14.8	47.3	United Kingdom	(Craigie et al., 2012)
Average		18.6	47.6		
Minimum		14.8	37.6		
Maximum		23.8	56.3		

[1]carcass weight (kg),
[2]dressing out percentage

Table 2.4 A summary table of representative studies examining carcass weight and dressing out percentage of offspring of pure and crossbred meat breeds with a hair or shedding fleece

Sire Breed	Dam Breed	CW[1]	DO%[2]	Location	Reference
Barbados Blackbelly	Barbados Blackbelly	14.1	56.0	United States	(Ockerman et al., 1982)
Damara	Damara	18.7	59.9	South Africa	(Tshabalala et al., 2003)
Dorper	Dorper	17.2	47.9	South Africa	(Brand et al., 2018)
Dorper	Dorper	21.6	62.9	South Africa	(Tshabalala et al., 2003)
Katahdin	Katahdin	18.1	47.1	United States	(Burke & Apple, 2007)
Katahdin	Katahdin	17.0	52.4	United States	(Turner et al., 2014)
St. Croix	St. Croix	16.8	49.1	United States	(Burke & Apple, 2007)
St. Croix	St. Croix	20.2	54.4	United States	(Ockerman et al., 1982)
Wiltshire	Wiltshire x Romney	21.8	42.3	New Zealand	(Rawidech, 2024)
Average		18.4	52.4		
Minimum		14.1	42.3		
Maximum		21.8	62.9		

[1]carcass weight (kg),
[2]dressing out percentage

2.2.2 Dressing Out Percentage

At meat processing companies, animals are weighed before they are slaughtered to obtain a pre-slaughter live weight (Muir, 2008). The percentage of the live weight that is retained in the hot CW is known as the dressing out percentage (DO%) (Johnson, Purchas, McEwan, et al., 2005; Scales et al., 2000; Schreurs & Kenyon, 2017a). Breed has been shown to have an impact on the dressing out percentage of sheep, however it is confounded by other factors (Kremer et al., 2004; Scales et al., 2000). Some of these factors are gender, CW, stage of maturity and age (Johnson, Purchas, McEwan, et al., 2005; Kremer et al., 2004; Muir, 2008; Schreurs & Kenyon, 2017a). These can contribute to differences in an animal's level of fat, muscularity, muscle-to-bone ratio (M:B) and the weight of non-carcass components (Litherland et al., 2010; Schreurs & Kenyon, 2017a).

Dressing out percentage was 47.6% on average for wool producing meat breeds as seen in Table 2.3. The lowest value was for Romney lambs with a dressing out percentage of 37.6% (Rawidech, 2024) and the highest value was 56.3% for Southdown lambs (Fourie et al., 1970). In comparison, the hair and shedding meat breeds had an average dressing out percentage of 52.4% as seen in Table 2.4. This is higher than that of the wool breeds; however it could be a result of the weight difference between hair and wool in pre-slaughter measurements (Kremer et al., 2004). The lowest value was 42.3% for 3/4 Wiltshire lambs (Rawidech, 2024), likely due to the fact that these animals were 1/4 Romney. The Romney may decrease the effect of the Wiltshire genetics, as Romney lambs have been shown to have heavier pelts than that of most breeds (Kirton et al., 1985). The highest dressing out value for hair and shedding sheep was 62.9% for Dorpers (Tshabalala et al., 2003), which is considerably higher than the maximum value for wool sheep. While there were five studies carried out in New Zealand for wool breeds the only New Zealand based study on hair and shedding breeds used 3/4 Wiltshire lambs and it was carried out by Rawidech (2024). The dressing out percentages for the wool vs haired and shedding sheep that are compared only give an indication of the potential difference between the breed types as this measurement can be affected by other factors including the varied age, fleece stage and gut fill level of the lambs across the studies.

2.2.3 Carcass Composition

The composition of a carcass is dictated by the proportion of muscle, fat and bone (Purslow, 2023; Schreurs & Kenyon, 2017b). These carcass components develop at different rates and

the amount of each component within the carcass is influenced by the animal's weight, age, diet, breed and maturity (Prache et al., 2022; Purslow, 2023; Schreurs & Kenyon, 2017b). As an animal's body weight gets larger the proportion of fat increases while the proportion of muscle and bone decreases (Brand et al., 2018). Carcasses with a higher proportion of muscle compared to other components produce a larger amount of retail product (Moloney & McGee, 2023). Therefore, producers aim to maximise the proportion of muscle in a carcass (Schreurs & Kenyon, 2017b).

As seen in Figure 2.1 Carcass composition of the offspring of pure and crossbred meat breeds with a wool versus hair or shedding fleece, muscle is the largest proportion of the carcass for all breeds. Fat is the second most common component in all wool-producing meat breeds and half of the hair and shedding meat breeds. Bone is the second largest component in the Barbados Blackbelly studied by Piña-Cárdenas et al. (2013), both the Dorper and Damara studied by Tshabalala et al. (2003) and the Dorper studied by Burger et al. (2013). The range for all components was considerably greater for hair and shedding sheep compared to wool breeds, as seen in
Table 2.5 and Table 2.6. The only study in Table 2.6 that was carried out in New Zealand was by Rawidech (2024) using 3/4 Wiltshire lambs, however four of the studies in
Table 2.5 were carried out in New Zealand. While these studies show the composition of wool vs haired and shedding sheep the difference could potentially be a result of differences in the age, sex and diet of the lambs so it can only give an indication of the possible variation.

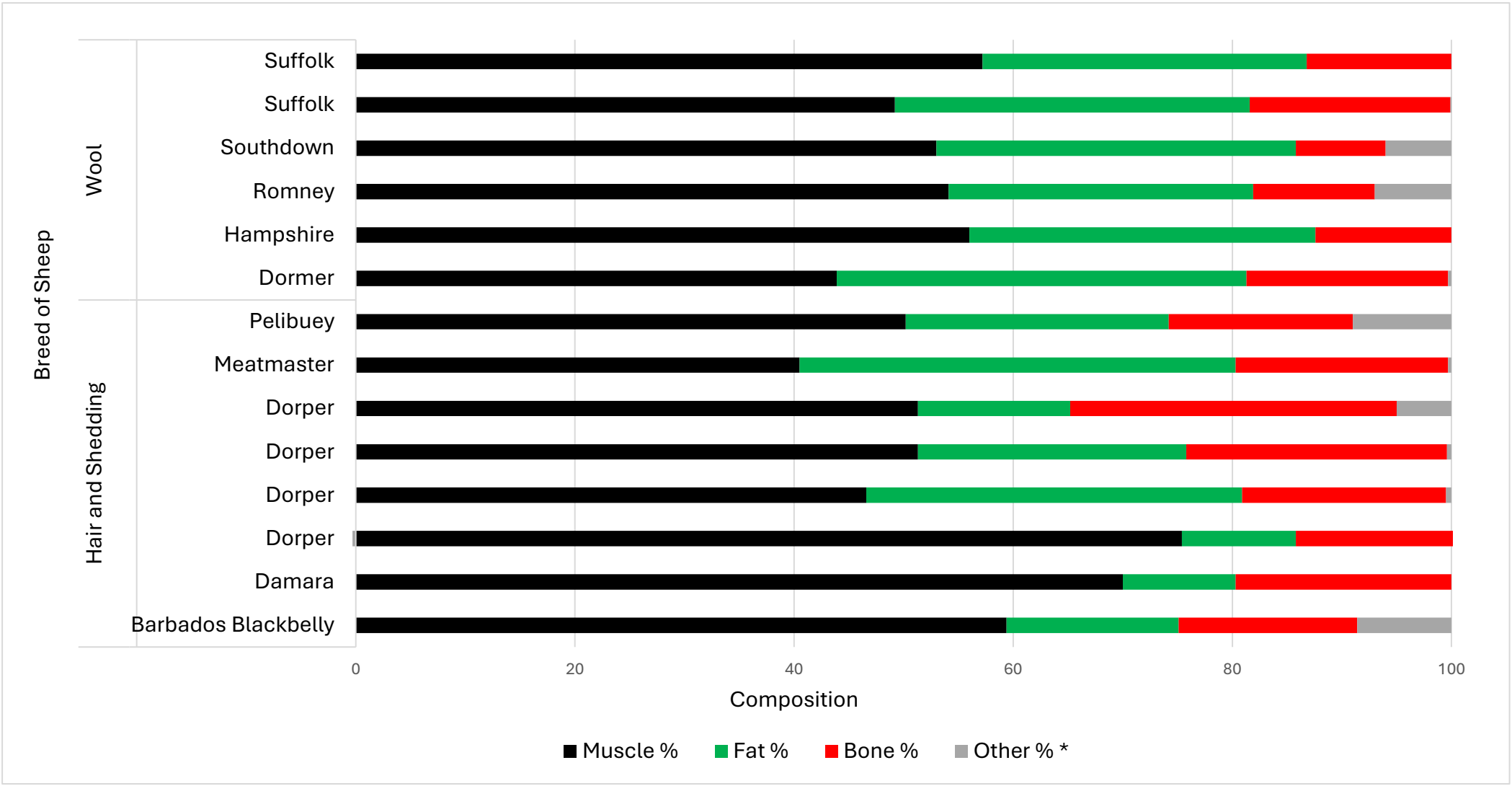


Figure 2.1 Carcass composition of the offspring of pure and crossbred meat breeds with a wool versus hair or shedding fleece

Note: Adapted from Brand et al. (2018); Burger et al. (2013); Fourie et al. (1970); Piña-Cárdenas et al. (2013); Tshabalala et al. (2003); Van der Merwe et al. (2020); Vesely and Peters (1972); Wood et al. (1980)

*percentage of other material such as tendon, waste and dissection loss

Table 2.5 A summary table of representative studies examining carcass composition of the offspring of purebred meat breeds with a wool fleece

Sire Breed	Dam Breed	Muscle %	Fat %	Bone %	Other[1]	Location	Reference
Dormer	Dormer	43.9	37.4	18.4	0.3	South Africa	(Van der Merwe et al., 2020)
Hampshire	Hampshire	56.0	31.6	12.4	-	United Kingdom	(Wood et al., 1980)
Romney	Romney	54.1	27.8	11.1	7.0	New Zealand	(Fourie et al., 1970)
Southdown	Southdown	53.0	32.8	8.2	6.0	New Zealand	(Fourie et al., 1970)
Suffolk	Suffolk	49.2	32.4	18.3	0.1	Canada	(Vesely & Peters, 1972)
Suffolk	Suffolk	57.2	29.6	13.2	-	United Kingdom	(Wood et al., 1980)
Average		52.2	31.9	13.6	3.4		
Minimum		43.9	27.8	8.2	0.1		
Maximum		57.2	37.4	18.4	7.0		

[1]percentage of other material such as tendon, waste and dissection loss calculated as 100 minus the reported values for muscle, fat and bone percentage

Table 2.6 A summary table of representative studies examining carcass composition of the offspring of pure and crossbred meat breeds with a hair or shedding fleece

Sire Breed	Dam Breed	Muscle %	Fat %	Bone %	Other[1]	Location	Reference
Barbados Blackbelly	Barbados Blackbelly	59.4	15.7	16.3	8.6	Mexico	(Piña-Cárdenas et al., 2013)
Damara	Damara	70.0	10.3	19.7	-	South Africa	(Tshabalala et al., 2003)
Dorper	Dorper	75.4	10.4	14.5	-0.3	South Africa	(Tshabalala et al., 2003)
Dorper	Dorper	46.6	34.3	18.6	0.5	South Africa	(Van der Merwe et al., 2020)
Dorper	Dorper	51.3	24.5	23.8	0.4	South Africa	(Brand et al., 2018)
Dorper	Dorper	51.3	13.9	29.8	5.0	South Africa	(Burger et al., 2013)
Meatmaster	Meatmaster	40.5	39.8	19.4	0.3	South Africa	(Van der Merwe et al., 2020)
Pelibuey	Pelibuey	50.2	24.0	16.8	9.0	Mexico	(Piña-Cárdenas et al., 2013)
Average		55.6	21.6	19.9	3.4		
Minimum		40.5	10.3	14.5	-0.3		
Maximum		75.4	39.8	29.8	9.0		

[1]percentage of other material such as tendon, waste and dissection loss calculated as 100 minus the reported values for muscle, fat and bone percentage

2.2.4 Muscle-to-Bone Ratio

Another measurement to consider is the muscle-to-bone ratio (M:B) which compares the weight of the muscle relative to the weight of the bone (Kirton & Morris, 1989). A greater M:B can be indicative of a greater lean meat yield (Schreurs & Kenyon, 2017b). As lambs mature there is typically a gradual increase in the M:B however at the same time the fat-to-muscle ratio also tends to increase (Kirton & Morris, 1989). Breed can influence the M:B and those that have higher mature weights tend to exhibit greater M:B ratios at the same stage of growth (Kirton & Morris, 1989). Wood et al. (1980) found that carcass weight had a larger influence on the M:B ratio than the breed of lamb. It is crucial to highlight that in some cases an animal with a long thin bone and moderate levels of muscle will have the same M:B as an animal with an average sized bone that is surrounded by thicker and heavier muscles (Purchas & Wilkin, 1995). Due to this M:B is a valuable measure when there is a clear basis of comparison, for example, when carcasses are compared at the same stage of maturity for animals of a similar mature size or at an equal carcass weight (Butterfield, 1988).

When looking at the M:B across studies for wool producing meat breeds the range of values were 1.75 – 6.69 with an average for the studies of 5.13 as shown in Table 2.7. Meanwhile the range for meat breeds with a haired or shedding fleece was from 3.10 to 5.59 with an average of 3.86 (Table 2.8). Four of the studies that recorded the M:B of meat breeds with a wool fleece were carried out in New Zealand. In comparison only one of the studies looking at the M:B of meat breeds with a hair or shedding fleece was carried out in New Zealand (Rawidech, 2024). This study by Rawidech (2024) was also the only study to compare the M:B of a wool breed to that of a hair or shedding breed and they found no difference in the M:B of 3/4 Wiltshire lambs compared to Romney lambs.

