Carcass and meat quality characteristics of Romney and three-quarter Wiltshire lambs

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Abstract

Self-shedding sheep breeds, like the Wiltshire, have been introduced into meat production systems in New Zealand to reduce costs such as shearing and crutching. However, there is limited information on the meat performance of Wiltshire-cross lambs. Therefore, this study aimed to assess carcass and meat quality attributes of Romney and ¾ Wiltshire lambs. Data were collected from Romney (n=11) and ¾ Wiltshire (n=12) ram lambs, managed and fed on pasture under the same conditions, and sent to slaughter, as one group when all lambs reached a minimum of 42 kg liveweight. Final on-farm liveweight, hot carcass weight and dressing-out percentage were obtained on the day of slaughter. Muscle and dissectible fat percentages, muscle-to-bone ratios for whole leg and femur, muscularity, and femur bone morphology were obtained from leg dissections. Objective meat quality assessments were conducted on a sample of the *Longissimus lumborum* muscle to obtain pH, colour, water-holding capacity, shear force value, intramuscular fat percentage and fatty acid composition. The start and, final on-farm liveweights and hot carcass weights of the ¾ Wiltshire lambs were heavier than Romney lambs ($P<0.05$). Muscle and intramuscular fat percentages, muscle-to-bone ratios and muscularity did not differ between treatments ($P>0.05$). The ¾ Wiltshire lambs had lower dissectible fat percentages and greater muscle weights surrounding the femur compared with the Romney lambs ($P<0.05$). The ¾ Wiltshire lambs had greater femur bone length, total bone content, density, cortical bone content and thickness, and bone stress strain index compared with the Romney lambs ($P<0.05$). However, total bone area, cortical bone density, and periosteal and endosteal circumferences of both treatments were the same ($P>0.05$). There was no difference between the two genetic differences in meat colour, water-holding capacity, shear force and fatty acid profile ($P>0.05$). The results suggest that the ¾ Wiltshire lambs produce carcass and meat quality characteristics that are comparable to Romney lambs when slaughtered at a similar age. Therefore, the use ¾ Wiltshire lambs will not negatively affect meat yield and meat quality and will not be disadvantaged when used in lamb meat production systems.

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Chapter 1: General Introduction

New Zealand is a country with a tradition in sheep production. While wool was a significant income source of the country in the 1950s, the demand has declined over the last decades due to competition from synthetic fibres (Hore, 1956; Pearson, 2006). The decline in wool prices has led to a shift in New Zealand's sheep industry from wool towards meat production (Beef and Lamb NZ, 2023c).

The Romney breed has dominated the sheep population in New Zealand due to its dual purpose of producing wool and having favourable carcass attributes when crossbreeding with terminal sires (Corner-Thomas et al., 2013; Beef and Lamb NZ, 2023a). However, the increasing costs associated with wool harvesting and activities such as crutching, have created interest in alternative self-shedding breeds such as the Wiltshire. Crossbreeding Wiltshire with other breeds like Merino and Romney has produced progeny with shedding ability (Farrell et al., 2020; Rathie et al., 1994), but the performance of Wiltshire-cross lambs in terms of carcass and meat quality characteristics is not well known.

Understanding carcass and meat quality characteristics is crucial for maintaining carcass value and returns for the producers, and also maintaining the quality of the meat for consumer acceptance (Troy & Kerry, 2010). Genetic variation in meat quality is known and sheep breeds can influence carcass and meat quality characteristics (Cameron & Drury, 1985) and so, an investigation into the carcass and meat quality characteristics of Wiltshire-cross lambs is needed to assess the viability of their use in New Zealand lamb production systems.

Therefore, this study aimed to objectively evaluate the carcass and meat quality attributes of Romney and ¾ Wiltshire lambs. Carcass characteristics measures included hot carcass weight, dressing-out, muscle and dissectible fat percentages, muscle-to-bone ratios, muscularity, and bone parameters. Meat quality measurements included meat pH, colour, water-holding capacity, shear force and fatty acid composition.

This study provides a summary of the available literature on sheep meat production systems in New Zealand, and carcass and meat quality characteristics of various sheep breeds (Chapter 2). The materials and methods explain how the characteristics were objectively assessed (Chapter 3), and the results are presented and discussed in the context of previous research (Chapters 4 and 5). The information from this research will identify if Wiltshire-cross lambs perform at least equally to Romney lambs, in terms of quantity and quality of meat produced.

Chapter 2: Literature Review

2.1 Introduction

2.1.1 Sheep meat production in the New Zealand red meat industry

Sheepmeat plays a vital role as a protein source in human diets, and like other red meats, it provides essential micronutrients such as iron, zinc and vitamins that are not as readily available in vegetables (Biesalski, 2005). Current global lamb (meat from young sheep) consumption is approximately 2.5 kg per capita per annum, with higher consumption in developed countries (Morris, 2009).

New Zealand is one of the largest sheepmeat exporters in the world. In the year ended June 2023, New Zealand exported 378,5150 tonnes of sheepmeat to 88 countries and contributed $3.9 billion to New Zealand's economy (Table 2.1) (Meat Industry Association of New Zealand, 2023a). Approximately 75% of the sheepmeat export was lamb (defined as sheep with no permanent incisor), while the remaining was mutton (ewe or wether with more than two permanent incisors). Since 1990, the national flock size has declined by 54%, but total lamb production has been maintained due to improved production efficiency and fecundity within the industry (Johnson et al., 2021). Around 95% of sheepmeat production is available for export, and as such product quality, shelf life and regulatory compliance need to meet the demands and standards of international markets (Meat Industry Association of New Zealand, 2023a; Morris, 2009).

Table 2.1. Major export destinations of New Zealand sheepmeat by volume and value for the year ended June 2023 (Meat Industry Association of New Zealand, 2023b).

Destinations	Export volumes (Tonnes)	Percentage of total sheepmeat volume (%)	Export value (NZ$ Million)
China	220,218	58%	1,573.7
EU + UK[1]	72,089	20%	1,086.9
USA[2]	24,325	6%	510.9
Others	61,883	16%	772.5
Total	378,515	100%	3,941.5

[1]EU + UK: European Union and United Kingdom

[2] USA: United States of America

New Zealand has diverse international markets to which it exports sheepmeat (Table 2.1) and each market has distinct preferences and consumption patterns. The largest market currently is China, where sheepmeat is exported as frozen cuts such as bone-in breast and bone-in shoulder

(Meat Industry Association of New Zealand, 2023b). The European Union and the United Kingdom constitute the second-largest market, followed by the United States of America. These markets have a demand for high-quality chilled cuts such as lamb racks (Meat Industry Association of New Zealand, 2023b).

On the contrary, New Zealand was the world's third-largest wool producer in the 1950s, contributing a significant amount of income to the country (Hore, 1956). Since the 1990s, the price of wool has continually dropped due to the competition from synthetic fibres (Pearson, 2006), while shearing expenses have increased (Beef and Lamb NZ, 2023c). The cost of shearing is approximately $5.88 per head, while the price for strong wool (at least 35 microns) is 233 cents/kg greasy (Beef and Lamb NZ, 2023c) and most animals produce an average of three and six kg of wool. Consequently, by the time additional costs associated with wool such as crutching are also accounted for, most sheep farmers received a negative net return for wool production. Some producers have reduced their farm input costs by reducing the shearing frequency and the ratio of sheep to cattle on the farm (Beef and Lamb NZ, 2023b; Morris, 2009). Furthermore, the production of the national sheep flock has shifted from wool to meat over recent years (Johnson et al., 2021). For this reason, there has been an increase in the use of terminal breeds such as Suffolk, Texel, and Down breeds to improve meat production (Kirton & Morris, 1989; Wolf et al., 1980). The transition from wool to meat production also resulted in the introduction of alternative sheep breeds to the flock to maximise productivity and profitability (Morris, 2017). Those alternatives, which are used to reduce input costs, are self-shedding breeds such as Wiltshire and Dorper (Johnson et al., 2007; Farrell et al., 2020).

2.1.2 The Importance of Carcass and Meat Quality of Lamb Meat

Sheepmeat producers receive returns from meat processors based on the carcass classification and the associated price schedule (Purchas, 2012). The carcass classification system for sheep in New Zealand was developed by the New Zealand Meat Board and Meat Industry Association of New Zealand, based on animal age, sex, carcass weight and fat depth (New Zealand Meat Classification Authority, 2004). Hot carcass weight and soft tissue depth over the 12th rib (GR site) define the classification and carcass value. Producing a high-quality carcass refers to a heavier carcass with moderate fatness that maximises the saleable meat yield (Golding et al., 2011; Pethick et al., 2014). High-fat content in the carcass results in a price penalty, as excessive fat requires trimming when producing the cuts, hence reducing the saleable meat yield (Stanford et al., 1998).

Consumer's perceptions and preferences are dynamic and different due to their cultural backgrounds and eating habits (Sañudo et al., 2007). To gain consumers' acceptance and decision to repurchase, the consumers' eating experience and consistent meat quality are important (Troy & Kerry, 2010).

In order to consistently produce high-quality carcass and meat, the producers and meat processors should understand the factors influencing carcass and meat quality variations, as carcass traits are indicators of the value of carcass (Schreurs & Kenyon, 2017a). Lamb meat quality is influenced by carcass composition and distribution of fat, which indirectly affect juiciness, flavour, and tenderness. On-farm factors, such as type of animal (sex, age and genetics) and general management (affecting nutrition and health), could assist the producers in obtaining better carcass quality and receiving better returns (Schreurs & Kenyon, 2017a; Warner et al., 2010). In turn, this would allow the processor to offer good-quality lambs that meet the market demand and consumer preferences (Ramirez-Retamal & Morales, 2014), so positively influencing the consumer decisions to repurchase and retainment of market share.

2.1.3 The Importance of Breed Consideration on Lamb Carcass and Meat Quality

The appropriate selection of animal breeds would increase the profitability and efficiency of the meat production systems (Crouse et al., 1981), mainly through fast growth rates and high meat yields. Dressing-out percentage and carcass composition also display variations across different sheep breeds, serving as key determinants of carcass weight and influencing carcass classification. A minor fluctuation in carcass weight can lead to significant variations in returns for farmers (Litherland et al., 2010).

Through differences in their mature size, sheep breeds can differ in carcass composition and fat content. Late-maturing breeds tend to be leaner and heavier compared to early-maturing breeds at a set weight or age (Schreurs & Kenyon, 2017a). Selecting sheep breeds based on maturity size or rate provides valuable insights into growth rates, carcass weights, and fatness levels, helping farmers make informed breeding and management decisions (Cameron & Drury, 1985). The effect of sheep breeds on meat quality is less clear but breeds indirectly influence meat quality through carcass characteristics (Purchas et al., 1991). For example, an increase in partitioning towards intramuscular fat (IMF) improves meat quality characteristics and overall liking through juicy and tender meat with better flavour acceptance (Pannier et al., 2018; Warner et al., 2017).

2.1.4 Romney and Wiltshire Sheep in New Zealand

The most dominant sheep breed in New Zealand is the Romney and its crossbred derivatives, which contribute to over 50% of the total sheep population (Beef and Lamb NZ, 2023a). The Romney sheep is considered a dual-purpose breed, producing meat and wool. They have good mothering and survival ability, which makes Romney a maternal breed (Cranston et al., 2018). Romney ewes are used to cross with other terminal breeds as the crossbred progeny has high growth rates and meat yields (Corner-Thomas et al., 2013).

The Wiltshire breed which is a self-shedding breed used in the New Zealand system, was developed from Wiltshire horn and Poll Dorset (Slee, 1959), with high fecundity and lambing percentages between 190 and 200 (Cranston et al., 2018). The shedding ability of this breed reduces the costs of shearing, clutching, and drenching (Wiltshire Sheep NZ, 2021). Crossbreeding between Wiltshire and other common breeds, such as Romney and Merino, produces progeny with the shedding ability, and the flock can become fully shedding after several crossbreeding generations (Farrell et al., 2020; Rathie et al, 1994). However, it is not well known how the progeny of Wiltshire perform on their carcass and meat production.

2.2 Effect of breeds on carcass characteristics

The carcass characteristics that will be discussed in this section are carcass weight and dressing-out percentage, carcass composition, carcass tissue distribution, carcass shape, and muscularity.

2.2.1 Carcass Weight and Dressing-out Percentage

Carcass weight expresses the growth achieved by the meat-producing animal at slaughter. Carcass weight is defined as the weight of the carcass immediately after removing inedible parts such as internal organs, pelt, and head (Muir et al., 2008). The average hot carcass weight of New Zealand's lamb was 19.4 kg in the 2022-23 season (Beef and Lamb NZ, 2023a). Hot carcass weight is used as a part of the carcass classification system and influences carcass value and financial returns to producers (Muir et al., 2008). The DO% is the proportion of the animal's carcass weight to its body weight. The DO% for lambs ranges between 41% and 45% (Schreurs & Kenyon, 2017a). The DO% has improved over the years due to selective breeding for meat production traits and a consequent increase in carcass weight at a set slaughter weight (Muir et al., 2008). To maximise the carcass value, meat producers must consider various factors influencing animal carcass weight and DO%.