Table 2.7 A summary table of representative studies examining the muscle-to-bone ratio and muscularity of the offspring of purebred meat breeds with a wool fleece

Sire Breed	Dam Breed	Muscle-to-Bone Ratio	Muscularity	Location	Reference
Hampshire	Hampshire	4.56	-	United Kingdom	(Wood et al., 1980)
Romney	Romney	4.87	-	New Zealand	(Fourie et al., 1970)
Romney	Romney	5.66	0.43	New Zealand	(Rawidech, 2024)
Romney	Romney	6.69	0.46	New Zealand	(Sobrinho et al., 2003)
Romney	Romney	6.69	0.45	New Zealand	(Wong, 2019)
Southdown	Southdown	6.46	-	New Zealand	(Fourie et al., 1970)
Suffolk	Suffolk	1.75	0.40	Brazil	(Vega Britez et al., 2020)
Suffolk	Suffolk	4.38	-	United Kingdom	(Wood et al., 1980)
Average		5.13	0.44		
Minimum		1.75	0.40		
Maximum		6.69	0.46		

Table 2.8 A summary table of representative studies examining the muscle-to-bone ratio and muscularity of the offspring of pure and crossbred meat breeds with a hair or shedding fleece

Sire Breed	Dam Breed	Muscle-to-Bone Ratio	Muscularity	Location	Reference
Morada Nova	Morada Nova	3.30	0.40	Brazil	(Costa et al., 2010)
Morada Nova	Morada Nova	3.10	0.40	Brazil	(Costa et al., 2011)
Santa Ines	Santa Ines	3.80	0.40	Brazil	(Moura et al., 2020)
Santa Ines	Santa Ines	3.49	0.36	Brazil	(de Oliveira et al., 2017)
Wiltshire	Wiltshire x Romney	5.59	0.43	New Zealand	(Rawidech, 2024)
Average		3.86	0.40		
Minimum		3.10	0.36		
Maximum		5.59	0.43		

2.2.5 Muscularity

Muscularity is the depth of the muscle per unit of bone (Purchas et al., 1991). A low muscularity indicates that the muscle is less deep over the bone (Purchas et al., 1991). Increases in muscularity are associated with an increase in the retail meat yield from a carcass and is generally also associated with greater M:B values (Schreurs & Kenyon, 2017b). A lambs age, weight and breed play a large role in influencing its muscularity (Abdullah, 1994; Navajas et al., 2008). Muscularity can also be impacted by the level of nutrition as it can cause variations in bone length relative to muscle growth (Cake et al., 2006).

The muscularity for meat sheep with a wool fleece ranges from 0.40 – 0.46 across studies with an average of 0.44 (Table 2.7). The range across studies for meat sheep with a haired or shedding fleece was between 0.36 and 0.43 with an average value of 0.40 as seen in Table 2.8. The majority of the meat breeds that produce wool were studied in New Zealand while only one of the studies on meat breeds with a haired or shedding fleece was carried out in New Zealand. This study by Rawidech (2024) found no difference in muscularity between 3/4 Wiltshire and Romney lambs.

2.3 The Effect of Different Sheep Breeds on Meat Quality

2.3.1 pH

The pH of lamb meat can impact a number of meat quality characteristics, however, it is not considered an eating quality characteristic because it cannot be ascertained by the consumer (Schreurs & Kenyon, 2017a). Differences in pH levels have been linked to changes in the water-holding capacity, colour and tenderness (Devine et al., 1993; Purchas, 1989). The conditions prior to slaughter play a large role in influencing the pH level with stress and excessive activity associated with a higher pH in meat (Devine et al., 1993). Along with this carcass weight, age and breed of lamb can play a role in determining the pH level (Devine et al., 1993; McGeehin et al., 2001). Between lab differences in pH measurement can also influence variation between studies (Korkeala et al., 1986). Devine et al. (1993) found that meat with a pH of less than 5.8 was more likely to be considered acceptable by consumers.

As seen in Table 2.9 the range for pH between studies for meat breeds with a wool fleece was 5.51 – 5.80 with an average of 5.65. In comparison, the range for the pH of meat breeds with a haired or shedding fleece was 5.45 to 6.15 while the average was 5.72 (Table 2.10). There were three studies that looked at the pH from wool producing meat sheep within New Zealand which were Rawidech (2024), Sobrinho et al. (2003) and Wong (2019). Meanwhile only one study measured the pH of haired or shedding breeds that produced meat in New Zealand which was Rawidech (2024). The study by Rawidech (2024) was the only one that compared wool to haired and shedding sheep within the same study and they found that Romney lambs had a greater pH than 3/4 Wiltshire lambs.

Table 2.9 A summary table of representative studies examining the pH of the offspring of purebred meat breeds with a wool fleece

Sire Breed	Dam Breed	pH	Location	References
Dormer	Dormer	5.52	South Africa	(Van der Merwe et al., 2020)
Oxford Down	Oxford Down	5.74	Czech Republic	(Komprda et al., 2012)
Romney	Romney	5.67	New Zealand	(Rawidech, 2024)
Romney	Romney	5.60	New Zealand	(Sobrinho et al., 2003)
Romney	Romney	5.51	New Zealand	(Wong, 2019)
Suffolk	Suffolk	5.80	Canada	(Aalhus et al., 1991)
Suffolk	Suffolk	5.69	Czech Republic	(Komprda et al., 2012)
Suffolk	Suffolk	5.72	Brazil	(Monaco et al., 2015)
Texel	Texel	5.58	United Kingdom	(Craigie et al., 2012)
Average		5.65		
Minimum		5.51		
Maximum		5.80		

Table 2.10 A summary table of representative studies examining the pH of the offspring of pure and crossbred meat breeds with a hair or shedding fleece

Sire Breed	Dam Breed	pH	Location	References
Damara	Damara	5.78	Australia	(Almeida et al., 2013)
Dorper	Dorper	5.89	Australia	(Almeida et al., 2013)
Dorper	Dorper	5.59	South Africa	(Van der Merwe et al., 2020)
Dorper	Dorper	5.94	United States	(Villatoro, 2019)
Dorper	Katahdin	5.58	Mexico	(Partida et al., 2012)
Katahdin	Katahdin	5.69	Mexico	(Estrada-León et al., 2022)
Meatmaster	Meatmaster	5.56	South Africa	(Van der Merwe et al., 2020)
Santa Ines	Santa Ines	6.15	Brazil	(Menezes et al., 2016)
Santa Ines	Santa Ines	5.45	Brazil	(Saldanha et al., 2022)
Wiltshire	Wiltshire x Romney	5.59	New Zealand	(Rawidech, 2024)
Average		5.72		
Minimum		5.45		
Maximum		6.15		

2.3.2 Colour

Colour affects consumers purchasing decisions even though there is minimal evidence of a correlation between observable colour and eating quality (Corlett, 2023; Tomasevic et al., 2021). The colour of meat is primarily influenced by the chemical state and concentration of myoglobin which is a protein found within the muscle (Suman & Joseph, 2013). The colour scale used to objectively measure differences in colour is the International Commission on Illumination system (CIE) which assesses the meat for lightness (L*), redness (a*) and yellowness (b*). L* shows the lightness or darkness of a cut of meat with a higher number indicating it is whiter, a* measures the intensity of red or green with a higher value indicating redder meat, and b* is the intensity of yellow or blue colour and the higher it is, the yellower the meat (Hunt et al., 2012). Khliji et al. (2010) reported that on average meat colour will be considered acceptable by consumers if it has an L* greater than 34 and an a* greater than 9.5. However, they also found that in order to be 95% confident that a cut of meat would be considered by a random consumer to have an acceptable L* and a* they should be greater than 44 and 14.5 respectively (Khliji et al., 2010).

Table 2.11 and Table 2.12 indicated that the meat from meat breeds that produce wool had a greater L* but a lesser a* and b* on average compared to meat breeds that produce hair or shed. However, some of this variation could be attributed to differences in environments or management practices (Calnan et al., 2014). Therefore, a more definitive indication of whether there is a difference between breeds can be obtained when animals are raised in the same conditions.

Rawidech (2024) conducted a study in New Zealand investigating the difference between Romney and 3/4 Wiltshire lamb meat which found that the Romney and Wiltshire meat had a similar lightness at around 36.3 and 36.4. There was also no difference in the level of redness for 3/4 Wiltshire lamb meat which was 16.37 compared to Romney meat which was 16.17. Similarly, there was no difference in yellowness as the 3/4 Wiltshire lamb meat was 7.16 and the Romney meat was 6.84.

Burke and Apple (2007) compared hair and shedding breeds, Katahdin and St. Croix, with a wool breed, Suffolk. This study found that the meat from Suffolk sheep was higher on average for lightness than the hair and shedding breeds. Meanwhile, there was a difference in both redness and yellowness found between the Katahdin and St. Croix however for both measures

neither of them differed significantly from the Suffolk. This indicated a difference between breeds but did not show a major difference when comparing wool with hair or shedding breeds.

Table 2.11 A summary table of representative studies examining the meat colour of the offspring of purebred meat breeds that have a wool fleece, measured using the International Commission on Illumination system (CIE, L*, a* and b* parameters)

Sire Breed	Dam Breed	L* lightness	a* redness	b* yellowness	Location	References
Dormer	Dormer	38.5	12.6	10.5	South Africa	(Van der Merwe et al., 2020)
Oxford Down	Oxford Down	50.1	9.2	13.4	Czech Republic	(Komprda et al., 2012)
Romney	Romney	36.3	16.2	6.8	New Zealand	(Rawidech, 2024)
Romney	Romney	37.3	7.9	4.2	New Zealand	(Sobrinho et al., 2003)
Suffolk	Suffolk	33.6	15.4	13.9	United States	(Burke & Apple, 2007)
Suffolk	Suffolk	47.2	8.6	12.1	Czech Republic	(Komprda et al., 2012)
Texel	Texel	43.9	23.3	9.8	United Kingdom	(Craigie et al., 2012)
Average		41.0	13.3	10.1		
Minimum		33.6	7.9	4.2		
Maximum		50.1	23.3	13.9		

Table 2.12 A summary table representative studies examining the meat colour of the offspring of pure and crossbred meat breeds with a hair or shedding fleece, measured using the International Commission on Illumination system (CIE, L*, a*, and b* parameters)

Sire Breed	Dam Breed	L* lightness	a* redness	b* yellowness	Location	References
Damara	Damara	38.1	13.9	5.6	Australia	(Almeida et al., 2013)
Dorper	Dorper	40.0	14.5	6.0	Australia	(Almeida et al., 2013)
Dorper	Dorper	36.9	13.8	10.2	South Africa	(Van der Merwe et al., 2020)
Dorper	Katahdin	36.8	13.6	7.4	Mexico	(Partida et al., 2012)
Katahdin	Katahdin	31.8	16.8	14.4	United States	(Burke & Apple, 2007)
Katahdin	Katahdin x Pelibuey	39.3	21.1	14.5	Mexico	(Pérez et al., 2021)
Meatmaster	Meatmaster	38.8	13.7	10.7	South Africa	(Van der Merwe et al., 2020)
Morada Nova	Morada Nova	26.5	12.5	17.8	Brazil	(Costa et al., 2009)
Pelibuey	Pelibuey	35.2	7.9	8.2	Mexico	(Arce-Recinos et al., 2022)
Santa Ines	Santa Ines	29.0	12.5	18.3	Brazil	(Costa et al., 2009)
Santa Ines	Santa Ines	37.3	21.6	5.1	Brazil	(Saldanha et al., 2022)
St. Croix	St. Croix	31.5	15.2	13.2	United States	(Burke & Apple, 2007)
Wiltshire	Wiltshire x Romney	36.4	16.4	7.2	New Zealand	(Rawidech, 2024)
Average		35.2	14.9	10.7		
Minimum		26.5	7.9	5.1		
Maximum		40.0	21.6	18.3		

2.3.3 Water Holding Capacity

Water makes up around 75% of lean muscle tissue in a living animal (Honikel, 2008). Once an animal dies the meat's ability to retain water is called the water-holding capacity (Honikel, 2008). If a large amount of water is lost it can result in decreased juiciness and impacts other traits closely associated with eating quality such as tenderness and colour (Warner, 2023). The water holding capacity can be affected by an animal's diet, breed, the level of stress before slaughter, the time the carcass was chilled, the aging time and the packaging method (Cheng & Sun, 2008; Ha et al., 2022). The water holding capacity of sheep meat can be measured objectively using a number of different methods including cooking loss percentage or drip loss percentage (Honikel, 2008; Warner, 2023). Drip loss percentage measures the amount of water lost from a sample of raw meat over a set time while cooking loss percentage measures the amount of water lost when a sample is heated to a defined temperature (Honikel, 2008).

Table 2.13 indicates that the meat from wool producing meat breeds had a higher average drip loss at 3.95% compared to hair and shedding meat breeds at 3.03% as seen in Table 2.14. Along with this the meat from wool producing meat breeds had a greater range for drip loss ranging between 1.30% and 6.20% while haired and shedding breeds ranged from 1.30% to 5.01%. The meat from wool sheep had higher values on average for cooking loss at 36.00% compared to hair and shedding sheep that had an average of 27.93%. However, the range for hair and shedding sheep meat was from 15.39% to 39.80% which is much greater than that of wool sheep at 31.59% to 40.20%. These differences between studies could be attributed to different cooking procedures or environmental conditions (Cheng & Sun, 2008).