Table 2.2. Carcass characteristics for common sheep breeds from studies in different countries where animals were slaughtered between 110 and 216 days of age (Adapted from Schreurs & Kenyon, 2017a).

Breed	Reference	Carcass weight (kg)	DO%	Muscle proportion		Fat %	Bone %
				EMA (cm^2)	Muscle %		
Merino	Kirton et al. (1974)	9.8	39.1	6.7		15.2	
	Kirton et al. (1995)	12.0	41.7	8.1		26.6	
	Van der Westhuizen (2010)	22.0	43.0		39.0	40.5	19.4
Dorper	Burger et al. (2013)	17.4			51.3	13.9	29.8
	Shackelford et al. (2012)	32.3	53.7	18.3		29.8	
	Van der Westhuizen (2010)	31.5	50.5		33.4	50.2	15.8
Texel	Ellis et al. (1997)	18.4	45.2		56.7	23.3	19.1
	Holloway et al. (1994)	21.4	44.8		68.4	14.0	17.6
	Wolf et al. (1980)		44.5		60.5	21.5	16.5
	Shackelford et al. (2012)	31.8	51.8	18.4		27.7	
	Kremer et al. (2004)	14.9	44.9		58.6	11.8	29.6
	Kempster et al. (1987)	19.5			57.4	25.4	17.2
Suffolk	Ellis et al. (1997)	18.7	44.4		54.3	24.0	19.9
	Shackelford et al. (2012)	33.8	51.6	18.2		28.4	
	Kremer et al. (2004)	15.1	43.4		56.8	12.5	30.6
	Wood & MacFie (1980)	17.9			57.2	29.6	13.2
	Kempster et al. (1987)	19.6			55.2	26.7	18.1
Romney	Kirton et al. (1974)	13.0	42.4	8.3		16.7	
	Kirton et al. (1995)	11.8	41.0	7.5		24.8	
	Fourie et al. (1970)	20.0			54.1	27.8	11.1
Southdown	Kremer et al. (2004)	14.8	43.3		56.8	13.0	30.1
	Kempster et al. (1987)	16.3			54.2	28.3	17.5
	Fourie et al. (1970)	20.0			53.0	32.8	8.2
Hampshire	Kirton et al. (1995)	14.8	43.7	9.8		29.1	
	Kremer et al. (2004)	14.8	43.2		57.4	13.0	30.1
	Kempster et al. (1987)	17.7			54.1	27.5	18.4
	Wood & MacFie (1980)	17.9			56.0	34.6	12.4
Average	Merino	14.6	41.3	7.4	39.0	27.4	19.4
	Dorper	27.1	52.1	18.3	42.4	31.3	22.8
	Texel	21.2	46.2	18.4	60.3	20.6	20.0
	Suffolk	21.0	46.5	18.2	55.9	24.2	20.5
	Romney	14.9	41.7	7.9	54.1	23.1	11.1
	Southdown	17.0	43.3		54.7	24.7	18.6
	Hampshire	16.3	43.5	9.8	55.8	26.1	20.3

Sheep breed moderately influences carcass weight and DO% (Table 2.2). The comparison of sheep breeds at a set weight shows that breeds with higher DO% exhibit higher carcass fat levels, greater M:B ratios, or fewer non-carcass components with other things being equal (Schreurs & Kenyon, 2017a). In contrast, some studies found no differences in carcass weight and DO% among different breeds.

Early-maturing breeds tend to have a higher DO% than late-maturing breeds at a set age. For example, Dorper lambs (early maturing breed) had a higher DO% than Merino, South African Mutton Merino (SAMM) and Dohne Merino lambs (later-maturing breeds) (Brand et al., 2018; Cloete et al., 2012; van der Westhuizen, 2010). On the contrary, similar carcass weights were found when comparing lambs sired by late-maturing Wiltshire horn to early-maturing breeds such as Dorset horn at a set slaughter weight (Rathie & Teasdale, 1994) and Poll Dorset at a set age (Hopkins & Brooks, 1990).

Terminal breeds are commonly used as sires to produce progeny for meat production, due to their higher mature weight, carcass weight and DO% compared to maternal breeds (Kempster et al., 1987; Kremer et al., 2004). Crossbreeding by using terminal sire breeds showed a hybrid vigour which increased growth rates and DO% of their crossbred progeny (Nitter, 1978). For instance, sire breeds such as Suffolk, Southdown, and Dorset (heavier mature weights), were used as terminal sires on Romney and Corriedale ewes, producing progeny with heavier carcass weights than purebred lambs (Clarke & Meyer, 1982; Kremer et al., 2004). Similarly, Texel-sired lambs (a breed developed for high muscle growth), produced heavier carcasses and higher DO% compared to Romney-sired lambs (Johnson et al., 2005), but they had lower DO% than Dorper and Dorset-sired lambs, despite their superior muscularity (Shackleford et al., 2012). In contrast, some studies did not report differences in DO% when comparing sire breeds and crossbreeds such as Romney, Borer Leicester x Poll Dorset, Finn x Texel to Texel x Poll Dorset (Purchas et al., 2002) and Oxford, Suffolk, and Southdown when slaughtered at a set age (Meyer et al., 1978).

Heavier non-carcass components reduce DO% as these components are removed during the dressing procedure. Animals with heavy and long wool tend to have a lower DO% than those with short wool, hair, or shedding ability at the same carcass weight. This is because wool weight increases the final liveweight before slaughter (Kirton & Morris, 1989; Kirton et al., 1974). For instance, breeds with longer and heavier wool such as Lincoln, Merino, Romney,

and Corriedale, had lower DO% than shorter wool breeds like Southdown, Dorset down, Poll Dorset and Perendale (Kirton et al., 1974; Kirton et al., 1995; Meyer et al., 1984).

2.2.2 Carcass Composition

Carcass composition refers to the contribution of muscle, fat, and bone relative to the total carcass weight (Purchas et al., 1989). In general, the different proportions of muscle, fat and bone in the carcass are influenced by nutrition, and also by animal type or breed-related traits, such as stage of maturity, potential mature size, and slaughter weight (Johnson et al., 2005). In general, the proportions of muscle and bone within the carcass decrease, while the fatness levels increase as the animal's liveweight increases (Santos-Silva et al., 2002). The variation in carcass composition among different sheep breeds is demonstrated in Table 2.2.

2.2.2.1 Muscle %

The potential mature weight of an animal influences various proportions of muscle (as % of carcass weight) at a certain slaughter weight or age (Safari et al., 2001; Taylor et al., 1980). Breeds with larger mature sizes are more likely to have leaner (less fat) carcasses than smaller breeds when compared to the same carcass weight (Kremer et al., 2004). Larger mature-sized breeds such as Texel, Suffolk, and Merino had higher muscle proportions than smaller mature-sized breeds such as Dorper, SAMM and Southdown (Brand et al., 2018; Kirton & Morris, 1989). The Wiltshire horn-crossed lambs had leaner carcasses when compared to the lambs sired by Dorset horn at a set slaughter weight (Rathie & Teasdale, 1994) and Poll Dorset at a set age (Hopkins & Brooks, 1990).

Terminal or meat-producing breeds, typically late-maturing, tend to have a higher muscle proportion compared to early-maturing maternal and wool breeds at equivalent liveweights and ages (Anderson et al., 2016; Berg & Butterfield, 1968; Ponnampalam et al., 2008). Using terminal breeds selected for high muscularity such as Texel and Suffolk as sires produced progeny with leaner carcasses when compared to other sire breeds such as Dorset Down, Oxford, Romney and Charollais (Ellis et al., 1997; Justice et al., 2023; Wolf et al., 1980).

The eye muscle area or EMA (*Longissimus thoracis et lumborum*) is often used to estimate carcass lean content (Mortimer et al., 2018). A larger EMA is associated with a higher proportion of *Longissimus* muscle to total muscle (Taylor et al., 1980). The late-maturing breeds such as Texel and Suffolk produced progeny with larger EMA compared to early-maturing breeds like Romanov (Shackelford et al., 2012). On the other hand, some studies

reported smaller EMA in Suffolk- and Texel-sired lambs when compared to other early maturing breeds such as Southdown, Poll Dorset, and South Dorset (Kirton et al., 1995). The Wiltshire horn and Poll Dorset lambs had greater EMA than the Suffolk lambs, and therefore the predicted lean meat yield was higher in Wiltshire horn and Poll Dorset lambs (Hopkins, 1994). Some studies reported that the animal's maturity rate did not influence EMA where Perendale, Merino and Romney lambs had similar mature sizes, but the Perendale lambs had larger EMA than other breeds (Kirton et al., 1974; Meyer et al., 1984).

When considering carcasses from animals slaughtered at the same degree of maturity, lambs from different breeds tend to have a similar carcass composition in terms of muscle and fat proportions (McClelland et al., 1972). This suggests that breed effects are mainly driven through differences in mature size. However, this is not always the case. For example, the carcasses from Scottish Blackface lambs had higher muscle percentages and lower fatness levels than those from Suffolk lambs at 0.45 of their mature weights, which were estimated to be 69 kg for the Scottish Blackface and 100 kg for the Suffolk (McFarlane et al., 2004).

2.2.2.2 Fat %

As an animal grows and its weight increases, the proportion of fat increases while the proportions of muscle and bone decrease (Berg & Butterfield, 1986; Santos-Silva et al., 2002).

An earlier-maturing animal deposits fat sooner and is typically of smaller mature size than a later-maturing animal (More O'Ferrall & Timon, 1977). Larger mature-sized breeds such as Suffolk, Texel, and Oxford, produced progeny with less carcass fat than smaller mature-sized breeds like Lincoln, Southdown, Dorset Down and Ryeland (Cloete et al., 2012; Kirton et al., 1995; More O'Ferrall & Timon, 1977). Dorper breed, which is considered an earlier maturing breed, had carcasses with greater fat proportions than later-maturing breeds such as Rambouillet, Suffolk, Merino and SAMM (Brand et al., 2018; Cloete et al., 2007; Moss et al., 2000; van der Westhuizen et al., 2010). Taylor et al. (1989) categorised sheep breeds in their study into two types based on their propensity for carcass fat deposition: low and high. Southdown, Wiltshire Horn, and Oxford Down lambs displayed a greater potential for fat deposition, depositing fat three times faster than Soay, Jacob and Finn lambs. On the other hand, maturity size did not directly determine the carcass fatness levels but were influenced by carcass weight (Wood & MacFie, 1980).

2.2.2.3 Bone % and Bone Development

Bone development occurs earlier than muscle and fat development. The proportion of bone to total body weight drastically reduces as an animal grows and starts depositing muscle and fat at a greater rate (Rouse et al., 1970; Brand et al., 2018).

Maturity type also plays an important role in bone growth and development (Cake et al., 2007). Late-maturing animals have prolonged bone growth, and differences in bone % between breeds are likely to reflect their different mature size (Gaili, 1978; McClelland et al., 1976). For example, the Suffolk breed, which is a later-maturing breed, had a higher proportion of carcass bone than the Charollais-sired lambs when compared at a set age (Ellis et al., 1997).

Wool breed sires such as Merino, seem to produce progeny with heavier bone weight than sires from maternal and terminal breeds such as Dorset and Texel (Cake et al., 2007). Similar results have been found at foetal or prenatal age (used as a predictor of mature bone weight), where Merino foetuses had a heavier femur weight than the Romney, Drysdale, and Merino x Romney foetuses, with no difference in femur weight compared to the Wiltshire foetuses (Sailer et al., 1995). Others used cannon bone weight as a predictor of total carcass bone weight and showed that at the same age, Merino wethers had the lowest carcass bone weight compared to Romney, Corriedale, and Perendale wethers (Kirton et al., 1974).

Besides the proportion of carcass bone, the development of bone is also important for structural body framework and determining meat yield. Ossification or bone formation initiates during the prenatal growth of the animals (Lonergan et al., 2018), and significantly impacts how postnatal bone growth and remodelling performs (Bell, 1992). There are two types of ossification including endochondral and intramembranous (Young, 1988). Endochondral growth forms the bone tissue outwards from the centre, allowing the bone to grow in length. This process occurs in cortical or hard bone, comprising about 80% of the total skeletal mass (Ham & Cormack, 1979). Intramembranous ossification promotes bone growth in diameter, taking place in trabecular or spongy bone, such as the skull and the ends of the long bones (Ham & Cormack, 1979). After ossification, the bone is still immature and requires a further process, called bone remodelling. Bone remodelling is a continuous process involving bone reabsorption and formation (Kahla & Barkaoui, 2021), to maintain the bone structure and integrity. Longitudinal bone growth ceases as the growth plate closes when the animal reaches maturity (Harada & Rodan, 2003).

To assess bone material properties, several objective tools can be used such as radiography, dual-energy X-ray Absorptiometry (DEXA), and peripheral quantitative computed tomography (pQCT). The use of pQCT is more commonly used to distinguish changes between cortical and trabecular bones (Choksi et al., 2018), to provide bone geometry data and the stress strain index (SSI) as an indicator of the bone strength to withstand bending strain including lateral, dorso-palmer, and tensional forces (Gasser, 1995).

The SSI is calculated by using the index of material stiffness (bone mineral density) and bone geometry (cross-sectional moment of inertia). The SSI is a measure of bone strength that is correlated with the loading force associated with locomotion and bodyweight (Gibson et al., 2021). Bones capable of withstanding higher forces had either larger bone geometry, higher bone mineral density or both (Augat & Schorlemmer, 2006). In cattle, an increase in body weight (or the weight of the muscles surrounding the bone), increases the strain on the bone, thereby requiring an increase in bone area and density (Alpak et al., 2019; Rubin & Lanyon, 1985). Therefore, muscle weight and bone density are positively associated with bone strength (Davies, 1984).

For sheepmeat production, understanding bone growth is crucial, as it can determine carcass meat yield. An increase in bone length and weight is generally associated with a reduction in muscularity and M:B (Purchas et al., 1991). However, having strong bones, especially limb bones is important to animals as they provide the structural framework supporting body weight (Etienne et al., 2021). Unfortunately, the reported data examining the relationship of bone strength and morphology in sheep breeds is limited.

Given that prenatal bone growth influences postnatal development, this suggests that the breed has a potential preprograming effect on the carcass frame. For instance, Merino foetuses had heavier femur, tibia and quadricep femoris muscle weights when compared to Romney, Merino x Romney, Drysdale, and Wiltshire foetuses (Sailer et al., 1995). In postnatal growth, the Merino lambs have been reported to have longer leg length and lower muscularity compared to other breeds (Brand et al., 2018; Kirton et al., 1974; Meyer & Kirton, 1984). A similar effect has been observed in bone morphology comparing other breeds, where lambs with higher cortical bone content and thickness, higher total bone density and content, and higher bone strength, had better bone structure and higher bone mineral density (Willems et al., 2013).

2.2.3 Carcass Tissue Distribution

2.2.3.1 Muscle Distribution

Muscle distribution refers to the weight of individual or muscle groups relative to the total muscle or carcass weight. Variations in muscle growth rates for the *Semitendinosus*, *Semimembranosus*, and *Gluteus* have been found in different sheep breeds (Taylor et al., 1980). Breeds developed for high muscle growth such as Texel tend to have a higher proportion of muscle in the leg compared to other purpose breeds such as Southdown, Romney, Coopworth and Dorset Horn x Coopworth (Hopkins & Fogarty, 1998; Justice et al., 2022). Smaller mature-sized lambs such as Dorper and White Dorper, had greater muscle distribution over the leg and loin when compared to larger mature-sized lambs such as Suffolk, Namaqua Afrikaner, and Finn (Burger et al., 2013; Shackelford et al., 2012; Snowder & Duckett, 2003).

2.2.3.2 Fat Partitioning

As an animal grows, they deposit fat in three different carcass fat depots orderly: subcutaneous, intermuscular, and intramuscular depots (Warris, 2010). Fat partitioning to different depots varies between breed and sex (Kirton et al., 1974; Schreurs & Kenyon, 2017a). Subcutaneous fat locates under the skin, and it insulates the carcass to prevent cold shortening (Schreurs & Kenyon, 2017b). The intermuscular fat is found between muscles while intramuscular fat (IMF) lies within the muscle (Johnson et al., 2016). Subcutaneous fat deposition is used for carcass classification and may contribute to carcass weight, but excessive subcutaneous fat reduces LMY% and saleable meat yield. Intramuscular fat is associated with meat eating quality through flavour, juiciness, and tenderness (Sañudo et al., 2000). To ensure eating quality in New Zealand lamb, a minimum of 3% IMF is required for desirable juiciness and tenderness (Realini et al., 2021).

Dairy and prolific breeds, such as East-Friesian, deposit lower amounts of subcutaneous fat compared to meat-producing and dual-purpose breeds such as Hampshire, Southdown, Suffolk, and Texel (Wood & MacFie, 1980; Kremer et al., 2004). When comparing wool breeds, the Merino breed had the least subcutaneous fat among Romney, Corriedale, and Perendale at the same carcass weight (Kirton et al., 1974). The subcutaneous proportions were found similar in Romney, Southdown and their crossbreds (Fourie et al., 1970; Snowder & Duckett, 2003).

Breeds selected for meat production, typically late-maturing type breeds, have a lower IMF deposition (Bunger et al., 2009), and a higher proportion of intermuscular fat (Anderson et al., 2016; Cameron & Drury, 1985). Lambs from meat-producing breeds (Suffolk, Texel, and

Dorset) showed lower IMF than maternal and dairy breeds (Finn and Romanov) (Shackelford et al., 2012). A comparison of meat breeds showed IMF content in descending order: Suffolk, Charollais and Texel (Leymaster & Jenkins, 1993; Kuchtik et al., 2012), but no IMF difference was reported when comparing meat breeds like Hampshire and Suffolk (Monaco et al., 2015).

2.2.4 Carcass Shape and Muscularity

2.2.4.2 Carcass Shape and Muscularity Measurements

Carcass shape refers to an animal's frame size and tissue contents deposited over the frame, (De Boer et al., 1974; Schreurs & Kenyon, 2017a). De Boer et al. (1974) defined muscularity as the thickness of muscle relative to a skeletal dimension while conformation considered both fat and muscle thickness relative to a skeletal dimension. Short and compact carcasses are considered of better shape and have higher conformation or muscularity scores (Jones et al., 2002).

Assessment of carcass shape can be performed through both objective and subjective means. Subjective assessments consist of scoring systems, with or without visual aids such as the EUROP conformation system (Johansen et al., 2006). When comparing animals with the same carcass composition, differences in carcass shape can be determined objectively by muscle thickness and bone length (Schreurs & Kenyon, 2017a). Purchas et al. (1991) proposed an objective measure of muscularity to represent average muscle depth relative to a skeletal dimension by assessing specific muscle weight (such as those of the eye or leg muscle), per unit length of an adjacent bone.

Breed has a moderate impact on carcass shape (Schreurs & Kenyon, 2017a), although differences in shape could depend on the breeds being compared (Kempster et al., 1987; Snowder & Duckett, 2013). Meat-producing breeds such as Texel (developed for muscularity) are more likely to have more compact and blocky carcasses than dual-purpose and maternal breeds such as Dorset, Finn, Romanov, and Montadale (Freking & Leymaster, 2004), Awassi (Hollaway et al., 1994), and Romney (Abdullah, 1994) due to their higher muscle depth and weight.

In terms of carcass conformation, breed types showed inconsistent results. When comparing meat breeds at an equal liveweight, Texel lambs had poorer conformation than Charollais lambs (Cameron & Drury, 1985). Terminal Southdown lambs had better conformation than dual-purpose Romney lambs (Fourie et al., 1970). Among wool breeds such as Merino and

Corriedale, Perendale lambs had better conformation because of higher fat proportion, which increased the thickness of muscle and fat layers (Kirton et al., 1974).

2.2.4.2 The Relationship between Muscularity, M:B and LMY%

The ratio of muscle to bone (M:B) refers to the weight of muscle relative to the weight of the bone (Purchas et al., 1989). A greater M:B is associated with superior carcass conformation and muscularity when comparing animals at the same femur weight and length (Anderson et al., 2016; Purchas et al., 1991). At the same age, an early-maturing animal has a higher M:B than a late-maturing one because the proportion of total bone decreases when animals start depositing fat (Lawrie & Ledward, 2006). For example, earlier-maturing breeds, such as Southdown, had higher M:B than later-maturing breeds like Finn, Wiltshire, and Oxford (Taylor et al., 1980). On the other hand, some studies reported higher M:B in lambs sired by later-maturing breeds such as Texel, Finn and Suffolk when compared to those sired by Romney, Awassi, and Hampshire Down (earlier-maturing breeds) (Abdullah, 1994; Holloway et al., 1994; Purchas et al., 2002; Wood & MacFie 1980). These breeds with higher M:B were also reported to have superior muscularity (Freking & Leymaster, 2004; Holloway et al., 1994).

Lean meat yield (LMY%) is the proportion of meat (muscle) weight without visible fat, to total carcass weight. It is equivalent to the muscle % (Purchas et al., 1989). LMY% can be increased when there is an increase in M:B, a decrease in fat % or both of these (Purchas et al., 2002). However, there is a small relationship between breeds and M:B, with fat % being a primary factor influencing LMY% (Taylor et al., 1980). A higher muscle proportion results in a blockier carcass shape (Jones et al., 2002; Purchas et al., 2002). Meat-producing breeds such as Texel and Soay showed higher LMY%, hence better muscularity than wool and maternal breeds such as Finn, Welsh Mountain and Corriedale (Kremer et al., 2004; Taylor et al., 1980).

2.3 Effect of Breeds on Meat Quality Characteristics

The meat quality characteristics that will be discussed in this section are meat pH, colour, juiciness, flavour, tenderness, and fatty acid composition which mainly are the results of objective assessments.

2.3.1 Meat pH

Meat pH is not a meat quality characteristic, but it is an important intrinsic determinant which influences meat colour, water-holding capacity, and tenderness (Hopkins & Fogarty, 1998;

Purchas & Aungsupakorn, 1993). High ultimate pH correlates with darker meat colour, poor colour stability (Warner et al., 2017; Young et al., 1993), poor water-holding capacity and reduced shelf life (Cheng & Sun, 2008; Egan & Shay, 1988). The relationship between pH and tenderness is shown as a quadratic pattern wherein meat with a pH between 5.8 - 6.2 is associated with higher shear forces and tougher meat (Purchas and Aungsupakorn, 1993; Thompson, 2002). Meat pH can be objectively measured by using a pH spear (Schreurs, 2013).

2.3.2 Meat Colour

Meat colour is a visual appearance influencing consumer preferences and purchasing decisions. A less intense red is an acceptable colour for lamb meat (Prieto et al., 2009). The browned meat is considered as a sign that the meat is not fresh (Calnan, 2016). Meat colour is determined by the concentration and form of the colour pigment within muscle tissues called myoglobin (Fraustman & Suman, 2017). The variation of lamb meat colour can be influenced by several factors such as IMF content, age of slaughter, diet, and meat pH (Prache et al., 2020).

As an animal grows, meat lightness decreases and redness increases (Berge et al., 2003) because of an increased myoglobin content (Calnan, 2017). Meat from younger animals tends to have a lighter colour due to a lower myoglobin concentration compared to meat from older animals (Berge et al., 2003; Mashele et al., 2017). An older animal sometimes displays lighter meat because an increase in IMF and connective tissue with age is associated with a paler appearance (Warner et al., 2010; Zhang et al., 2022). An increase in stress that animals have been exposed to pre-slaughter promotes muscle glycogen depletion, resulting in a higher ultimate pH and darker meat (Sheath et al., 2001).

The effect of breed on lamb meat colour has been reported differently across studies with substantial variation (Table 2.3), suggesting that breed may not be the direct contributor to meat colour. Colour differences between breeds are likely mediated by aspects such as IMF content, age at slaughter, nutrition, or susceptibility to stress.

Wool breed lambs, such as Merino, produced meat with a darker colour than maternal and terminal breeds (Greenwood et al., 2006). Merino-sired lambs had darker meat compared to Hampshire-, Poll Dorset-, Southdown-, and Suffolk-sired lambs (Calnan et al., 2016) and Dormer-sired lambs (Cloete et al., 2012), possibly due to Merino lambs being more susceptible to pre-slaughter stress and thus higher pH which higher than other breeds.