Van der Merwe et al. (2020) compared the meat from a wool breed with meat from shedding and haired breeds with the same environmental conditions and procedures and found no difference in both drip loss and cooking loss. Another study was Rawidech (2024), who also found no difference in the cooking loss or drip loss percentage between Romney and 3/4 Wiltshire lambs. This was also the only study in Table 2.14 that was conducted in New Zealand, while three studies in Table 2.13 were carried out in New Zealand.

Table 2.13 A summary table of representative studies examining the water holding capacity of the offspring of purebred meat breeds with a wool fleece

Sire Breed	Dam Breed	Drip Loss Percentage	Cooking Loss Percentage	Location	Reference
Dormer	Dormer	1.30	40.20	South Africa	(Van der Merwe et al., 2020)
Romney	Romney	4.29	34.60	New Zealand	(Rawidech, 2024)
Romney	Romney	-	38.40	New Zealand	(Sobrinho et al., 2003)
Romney	Romney	3.99	38.00	New Zealand	(Wong, 2019)
Suffolk	Suffolk	6.20	-	Canada	(Aalhus et al., 1991)
Suffolk	Suffolk	-	33.20	United States	(Burke & Apple, 2007)
Texel	Texel	-	31.59	United Kingdom	(Craigie et al., 2012)
Average		3.95	36.00		
Minimum		1.30	31.59		
Maximum		6.20	40.20		

Table 2.14 A summary table of representative studies examining the water holding capacity of the offspring of pure and crossbred meat breeds with a hair or shedding fleece

Sire Breed	Dam Breed	Drip Loss Percentage	Cooking Loss Percentage	Location	Reference
Dorper	Dorper	1.30	39.80	South Africa	(Van der Merwe et al., 2020)
Dorper	Dorper	-	15.39	United States	(Villatoro, 2019)
Dorper	Dorper	2.15	20.65	Australia	(Zhang et al., 2021)
Katahdin	Katahdin	5.01	32.77	Mexico	(Estrada-León et al., 2022)
Katahdin	Katahdin x Pelibuey	4.87	18.35	Mexico	(Pérez et al., 2021)
Meatmaster	Meatmaster	1.40	39.50	South Africa	(Van der Merwe et al., 2020)
Pelibuey	Pelibuey	-	28.70	Mexico	(Arce-Recinos et al., 2022)
Santa Ines	Santa Ines	-	31.25	Brazil	(Castro et al., 2017)
Santa Ines	Santa Ines	-	18.56	Brazil	(Saldanha et al., 2022)
Wiltshire	Wiltshire x Romney	3.46	34.30	New Zealand	(Rawidech, 2024)
Average		3.03	27.93		
Minimum		1.30	15.39		
Maximum		5.01	39.80		

2.3.4 Tenderness

Tenderness can be assessed using a subjective sensory panel assessment, or an objective test that measures the amount of force required to shear through a cut of meat (Hopkins & Ertbjerg, 2023; Tornberg, 1996). The tenderness of meat is influenced by several attributes including the pH, the amount of fat, the concentration and solubility of muscle collagen, the extent of contraction and the activity of proteolytic enzymes (Schreurs & Kenyon, 2017a). A commonly utilised method to assess tenderness is the Warner-Bratzler Shear Force test (Wheeler et al., 1997). This method uses knife movement and compression to measure the maximum force (N) needed to shear (cut off) a piece of meat (Novaković & Tomašević, 2017). Producers aim to minimise shear force (SF) values as lower shear force values indicate a more tender cut of meat (Hopkins & Ertbjerg, 2023). Hopkins et al. (2006) identified that consumers considered a shear force of less than 4.08 kgF to be a good everyday level of tenderness.

The meat from meat breeds that produce wool had, on average, a shear force of 5 kgF as seen in Table 2.15. In comparison, the average shear force of the meat from hair and shedding meat breeds was considerably lower at 2.6 kgF as seen in Table 2.16. The range for the meat from wool sheep for shear force was between 3.6 kgF and 8.4 kgF, which was much greater than that of hair and shedding sheep at 1.7 kgF to 3.6 kgF. This indicates that the tenderness of wool breeds was considerably worse than that of haired and shedding breeds. Rawidech (2024) was the only study that compared the meat from wool breeds to that of hair and shedding breeds within the same research trial. The findings showed that 3/4 Wiltshire, a haired and shedding meat breed, had meat that did not differ in tenderness to that of the wool producing breed, Romney. Rawidech (2024) who compared Romney lambs to 3/4 Wiltshire lambs was the only study in Table 2.16 conducted in New Zealand, while three of the studies in Table 2.15 were carried out in New Zealand.

Table 2.15 A summary table of representative studies examining the tenderness of the offspring of purebred meat breeds with a wool fleece

Sire Breed	Dam Breed	Age[1]	Shear Force[2]	Location	Reference
Hampshire Down	Hampshire Down	3.3-4.3	3.6	Brazil	(Monaco et al., 2015)
Romney	Romney	7.0	3.7	New Zealand	(Rawidech, 2024)
Romney	Romney	4.9-9.9	8.4	New Zealand	(Sobrinho et al., 2003)
Romney	Romney	3.2-5.0	4.5	New Zealand	(Wong, 2019)
Suffolk	Suffolk	4.1	5.2	Canada	(Aalhus et al., 1991)
Suffolk	Suffolk	3.3-4.3	5.3	Brazil	(Monaco et al., 2015)
Texel	Texel	4.7	4.5	United Kingdom	(Craigie et al., 2012)
Average			5.0		
Minimum			3.6		
Maximum			8.4		

[1]age at slaughter rounded to the nearest month
[2] objective shear force (kgF)

Table 2.16 A summary table of representative studies examining the tenderness of the offspring of pure and crossbred meat breeds with a hair or shedding fleece

Sire Breed	Dam Breed	Age[1]	Shear Force[2]	Location	Reference
Dorper	Dorper	5.6-7.3	3.3	United States	(Heimbuch et al., 2023)
Dorper	Dorper	7.0	2.0	Brazil	(Saldanha et al., 2022)
Katahdin	Katahdin x Pelibuey	5.2–6.3	3.6	Mexico	(Pérez et al., 2021)
Santa Ines	Santa Ines	7.7	1.7	Brazil	(Menezes et al., 2016)
Santa Ines	Santa Ines	7.0	2.4	Brazil	(Saldanha et al., 2022)
St. Croix	St. Croix	7.0	2.2	United States	(Bunch et al., 2004)
Wiltshire	Wiltshire x Romney	7.0	3.2	New Zealand	(Rawidech, 2024)
Average			2.6		
Minimum			1.7		
Maximum			3.6		

[1]age at slaughter rounded to the nearest month
[2] objective shear force (kgF)

2.4 Research Objective

This literature review has identified that there is a lack of data comparing carcass and meat quality characteristics for Romney and Wiltshire sheep in New Zealand. The predominant sheep breeds farmed in New Zealand produce strong wool which currently does not return a profit due to decreased value and increased shearing costs. As a result, farmers are increasingly interested in transitioning to hair or shedding sheep breeds, such as the Wiltshire, that do not require shearing. There are a number of confounding factors such as management practices, environmental conditions, meat processing methods and measurement techniques that can influence carcass and meat quality characteristics, so the studies discussed in the literature review will only give an indication of the expected values. While the comparisons of wool vs haired and shedding breeds reviewed in the literature give an indication of whether a characteristic is influenced by breed there is no research comparing purebred Wiltshire lambs to Romney lambs. The only study that can be used to predict the suitability of the Wiltshire as a replacement breed in New Zealand compares Romney lambs to 3/4 Wiltshire lambs (Rawidech, 2024). Collection and analysis of data comparing the differences between Wiltshire lambs and the primary breed currently utilised for meat production will allow farmers to make informed decisions regarding the breeding of their flock.

Therefore, the objective of this study was to investigate whether 7/8 and 15/16 Wiltshire lambs have differing carcass and meat quality characteristics to Romney lambs. 7/8 and 15/16 Wiltshire lambs were sourced from a larger study investigating the process of grading up to a Wiltshire flock of shedding sheep. The Wiltshire lambs are considered to be purebred once they reach the fourth cross and are 15/16 Wiltshire (Farrell et al., 2020). The hypothesis is that the 7/8 and 15/16 Wiltshire lambs will have carcass and meat characteristics that do not differ from Romney lambs. As a result, transitioning to a Wiltshire flock should not negatively affect the sale of offspring born to Romney composites as they grade up to Wiltshire, if breed is the only factor that is changed. The results of this study will address the gap in knowledge and supply producers with robust information regarding carcass characteristics and meat quality that is currently not available. A greater understanding of these characteristics will also ensure that processors accurately compensate growers for finishing these composite and purebred lambs.

Chapter 3: Materials and Methods

All animal procedures were carried out with the approval of the Massey University Animal Ethics Committee (MUAEC 20/44). The entire male lambs used within this study were born in 2023 and 2025 in Masterton, New Zealand, on the Massey University Riverside Farm (-40.844139, 175.622337). Within 12 hours of birth the lambs were caught, tagged with an identification number, and their date of birth, mother's identification number, birth rank and birth weight were recorded against their tag. All lambs used within this study were born as twins. The lamb's weight was recorded at docking and weaning, and these weights were used to ensure a representative sample was selected to participate in the study.

At weaning, the lambs selected for the trial were moved to the Pasture and Crop Research Unit (PCRU) at Massey University in Palmerston North (-40.390386, 175.607039). Upon arrival, a starting weight was recorded and linked with their electronic identification tags. Throughout their time at PCRU, lambs were grazed together on a perennial ryegrass (*Lolium perenne*)-based pasture with supplementation of a chicory crop (*Cichorium intybus*). Every four weeks, the lambs were orally treated with an anthelmintic and weighed. Once the lambs met an average slaughter weight of 40 kg, a final weight was measured on-farm before they were sent to slaughter as one group.

In 2024, fourteen purebred Romney lambs were compared with fourteen 7/8 Wiltshire x Romney lambs (progeny of a 3/4 Wiltshire x Romney ewe bred to a purebred Wiltshire ram). On average, the Romney lambs were born on the 4th of September 2023 with a 12 day spread while the average birthdate for the 7/8 Wiltshire lambs was the 8th of September 2023 with a spread of 27 days. The lambs were sent to slaughter together as one group on the 8th of April 2024, with an average age of 217 days for the Romney lambs and 213 days for the 7/8 Wiltshire lambs.

In 2026, thirteen purebred Romney lambs were compared to fifteen 15/16 Wiltshire x Romney lambs (progeny of a 7/8 Wiltshire x Romney ewe bred to a purebred Wiltshire ram). The average date of birth was the 3rd of September 2025 with a spread of 14 days for the Romney lambs and the 4th of September 2025 with a spread of 16 days for the 15/16 Wiltshire lambs. These lambs were slaughtered together as one group on the 13th of April 2026. The Romney

lambs had an average age of 222 days while the 15/16 Wiltshire lambs had an average age of 221 days.

In both 2024 and 2026, the lambs were slaughtered at a commercial meat processing plant (Ovation, Feilding). Each animal's electronic identification tag was linked to a slaughter order number to identify the carcass. Commercial dressing procedures were performed, and a hot carcass weight (CW) was recorded. The carcasses were chilled at 4°C for 24 hours. Carcasses were then boned out and two separate cuts, the hind leg (bone-in, short leg) and the bone-in saddle, were collected and identified by slaughter order number. The saddles were aged for 14 days in a chiller at 4°C. For long term storage and subsequent analysis, the cuts were placed in a -20°C freezer at Te Ohu Rangahau Kai Facility at Massey University, Palmerston North.

3.1 Carcass Characteristics

The dressing out percentage (DO%) was calculated by finding the percentage of the final live weight (measured on-farm) that is retained in the hot CW (Equation 1).

Equation 1:

$$\text{Dressing out percentage} = \frac{\text{hot carcass weight (kg)}}{\text{final live weight (kg)}} \times 100$$

Dissections of the hind legs were carried out at the Te Ohu Rangahau Kai Facility at Massey University, Palmerston North, to identify the carcass characteristics. Twenty-four hours prior to dissection, the hind legs were removed from the freezer and left to thaw at 10°C (pilot plant room temperature). Following this, any packaging was removed, a paper towel was used to remove excess drip from the cuts of meat, and the weight of each whole leg was recorded. Then the legs were dissected into eight named muscles plus other muscles of the leg collected together, and each one was weighed. These muscles were the *Gracilis, Sartorius, Pectineus, Semimembranosus, Adductor, Bicep femoris, Semitendinosus* and *Quadriceps femoris*. The weight of the muscles of the femur was also calculated, which refers to the sum of the *Adductor*, *Semimembranosus*, *Semitendinosus*, *Bicep femoris* and *Quadricep femoris*. Muscle percentage was calculated as the proportion of total muscle weight to the weight of the whole leg (Equation 2). The dissectible fat percentage was found by calculating the weight of all fat that was able to be dissected as a percentage of the weight of the whole leg (Equation 3).