Table 2.3. Studies comparing the effect of breeds on lamb meat colour objectively measured in the International Commission on Illumination system (CIE, L*, a*, and b* parameters)

Origin of study	References	Breeds	Muscle	Time after cutting	Colour variables		
					L*	a*	b*
Morocco	Belhaj et al. (2021)	Beni-Guil	*Longissimus lumborum*	immediately	41.6	21.0	7.0
		Ouled-Djellal			41.2	21.0	7.0
South Africa	Cloete et al. (2008)	Dormer	*Longissimus lumborum*	30 mins	36.5[a]	12.1	8.9
		Suffolk			37.7[b]	12.1	9.2
South Africa	Cloete et al. (2012)	Merino	*Longissimus dorsi*	30 mins	34.9[a]	12.5	9.0
		Dohne Merino			33.2[ab]	12.4	8.8
		SAMM			34.2[ab]	13.4	9.2
		Dormer			32.8[b]	12.8	9.2
United Kingdom	Dawson et al. (2002)	Texel	*Longissimus*	-	38.5	15.6	10.7
		Suffolk			37.9	16.5	11.7
New Zealand	Holloway et al. (1994)	Awassi	*Semimembranosus*	90 mins	34.4	20.7	8.9[a]
		Texel			35.5	21.6	9.8[b]
Czech Republic	Komprda et al. (2012)	Zwartbles	*Quadricep femoris*	60 mins	48.4	8.5	12.5
		Suffolk			47.2	8.6	12.1
		Oxford Down			50.1	9.2	13.4
Czech Republic	Kuchtik et al. (2012)	Charollais	*Quadricep femoris*	immediately	46.6[b]	8.3	11.8[b]
		Suffolk			48.2[a]	7.74	12.3[a]
Spain	Martínez-Cerezo et al. (2005)	Rasa Aragonesa	*Longissimus*	60 mins	39.0[a]	16.2[b]	7.0
		Churra			41.6[b]	14.5[a]	7.0
		Spanish Merino			39.7[a]	15.6[b]	7.1
Portugal	Santos-Silva et al. (2001)	Merino Branço	*Longissimus dorsi et lumborum*	30 mins	48.7	13.8	6.1
		Ile-De-France x Merino Branço			49.1	13.7	6.2
Spain	Sañudo et al. (1997)	Churra	*Longissimus thoracis*	24 hours	49.5[a]	9.2	10.8[a]
		Castellana			46.1[b]	9.4	8.8[b]
		Manchega			48.6[a]	8.2	9.7[ab]
		Awassi			47.8[ab]	9.9	9.9[ab]

[a, b] superscripts that are different indicate means within breed and colour variable are significantly different ($P<0.05$) within each study.

On the other hand, Suffolk-sired meat was lighter and yellower than Charollais-sired meat (Kuchtik et al., 2012) and Dormer-sired meat (Cloete et al., 2008). Some studies have found no significant breed effect on meat colour (Belhaj et al., 2021; Komprda et al., 2012; Monaco et al., 2015; Santos-Silva et al., 2001).

2.3.3 Meat Juiciness

Juiciness is one of the eating quality attributes which refers to the muscle's capacity to release moisture and fat content while eating (Dryden & Maechello, 1970). The intrinsic determinants of meat juiciness can be water content, water-holding capacity, pH, and IMF content (Pethick et al., 2005; Smith & Carpenter, 1974).

Water-holding capacity (WHC) describes the ability of the meat to retain water and remain firm under conditions such as pressure, centrifugation, or cooking process (Pearce et al., 2011; Purchas et al., 1989). Drip loss, a WHC measurement for fresh meat, considers the loss of muscle fluid (water) released during storage (Huff-Lonergan, 2009). Cooking loss measures water lost during the cooking process which involves heat (Smith & Carpenter, 1974). Protein degeneration occurs during cooking, and the water is released. Both measures of WHC are affected by pH, as the pre-rigour pH drop reduces the space between myofilaments where water resides, leading to myofibril contraction and water emerging on the meat surface (Pearce et al., 2011). There is a negative correlation between WHC (drip and cooking losses), and juiciness since an increase in water loss is associated with poorer juiciness (Seisibe, 2008; Warner et al., 2017).

Besides water content, IMF content also influences meat juiciness. IMF enhances palatability as it increases meat juiciness through the lubrication effect stimulating saliva production (Pethick et al., 2005; Thompson et al., 2004). Moreover, a higher proportion of IMF in lamb meat contributes to a reduction in drip loss (Olivan et al., 2004).

Lamb breed has a significant impact on objective measures of WHC, including drip and cooking losses (Abdullah et al., 2011; Jandasek et al., 2014; Kuchtik et al., 2012; Safari et al., 2011). For example, a higher cooking loss % was found in the *Semitendinosus* muscle of purebred Awassi lambs when compared to their crossbreds with Romanov and Charollais (Abdullah et al., 2011). For the *Longissimus lumborum et thoracis* muscles, Texel-sired lambs had a higher drip loss % than the Oxford Down- and Charollais -sired lambs but similar to the Suffolk-sired lambs (Jandasek et al., 2014). However, the *Quadricep femoris* muscle of

Charollais-crossed lambs showed a higher cooking loss % than those from the Suffolk-cross lambs (Kuchtik et al., 2012). The combination of Texel, Poll Dorset, Border Leicester, and Merino rams, and Border Leicester x Merino and Merino ewes showed a lower cooking loss % in the *Longissimus* muscles of Border Leicester x Merino and Texel x Border Leicester x Merino lambs (Safari et al., 2001).

In contrast, some studies suggested no WHC differences between breeds and sire breeds (Hoffman et al., 2003; Komprda et al., 2012; Santos-Silva et al., 2001). The *Quadricep femoris* muscle of the meat breeds, such as Suffolk, and Oxford Down lambs had similar cooking loss % (Komprda et al., 2012). The use of meat and wool breeds such as Dormer, Suffolk, Merino, and Dohne Merino produced progeny that had similar drip and cooking losses on the *Longissimus dorsi* muscle (Hoffman et al., 2003).

The effect of breed on juiciness has been found in subjective sensory studies (Cloete et al., 2012; Fisher et al., 2000; Hopkins et al., 2011). For instance, meat from Welsh mountain lambs scored higher juiciness than Suffolk and Soay lambs (Fisher et al., 2000). In general, dual-purpose and meat-producing breeds had higher juiciness scores than wool breeds because these breeds had a thicker fat depth and a higher carcass fat proportion (Cloete et al., 2012). On the other hand, an increase in the Merino genotype in the breed composition has been associated with lower juiciness (Hopkins et al., 2011). Nevertheless, there have also been studies where lamb breeds and crossbreeds, such as Dorper, Suffolk, Texel, and Charollais, did not affect the sensory panel assessment of meat juiciness (Dransfield et al., 1979; Ellis et al., 1997; Shackelford et al., 2012).

2.3.4 Meat Flavour

Meat flavour is the most important eating quality consideration that influences the consumer's decision to repurchase. Flavour comprises of two senses: taste and smell (Purchas et al., 1989). These senses are stimulated by the volatile compounds of lean and fat tissues from lamb meat after cooking (Mottram, 1998). The perception of taste and smell is dependent on the volatile compound concentration in the meat and the detection threshold which is different for individual consumers (Farmer, 1994). Thus, the flavour preference is dependent on cultural backgrounds and exposure experiences (Duckett, 2013; Prache et al., 2020).

There are over 1000 volatile substances that have been identified as being produced during cooking lamb meat (Mottram, 1998). Lean lamb meat produces a meaty flavour, but the fat

tissue properties of different species create a distinct flavour. For example, the methyl branched-chain fatty acid group is found in lamb meat and its detection threshold is very low. Consumers can sense a specific flavour only found in sheepmeat, called a mutton flavour (Priolo et al., 2001; Channon et al., 2003). Other flavours different to the normal meat flavour can be unacceptable to consumers (Schreurs, 2013).

The common method of assessing meat flavour is the subjective sensory taste panel assessment (Purchas et al., 1989). It is difficult to explain the flavour in objective scientific terms, but the evaluation of a profile of flavour and odour in the meat can inform the concentrations of different volatile compounds (Schreurs & Kenyon, 2017b).

Sensory studies have found breed effects on meat flavour (Cramer et al., 1970a; Martinez-Cerezo et al., 2005; Safari et al., 2010; Sulliman et al., 2021; Young et al., 1993). The *Semimembranosus* and *Longissimus lumborum* muscles of dual-purpose Scottish Blackface were reported to have a stronger flavour and higher overall acceptability than those from meat-producing Texel lambs by taste panellists (Navajas et al., 2008). Meat from fine-woolled Rambouillet lambs produced a more intense mutton flavour than coarse-woolled Columbia and Hampshire lambs (Cramer et al., 1970a), due to more unsaturated fatty acids in the subcutaneous fat, resulting in different volatile compounds (Cramer et al., 1970b). On the contrary, other studies observed higher foreign flavour, which was associated with higher pH in the meat from Merino lambs compared to Coopworth lambs (Young et al., 1993), and higher flavour strength when compared to the Merino x Border Leicester lambs, resulting in lower acceptability (Safari et al., 2001).

Nevertheless, other studies reported no differences in meat flavour between breeds or crossbreeds. The flavour intensity ratings were similar in the meat from lambs sired by Dorper, Columbia and Suffolk when compared the animal age and level of fatness at equal (Snowder & Duckett, 2003; Crouse et al., 1981; Crouse et al., 1983). The study of Elmore et al. (2000) reported that the meat from Suffolk and Soay lambs had similar flavour, even though more than 54 volatile compounds were found in different concentrations between the two breeds.

2.3.5 Meat Tenderness

Meat tenderness is the firmness of the meat surface, or the ability to be easily chewed by the consumer (Purchas, 2014). Meat tenderness is intrinsically influenced by the concentration and solubility of muscle collagen, muscle fibre characteristics, proteolytic enzyme activity, fatness

level and meat pH (Abdullah et al., 2011; Schreurs & Kenyon, 2017b). The objective tenderness measurement can be done with the Warner-Bratzler shear force, assessing the force used to shear through a meat sample in newton (N) or kilogram of force (kgF). Meat should have shear force values below 4 kgF to be acceptable for consumers (Justice et al., 2022).

Many differences in shear force between sheep breeds have been reported (Table 2.4). When using Suffolk as a sire breed, the progeny seems to produce tougher meat due to higher shear force values than the progeny sired by Finn and Romanov (Shackelford et al., 2012), Dorper (Snowder & Duckett, 2003), and Hampshire, Dorper and Ile de France (Monaco et al., 2015).

Table 2.4. Studies comparing the effect of lamb and sire breeds on meat tenderness were measured by the Warner-Bratzler shear force methodology.

References	**Breeds/ Sire breeds**	**Muscle**	**Shear Force Values**	
			(N)	**(kgf)**
Hoffman et al. (1993)	Suffolk-sired lambs	*Longissimus dorsi*	69.5	
	Dormer-sired lambs		85.2	
Santos-Silva et al. (2001)	Merino Branço (MB)	*Longissimus lumborum*		3.1^{b}
	Ile de France x MB			3.4^{a}
Holloway et al. (1994)	Awassi-sired lambs	*Semimembranosus*		3.5
	Texel-sired lambs			3.6
Monaco et al. (2015)	Dorper	*Longissimus lumborum*		4.0^{a}
	Hampshire Down			3.6^{a}
	Suffolk			5.3^{ab}
	Santa Ines			6.0^{ab}
	Ile de France			4.8^{a}
	No defining breed			7.7^{b}
Cloete et al. (2012)	Merino	*Longissimus dorsi*	112.2	
	Dohne Merino		100.1	
	SAMM		111.5	
	Dormer		116.2	
Purchas et al. (2002)	Romney-sired lambs	*Semimembranosus*		8.1
	East-Friesian-sired			8.6
Snowder & Duckett (2003)	Dorper-sired lamb	*Longissimus dorsi*		2.8^{a}
	Suffolk-sired lamb			4.0^{b}

[a, b] superscripts that are different indicate means within breed and shear force values are significantly different ($P<0.05$) within each study.

Moreover, crossbreeding Suffolk sire with Texel ewe produced crossbred lambs with higher shear force values over *Longissimus lumborum* and *Gluteus medius* muscles than purebred Suffolk (Justice et al., 2022). Overall, differences in tenderness between lamb breeds seem to be influenced by the variation of collagen concentrations among breeds (Martines-Cerezo et al., 2005) as a higher collagen concentration and less soluble collagen are associated with a higher shear force and therefore tougher meat.

Some studies did not observe an effect of breed on tenderness measured by Warner-Bratzler shear force (Cloete et al., 2012; Hoffman et al., 1993; Holloway et al., 1994; Hopkins & Fogarty, 1998; Purchas et al., 2002). A study comparing meat tenderness of wool, dual-purpose and mutton breeds showed that breed types did not influence the shear force required to cut a piece of cooked meat of the *Longissimus dorsi* muscle (Cloete et al., 2012). The use of Suffolk and Dormer (Hoffman et al., 1993), Awassi and Texel (Holloway et al., 1994), and Romney and East-Friesian (Purchas et al., 2002) as a sire did not produce progenies with different meat tenderness.

2.3.6 Fatty Acid Composition

Lamb meat is abundant with nutrients such as vitamins, minerals, and essential fatty acids (Biesalski, 2005). The fatty acid profiles of lamb meat influence eating quality through flavour intensity and nutritive values of fat for human consumption (Enser & Wood, 1993; Wood et al., 2008). Dietary fatty acids are essential for the human immunity system and fat-soluble vitamin absorption (Junkuszew et al., 2020). However, there is a consumer concern that red meat consumption has negative health outcomes due to higher saturated fatty acids (SFA) than white meats, such as an increase in blood cholesterol and cardiovascular diseases (Johnson et al., 2021). The biohydrogenation by ruminal microorganisms converts unsaturated fatty acids to SFA (Hoffman et al., 2003). Within dietary polyunsaturated fatty acids (PUFA) in lamb meat, an increase in omega-3 PUFA (n3 PUFA) reduces the total cholesterol level and the risk of cardiovascular and inflammatory diseases (New Zealand Ministry of Health, 2015), while an excessive omega-6 PUFA (n6 PUFA) induces blood clotting and vasoconstriction (Simopoulos, 2002). The recommended ratio of PUFA to SFA is at least 0.45, while the ratio of n6 to n3 should be lower than 4 (Department of Health, 1994).

Diverse fatty acid profiles of lamb meat were observed in different breeds (Fisher et al., 2000; Justice et al., 2022; Mercan et al., 2022; Sanũdo et al., 2000). The n3 PUFA, n6 PUFA and total PUFA were lower in Southdown lambs when compared to Suffolk and Suffolk x Texel lambs,

while Suffolk-Texel lambs had a lower SFA and PUFA:SFA (Justice et al., 2022). Comparing British breeds (Welsh Mountain and typical early lambs) with Spanish breeds (Rasa Aragonesa and Spanish Merino), the loin of Spanish lambs had a higher n6 PUFA content and lower SFA content, resulting in a higher n6:n3 and PUFA:SFA than a British group (Sanũdo et al., 2000). In a comparison of Turkish breeds, the Karayaka lambs had the lowest PUFA and the ratios of PUFA:SFA and n6:n3, while the Arth1 had the highest MUFA, PUFA and PUFA:SFA ratio (Mercan et al., 2022). The Soay, Welsh Mountain, and grass-fed Suffolk were reported to have a higher n3 PUFA and a lower n6 PUFA in *Semimembranosus* muscle than the concentrate-fed Suffolk, but it was suggested to be an effect of diets rather than breeds (Fisher et al., 2000).

Other studies reported minimal breed effect on fatty acid compositions (Hoffman et al., 2003; Kuchtik et al., 2012; Snowder & Duckett, 2003). Only n3 PUFA content was found different between Charollais- and Suffolk-sired lambs (Kuchtik et al., 2012). The MUFA was higher in Suffolk-sired lambs compared to Dorper-sired lambs (Snowder & Duckett, 2003). The combination of Dormer and Suffolk sire and Merino, Dohne Merino, and SAMM ewe showed a higher MUFA and a lower SFA in the Dormer x Dohne Merino lambs (Hoffman et al., 1993). The differences in fatty acid groups were not observed in the *Quadricep femoris* of Zwartles, Suffolk and Oxford Down lambs (Komprda et al., 2012). The fatty acid compositions in *Longissimus thoracis* muscle of the Merino Branço and Ile-de-France x Merino Branço were not different (Santos-Silva et al., 2002).

2.4 Research Objectives

Based on the preceding literature review, sheep breeds have influences on various carcass characteristics but there is minimal breed effect on meat quality characteristics. Romney is the most common breed for wool and meat production in New Zealand. However, with increasing shearing costs and decreasing wool prices, the production system has shifted towards meat production. The introduction of the Wiltshire, which is a self-shedding breed, aimed to minimise input costs while maintaining productivity in meat production. Although some research has focused on differences in meat production across common breeds, specific comparisons between Romney and alternative breeds such as Wiltshire, and their crossbred lambs, remain unexplored.

The objective of this study is to investigate whether the ¾ Wiltshire lambs can produce equally as the Romney lambs, in terms of carcass and meat quality attributes. The hypothesis is that the ¾ Wiltshire lambs are as acceptable as purebred Romney lambs in their carcass and meat characteristics. Therefore, ¾ Wiltshire lambs will not produce disadvantages when used in lamb meat production systems. The key results from this study would fill the current knowledge gap and provide a better understanding of the differences in carcass and meat quality between Romney and ¾ Wiltshire lambs. These results will help to inform meat producers and processors in their alternative breed selection to optimise carcass value, farm profitability and meat quality consistency.

Chapter 3: Material and Methods

A study was conducted to investigate and assess the carcass and meat quality characteristics of Romney and ¾ Wiltshire lambs.

3.1 On-farm Management

The 2022 spring-born (late August - early September) lambs were sourced from Massey University's Riverside farm, Masterton, New Zealand. All animal procedures were carried out with the approval of the Massey University Animal Ethics Committee (MUAEC 20/44). A total of 24 entire male lambs (twelve Romney lambs and twelve ¾ Wiltshire-Romney cross lambs) were used in this study. The ¾ Wiltshire lambs were the progeny of two-tooth ½ Wiltshire-Romney ewes bred with a Wiltshire ram. The average birth date of the Romney lambs was on the fifth of September and the ¾ Wiltshire was on the 31st of August 2022. The birth rank of the lambs in each treatment comprised of seven singletons and five twins. Therefore, the lambs were balanced for birth rank. Birthweights were measured. One Romney lamb was removed from the trial due to flystrike.

At weaning in December 2022, lambs were transferred to the Massey University Pasture and Crop Research Unit, Palmerston North and their starting weights were recorded. Throughout the study, the lambs were managed as one group and offered unrestricted perennial-ryegrass-based pasture. Each lamb was individually identified using electronic identification (EID), and they were weighed and orally treated with an anthelmintic every four weeks. Prior to transportation to the processing plant, all lambs had a final, on-farm liveweight measured on 15th March 2023 when all lambs reached seven months of age and a minimum set slaughter liveweight of 40 kg.

3.2 Abattoir Management

Lambs were slaughtered at a commercial meat processing plant (Ovation, Fielding, New Zealand) audited by the New Zealand Ministry for Primary Industries. Following commercial dressing procedures, carcasses were chilled and stored at 4°C for 24 hours. Each carcass was given an identification number (ID) that was linked to the EID of each lamb. Hot carcass weight was recorded at the processing plant. The carcasses were boned out, and the hind leg (bone-in, short leg) and bone-in saddle were obtained from each carcass and identified with the carcass ID. The samples were transferred to Massey University and stored at 1°C in a chiller for a 14-day aging, then transferred to a -20°C freezer for longer-term storage and subsequent analysis.

3.3 Dissection of Lamb Leg and Carcass Characteristics Analysis

The dressing-out percentage was calculated as the proportion of hot-carcass weight to the final, on-farm liveweight (Equation 1). Two Romney carcasses were removed from the carcass characteristics analysis due to severe pleurisy which was identified at slaughter and resulted in a significant carcass trimming and a reduction in carcass weight after dressing procedures.

Equation 1:

$$\text{Dressing-out (\%)} = \text{hot carcass weight (kg)} \,/\, \text{on-farm final live weight (kg)} \times 100$$

At the laboratory of the Te Ohu Rangahau Kai facility (Massey University, Palmerston North), the legs were dissected to investigate the differences in carcass characteristics between breeds. Prior to dissection, the leg samples (n=21) were thawed for 24 hours. The legs were removed from the packaging and dried with a paper towel before weighing (whole leg weight). Each leg was dissected into its eight muscles: *Gracilis, Sartorius, Pectineus, Semimembranosus, Adductor, Bicep femoris, Semitendinosus and Quadriceps femoris*. Individual muscles were weighed and recorded. Muscle percentage was expressed as a proportion of total muscle weight to the whole leg weight. The total dissectible fat was obtained from the whole leg to calculate the dissectible fat percentage.

After dissection of the muscles, the clean femur and tibia bones were weighed. The femur length (mm) was also measured and kept in the freezer for later morphology analysis. The muscle-to-bone ratio (M:B) (Equation 2) was described previously in Jonhson et al. (2005) and muscularity was calculated following the procedure of Purchas et al. (1991). M:B ratios were expressed in two ways. The whole leg M:B ratio considered all eight-leg muscles and the weight of the partial tibia plus femur while the femur M:B ratio took account into only five muscle weights (*Semimembranosus, Adductor, Bicep femoris, Semitendinosus* and *Quadricep femoris*) to the femur bone weight. Muscularity was calculated as the depth of muscle for five muscles that surround the femur to the relative length of the femur (Equation 3).

Equation 2:

$$M{:}\,B = \textit{muscle weight}\ (\text{g}) \,/\, \textit{bone weight}\ (\text{g})$$

Equation 3:

$$\textit{Muscularity} = \sqrt{(\text{muscle weight (g)} \times (\text{ femur length (mm)}^{-1}))} \times \text{femur length (mm)}^{-1}$$

3.4 Femur Bone Morphology

To assess the morphology and strength of the femur of the lambs in both treatments, the peripheral quantitative computative tomography (pQCT) technique was utilised. The pQCT scanning was conducted using an XCT 2000 peripheral quantitative computed tomography machine (Stratec Medical) at the School of Veterinary Sciences, Massey University, using the protocol outlined by Gibson et al. (2020).

The data derived from the scanning included the total bone area, total bone density, total bone content, cortical bone content, cortical bone thickness, cortical bone density, periosteal circumference, endosteal circumference and stress strain index (SSI). The SSI is calculated by the pQCT scanner using the incorporation of an index of material stiffness (mineral density) and bone geometry (cross-sectional moment of inertia) (Gibson et al., 2020). The ratios of cortical bone content to muscle weight, cortical bone thickness to muscle weight and stress strain index to muscle weight were analysed to investigate the influence of muscle weight (*Semimembranosus, Adductor, Bicep femoris, Semitendinosus, Quadricep femoris*) on bone strength. These are referred to as bone parameters in the statistical models.

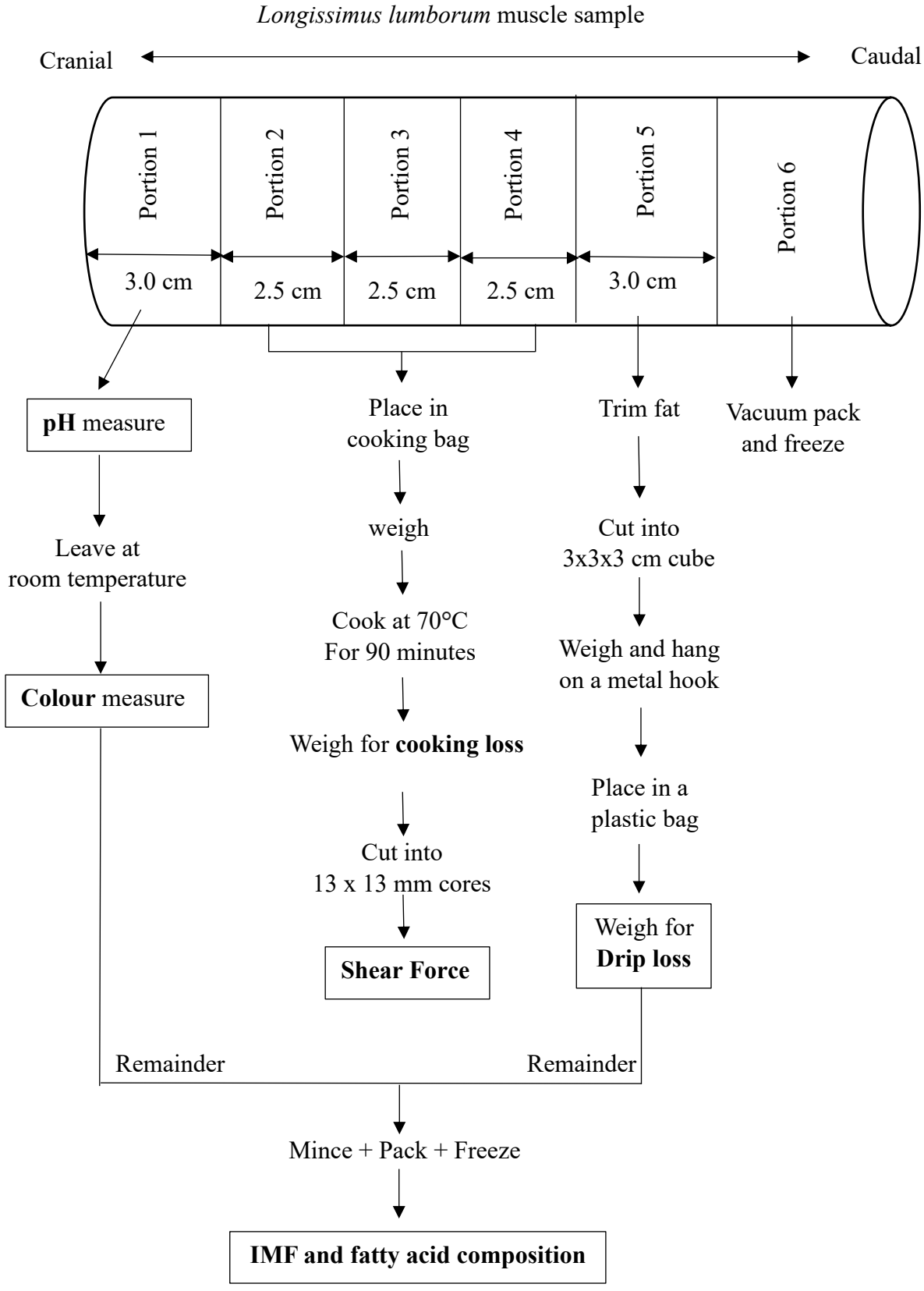
3.5 Meat Quality Analysis

The bone-in saddle samples (n=23) were boned out to produce the *Longissimus lumborum* muscle (loin), which was assessed for meat quality using objective measurements. The meat quality analysis included objective measures of pH, colour, water-holding capacity, and shear force, which were conducted at the Te Ohu Rangahau Kai facility, Massey University, Palmerston North. The loin was sub-portioned to allocate samples for all the objective tests (Figure 3.1).