Equation 2:

$$\text{Muscle percentage} = \frac{\text{total muscle weight (g)}}{\text{weight of the whole leg (g)}} \times 100$$

Equation 3:

$$\text{Dissectible fat percentage} = \frac{\text{dissectible fat weight (g)}}{\text{weight of the whole leg (g)}} \times 100$$

After all the meat was removed, both the femur and tibia bones were weighed, and the length of the femur was measured. The muscle-to-bone ratio (M:B) (Equation 4) calculation was done two ways, to find the M:B of the whole leg and the M:B of the femur as described by Johnson, Purchas and Blair (2005). The M:B of the whole leg compared the weight of the partial tibia and femur with all leg muscles. Meanwhile, the M:B of the femur compared the weight of the femur with the weight of five muscles the *Semimembranosus, Adductor, Bicep femoris, Semitendinosus* and *Quadricep femoris*. The procedure from Purchas et al. (1991) was used to calculate the muscularity index (Equation 5) as the depth of the muscle over the femur relative to the length of the femur. The muscle weights used in this calculation were the *Semimembranosus, Adductor, Bicep femoris, Semitendinosus* and *Quadricep femoris.*

Equation 4:

$$\text{M:B} = \frac{\text{muscle weight (g)}}{\text{bone weight (g)}}$$

Equation 5:

$$\text{Muscularity index} = \sqrt{\left(\frac{\sum \text{weight of the muscles of the femur (g)}}{\text{femur length (cm)}}\right)} \div \text{femur length (cm)}$$

Where: muscles of femur are the *Semimembranosus, Adductor, Bicep femoris, Semitendinosus* and *Quadricep femoris*

3.2 Meat Quality

Objective meat quality analysis was performed on the *Longissimus lumborum* muscle (loin) at the Te Ohu Rangahau Kai facility at Massey University, Palmerston North, the loin was obtained by boning out the bone-in saddle samples. The loin was split into separate portions, to allow enough muscle for each of the objective tests to be carried out, following the method from Rawidech (2024) as seen in Figure 3.1. The objective tests carried out measured the water holding capacity (cook and drip loss), pH, shear force and colour.

3.2.1 Ultimate pH

Ultimate pH was measured using a pH spear (Eutech Instruments, Malaysia) that was calibrated to standard buffers of pH 4.01, 7.00 and 10.01. Triplicate measurements at approximately 1-1.5 cm deep were taken at three locations across a transverse internal cut of a segment of the loin (Portion 1, Figure 3.1). The ultimate pH value for each sample was found by averaging the triplicate measurements.

3.2.2 Meat Colour

Meat colour was measured using the International Commission on Illumination (CIE) system, which assesses the meat lightness (L*), redness (a*) and yellowness (b*). This was done using a Minolta chromometer CR-400 which was manufactured and calibrated with a white calibration plate (Konica Minolta Photo Imaging Inc. Mahwah, NJ, USA). After portion 1 (Figure 3.1) of the loin had been exposed to air for 30 minutes, the chromometer was used to measure three separate points across a transverse cut of the meat sample. The L*, a* and b* for each sample were found by averaging the values of the three points.

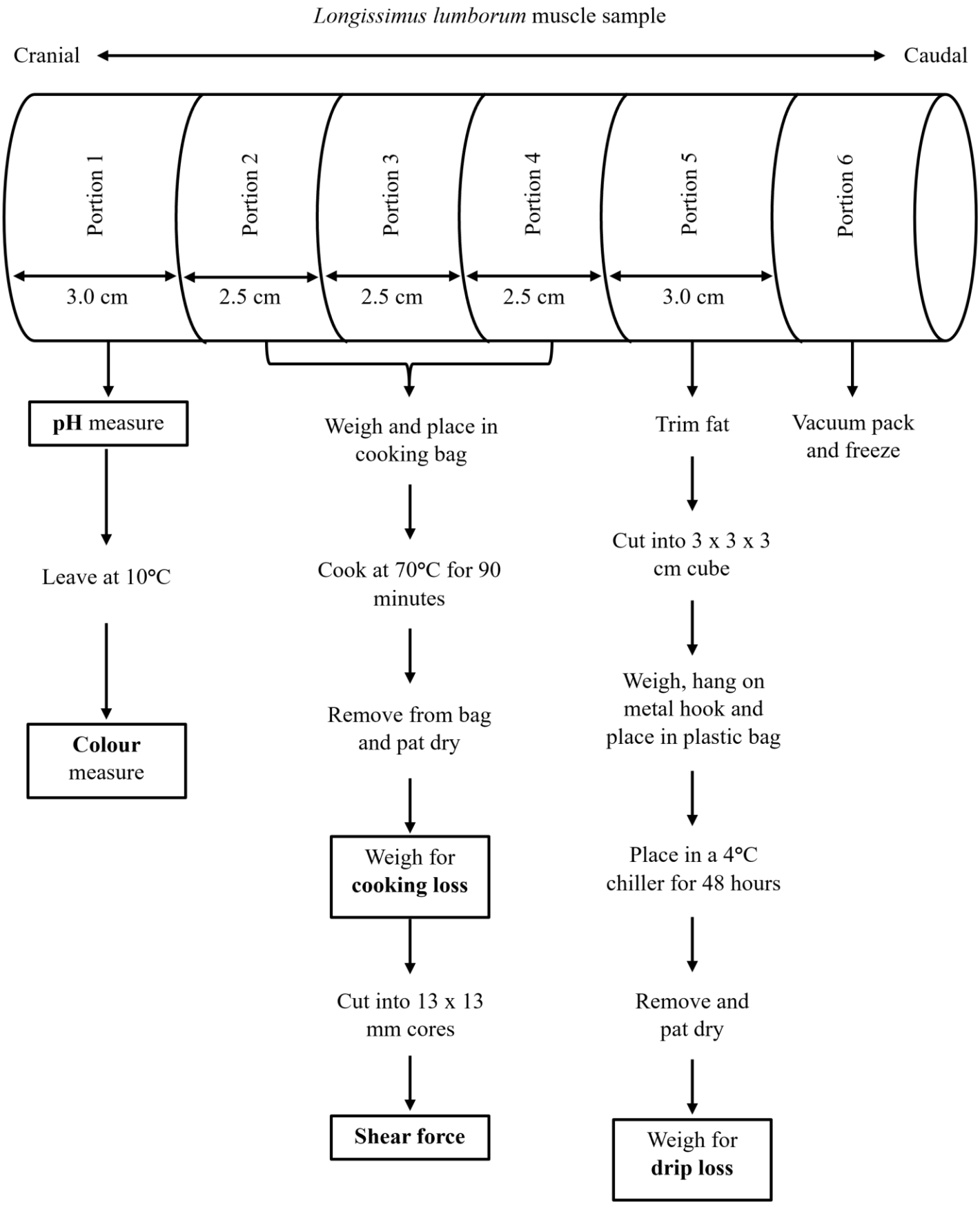


Figure 3.1 A schematic diagram showing the partitioning of the lamb Longissimus lumborum muscle for meat quality assessment. Adapted from Rawidech (2024)

3.2.3 Water Holding Capacity

There were two measurements used to assess the water holding capacity: drip loss and cooking loss. Drip loss was measured using a cube of raw meat that was 3 cm x 3 cm x 3 cm, which was cut from portion 5 of the loin (Figure 3.1). This cube was weighed, hung on a metal hook and then placed in a plastic bag in a 4°C chiller for 48 hours. After completing the 48 hours, the cube was gently dried with paper towels and reweighed. The difference between the final and initial weight was expressed as a percentage of the initial weight and used to represent drip loss (Equation 6).

Equation 6:

$$\text{Drip loss}_{48\text{hr}}\ (\%) = \frac{\text{weight}_{0\text{hr}}(\text{g}) - \text{weight}_{48\text{hr}}(\text{g})}{\text{weight}_{0\text{hr}}(\text{g})} \times 100$$

The cooking loss was measured using three slices of the loin (Portions 2-4, Figure 3.1) that were 2.5 cm thick. The weight of all three slices combined was recorded, then they were positioned alongside each other in a plastic bag and placed in a 70°C water bath (Contherm®, Model 370HL, Australia) to cook for 90 minutes. Once removed from the water bath, the meat in the bag was cooled to 10°C (pilot plant room temperature) before being chilled to 4°C for a minimum of 3 hours. After this, the slices were dried with a paper towel, and the total weight was recorded. The difference between the weights before and after cooking, as a percentage of the weight before cooking, represents the cooking loss percentage (Equation 7).

Equation 7:

$$\text{Cooking loss}\ (\%) = \frac{\text{weight before cooking (g)} - \text{weight after cooking (g)}}{\text{weight before cooking (g)}} \times 100$$

3.2.4 Shear Force

A TMSPilot Texture (USA) analyser fitted with a V-Blade was used to find both the total shear force (kgF) and the peak shear force (kgF). From the three cooked portions of the loin (Portions 2-4, Figure 3.1) six cores were obtained that had a cross sectional area measuring 13 x 13 mm running parallel to the muscle fibres. A shear of each core was performed cutting perpendicular to the direction of the muscle fibres. The average for both total and peak shear force was found by calculating the average between the six cores for each sample.

3.3 Statistical Analysis

The Statistical Analysis Software version 9.4 (SAS 9.4, SAS Institute Inc., Carey, NC, USA) was used to analyse the data. A general linear model was used to perform an analysis of variance to compare 7/8 Wiltshire to Romney and 15/16 Wiltshire to Romney in their respective experiments. The least square means were compared with a p-value of $P<0.05$ considered significant. The statistical models included a fixed effect of breed. Hot CW was used as a covariate for models analysing carcass composition and shape including muscles of femur weight, total muscle weight, muscle-to-bone ratios for the whole leg and femur, muscularity index, muscle percentage and the dissectible fat percentage. Ultimate pH was fitted as a covariate for models analysing meat quality characteristics including lightness (L*), redness (a*), yellowness (b*), cooking loss percentage, drip loss percentage, total shear force and peak shear force.

Chapter 4: Results

4.1 Carcass Characteristics – Romney versus 7/8 Wiltshire

The 7/8 Wiltshire lambs had a heavier final live weight and hot carcass weight (CW) along with greater dressing out (DO%) and muscle percentage than the Romney lambs ($P<0.05$; Table 4.1). The Romney had a greater ($P<0.05$) dissectible fat percentage than the 7/8 Wiltshire lambs.

Hot CW was a significant covariate for the weight of the muscles of the femur, total muscle weight, femur length, dissectible fat percentage and the muscle-to-bone ratio (M:B) of the whole leg ($P<0.05$; Table 4.1).

There was no difference between treatments for birth weight, starting live weight, weight of the muscles of the femur, total muscle weight, femur length, M:B of the whole leg, M:B of the femur and the muscularity index ($P>0.05$; Table 4.1).

Table 4.1 Live weight and carcass performance (mean ± SEM) of Romney and 7/8 Wiltshire lambs. Hot carcass weight (CW) was fitted as a covariate for carcass composition and shape obtained by physical dissection of the hind leg.

Carcass Characteristic	Romney	7/8 Wiltshire	P-value	
			Breed	Hot CW Covariate
Live weight and carcass performance				
Birth weight (kg)	4.8 ± 0.20	4.9 ± 0.20	0.645	-
Start live weight (kg)	37.5 ± 0.80	39.2 ± 0.80	0.136	-
Final live weight (kg)	44.4 ± 0.85	47.9 ± 0.85	0.008	-
Hot carcass weight (kg)	18.8 ± 0.43	21.2 ± 0.43	0.001	-
Dressing-out (%)	42.4 ± 0.55	44.3 ± 0.55	0.019	-
Carcass composition and shape				
Muscles of femur (g)[1]	1136 ± 21.6	1189 ± 21.6	0.127	<.001
Total muscle (g)[2]	1845 ± 34.7	1929 ± 34.7	0.133	<.001
Femur length (mm)	180.3 ± 1.73	183.0 ± 1.73	0.346	0.025
Muscle (%)	73.7 ± 0.53	76.0 ± 0.53	0.011	0.068
Dissectible fat (%)	13.6 ± 0.55	11.1 ± 0.55	0.010	0.011
M:B of whole leg[3]	6.23 ± 0.10	6.30 ± 0.10	0.650	0.017
M:B of femur[4]	6.56 ± 0.12	6.67 ± 0.12	0.550	0.087
Muscularity index	0.44 ± 0.01	0.44 ± 0.01	0.942	0.335

[1] Muscle of femur weight refers to the sum of *Adductor, Semimembranosus, Semitendinosus, Bicep femoris* and *Quadricep femoris*.
[2] Total muscle weight refers to all muscles found in the whole hind leg
[3] M:B of whole leg calculated with all muscle and all bones of hind leg
[4] M:B of femur calculated using muscle*s* of femur and femur bone weight

4.2 Carcass Characteristics – Romney versus 15/16 Wiltshire

Compared to Romney lambs, the 15/16 Wiltshire lambs had a heavier final live weight and hot CW, greater dressing out and muscle percentage and a longer femur length ($P<0.05$; Table 4.2).

Hot CW was a significant covariate for the weight of the muscles of the femur, total muscle weight, dissectible fat percentage, M:B of the whole leg, M:B of the femur and the muscularity index ($P<0.05$; Table 4.2).

When compared at the same hot CW Romney lambs had a greater dissectible fat percentage and muscularity index ($P<0.05$; Table 4.2). Birth weight, starting live weight, weight of the muscles of the femur, total muscle weight, the M:B of the whole leg and the M:B of the femur did not differ between the breeds ($P>0.05$; Table 4.2).

Table 4.2 Live weight and carcass performance (mean ± SEM) of Romney and 15/16 Wiltshire lambs. Hot carcass weight (CW) was fitted as a covariate for carcass composition and shape obtained by physical dissection of the hind leg.