3.5.1 Meat pH

The pH was measured on the meat sample (Portion 1; Figure 3.1) using a pH spear (Eutech Instruments, Malaysia) which was calibrated to standard buffers (pH 4.01, 7.00 and 10.01). Triplicate measurements were taken at three locations across a transverse internal cut at a depth of approximately 1-1.5 cm into the *Longissimus lumborum* muscle. Triplicate measurements were averaged to determine the pH value for each sample.

Figure 3.1. A schematic diagram showing of the partitioning of the lamb *Longissimus lumborum* muscle for meat quality assessment. IMF = intramuscular fat.



3.5.2 Meat Colour

The Minolta chromometer CR-400 was calibrated to a white calibration plate supplied by the manufacturer (Konica Minolta Photo Imaging Inc. Mahwah, NJ, USA). The chromometer assessed meat lightness (L^*), redness (a^*) and yellowness (b^*). The assessment was taken at three points across the transverse cut of the meat sample (Portion 1; Figure 3.1) after it had been exposed to air for 30 minutes. The three replicates were averaged to obtain the L^*, a^* and b^* values for each sample.

3.5.3 Water-Holding Capacity (WHC)

Water holding capacity was measured as drip and cooking losses. To measure drip loss, 3 x 3 x 3 cm cubes of raw meat (Portion 5; Figure 3.1) were weighed and hung on a metal hook inside of a plastic bag and chilled at 4°C. After chilling for 48 hours, the meat cubes were patted dry with paper towels and reweighed. Drip loss was expressed as the percentage of the difference between the initial weight and the final weight (Equation 5).

Equation 5:

$$Driploss_{48hr}\ (\%) = \frac{weight_{0hr}\ (g) - weight_{48hr}\ (g)}{weight_{0hr}(g)} \times 100$$

Cooking loss percentage was measured from three 2.5 cm thick slices of meat (Portion 2, 3, and 4; Figure 1). The portions were weighed together and placed into a plastic bag, and then cooked in a water bath (Contherm®, Model 370HL, Australia) at 70°C for 90 minutes. The portions were allowed to cool to room temperature and then chilled for a minimum of 3 hours. The three slices from each sample were patted dry and reweighed. Cooking loss was expressed as the percentage of the difference between the weight before cooking and the weight after cooking (Equation 6).

Equation 6:

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

3.5.4 Shear Force

Objective meat tenderness was assessed from the force required to shear across the muscle fibres of the cooked samples (portion 2, 3 and 4; Figure 3.1). Six cores with a 13 x 13 mm

cross-sectional area from each meat sample were cut parallel to the direction of the muscle fibres. Peak shear force (kgF) and total shear force work (kgF) were assessed by shearing perpendicular to the muscle fibre direction (one shear per core) with a V-shaped blade (TMS-Pilot Texture analyser, USA). The six core measurements were averaged to obtain the peak shear force area and total workload for each sample.

3.5.5 Intramuscular Fat (IMF)

The remaining portions of meat from each sample were trimmed off external fat, minced (Kenwood MG450, 3mm hole-plate) and then individually packed in a zip-lock plastic bag. The bags were stored at -20°C. Six samples from each treatment were randomly selected for analysis of IMF percentage and fat content using solvent extraction with the Soxtec System (AOAC 991.36).

3.5.6. Fatty Acid Composition

Six samples of each treatment that were randomly selected for IMF percentage were also measured for fatty acid composition analysis using a one-step procedure for quantitative analysis of fatty acids in animal meat, developed by Agnew et al. (2019). This method determined fatty acids composition including saturated, unsaturated and long-chain polyunsaturated fatty acids. The samples were freeze-dried for fatty acid composition analysis. A 300 mg freeze-dried sample was weighed into a kimax 15 mL tube. The 3 g of Internal standard (tri C11 in Toulene) was added to the samples, followed by 4 mL of toluene and 4 mL of 5% sulfuric acid (H2SO4) in methanol. The tubes were sealed and vortexed before incubation at 70°C for 2 hours with interim mixing by inversion at 30, 60 and 90 min for 15 seconds. After cooling to room temperature, 5 mL of saturated Sodium Chloride (NaCl) solution was added to each tube. The samples were centrifuged at 1000× g for 10 minutes. An aliquot of the top layer was transferred into a 1.5 mL gas chromatography vial and analysed by gas chromatography flame ionisation detection (GC-FID).

Fatty acids methyl esters (FAMEs) were analysed with a GC-2010 (Shimadzu, Kyoto, Japan) and an RTX 2330 (90% biscyanopropyl—105m × 0.25 mm i.d × 0.2 µm film thickness) from Restek. The column temperature was maintained at 175 ℃ for 17 minutes, then raised to 220 ℃ at a rate of 6 ℃ /min and held for 10 minutes. Hydrogen was a carrier gas at a constant linear velocity of 50 cm/sec, with a split ratio of 50. Injection of a 1 µL aliquot of the FAME

sample was performed, and individual FAME isomers, including conjugated linoleic acid and C18:1 isomer, were identified by comparison with commercial standards.

3.6 Statistical Analysis

Carcass and meat quality characteristics were presented as the mean and standard error of the mean. The data was analysed using a general linear model (PROC GLM, SAS) in the Statistical Analysis Software version 9.4 (SAS 9.4, SAS institute Inc., Carey, NC, USA) with breed treatment as the fixed effect. Two Romney carcasses had major faults which resulted in a significantly lower carcass weight, and they were removed from the analyses of carcass characteristics and bone morphology. Hot carcass weight was fitted as a covariate to the analysis of carcass characteristics consisting of five-femur muscle weights (*Semimembranosus, Adductor, Bicep femoris, Semitendinosus, and Quadricep femoris*), muscle, dissectible fat, and intramuscular fat percentages, muscle to bone ratios for whole leg and femur bone, and muscularity. For bone parameters, hot carcass weight was fitted as a covariate. Ultimate pH was used as a covariate for objective meat quality characteristics of colour, water-holding capacity, and shear force (total workload and peak shear force). Intramuscular fat percentage was fitted as a covariate for analysing fatty acid compositions.

Chapter 4: Results

4.1 Carcass Characteristics

The birthweights of both treatments were comparable (P>0.05; Table 4.1). The start and final liveweights and hot carcass weight and dressing-out of the ¾ Wiltshire lambs were greater than those from Romney lambs (P<0.05; Table 4.1). When including the weight data of the two Romney lambs where carcasses were excluded due to pleurisy carcass faults, the start and final liveweights remained unchanged. Hot carcass weight was a significant covariate for muscle weight, dissectible fat, M:B of the whole leg and M:B of the femur (P<0.05; Table 4.1). When compared at an equal hot carcass weight, the ¾ Wiltshire lambs had heavier muscle weights and lower dissectible fat than the Romney lambs (P<0.05; Table 4.1). The muscle and intramuscular fat percentages, M:B ratios and muscularity were similar for both treatments (P>0.05; Table 4.1).

Table 4.1. Carcass characteristics (mean ± SEM) for Romney and ¾ Wiltshire lambs. Hot carcass weight (HCW) was fitted as a covariate in the statistical model for muscle, dissectible fat, M:B, intramuscular fat (IMF), muscle to bone ratio (M:B) for femur and M:B for whole leg and muscularity obtained by physical dissection.

Carcass characteristic	Romney (n=9)	¾ Wiltshire (n=12)	P-value Breed	P-value HCW covariate
Birthweight (kg)	5.82 ± 0.34	5.75 ± 0.31	0.885	-
Start liveweight (kg)	38.50 ± 1.13	42.41 ± 1.02	**0.019**	-
Final liveweight (kg)	45.11 ± 1.47	51.42 ± 1.27	**0.004**	-
Hot carcass weight (kg)	17.0 ± 0.7	21.8 ± 0.6	**<0.0001**	-
Dressing-out (%)	37.6 ± 0.5	42.3 ± 0.4	**<0.0001**	-
Muscle weight (g)[1]	1060.9 ± 28.6	1168.7 ± 23.3	**0.025**	**<0.0001**
Muscle (%)	72.24 ± 0.76	74.15 ± 0.62	0.123	0.202
Dissectible fat (%)	13.69 ± 0.69	11.16 ± 0.56	**0.029**	**0.006**
IMF (%)[2]	1.74 ± 0.34	2.51 ± 0.34	0.211	0.439
M:B of Whole leg	5.66 ± 0.17	5.59 ± 0.14	0.820	**0.018**
M:B of Femur	5.69 ± 0.18	5.78 ± 0.15	0.758	**0.015**
Muscularity	0.43 ± 0.01	0.43 ± 0.01	0.895	0.498

[1] Muscle weight refers to the sum of *Semimembranosus, Adductor, Bicep femoris, Semitendinosus,* and *Quadricep femoris*.
[2] Six animals of each treatment were randomly selected for the IMF analysis.

Hot carcass weight was a significant covariate on the femur bone length and the ratios of cortical bone content to muscle weight, cortical bone thickness to muscle weight and stress strain index to muscle weight ($P<0.05$; Table 4.2). When compared at an equal hot carcass weight, the length of the femur, the total bone content and density and the cortical bone content and thickness of the ¾ Wiltshire lambs were greater than those of Romney lambs ($P<0.05$; Table 4.2). The ¾ Wiltshire lambs had a greater stress-strain index compared with Romney lambs when compared at an equal hot carcass weight ($P<0.05$; Table 4.2).

Table 4.2. Femur bone morphology at the mid-diaphysis (mean ± SEM) obtained from Romney and ¾ Wiltshire lambs. Hot carcass weight (HCW) was fitted as a covariate in the statistical model.

Bone parameters	**Romney (n=9)**	**¾ Wiltshire (n=12)**	**P-value Breed**	**P-value HCW covariate**
Femur length (mm)	178.5 ± 1.9	185.4 ± 1.6	**0.032**	**0.001**
Total bone				
Content (mg/mm)	196.0 ± 8.7	240.6 ± 7.0	**0.004**	0.717
Density (mg/cm^3)	544.2 ± 23.7	626.8 ± 19.3	**0.036**	0.366
Area (mm^2)	362.1 ± 12.6	384.1 ± 10.3	0.273	0.435
Cortical Bone				
Content (mg/mm)	179.7 ± 8.6	222.0 ± 7.0	**0.005**	0.814
Density (mg/mm^3)	1352.9 ± 8.4	1359.0 ± 6.8	0.642	0.568
Thickness (mm)	2.2 ± 0.1	2.7 ± 0.1	**0.009**	0.611
Periosteal circumference (mm)	67.4 ± 1.2	69.4 ± 0.9	0.269	0.433
Endosteal circumference (mm)	53.6 ± 1.4	52.6 ± 1.1	0.650	0.368
Stress strain index (SSI) (mm^3)	1110.3 ± 60.2	1389.5 ± 49.0	**0.008**	0.450
Ratios				
Cortical content: Muscle weight	0.173 ± 0.010	0.193 ± 0.008	0.123	**0.010**
Cortical thickness: Muscle weight	0.0021 ± 0.0001	0.0023 ± 0.0001	0.358	**0.011**
SSI: Muscle weight (mm^3/g)	1.05 ± 0.05	1.20 ± 0.05	0.103	**0.028**

4.2 Meat Quality Characteristics

The ultimate pH from the loin meat of Romney lambs was higher than ¾ Wiltshire lambs ($P<0.05$; Table 4.3). The ultimate pH was not a significant covariate on any meat quality attributes ($P>0.05$; Table 4.3). When comparing colour, water-holding capacity and tenderness at an equal pH, there was no effect of treatment on any of these measures ($P>0.05$, Table 4.3).

There was no effect of genetic treatment on the fatty acid profiles or ratios of PUFA: SFA and n6: n3 when compared at the same IMF% ($P>0.05$; Table 4.4). Intramuscular fat was a significant covariate in every fatty acid group ($P<0.05$, Table 4.4), except for n6 PUFA, long-chained n3 PUFA and the ratio of PUFA:SFA and n6:n3 ($P>0.05$; Table 4.4).

Table 4.3. Meat quality characteristics (mean ± SEM) from *Longissimus lumborum* muscle samples of Romney and ¾ Wiltshire lambs. Ultimate pH was used as a covariate for colour, water-holding capacity, and tenderness measures.

Meat quality characteristic	Romney (n=11)	¾ Wiltshire (n=12)	P-value breed	P-Value pH Covariate
Ultimate pH	5.67 ± 0.02	5.59 ± 0.02	**0.010**	-
Colour parameters				
Lightness (*L**)	36.32 ± 0.35	36.38 ± 0.34	0.911	0.680
Redness (*a**)	16.17 ± 0.33	16.37 ± 0.31	0.684	0.389
Yellowness (*b**)	6.84 ± 0.35	7.16 ± 0.33	0.545	0.577
Water holding capacity				
Drip loss (%)	4.29 ± 0.61	3.46 ± 0.58	0.371	0.073
Cooking loss (%)	34.6 ± 0.5	34.3 ± 0.4	0.604	0.716
Tenderness				
Total shear work (kgF)	15.85 ± 0.67	14.76 ± 0.64	0.287	0.296
Peak shear force (kgF)	3.71 ± 0.18	3.18 ± 0.17	0.055	0.634

Table 4.4. Fatty acid composition (mg per 100g fresh meat) (mean ± SEM) from *Longissimus lumborum* muscle samples of Romney and ¾ Wiltshire lambs. Intramuscular fat percentage (IMF%) was fitted as a covariate for the statistical analysis.

Fatty acid composition[1]	**Romney (n=6)**	**¾ Wiltshire (n=6)**	**Breed P-value**	**P-value IMF% Covariate**
Saturated fatty acids (SFA)	1111.25 ± 60.43	1079.92 ± 60.43	0.703	**0.003**
Monounsaturated fatty acids (MUFA)	938.47 ± 45.91	942.20 ± 45.91	0.957	**0.001**
Polyunsaturated fatty acids (PUFA)	228.43 ± 9.58	212.73 ± 9.58	0.290	**0.011**
Branch-chained fatty acids (BCFA)	30.29 ± 1.67	27.71 ± 1.67	0.317	**0.007**
Omega-6 PUFA (n6)	102.41 ± 5.87	94.92 ± 5.87	0.404	0.133
Omega-3 PUFA (n3)	87.85 ± 2.94	85.48 ± 2.94	0.594	**0.005**
Long-chained omega-3 PUFA	48.52 ± 1.43	48.64 ± 1.43	0.956	0.175
PUFA: SFA	0.21 ± 0.01	0.20 ± 0.01	0.503	0.252
n6: n3	1.17 ± 0.04	1.11 ± 0.04	0.280	0.413

[1] SFA comprised of C10:0, C12:0, C14:0, iso C15, anteiso C15, C15:0, iso C16, C16:0, isoC17:0, anteiso C17, C17:0, C18:0, C20:0 and C24:0
MUFA comprised of C14:1, C16:1, C17:1, C18:1t9, C18:1 t11, C18:1c9 and C18:1 c11
PUFA comprised of C18:2 n6, gC18:3, C18:3 n3, 9 11 CLA, C20:3 n6, C20:4 n6, C20:5 n3, C22:5 and C22:6 n3
BCFA comprised of iso C15, anteiso C15, iso C16, iso C17, and anteiso C17
n6 comprised of C18:2 n6 and C20:4 n6
n3 comprised of C18:3 n3, C20:5 n3, C22:5 and C22:6 n3
Long-chained omega-3 PUFA comprised of C20:5 n3, C22:5 and C22:6 n3

Chapter 5: Discussion

The objective of this study was to investigate the carcass and meat quality characteristics of the ¾ Wiltshire and Romney lambs. This was done by managing all lambs under the same conditions, feeding them as one group and sending them to slaughter on the same day when all lambs reached a minimum liveweight of 40 kg in order to observe the genetic difference in their carcass and meat quality characteristics.

5.1 Carcass Characteristics

The ¾ Wiltshire lambs had heavier weaning weights despite similar birthweights and birth ranks when compared to the Romney lambs. This aligns with previous studies where the Wiltshire lambs were heavier at weaning compared to Romney and Perendale lambs (Litherland et al., 1992; Sumner et al., 2012). However, this contradicts other studies where the ½ Wiltshire and the ¾ Wiltshire lambs had similar weaning weights to purebred Romney (Corner-Thomas et al., 2021; Morris et al., 2022).

This suggests that the ¾ Wiltshire lambs had greater pre-weaning growth, possibly due to a higher maternal ability of Wiltshire ewes compared to Romney ewes, as both treatments had similar birthweights (Dwyer, 2008; Rathie et al., 1994). Variations in maternal ability across sheep breeds are known to influence lamb growth and survival both pre- and post-weaning (Afolayan et al., 2009).

The ¾ Wiltshire lambs also achieved heavier final on-farm liveweight than the Romney lambs. Heavier animals at weaning are likely to remain heavier at slaughter (Fraser & Saville, 2000). Consequently, the ¾ Wiltshire lambs had higher carcass weights than Romney lambs. Similar findings reported that crossbred progeny had higher slaughter and carcass weights compared to purebred (Nitter, 1987; Kremer et al., 2004; Kirton et al., 1981). An increased carcass weight is correlated with higher DO% (Purchas et al., 2002; Santos-Silva et al., 2002), which is reflected in the higher DO% in the ¾ Wiltshire lambs.

As slaughter weight increases, the proportion of fat within the carcass increases, while the proportions of muscle and bone reduce (Santos-Silva et al., 2002). This was not observed in the ¾ Wiltshire lambs that were heavier at slaughter and had similar muscle percentages, but lower fat compared to the Romney lambs, suggesting that carcass composition characteristics between treatments were not solely driven by slaughter weight.

Although muscle proportions were similar, the dissectible fat percentages were higher in the Romney compared to the ¾ Wiltshire lambs. Similarly to other studies, lower fat proportions in Wiltshire horn-sired lambs were previously reported when compared to Dorset horn-sired lambs (Rathie & Teasdale, 1994) and Poll Dorset-sired lambs (Hopkins & Brooks, 1990), explained as being due to a larger mature size of the Wiltshire horn animals. Additionally, because the Wiltshire lambs were heavier at weaning in this current study, they may have reached their target slaughter weight at an earlier tissue development stage, having more muscle and less fat deposited than the Romney lambs (Jones et al., 2021). These results also align with research reporting that crossbred carcasses were less fat than purebreds due to the heterosis effect from crossbreeding (Alkass & Hassan, 2014).

The ¾ Wiltshire lambs had similar intramuscular fat (IMF) percentages to the Romney lambs, ranging from 1.7% to 2.5%. A study comparing six lamb breeds also found no difference in IMF (Monaco et al., 2015). The range of IMF% observed in this study was lower than in other studies, where the animals grazed on pasture at finishing, which reported an IMF range between 4.1% and 4.5% (Anderson et al., 2015; Pannier et al., 2014). This can be due to the animals in this study were slaughtered at a younger age and lighter weight compared to those with higher IMF%. However, the results of this present study were not unexpected. The deposition of IMF is determined by factors such as sex, feeding level and age (Berge et al., 2007), where younger and male animals have lower IMF percentages compared to older and female animals (Anderson et al., 2015; Craigie et al., 2012). Since the lambs in this study were all rams, were managed as one group and finished on pasture, the IMF depositions were expected to be similar and in lower ranges.

The lack of difference in M:B ratios of the whole leg and femur was expected since muscle proportions were similar for both treatments. Muscularity around the femur was similar for both treatments and comparable to other studies (Hopkins et al., 1996; Hopkins et al., 1997). Muscularity is largely influenced by animal age, and thus, muscularity can be similar when slaughtering animals at the same age (Prache et al., 2020). Despite the ¾ Wiltshire having a longer femur than the Romney lambs, their five-muscle weights over the femur were heavier than those of the Romney lambs, resulting in similar muscularity for both treatments. A similar comparison was previously reported where bone length and muscle weight influenced muscularity (Sailer et al., 1995).

The longer femur bone in the ¾ Wiltshire, compared to the Romney lambs indicates that the ¾ Wiltshire is associated with a larger frame size. The larger frame size could potentially be associated with a late-maturing type of animal or can be a consequence of crossbreeding, which promotes hybrid vigour and hence, greater growth across the body, including bone tissue (Leymaster, 2002).

Greater total bone growth was observed in the ¾ Wiltshire lambs compared to the Romney lambs, as indicated by higher total bone content and density. Similar findings have been previously reported, where femur bone weights were measured in Wiltshire, Romney and other breeds during foetal development to predict postnatal bone development (Sailer et al., 1995). The results of the previous studies showed a heavier femur in the Wiltshire foetuses, potentially preprograming them for a greater frame size. It is also possible that the Romney lambs potentially are more likely to partition more nutrients towards wool growth rather than bone growth (Adams & Liu, 2003; Harris et al., 1990).

Although the periosteal and endosteal circumferences for both treatments were similar, the ¾ Wiltshire lambs showed thicker cortical bones, indicating lower cortical content in the Romney lambs. The total bone density was higher in the ¾ Wiltshire lambs than the Romney lambs, while cortical bone density was similar, indicating differences in soft bone density. Overall, these bone parameters indicated that the ¾ Wiltshire lambs had greater bone growth and development than the Romney lambs.

The greater stress-strain index (SSI) in the ¾ Wiltshire lambs may be explained by heavier liveweights and weights of muscles around the femur, which increase the strain on the femur and increased bone deposition to account for more muscle force. A similar trend of stronger bones in animals with heavier liveweights was previously reported in cattle (Alpak et al., 2019; Rubin & Lanyon, 1985). Although the ratios of cortical content and thickness and SSI to muscle weights were similar for both treatments, they were correlated with hot carcass weight. The hot carcass weight did not influence SSI directly, suggesting that SSI was influenced by the development of muscle, which in turn was dependent on the extent of carcass development and growth.

These bone development measures suggest that the increased growth and heavier carcass of the ¾ Wiltshire in this study were associated with more bone growth, particularly greater hard bone deposition and denser bones. Although the femur bone was longer and more dense in the ¾

Wiltshire, this did not result in a difference in the muscle percentages, M:B or muscularity compared to the Romney. This indicated that the longer and heavier bone structure of the ¾ Wiltshire did not negatively impact muscle production and meat yield.

The initial sample size of 12 animals per treatment was sufficient to identify the differences in carcass traits (Fourie et al., 1970; Holloway et al., 1994), but the variation in carcass characteristics was greater than previously observed in other studies of New Zealand lambs (Purchas et al., 2002; Young et al., 1993) and then there were three Romney lambs removed from the trial due to health-related issues and issues only found at carcass grading. With the reduction to nine Romney lambs, the ability to identify the carcass trait differences between treatments may have become limited.

5.2 Meat Quality Characteristics

The Romney lambs had higher pH than the ¾ Wiltshire lambs. However, other meat quality attributes such as meat colour, water-holding capacity and tenderness, were similar when adjusted for ultimate pH. There is evidence that supports the results that lamb breed and genetics generally do not have an effect on meat colour (Belhaj et al., 2021; Komprda et al., 2012; Monaco et al., 2015; Santos-Silva et al., 2001), water-holding capacity (Hoffman et al., 2003; Komprda et al., 2012; Santos-Silva et al., 2001) and tenderness (Cloete et al., 2012; Hoffman et al., 2003; Holloway et al., 1994; Purchas et al., 2002).

The meat colour values (L^*, a^* and b^*) in this study ranged within the typical values found by other studies (Chapter 2, Table 2.3). As the animals were grazing under the same management conditions and slaughtered at similar ages, differences in meat colour were not expected, and lamb breed itself is not a strong determinant of meat colour (Schreurs & Kenyon, 2017b). The cooking loss observed in this study was consistent with previous studies as well (De Brito et al., 2016; Santos-Silva et al., 2001), whereas the drip loss was higher than previously reported, which ranged between 1-3% (Hoffman et al., 1993; Jandasek et al., 2014). It is important to note that while previous studies measured drip loss at 24 hours, this study measured it over 48 hours.

The tenderness of the meat from both treatments was considered acceptable as the shear force values were below 4 kgF (Justice et al., 2020) and within the average values observed in other research (Chapter 2, Table 2.4). However, IMF% was similar for both treatments and was below the minimum IMF required to improve the consumer's eating quality (3%; Realini et al., 2021).

An increase in IMF proportion is usually associated with more tender meat because IMF can alter muscle fibre characteristics to be less tough (Zhang et al., 2022). Despite lower IMF% than other studies, the low shear force indicating tender meat was attributed to the young age at slaughter, resulting in less total collagen and collagen that is more soluble with heating (Young et al., 1993).