Carcass Characteristic	Romney	15/16 Wiltshire	P-value	
			Breed	Hot CW Covariate
Live weight and carcass performance				
Birth weight (kg)	5.2 ± 0.18	4.9 ± 0.16	0.226	-
Start live weight (kg)	36.7 ± 1.00	35.0 ± 0.96	0.235	-
Final live weight (kg)	40.9 ± 1.26	44.6 ± 1.17	0.042	-
Hot carcass weight (kg)	16.1 ± 0.66	20.0 ± 0.61	<.001	-
Dressing-out (%)	39.2 ± 0.74	44.8 ± 0.69	<.001	-
Carcass composition and shape				
Muscles of femur (g)[1]	1033 ± 19.6	1090 ± 17.9	0.069	<.001
Total muscle (g)[2]	1708 ± 30.1	1772 ± 27.5	0.172	<.001
Femur length (mm)	174.5 ± 1.42	183.7 ± 1.30	<.001	0.079
Muscle (%)	74.4 ± 0.65	76.6 ± 0.59	0.038	0.289
Dissectible fat (%)	12.3 ± 0.56	9.7 ± 0.51	0.006	0.012
M:B of whole leg[3]	6.01 ± 0.15	6.20 ± 0.14	0.424	<.001
M:B of femur[4]	5.98 ± 0.15	6.34 ± 0.14	0.131	<.001
Muscularity index	0.44 ± 0.01	0.42 ± 0.01	0.038	<.001

[1] Muscles of femur weight refers to the sum *of Adductor, Semimembranosus, Semitendinosus, Bicep femoris* and *Quadricep femoris*.
[2] Total muscle weight refers to all muscles found in the whole hind leg
[3] M:B of whole leg calculated with all muscle and all bones of hind leg
[4] M:B of femur calculated using muscle*s* of femur and femur bone weight

4.3 Meat Quality – Romney versus 7/8 Wiltshire

The pH did not influence any meat quality characteristics (P>0.05; Table 4.3). When compared at an equal pH, there was no difference between the meat from each of the breed treatments for lightness, redness, yellowness, cooking loss percentage, drip loss percentage, total shear force or peak shear force (P>0.05; Table 4.3).

Table 4.3 Meat quality characteristics (mean ± SEM) from *Longissimus lumborum* muscle samples of Romney and 7/8 Wiltshire lambs. Ultimate pH was fitted as a covariate for colour, water holding and tenderness characteristics.

Meat Quality Characteristics	Romney	7/8 Wiltshire	P-value	
			Breed	pH Covariate
Ultimate pH	5.66 ± 0.01	5.64 ± 0.01	0.423	-
Meat colour				
Lightness (*L**)	36.0 ± 0.25	35.9 ± 0.25	0.754	0.446
Redness (*a**)	14.5 ± 0.20	15.0 ± 0.20	0.106	0.079
Yellowness (*b**)	6.2 ± 0.20	6.4 ± 0.20	0.376	0.236
Water holding capacity				
Cooking loss (%)	32.4 ± 0.34	31.5 ± 0.34	0.067	0.651
Drip loss (%)	3.4 ± 0.22	3.7 ± 0.22	0.344	0.414
Tenderness				
Total shear force (kgF)	14.2 ± 0.71	13.4 ± 0.71	0.412	0.610
Peak shear force (kgF)	3.1 ± 0.16	2.9 ± 0.16	0.342	0.402

4.4 Meat Quality – Romney versus 15/16 Wiltshire

The meat from Romney lambs had a greater ultimate pH, total shear force and peak shear force compared to the meat from 15/16 Wiltshire lambs ($P<0.05$; Table 4.4). The 15/16 Wiltshire lambs had redder meat (a* values) compared to Romney lambs ($P<0.05$; Table 4.4). There were no other differences ($P>0.05$; Table 4.4).

Table 4.4 Meat quality characteristics (mean ± SEM) from *Longissimus lumborum* muscle samples of Romney and 15/16 Wiltshire lambs. Ultimate pH was fitted as a covariate for colour, water holding and tenderness characteristics.

Meat Quality Characteristics	Romney	15/16 Wiltshire	P-value	
			Breed	pH Covariate
Ultimate pH	5.71 ± 0.03	5.61 ± 0.03	0.014	-
Meat colour				
Lightness (*L**)	36.8 ± 0.34	36.7 ± 0.31	0.898	0.439
Redness (*a**)	15.5 ± 0.27	16.4 ± 0.25	0.025	0.368
Yellowness (*b**)	6.7 ± 0.29	7.4 ± 0.27	0.108	0.379
Water holding capacity				
Cooking loss (%)	32.7 ± 0.29	32.1 ± 0.27	0.165	0.008
Drip loss (%)	2.7 ± 0.32	3.3 ± 0.30	0.212	0.641
Tenderness				
Total shear force (kgF)	12.2 ± 0.32	10.5 ± 0.30	0.001	0.765
Peak shear force (kgF)	3.0 ± 0.09	2.4 ± 0.08	<.001	0.472

Chapter 5: Discussion

The primary objective of this study was to investigate whether the carcass characteristics and meat quality attributes of 7/8 Wiltshire and 15/16 Wiltshire ram lambs differed to Romney ram lambs in each of their respective studies. This research was a part of a larger trial being undertaken by Massey University, studying the transition from a Romney flock to a Wiltshire flock by breeding, over several years. This trial began with two flocks of Romney ewes, while one remained a purebred Romney flock the other was crossed with Wiltshire rams. The resulting crossbred offspring were then also mated with a Wiltshire ram and so forth until they reached 15/16 Wiltshire. Throughout these two studies, the two flocks in each and their offspring had identical management and were paddocked and slaughtered as one group.

5.1 Carcass Characteristics

5.1.1 Live weight and Carcass Performance

Despite having no difference in birth weight and start live weight both the 7/8 and 15/16 Wiltshire lambs had a heavier final live weight than Romney lambs. These findings were similar to Corner-Thomas et al. (2021) and Corner-Thomas et al. (2022) who found no difference in birth weight and weaning weight for Romney versus 1/2 Wiltshire or 3/4 Wiltshire lambs respectively. Studies by Litherland et al. (1992) and Sumner et al. (2012) found Wiltshire were heavier at weaning compared to Romney and Perendale lambs respectively. Along with this Rawidech (2024) observed that 3/4 Wiltshire lambs had comparable birth weights to Romney lambs but higher live weights after weaning.

The faster growth after weaning, despite identical management practices, may stem from a genetic difference that results in greater feed intakes or different nutritional requirements (Greeff et al., 1995; Khan et al., 2012). It is also a possibility that the faster growth exhibited by the Wiltshire crossbreds could be a result of hybrid vigour. The process of shedding potentially influences liveweight gain as it may lower energy requirements for wool production or it could be associated with a hormone concentration or flux that influences wool growth pattern and shedding but alongside the nutrient partitioning and growth. An animal's growth is affected by the hormones of the somatotropic axis such as GH-releasing hormone and somatostatin which can be influenced by a number of factors including different genes (Bass

& Clark, 1989; Gluckman et al., 1987; Katoh et al., 2007). In wool producing sheep the wool follicle grows continuously while shedding sheep experience follicle growth cycles (Johnson et al., 2007; Pearson et al., 1996). These cycles are likely influenced by changes in photoperiod that results in seasonal variations in the secretion of the pituitary hormone prolactin (Johnson et al., 2007; Pearson et al., 1996).

The 7/8 and the 15/16 Wiltshire lambs had a heavier hot carcass weight (CW) and greater dressing out percentage (DO%) than Romney lambs. This was also found by Rawidech (2024) for 3/4 Wiltshire compared to Romney lambs. This indicates that the heavier final live weight is translating to a greater proportion of carcass in the body for Wiltshire lambs. There is a high correlation between the live weight at slaughter and both the hot CW and the dressing out percentage (Kirton et al., 1984; López et al., 2012). The greater live weight of the 7/8 and 15/16 Wiltshire lambs compared to their Romney counterparts, likely contributed to the greater hot CW and dressing out percentage that was recorded. The dressing out percentage of both proportions of Wiltshire may have also been higher due to the fact some lambs had shed some or all of their fleece making the overall non-carcass component lighter (Kirton et al., 1984).

5.1.2 Carcass Composition and Shape

The analysis revealed that both 7/8 and 15/16 Wiltshire lambs had a greater percentage of muscle and a lower dissectible fat percentage than their individual Romney lamb counterparts. The percentage of dissectible fat measured for 7/8 Wiltshire lambs was 2.5 percentage points less than their Romney counterparts while 15/16 Wiltshire lambs had a dissectible fat percentage that was 2.6 percentage points lower than their Romney counterparts. As the lambs were of a similar age the results suggest that the Wiltshire is a breed associated with lean growth as sheep breeds are known to differ in their growth composition (Hogg et al., 1992; Kremer et al., 2004; Moloney & McGee, 2023). In comparison Rawidech (2024) did not find a difference in the muscle percentage of 3/4 Wiltshire compared to Romney lambs but did identify that 3/4 Wiltshire lambs had a lower percentage of dissectible fat. Similarly Rathie and Teasdale (1994) found that lambs sired by Wiltshire Horn-Merinos had less fat than those sired by a Border Leicester-Merino ram. Van der Merwe et al. (2020) found varying results when comparing the muscle and fat percentages of wool and hair or shedding breeds with large variation between the two haired or shedding breeds.

The 7/8 Wiltshire and Romney likely were similar in frame size as there was no difference with femur length. In comparison the 15/16 Wiltshire lambs had a longer femur than their Romney counterpart's indicative of a taller stature. The 3/4 Wiltshire lambs studied by Rawidech (2024) were also found to have a longer femur length than Romney lambs. Similarly Sobrinho et al. (2003) observed that Romney sired lambs had a shorter femur length than sheep sired by East Friesian or Finn rams which are both breeds that are considered to have a visually leggy build similar to what is observed with the Wiltshire.

However, despite having a greater muscle percentage the 15/16 Wiltshire exhibited a lower muscularity index than Romney lambs. This is due to the fact that the muscularity index is the depth of the muscle per unit of bone, meaning that the muscle in 15/16 Wiltshire lambs is stretched over a longer bone reducing the depth of the muscle over the bone (Purchas et al., 1991). In contrast Rawidech (2024) identified no difference in the muscularity index despite 3/4 Wiltshire lambs having a longer femur and no difference in muscle percentage. However in New Zealand it is not standard to consider carcass shape during classification so differences in the muscularity index are unlikely to directly impact carcass value (New Zealand Meat Classification Authority, 2004).

5.2 Meat Quality

Each of the meat quality characteristics measured for 7/8 Wiltshire, 15/16 Wiltshire and Romney lambs were within the typical range for pasture-raised lamb (Johnson, Purchas, & Blair, 2005; Kok, 2019; Ye et al., 2020). The ultimate pH values of the meat from 7/8 Wiltshire lambs and their Romney counterparts did not differ. Similarly Van der Merwe et al. (2020) found no difference in pH when comparing the meat from wool versus haired or shedding breeds. In the study considering the 15/16 Wiltshire lambs, the meat from Romney lambs was found to have greater ultimate pH. However, as the ultimate pH of the meat from both breeds was below 5.8 there are unlikely to be negative effects on meat quality with these pH values (Devine et al., 1993). These findings correspond with those of Rawidech (2024) where a statistical difference in ultimate pH was found between the meat from Romney and Wiltshire crossbred lambs but the ultimate pH values were within the typical ranges for lamb.

The meat from 7/8 Wiltshire lambs and their Romney counterparts had the same level of redness while the meat from 15/16 Wiltshire lambs was found to be redder than that of their Romney counterparts. The 15/16 Wiltshire meat may have been redder due to a higher level of

myoglobin which can be influenced by a number of factors such as differing fibre types within the muscle or a higher level of physical activity (Bekhit et al., 2019). Increased physical activity is a possible explanation as Wiltshire sheep have been anecdotally observed to be a more active breed (Wiltshire Sheep of New Zealand, n.d.). Nevertheless it is important to note that the redness of the meat for both breeds was above 14.5, which is considered the threshold at which there is a 95% chance that a randomly selected consumer would score the sample as acceptable for colour (Khliji et al., 2010). This means the colour of the meat in the study would not have a negative effect on the visual appearance of the meat and therefore is unlikely to have a large influence on consumer perception. When comparing a range of shedding and wool breeds, Van der Merwe et al. (2020) found no consistent trend in meat colour. While the meat from two haired and shedding breeds, Dorper and Namaqua Afrikaner, was redder than the meat from the wool producing breeds of South African Mutton Merinos and Dormer, the colour of meat from another shedding breed, the Meatmaster, did not differ (Van der Merwe et al., 2020).

The water holding capacity of meat from both 7/8 Wiltshire and 15/16 Wiltshire lambs did not differ to that of Romney lambs. No difference in water holding capacity was also found by Rawidech (2024) when comparing the meat from 3/4 Wiltshire to Romney lambs. In contrast Van der Merwe et al. (2020) found a difference in cooking loss between the meat from haired or shedding breeds versus wool producing breeds but found no difference in drip loss.

There was no difference in the tenderness of meat, measured by shear force, between the 7/8 Wiltshire and their Romney lamb counterparts. Similarly Rawidech (2024) found no difference in shear force between the meat from 3/4 Wiltshire and Romney lambs. A study by Partida et al. (2012) found no difference in the tenderness of meat from lambs with wool compared to hair and shedding sires. In comparison the meat from 15/16 Wiltshire compared to their Romney lamb counterparts had a lower shear force indicating more tender meat. However, the meat from both breeds was well below 4.08 kgF, which indicates a level of tenderness that is considered acceptable to consumers (Hopkins et al., 2006). This means that there is likely no negative impact of using either breed when it comes to tenderness of lamb meat.

5.3 Implications

The findings of this study showed that 7/8 and 15/16 Wiltshire had the potential to have greater than or equal to carcass characteristics to Romney lambs, this builds on the information found by Rawidech (2024) who showed that 3/4 Wiltshire lambs had carcass characteristics that were

equal to those of Romney lambs. It can be inferred from the data that there will be no substantial impact on meat quality when using Wiltshire sheep versus Romneys. The results show that as the proportion of Wiltshire increases from 7/8 to 15/16 during the grading up process there is the potential for a further increase in production. The superior characteristics exhibited by the 7/8 and 15/16 Wiltshire compared to Romney despite being raised in identical management systems both years indicates that minimal changes to a farmer's current system would need to be made for the increased yields to be showcased. Wiltshire will be lower in fat and in a larger weight class which will result in a favourable carcass classification for prime lamb without getting over fat. This implies that subjective assessments of Wiltshire meat production are unreliable, and that farmers should not be concerned about the ability of Wiltshire and Wiltshire crossbreeds to produce sufficient, high-quality meat yield. The implication of this is that changing from Romney to Wiltshire will not result in a decrease in productive lamb output for farmers.

5.4 Limitations

The accuracy of the outcomes might be negatively impacted by the small sample sizes used within this study and hence, there is potential that the actual population is not represented. As the goal was to compare the lambs at the same age there was a variation in the final live weight. To alleviate this hot CW was used as a covariate as there is a possibility that the different hot CWs influenced the composition and other carcass traits. Similar to this the meat quality characteristics were adjusted for ultimate pH as it has been found to affect the overall meat quality.

Another limitation was that within the wider study the goal was to investigate the effects of changing a farms entire flock from a breed which was developed to produce both meat and wool (Romney) to a breed which was developed with the focus of producing meat (Wiltshire). This could explain some of the differences in the final weights despite them being raised in the same environment. Additional studies might compare the characteristics of Wiltshire lambs to those of another solely meat producing breed.

Due to the wider study being self-replacing a limited number of ewe lambs are available for slaughter hence the use of male lambs within this study. This is a limitation because despite the fact the ram lambs were killed at a young age, utilising entire males could negatively influence the quality of the meat due to differences in fat deposition. It therefore may be beneficial to

carry out further studies examining the difference in meat quality for ewe or wether lambs from each breed.

This current study only measured objective meat quality characteristics due to sensory studies being costly. If another study were to be conducted it would be beneficial to carry out sensory tests of meat quality using consumers or trained sensory panels. However, given limited differences in the objective tests, sensory studies are unwarranted. Future research could also investigate the flavour of the meat from each of these breeds as within this study there were no measures of flavour assessed due to the highly sensitive equipment and large expenses associated with using trained sensory panels.

5.5 Conclusion

The objective of these two studies was to identify if the carcass and meat quality characteristics of 7/8 and 15/16 Wiltshire lambs differed to those of their respective Romney counterparts. The findings showed that both 7/8 and 15/16 Wiltshire lambs have the potential to produce equal to or greater amounts of lean meat to that of Romney lambs. An increase in the length of the femur and a decrease in the muscularity index was exhibited in 15/16 Wiltshire lambs that was not found in the 7/8 Wiltshire; however, this did not influence the percentage of muscle produced. The findings indicated that utilising 7/8 or 15/16 Wiltshire lambs would not negatively impact potential meat yields. The meat quality values for the meat from both the 7/8 and 15/16 Wiltshire and Romney lambs were similar and associated with values that indicate an acceptable eating quality. Therefore, it is likely that utilising 7/8 and 15/16 Wiltshire lambs would not negatively impact the quality of the meat produced. Overall, this means that there is likely no negative impact on the amount and quality of product produced if a farmer were to transition from a Romney flock to a Wiltshire flock.

Chapter 6: References

Aalhus, J., Price, M., Shand, P., & Hawrysh, Z. (1991). Endurance-exercised growing sheep: II. Tenderness increase and change in meat quality. *Meat science*, *29*(1), 57-68.

Abdullah, A. Y. (1994). *Investigations into muscularity as a characteristic of sheep carcasses at various stages of growth* [Doctoral dissertation, Massey University]. Massey Research Online. ***https://mro.massey.ac.nz/items/5cff5583-ecd1-4faf-81b2-4b97da8d1d83***

Almeida, A. M., Kilminster, T., Scanlon, T., Araújo, S. S., Milton, J., Oldham, C., & Greeff, J. C. (2013). Assessing carcass and meat characteristics of Damara, Dorper and Australian Merino lambs under restricted feeding. *Tropical animal health and production*, *45*, 1305-1311. ***https://doi.org/10.1007/s11250-013-0361-z***

Arce-Recinos, C., Ramos-Juárez, J. A., Hernández-Cázares, A. S., Crosby-Galván, M. M., Alarcón-Zúñiga, B., Miranda-Romero, L. A., Zaldívar-Cruz, J. M., Vargas-Villamil, L., Aranda-Ibáñez, E. M., & Vargas-Bello-Pérez, E. (2022). Interplay between feed efficiency indices, performance, rumen fermentation parameters, carcass characteristics and meat quality in Pelibuey lambs. *Meat science*, *183*, Article 108670. ***https://doi.org/10.1016/j.meatsci.2021.108670***

Aryal, J., Kulasiri, D., Carnaby, G., & Samarasinghe, S. (2009). Investigating the price of the New Zealand wool clip using modelling approaches. 18th World IMACS / MODSIM Congress, Cairns, Australia.

Bass, J. J., & Clark, R. G. (1989). The endocrine control and coordination of animal growth. In R. Purchas, B. Butler-Hogg, & A. Davies (Eds.), *Meat Production and Processing* (Vol. 11, pp. 103-112). New Zealand Society of Animal Production (Inc).

Beef + Lamb New Zealand. (2023). *Compendium of New Zealand Farm Facts 2023*. ***https://beeflambnz.com/knowledge-hub/PDF/farm-facts-2023.pdf***

Beef + Lamb New Zealand. (2024a). *Benchmarking Tool*. Retrieved September 2, 2025 from ***https://tools.beeflambnz.com/benchmarking-tool***

Beef + Lamb New Zealand. (2024b). *Stock Number Survey*. ***https://beeflambnz.com/knowledge-hub/PDF/stock-number-survey-30-june-2024.pdf***

Beef + Lamb New Zealand. (2025a). *Farm classes*. Retrieved September 2, 2025 from ***https://beeflambnz.com/industry-data/farm-data-and-industry-production/farm-classes***

Beef + Lamb New Zealand. (2025b). *Mid-Season Update 2024-25* ***https://beeflambnz.com/knowledge-hub/PDF/mid-season-update-2024-2025.pdf***

Beef + Lamb New Zealand. (2025c). *Stock Number Survey*. ***https://beeflambnz.com/knowledge-hub/PDF/stock-number-survey-report-30-june-2025.pdf***

Beef + Lamb New Zealand. (n.d.-a). *Sheep Breeds in New Zealand*. ***https://beeflambnz.com/knowledge-hub/PDF/sheep-breeds-poster.pdf***

Beef + Lamb New Zealand. (n.d.-b). *Taste Pure Nature origin brand*. Retrieved March 31, 2025 from ***https://beeflambnz.com/markets/nz-red-meat-story/taste-pure-nature-origin-brand***

Bekhit, A., Morton, J. D., Bhat, Z. F., & Kong, L. (2019). Meat color: Factors affecting color stability. *Encyclopedia of food chemistry*, *2*, 202-210. ***https://doi.org/10.1016/B978-0-08-100596-5.21665-X***

Brand, T., Van Der Westhuizen, E., van Der Merwe, D., & Hoffman, L. (2018). Analysis of carcass characteristics and fat deposition of Merino, South African Mutton Merino and Dorper lambs housed in a feedlot. *South African Journal of Animal Science*, *48*(3), 477-488. ***https://doi.org/10.4314/sajas.v48i3.8***

Bunch, T. D., Evans, R., Wang, S., Brennand, C., Whittier, D., & Taylor, B. (2004). Feed efficiency, growth rates, carcass evaluation, cholesterol level and sensory evaluation of lambs of various hair and wool sheep and their crosses. *Small Ruminant Research*, *52*(3), 239-245. ***https://doi.org/10.1016/j.smallrumres.2003.07.001***

Burger, A., Hoffman, L. C., Cloete, J., Muller, M., & Cloete, S. (2013). Carcass composition of Namaqua Afrikaner, Dorper and SA Mutton Merino ram lambs reared under extensive conditions. *South African Journal of Animal Science*, *43*(5), S27-S32. ***https://doi.org/10.4314/sajas.v43i5.5***

Burke, J. M., & Apple, J. K. (2007). Growth performance and carcass traits of forage-fed hair sheep wethers. *Small Ruminant Research*, *67*(2), 264-270. ***https://doi.org/10.1016/j.smallrumres.2005.10.014***

Butterfield, R. M. (1988). *New concepts of sheep growth*. The Department of Veterinary Anatomy, University of Sydney.

Cake, M., Gardner, G. E., Hegarty, R., Boyce, M., & Pethick, D. W. (2006). Effect of nutritional restriction and sire genotype on forelimb bone growth and carcass composition in crossbred lambs. *Australian Journal of Agricultural Research*, *57*(6), 605-616.

Calnan, H., Jacob, R., Pethick, D., & Gardner, G. (2014). Factors affecting the colour of lamb meat from the longissimus muscle during display: The influence of muscle weight and muscle oxidative capacity. *Meat science*, *96*(2), 1049-1057. ***https://doi.org/10.1016/j.meatsci.2013.08.032***

Castro, D. P., Yamamoto, S. M., Araújo, G. G., Pinheiro, R. S., Queiroz, M. A., Albuquerque, Í. R., & Moura, J. H. (2017). Influence of drinking water salinity on carcass characteristics and meat quality of Santa Inês lambs. *Tropical animal health and production*, *49*, 1095-1100. ***https://doi.org/10.1007/s11250-017-1289-5***

Cheng, Q., & Sun, D.-W. (2008). Factors affecting the water holding capacity of red meat products: A review of recent research advances. *Critical reviews in food science and nutrition*, *48*(2), 137-159. ***https://doi.org/10.1080/10408390601177647***

Corlett, M. T. (2023). *Consumer Perceptions Towards Lamb Meat Colour and Eating Quality* [Doctoral dissertation, Murdoch University]. Murdoch University Research Portal. ***https://researchportal.murdoch.edu.au/esploro/outputs/doctoral/Consumer-Perceptions-Towards-Lamb-Meat-Colour/991005593753707891***

Corner-Thomas, R., Kenyon, P., Morris, S., Greer, A., Logan, C., Ridler, A., Hickson, R., & Blair, H. (2013). A survey examining the New Zealand breed composition, management tool use and research needs of commercial sheep farmers and ram breeders. Proceedings of the 20th Conference of the Association for the Advancement of Animal Breeding and Genetics Napier, New Zealand.

Corner-Thomas, R., Ridler, A., Kenyon, P., Andrews, C., Burnham, D., Blair, H., & Morris, S. (2022). A comparison of the performance of Romney and Wiltshire cross lambs to weaning. *New Zealand Journal of Animal Science and Production*, *82*, 45-49.

Corner-Thomas, R., Ridler, A., Kenyon, P., Blair, H., & Morris, S. (2021). A comparison of the ewe reproductive performance of Romney ewes bred to Romney or Wiltshire rams and the growth of their progeny to weaning. *New Zealand Journal of Animal Science and Production*, *81*, 136-140.

Costa, R. G., Araújo Filho, J. T. d., Sousa, W. H. d., Gonzaga Neto, S., Madruga, M. S., & Fraga, A. B. (2010). Effect of diet and genotype on carcass characteristics of feedlot hair sheep. *Revista Brasileira de Zootecnia*, *39*(12), 2763-2768.

Costa, R. G., Batista, A. S. M., Madruga, M. S., Neto, S. G., do Egypto, R. d. C. R., de Araújo Filho, J. T., & Villarroel, A. S. (2009). Physical and chemical characterization of lamb meat from different genotypes submitted to diet with different fibre contents. *Small Ruminant Research*, *81*(1), 29-34. ***https://doi.org/10.1016/j.smallrumres.2008.10.007***

Costa, R. G., Silva, N. V. d., Azevedo, P. S. d., Medeiros, A. N. d., Carvalho, F. F. R. d., Queiroga, R. d. C. R. d. E., & Medeiros, G. R. d. (2011). Meat quality of lambs fed silk flower hay (Calotropis procera SW) in the diet. *Revista Brasileira de Zootecnia*, *40*, 1266-1271.

Craigie, C., Lambe, N., Richardson, R., Haresign, W., Maltin, C., Rehfeldt, C., Roehe, R., Morris, S., & Bunger, L. (2012). The effect of sex on some carcass and meat quality traits in Texel ewe and ram lambs. *Animal Production Science*, *52*(7), 601-607. ***https://doi.org/10.1071/AN11282***

de Oliveira, J. P. F., de Andrade Ferreira, M., Alves, A. M. S. V., de Melo, A. C. C., de Andrade, I. B., Urbano, S. A., Suassuna, J. M. A., de Barros, L. J. A., & de Barros Melo, T. T. (2017). Carcass characteristics of lambs fed spineless cactus as a replacement for sugarcane. *Asian-Australasian Journal of Animal Sciences*, *31*(4), 529.

Devine, C., Graafhuis, A., Muir, P., & Chrystall, B. (1993). The effect of growth rate and ultimate pH on meat quality of lambs. *Meat science*, *35*(1), 63-77.

Doyle, E. K., Preston, J. W., McGregor, B. A., & Hynd, P. I. (2021). The science behind the wool industry. The importance and value of wool production from sheep. *Animal Frontiers*, *11*(2), 15-23. ***https://doi.org/10.1093/af/vfab005***

Duffin, P. (2022). Grading up to a Wiltshire flock of shedding sheep. Retrieved September 18, 2025, from ***https://www.massey.ac.nz/about/news/grading-up-to-a-wiltshire-flock-of-shedding-sheep/***

Estrada-León, R. J., Moo-Huchin, V. M., Mena-Arceo, D., Cárdenas-Medina, J. V., Ortíz-Fernández, A., & Canto-Pinto, J. C. (2022). Meat quality physicochemical traits in hair sheep in southeast Mexico. *Rev MVZ Cordoba*, *27*, Article 2563. ***https://doi.org/10.21897/rmvz.2563***

FAOSTAT. (2023). *Crops and livestock products*. ***https://www.fao.org/faostat/en/#data/QCL***

Farrell, L. J., Morris, S. T., Kenyon, P. R., & Tozer, P. R. (2020). Modelling a transition from purebred romney to fully shedding wiltshire–romney crossbred. *Animals*, *10*(11), Article 2066. ***https://doi.org/10.3390/ani10112066***

Fisher, A. D., & Roadknight, N. (2024). Welfare of Sheep. In K. Abbott (Ed.), *Sheep Veterinary Practice* (pp. 19-38). CRC Press. ***https://doi.org/10.1201/9781003344346-2***

Fourie, P., Kirton, A., & Jury, K. (1970). Growth and development of sheep: II. Effect of breed and sex on the growth and carcass composition of the Southdown and Romney and their cross. *New Zealand Journal of Agricultural Research*, *13*(4), 753-770. ***https://doi.org/10.1080/00288233.1970.10430508***

Gehring, K. B. (2023). Meat and health. In F. Toldrá (Ed.), *Lawrie's Meat Science* (9 ed., pp. 687-705). Woodhead Publishing. ***https://doi.org/10.1016/B978-0-323-85408-5.00009-1***

Gluckman, P., Breier, B., & Davis, S. (1987). Physiology of the somatotropic axis with particular reference to the ruminant. *Journal of Dairy Science*, *70*(2), 442-466.

Greeff, J., Bouwer, L., & Hofmeyr, J. (1995). Biological efficiency of meat and wool production of seven sheep genotypes. *Animal Science*, *61*(2), 259-264. ***https://doi.org/10.1017/S1357729800013783***

Ha, M., Warner, R. D., King, C., Wu, S., & Ponnampalam, E. N. (2022). Retail packaging affects colour, water holding capacity, texture and oxidation of sheep meat more than breed and finishing feed. *Foods*, *11*(2), Article 144. ***https://doi.org/10.3390/foods11020144***

Heimbuch, M. L., Van Buren, J. B., Epperson, B. S., Jepsen, S. M., Oliver, K. F., Nasados, J. A., Vinci, D. A., Larson, M., Konetchy, D. E., Price, W. J., Vierck, K. R., Legako, J. F., Loomas, K., Insausti, K., Bass, P. D., & Colle, M. J. (2023). Evaluation of growth, meat quality, and sensory characteristics of wool, hair, and composite lambs. *Journal of Animal Science*, *101*, 1-12. ***https://doi.org/10.1093/jas/skad076***

Hogg, B., Mercer, G., Mortimer, B., Kirton, A., & Duganzich, D. (1992). Carcass and meat quality attributes of commercial goats in New Zealand. *Small Ruminant Research*, *8*(3), 243-256.

Honikel, K. O. (2008). Moisture and water-holding capacity. In L. M. L. Nollet & F. Toldrá (Eds.), *Handbook of muscle foods analysis* (pp. 315-334). CRC Press.

Hopkins, D., Hegarty, R., Walker, P., & Pethick, D. (2006). Relationship between animal age, intramuscular fat, cooking loss, pH, shear force and eating quality of aged meat from sheep. *Australian Journal of Experimental Agriculture*, *46*(7), 879-884. ***https://doi.org/10.1071/EA05311***

Hopkins, D. L., & Ertbjerg, P. (2023). The eating quality of meat: II—Tenderness. In F. Toldrá (Ed.), *Lawrie's meat science* (9 ed., pp. 393-420). Woodhead Publishing. ***https://doi.org/10.1016/B978-0-323-85408-5.00022-4***

Hunt, M., King, A., Barbut, S., Claus, J., Cornforth, D., Hanson, D., Lindahl, G., Mancini, R., Milkowsk, A., Mohan, A., Pohlman, F., Raines, C., Seyfert, M., Sørheim, O., Suman, S., & Weber, M. (2012). *AMSA Meat Color Measurement Guidelines* (American Meat Science Association, Ed.).

Johnson, P., O'Connell, D., Dodds, K., Sumner, R., McEwan, J., & Pearson, A. (2007). Wool shedding as a trait for genetic improvement using marker assisted selection. Proceedings of the Association for the Advancement of Animal Breeding and Genetics,

Johnson, P., Purchas, R., & Blair, H. (2005). Effect of slaughter group and sire on carcass composition and meat quality characteristics of Texel-sired lambs. New Zealand Society of Animal Production,

Johnson, P., Purchas, R., McEwan, J., & Blair, H. (2005). Carcass composition and meat quality differences between pasture-reared ewe and ram lambs. *Meat science*, *71*(2), 383-391. ***https://doi.org/10.1016/j.meatsci.2005.04.021***

Johnson, T., Newman, S.-A., McRae, K., van der Weerden, T., Brown, M., & Scobie, D. (2021). A review of the current sheep industry in New Zealand and opportunities for change to meet future challenges. *New Zealand Journal of Animal Science and Production 81*, 1-15.

Journeaux, P., van Reenen, E., Manjala, T., Pike, S., Hanmore, I., & Millar, S. (2017). *Analysis of Drivers and Barriers to Land Use Change*. ***https://www.mpi.govt.nz/dmsdocument/23056-ANALYSIS-OF-DRIVERS-AND-BARRIERS-TO-LAND-USE-CHANGE***

Katoh, K., Takahashi, T., Kobayashi, Y., & Obara, Y. (2007). Somatotropic axis and nutrition in young ruminants around weaning time. *Asian-Australasian Journal of Animal Sciences*, *20*(7), 1156-1168.

Khan, M. J., Abbas, A., Ayaz, M., Naeem, M., Akhter, M. S., & Soomro, M. H. (2012). Factors affecting wool quality and quantity in sheep. *African journal of Biotechnology*, *11*(73), 13761-13766. ***https://doi.org/10.5897/AJBX11.064***

Khliji, S., Van de Ven, R., Lamb, T., Lanza, M., & Hopkins, D. (2010). Relationship between consumer ranking of lamb colour and objective measures of colour. *Meat science*, *85*(2), 224-229. ***https://doi.org/10.1016/j.meatsci.2010.01.002***

Kirton, A., Carter, A., Clarke, J., & Duganzich, D. (1984). Dressing percentages of lambs. New Zealand Society of Animal Production,

Kirton, A., & Pickering, F. (1967). Factors associated with differences in carcass conformation in lamb. *New Zealand Journal of Agricultural Research*, *10*(2), 183-200. ***https://doi.org/10.1080/00288233.1967.10425126***

Kirton, A., Winn, G., Duganzich, D., & Dalton, D. (1985). Body composition of cull Romney, Dorset × Romney, and Cheviot ewes from New Zealand hill country. *New Zealand Journal of Agricultural Research*, *28*(2), 241-247. ***https://doi.org/10.1080/00288233.1985.10420934***

Kirton, A. H., & Morris, C. A. (1989). The effect of mature size, sex and breed on patterns of change during growth and development. In R. Purchas, B. Butler-Hogg, & A. Davies (Eds.), *Meat Production and Processing* (Vol. 11, pp. 73-85). New Zealand Society of Animal Production (Inc).

Kok, J. C. (2019). *Investigating the relationship between lamb weaning age and forage diet on carcass and meat quality* [Master's thesis, Massey University]. Massey Research Online. ***https://mro.massey.ac.nz/items/0bf91c9a-033c-45d6-bd29-b1a5dee53cd3***

Komprda, T., Kuchtík, J., Jarošová, A., Dračková, E., Zemánek, L., & Filipčík, B. (2012). Meat quality characteristics of lambs of three organically raised breeds. *Meat science*, *91*(4), 499-505. ***https://doi.org/10.1016/j.meatsci.2012.03.004***

Korkeala, H., Mäki-Petäys, O., Alanko, T., & Sorvettula, O. (1986). Determination of pH in meat. *Meat science*, *18*(2), 121-132.

Kremer, R., Barbato, G., Castro, L., Rista, L., Rosés, L., Herrera, V., & Neirotti, V. (2004). Effect of sire breed, year, sex and weight on carcass characteristics of lambs. *Small Ruminant Research*, *53*(1-2), 117-124. ***https://doi.org/10.1016/j.smallrumres.2003.09.002***

Litherland, A., Dynes, R., & Moss, R. (2010). Factors affecting dressing-out percentage of lambs. New Zealand Society of Animal Production,

Litherland, A., Sorenson, E., Niezen, J., & Bishop, D. (1992). A pilot evaluation of shedding sheep breeds compared with non-shedding breeds for susceptibility to nematodes and flystrike. New Zealand Society of Animal Production

López, E. J., Peraza-Mercado, G., Holguiny, F. M., & Ortiz, M. F. I. (2012). Relationship between live animal weight, warm and cold carcass weight and carcass principal components. *Global Veterinaria*, *9*(2), 179-183.

Mao, N. (2025). Advances in understanding and optimising sheep wool quality. In L. Stubbings & K. Phillips (Eds.), *Advances in sheep production* (pp. 391-421). Burleigh Dodds Science Publishing Limited. ***https://doi.org/10.19103/as.2024.0147.22***

McEwan, J., Davis, G., Fennessy, P., & Clarke, J. (1995). Sires for more valuable lambs. New Zealand Society of Animal Production,

McGeehin, B., Sheridan, J., & Butler, F. (2001). Factors affecting the pH decline in lamb after slaughter. *Meat science*, *58*(1), 79-84.

McRae, K., Rowe, S., & McEwan, J. (2018). Brief Communication: Potential alterations in New Zealand sheep, beef, cattle and deer numbers due to climate change: What can genetics offer. *New Zealand Journal of Animal Science and Production*, *78*, 146-150.

Meat Industry Association of New Zealand. (2024a). *Industry Fact Sheet - Sheep Meat 2023/2024 Summary*. ***https://mia.co.nz/wp-content/uploads/2024/11/Sheepmeat-Factsheet-2024.pdf***

Meat Industry Association of New Zealand. (2024b). *Red meat export trends in selected markets up to June 2024*. ***https://mia.co.nz/wp-content/uploads/2024/08/June-2024-global-trade-statistics.pdf***

Menezes, A. M. d., Cruz Junior, C., Tanure, C. B., Peripolli, V., Castro, M., Louvandini, H., & McManus, C. (2016). Evaluation of carcass and muscle traits in Santa Ines female lambs finished with different agricultural products. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia*, *68*, 1259-1266. ***https://doi.org/10.1590/1678-4162-8681***

Ministry for Primary Industries. (2019). *Wool Data Book*. ***https://www.mpi.govt.nz/dmsdocument/43201-Wool-Data-Book***

Moloney, A. P., & McGee, M. (2023). Factors influencing the growth of meat animals. In F. Toldrá (Ed.), *Lawrie's Meat Science* (9 ed., pp. 21-49). Woodhead Publishing. ***https://doi.org/10.1016/B978-0-323-85408-5.00006-6***

Monaco, C. A., Freire, M. T. A., Melo, L., Rosa, A. F., Carrer, C. d. C., & Trindade, M. A. (2015). Eating quality of meat from six lamb breed types raised in Brazil. *Journal of the Science of Food and Agriculture*, *95*(8), 1747-1752. ***https://doi.org/10.1002/jsfa.6894***

Montossi, F., Font-i-Furnols, M., del Campo, M., San Julián, R., Brito, G., & Sañudo, C. (2013). Sustainable sheep production and consumer preference trends: Compatibilities, contradictions, and unresolved dilemmas. *Meat science*, *95*(4), 772-789. ***https://doi.org/10.1016/j.meatsci.2013.04.048***

Morris, S. T. (2013). Sheep and beef cattle production systems. In J. Dymond (Ed.), *Ecosystem Services in New Zealand* (pp. 79-84). Manaaki Whenua Press.

Morris, S. T. (2017). Overview of sheep production systems. In D. M. Ferguson, C. Lee, & A. Fisher (Eds.), *Advances in sheep welfare* (pp. 19-35). Woodhead Publishing. ***https://doi.org/10.1016/B978-0-08-100718-1.00002-9***

Moura, M. d. S. C., Guim, A., Batista, Â. M. V., do Vale Maciel, M., Cardoso, D. B., de Lima Júnior, D. M., & de Carvalho, F. F. R. (2020). The inclusion of spineless cactus in the diet of lambs increases fattening of the carcass. *Meat science*, *160*, 107975.

Muir, P. D., Thomson, B. C., & Askin, D. C. . (2008). *A review of dressing out percentage in New Zealand livestock*. M. o. A. a. Forestry. ***https://www.mpi.govt.nz/dmsdocument/2963-review-dressing-out-percentage-in-nz-livestock***

Navajas, E., Lambe, N., Fisher, A., Nute, G., Bünger, L., & Simm, G. (2008). Muscularity and eating quality of lambs: Effects of breed, sex and selection of sires using muscularity measurements by computed tomography. *Meat science*, *79*(1), 105-112.

New Zealand Meat Classification Authority. (2004). *New Zealand Meat Guide to Lamb and Mutton Carcass Classification*. ***https://www.interest.co.nz/files/rural/lambgrade.pdf***

New Zealand Sheep Breeders Association. (n.d.). *Australian Whites NZ*. Retrieved March 26, 2026 from ***https://nzsheep.co.nz/australian-whites-nz/***

Novaković, S., & Tomašević, I. (2017). A comparison between Warner-Bratzler shear force measurement and texture profile analysis of meat and meat products: A review. IOP Conference Series: Earth and Environmental Science,

Nsoso, S., Young, M., & Beatson, P. (2000). A review of carcass conformation in sheep: assessment, genetic control and development. *Small Ruminant Research*, *35*(2), 89-96.

Ockerman, H., Emsen, H., Parker, C., & Pierson, C. (1982). Influence of type (wooled or hair) and breed on growth and carcass characteristics and sensory properties of lamb. *Journal of Food Science*, *47*(4), 1365-1368.

Partida, J. A., Vázquez, E., Rubio, M. S., & Méndez, D. (2012). Effect of breed of sire on carcass traits and meat quality of Katahdin lambs. *Journal of Food Research*, *1*(4), 141-149. ***https://doi.org/10.5539/jfr.v1n4p141***

Pearson, A., Parry, A., Ashby, M., Choy, V., Wildermoth, J., & Craven, A. (1996). Inhibitory effect of increased photoperiod on wool follicle growth. *Journal of Endocrinology*, *148*(1), 157-166.

Pérez, B., Rojas-Román, L., Estrada-Angulo, A., Muro, O., Barreras, A., & Plascencia, A. (2021). Effects of long-term supplementation of different levels of tannins extract on meat quality and carcass traits of hairy lambs. *Advances in Animal and Veterinary Sciences*, *9*(11), 1973-1977. ***https://doi.org/10.17582/journal.aavs/2021/9.11.1973.1977***

Piña-Cárdenas, B. A., García-Macías, J. A., Rodríguez-Almeida, F. A., Aguilar-Palma, G. N., & Villagómez-Cortés, J. A. (2013). Carcass Traits in Hair and Crossbred Lambs in Mexico. *World Applied Sciences Journal*, *28*(6), 778-784.

Prache, S., Schreurs, N., & Guillier, L. (2022). Factors affecting sheep carcass and meat quality attributes. *Animal*, *16*, Article 100330. ***https://doi.org/10.1016/j.animal.2021.100330***

Price, M. (1995). Development of carcass grading and classification systems. In *Quality and grading of carcasses of meat animals* (pp. 173-199). CRC Press.

Purchas, R. (1989). On-farm factors affecting meat quality characteristics. In R. Purchas, B. Butler-Hogg, & A. Davies (Eds.), *Meat Production and Processing* (Vol. 11, pp. 159-171). New Zealand Society of Animal Production (Inc).

Purchas, R., Davies, A., & Abdullah, A. (1991). An objective measure of muscularity: changes with animal growth and differences between genetic lines of Southdown sheep. *Meat science*, *30*(1), 81-94.

Purchas, R., & Wilkin, G. (1995). Characteristics of lamb carcasses of contrasting subjective muscularity. *Meat science*, *41*(3), 357-368.

Purslow, P. P. (2023). The structure and growth of muscle. In F. Toldrá (Ed.), *Lawrie's meat science* (9 ed., pp. 51-103). Woodhead Publishing. ***https://doi.org/10.1016/B978-0-323-85408-5.00004-2***

Rare Breeds. (n.d.). *New Zealand Meatmaster Sheep*. Retrieved September 22, 2026 from ***https://www.rarebreeds.co.nz/meatmaster.html***

Rathie, K., & Teasdale, C. (1994). Assessing Wiltshire Horn-Merino crosses. 3. The 50% Wiltshire Horn as a prime lamb producer. *Australian Journal of Experimental Agriculture*, *34*(6), 733-739.

Rawidech, R. (2024). *Carcass and meat quality characteristics of Romney and three-quarter Wiltshire lambs* [Master's thesis, Massey University]. Massey Research Online. ***https://mro.massey.ac.nz/items/d57c77af-5b59-46dc-baae-21ae5e83385b***

Saldanha, R. B., Cirne, L. G. A., Brant, L. M. S., Rodrigues, C. S., dos Santos Pina, D., de Carvalho Matos, S., Grimaldi, A. B., Bento, S. C., Tosto, M. S. L., Santos, S. A., Alba, H. D. R., & Pinto de Carvalho, G. G. (2022). Productive characteristics of feedlot Santa Inês and Dorper lambs: intake, digestibility, feeding behavior, performance, carcass traits, and meat quality. *Tropical animal health and production*, *54*(17). ***https://doi.org/10.1007/s11250-021-03011-8***

Scales, G., Bray, A., Baird, D., O'Connell, D., & Knight, T. (2000). Effect of sire breed on growth, carcass, and wool characteristics of lambs born to Merino ewes in New Zealand. *New Zealand Journal of Agricultural Research*, *43*(1), 93-100. ***https://doi.org/10.1080/00288233.2000.9513412***

Schreurs, N., Lane, G., Tavendale, M., Barry, T., & McNabb, W. (2008). Pastoral flavour in meat products from ruminants fed fresh forages and its amelioration by forage condensed tannins. *Animal Feed Science and Technology*, *146*(3–4), 193-221. ***https://doi.org/10.1016/j.anifeedsci.2008.03.002***

Schreurs, N. M., & Kenyon, P. R. (2017a). Animal and on-farm factors affecting sheep and lamb meat quality. In J. Greyling (Ed.), *Achieving sustainable production of sheep* (pp. 29-52). Burleigh Dodds Science Publishing Limited. ***https://doi.org/10.19103/AS.2016.0019.24***

Schreurs, N. M., & Kenyon, P. R. (2017b). Factors affecting sheep carcass characteristics. In J. Greyling (Ed.), *Achieving sustainable production of sheep* (pp. 3-27). Burleigh Dodds Science Publishing Limited. ***https://doi.org/10.19103/AS.2016.0019.01***

Slee, J. (1959). Fleece shedding, staple length and fleece weight in experimental Wiltshire Horn-Scottish Blackface sheep crosses. *The Journal of Agricultural Science*, *53*(2), 209-223. ***https://doi.org/10.1017/S002185960002027X***

Sneddon, N. W., Handcock, R. C., Corner-Thomas, R. A., Kenyon, P. R., Burnham, D. L., Garrick, D. J., Littlejohn, M. D., Blair, H. T., & Morris, S. T. (2024). Wool shedding and lamb fleece weights: first-cross and backcross Wiltshire–Romney sheep scored at lamb, hogget and two-tooth ages. *New Zealand Journal of Agricultural Research*, *67*(3), 394-401. ***https://doi.org/10.1080/00288233.2023.2287110***

Sobrinho, A. S., Kadim, I., & Purchas, R. (2003). Effect of genotypes and age on carcass and meat quality characteristics of ram lambs. *Agricultural and Marine Sciences*, *8*(2), 73-78.

Suman, S. P., & Joseph, P. (2013). Myoglobin chemistry and meat color. *Annual review of food science and technology*, *4*(1), 79-99. ***https://doi.org/10.1146/annurev-food-030212-182623***

Sumner, R., Scobie, D., O'Connell, D., & Henderson, H. (2012). Relative performance of Wiltshire and Perendale sheep. New Zealand Society of Animal Production,

Tomasevic, I., Djekic, I., Font-i-Furnols, M., Terjung, N., & Lorenzo, J. M. (2021). Recent advances in meat color research. *Current Opinion in Food Science*, *41*, 81-87. ***https://doi.org/10.1016/j.cofs.2021.02.012***

Tornberg, E. (1996). Biophysical aspects of meat tenderness. *Meat science*, *43*, 175-191.

Tshabalala, P. A., Strydom, P. E., Webb, E. C., & de Kock, H. L. (2003). Meat quality of designated South African indigenous goat and sheep breeds. *Meat science*, *65*(1), 563-570. ***https://doi.org/10.1016/S0309-1740(02)00249-8***

Turner, K., Belesky, D., Cassida, K., & Zerby, H. (2014). Carcass merit and meat quality in Suffolk lambs, Katahdin lambs, and meat-goat kids finished on a grass–legume pasture with and without supplementation. *Meat science*, *98*(2), 211-219. ***https://doi.org/10.1016/j.meatsci.2014.06.002***

Van der Merwe, D. A., Brand, T. S., & Hoffman, L. C. (2020). Slaughter characteristics of feedlot-finished premium South African lamb: effects of sex and breed type. *Foods*, *9*(5), Article 648. ***https://doi.org/10.3390/foods9050648***

Vega Britez, G. D., Vargas Junior, F. M., Retore, M., Silva, M. C., Ledesma, L. L. M., Silva, A. L. A., Monteschio, J. O., & Fernandes, T. (2020). Effects of type of tropical pasture and concentrate supplementation level on the carcass traits of grazing lambs. *Archives Animal Breeding*, *63*(2), 283-291.

Vesely, J., & Peters, H. F. (1972). Muscle, bone, and fat and their interrelations in five breeds of lamb. *Canadian Journal of Animal Science*, *52*(4), 629-636.

Villatoro, K. M. (2019). *Nutritional, quality and sensory characteristics of Dorper, domestic commercial crossbred and Australian commercial lamb meat* [Master's thesis, University of California, Davis]. ProQuest LLC.

https://www.proquest.com/openview/2682e069a68e2df2910108d445c78bb9/1?pq-origsite=gscholar&cbl=18750&diss=y

Warner, R. D. (2023). The eating quality of meat: IV—Water holding capacity and juiciness. In F. Toldrá (Ed.), *Lawrie's meat science* (9 ed., pp. 457-508). Woodhead Publishing. ***https://doi.org/10.1016/B978-0-323-85408-5.00008-X***

Wheeler, T., Shackelford, S., & Koohmaraie, M. (1997). Standardizing collection and interpretation of Warner-Bratzler shear force and sensory tenderness data. Reciprocal Meat Conference, USA.

Wiltshire Sheep of New Zealand. (n.d.). *Wiltshire Sheep*. Retrieved 25 September, 2026 from ***https://www.wiltshiresheepnz.com/***

Wong, H. X. (2019). *Effects of early weaning onto herb-clover mix on lamb carcass and meat quality characteristics* [Master's thesis, Massey University]. Massey Research Online. ***https://mro.massey.ac.nz/items/c1b049a0-7fd8-4a45-b6ad-07f4645b14ae***

Wood, J., MacFie, H., Pomeroy, R., & Twinn, D. (1980). Carcass composition in four sheep breeds: the importance of type of breed and stage of maturity. *Animal Science*, *30*(1), 135-152. ***https://doi.org/10.1017/S0003356100023886***

Ye, Y., Schreurs, N. M., Johnson, P. L., Corner-Thomas, R. A., Agnew, M. P., Silcock, P., Eyres, G. T., Maclennan, G., & Realini, C. E. (2020). Carcass characteristics and meat quality of commercial lambs reared in different forage systems. *Livestock Science*, *232*, Article 103908. ***https://doi.org/10.1016/j.livsci.2019.103908***

Zhang, M., Warner, R. D., Dunshea, F. R., DiGiacomo, K., Joy, A., Abhijith, A., Osei-Amponsah, R., Hopkins, D. L., Ha, M., & Chauhan, S. S. (2021). Impact of heat stress on the growth performance and retail meat quality of 2nd cross (Poll Dorset×(Border Leicester× Merino)) and Dorper lambs. *Meat science*, *181*, Article 108581. ***https://doi.org/10.1016/j.meatsci.2021.108581***

Chapter 7: Appendices

7.1 Appendix: SAS Code for Carcass Characteristics

```
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename Wilt2024 dde 'Excel|C:\Users\yorke\OneDrive\Documents\Important\2025\SAS\[Wilt2024.xlsx]carcass!R2C1:R29C30';
data Wilt2024;
infile Wilt2024 lrecl=6000 dlm='09'x notab dsd missover;
input Treatment$ CCID Day Order Birthwt Startwt EndWt DO HCW wholeleg
Gracilis Sartorius Pectineus semimem adductor Bicep Semitend Quadricep
others FemurWt FemurLength Tibia Fat MuscleP FatP MBFemur MBLeg Muscularity
PriMuscle TotMuscle;
run;
proc mixed data=Wilt2024;
class Treatment;
model Birthwt = Treatment/solution ;
LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2024;
class Treatment;
model Startwt = Treatment/solution;
LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2024;
class Treatment;
model EndWt = Treatment/solution;
LSMeans Treatment/pdiff;
run;
quit;
proc mixed data=Wilt2024;
class Treatment;
model HCW = Treatment/solution;
LSMeans Treatment/pdiff;
run;
quit;
proc mixed data=Wilt2024;
class Treatment;
model DO = Treatment/solution;
LSMeans Treatment/pdiff;
run;
quit;
Proc glm data=Wilt2024;
class Treatment;
```

```
model PriMuscle = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class Treatment;
model TotMuscle = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class Treatment;
model MuscleP = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class Treatment;
model FemurLength = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class Treatment;
model FatP = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class Treatment;
model MBLeg = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class Treatment;
model MBFemur = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class Treatment;
model Muscularity = treatment HCW/ solution;
lsmeans treatment/ stderr;
run;
```

7.2 Appendix: SAS Code for Meat Quality

```
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename Wilt2024 dde 'Excel|C:\Users\yorke\OneDrive\Documents\Important\2025\SAS\[Wilt2024.xlsx]MQ!R3C1:R30C49';
data Wilt2024;
infile Wilt2024 lrecl=6000 dlm='09'x notab dsd missover;
input Treatment$ CCID Day Order EndWt HCW DO pH1 pH2 pH3 pH L1 a1 b1 L2
```

```
a2 b2 L3 a3 b3 L a b cookbfr cookaft Cookloss Drpbfr Drpaft Drip PA1 PL1
SF1 PA2 PL2 SF2 PA3 PL3 SF3 PA4 PL4 SF4 PA5 PL5 SF5 PA6 PL6 SF6 Wkdone
PkForce;
run;
proc mixed data=Wilt2024;
class Treatment;
model pH = Treatment/solution ;
LSMeans Treatment/pdiff ;
run;
quit;
Proc glm data=Wilt2024;
class treatment;
model L = treatment pH/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class treatment;
model a = treatment pH/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class treatment;
model b = treatment pH/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class treatment;
model Cookloss = treatment pH/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class treatment;
model Drip = treatment pH/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class treatment;
model WkDone = treatment pH/ solution;
lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2024;
class treatment;
model PkForce = treatment pH/ solution;
lsmeans treatment/ stderr;
run;
```