There was no genetic effect on the fatty acid profiles. IMF% was a significant covariate for SFA, MUFA, PUFA, BCFA and n3-PUFA, suggesting that genetic background differences did not directly influence these profiles and that the changes in fatty acid profiles are more influenced by changes in IMF%. When IMF% increases, there is a tendency for SFA concentrations to increase while PUFA concentrations decrease (Purchas et al., 2005; Wood et al., 2008). The ratios of PUFA:SFA and n6-PUFA: n3-PUFA were similar for both treatments in this study. The PUFA:SFA ratios (0.20-0.21) were lower than the recommendation of the New Zealand Ministry of Health (2015) of at least 0.45 to be able to make health claims regarding PUFA. Meat from ruminants has higher SFA due to the biohydrogenation by ruminal micro-organisms, which convert unsaturated fatty acids into SFA (Hoffman et al., 2003) and so reaching a PUFA:SFA above 0.45 can be difficult to achieve. The ratios of n6:n3 (1.11-1.17) of both treatments were within the recommendations of the New Zealand Ministry of Health (2015) of being lower than 4, preventing the diseases associated with fat intake.

5.3 Recommendations and Future Research

This study included a broad range of slaughter weights, with lambs weighing between 40 and 60 kg, while the minimum final liveweight was 40 kg to slaughter. The variations in slaughter weights could affect the consistency of the results as carcass characteristics can be influenced by the weight at slaughter. Therefore, the statistical analyses of carcass characteristics were adjusted by hot carcass weight to compare animals at the same carcass weight, rather than comparing the results at the same slaughter weight.

The dissection of muscles to analyse carcass characteristics was conducted on the leg, which might not accurately represent the muscle and fat compositions of the entire carcass. Despite this, the use of the leg dissection method (Purchas et al., 1991) ensures that the results are indicative of the overall carcass composition. An ideal dissection would include a whole carcass or a side (half) of the carcass for more precise results. However, due to practical constraints of time and resources, this was not feasible.

The relatively small sample size of lambs used in the study might affect the accuracy of the outcomes. This study somewhat mitigated this by replicating the measures taken for meat quality characteristics to enhance the reliability of the data for further analysis. Future studies might include a larger sample size so that they could represent the breed population, and the statistical analysis could provide a better estimate of the treatment effect on carcass and meat quality characteristics.

The ¾ Wiltshire lambs are not likely to be produced in the future as the farmers would focus on breeding full-shedding ewe flocks that will be mated with Wiltshire sires to provide replacements or with other terminal sires for lambs destined for slaughter. In this study, the use of ¾ Wiltshire lambs in comparison to Romney lambs aimed to understand how Wiltshire-cross lambs or Wiltshire as a sire perform in terms of meat production and meat quality, rather than focusing specifically on the ¾ Wiltshire lambs.

In addition, this study focused on objective measures of carcass and meat quality characteristics, but aspects of meat flavour were not included. Analysing flavour is complicated and requires highly sensitive equipment, or the use of trained sensory panels, which was beyond the scope of this study. Further studies could include objective flavour evaluations such as gas chromatography-mass spectrometry to identify and qualify volatile compounds between breeds. Similarly, future research could also involve subjective sensory tests in meat quality characteristics involving lamb consumers or trained sensory panels. This would provide insights into consumer perceptions and preferences when consuming meat from Romney and ¾ Wiltshire lambs in terms of flavour, juiciness, tenderness, and overall eating experience.

5.4 Conclusion

The current study investigated the carcass and meat quality characteristics of Romney and ¾ Wiltshire lambs when slaughtered at a similar age. Compared to the Romney, the ¾ Wiltshire lambs were associated with marginally greater meat production expressed in terms of greater slaughter weights, carcass weights, dressing-out %, and muscle weights, and lower fat percentages. The ¾ Wiltshire lambs had longer and denser hard bone, and stronger femur bones than the Romney lambs, but these did not negatively affect the muscle production or meat yield. The meat quality attributes, including meat pH, colour, water-holding capacity, shear force and nutritive values were similar for both treatments. The consistency in meat quality between both treatments is likely to provide a similar visual appearance, dietary nutrients and eating experience for consumers.

Overall, the ¾ Wiltshire lambs have the potential to produce carcass characteristics and meat quality that is equal to Romney lambs. Therefore, the use of the ¾ Wiltshire lambs will not negatively affect meat yield or quality and the use of a Wiltshire sire will not disadvantage lamb meat production. The self-shedding ability of the Wiltshire lambs can minimise costs such as shearing, thereby providing a better net return to meat producers. The results of this study would be useful for a further study of farm economics using self-shedding Wiltshire lambs.

Chapter 6: References

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Chapter 7: Appendices

7.1 Appendix: SAS Code for Carcass Characteristics

```
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename Wilt2023 dde 'Excel|C:\Users\rawis\OneDrive\wiltshire vs
romney\[Wiltshire2023.xlsx]carcass!R3C1:R23C30';
data Wilt2023;
infile Wilt2023 lrecl=6000 dlm='09'x notab dsd missover;
input Treatment$ CCID Day Order Birthwt Startwt EndWt HCW DO wholeleg
Gracilis Sartorius Pectineus semimem adductor Bicep Semitend Quadricep
others FemurWt FemurLength Tibia Fat MuscleP FatP MBFemur MBLeg Muscularity
FemurM IMF;
run;
proc mixed data=Wilt2023;
    class Treatment;
    model Birthwt = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model Startwt = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model EndWt = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model DO = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model HCW = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
Proc glm data=Wilt2023;
   class Treatment;
   model MuscleP = treatment HCW/ solution;
   lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2023;
   class Treatment;
    model FatP = treatment HCW/ solution;
```

```
    lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model MBFemur = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model MBLeg = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model Muscularity = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model FemurM = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model IMF = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
```

7.2 Appendix: SAS Code for Bone Morphology

```
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename WiltBone dde 'Excel|C:\Users\Fai\Desktop\wiltshire vs romney\Bone
comparison\[Wiltshire2023 HF50.xlsx]21 lambs!R2C1:R22C19';
data WiltBone;
infile WiltBone lrecl=6000 dlm='09'x notab dsd missover;
input Order treatment$ EndWt HCW DO TOTCNT TOTDEN TOTA CRTCNT CRTDEN
CRTTHKC PeriC EndoC RPCMW MUSCLEWT CRTCONR CRTTHKR SSIR FemurL;
run;
Proc glm data=WiltBone;
  class treatment;
  model EndWt = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
  Proc glm data=WiltBone;
  class treatment;
  model DO = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model TOTCNT = treatment HCW/ solution;
```

```
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model TOTDEN = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model TOTA = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model CRTCNT = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model CRTDEN = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model CRTTHKC = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model PeriC = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model EndoC = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model RPCMW = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model CRTCONR = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model CRTTHKR = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
```

```
  class treatment;
  model SSIR = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltBone;
  class treatment;
  model FemurL = treatment HCW/ solution;
  lsmeans treatment/ stderr;
run;
```

7.3 Appendix: SAS Code for Meat Quality Characteristics

```
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename WiltMQ23 dde 'Excel|C:\Users\rawis\OneDrive\wiltshire vs
romney\[Wiltshire2023.xlsx]MQ!R3C1:R25C49';
data WiltMQ23;
infile WiltMQ23 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=WiltMQ23;
    class Treatment;
    model pH = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
Proc glm data=WiltMQ23;
  class treatment;
  model L = treatment pH/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltMQ23;
  class treatment;
  model a = treatment pH/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltMQ23;
  class treatment;
  model Cookloss = treatment pH/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltMQ23;
  class treatment;
  model Drip = treatment pH/ solution;
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltMQ23;
  class treatment;
  model WkDone = treatment pH/ solution;
```

```
  lsmeans treatment/ stderr;
run;
Proc glm data=WiltMQ23;
  class treatment;
  model PkForce = treatment pH/ solution;
  lsmeans treatment/ stderr;
run;
```

7.4 Appendix: SAS Code for Fatty Acid Composition

```
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename Wilt2023 dde 'Excel|C:\Users\Fai\Desktop\wiltshire vs romney\SAS
analysis\[Wiltshire 2023 - Fatty acids.xlsx]data for SAS!R2C1:R13C11';
data Wilt2023;
infile Wilt2023 lrecl=6000 dlm='09'x notab dsd missover;
input Treatment$ SFA MUFA PUFA BCFA n6PUFA n3PUFA LCn3PUFA PUSFA n6n3 IMF;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model SFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model MUFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model PUFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model BCFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model n6PUFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model n3PUFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model LCn3PUFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
```

```
run;
Proc glm data=Wilt2023;
  class Treatment;
  model PUSFA = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
run;
Proc glm data=Wilt2023;
  class Treatment;
  model n6n3 = Treatment IMF/ solution;
  lsmeans Treatment/ stderr;
  run;
```

7.5 Appendix: SAS Code for Individual Fatty Acid Composition

```
dm 'clear log';
dm 'clear out';
options ls=255 ps=6000 nocenter;
filename Wilt2023 dde 'Excel|C:\Users\rawis\OneDrive\wiltshire vs
romney\SAS analysis\[Wiltshire 2023 - Fatty acids.xlsx]data for
SAS!R33C1:R44C33';
data Wilt2023;
infile Wilt2023 lrecl=6000 dlm='09'x notab dsd missover;
input Treatment$ SUM UnreFA   C10   C12   C14   isoC15 antC15 C141 C150
isoC16 C160 isoC17 C161 antC17 C170 C171 C180 C181t9 C181t11 C181c9 C181c11
C182n6 gC183 C200 C183n3 911CLA C203n6 C204n6 C205n3 C240 C225 C226n3;
run;
proc mixed data=Wilt2023;
     class Treatment;
     model SUM = Treatment/solution ;
     LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model UnreFA = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C10 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run.
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C12 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
   class Treatment;
   model C14 = Treatment/solution ;
```

```
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model isoC15 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model antC15 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C141 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C150 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model isoC16 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C160 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model isoC17 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C170 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
```

```
    model C161 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model antC17 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C170 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C171 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C180 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C181t9 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C181t11 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C181c9 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C181c11 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
```

```
    class Treatment;
    model C182n6 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C200 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C183n3 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model 911CLA = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C203n6 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C204n6 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C205n3 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C225 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
proc mixed data=Wilt2023;
    class Treatment;
    model C226n3 = Treatment/solution ;
    LSMeans Treatment/pdiff ;
run;
quit;
```

7.6 Appendix: Individual Fatty Acid Composition

Table 7.1. Individual fatty acid composition (mg per 100g raw meat) (mean ± SEM) from *Longissimus lumborum* muscle samples of Romney and ¾ Wiltshire.

Fatty acid	Romney (n=6)	¾ Wiltshire (n=6)	P-value
C10:0	3.55 ± 0.28	3.60 ± 0.28	0.902
C12:0	7.22 ± 0.53	6.59 ± 0.53	0.422
C14:0	75.76 ± 6.88	76.32 ± 6.88	0.955
Iso C15	3.44 ± 0.28	3.52 ± 0.28	0.841
anteiso C15	4.71 ± 0.34	4.28 ± 0.34	0.386
C14:1	1.83 ± 0.23	1.98 ± 0.23	0.650
C15:0	9.54 ± 0.75	9.51 ± 0.75	0.977
Iso C16	2.99 ± 0.25	28.93 ± 0.25	0.781
C16:0	491.02 ± 48.52	561.42 ± 48.52	0.329
Iso C17	8.48 ± 0.63	8.94 ± 0.63	0.619
C16:1	18.48 ± 1.94	21.84 ± 1.94	0.248
anteiso C17	9.17 ± 0.91	9.58 ± 0.91	0.761
C17:0	19.40 ± 1.63	20.83 ± 1.63	0.548
C17:1	8.74 ± 0.70	9.73 ± 0.70	0.341
C18:0	414.59 ± 35.81	432.68 ± 35.81	0.728
C18:1 t9	4.15 ± 0.52	4.36 ± 0.52	0.775
C18:1 t11	80.57 ± 6.79	71.33 ± 6.79	0.360
C18:1 c9	751.66 ± 69.82	864.18 ± 69.82	0.281
C18:1 c11	18.861 ± 2.083	22.636 ± 2.083	0.229
C18:2 n6	72.28 ± 4.75	72.59 ± 4.75	0.964
C20:0	0.386 ± 0.275	0.623 ± 0.275	0.556
C18:3 n3	37.20 ± 3.13	39.05 ± 3.13	0.685
CLA 9c, 11t	32.02 ± 3.66	31.48 ± 3.66	0.919
C20:3 n6	3.69 ± 0.18	3.26 ± 0.18	0.118
C20:4 n6	27.65 ± 1.67	24.74 ± 1.67	0.244
C20:5 n3	22.06 ± 0.73	22.62 ± 0.73	0.597
C22:5	20.38 ± 0.45	20.46 ± 0.45	0.892
C22:6 n3	5.56 ± 0.48	6.02 ± 0.48	0.512
Unreported FA	171.39 ± 6.87	172.01 ± 6.87	0.950
Total	**2326.76 ± 186.43**	**2529.07 ± 186.43**	**0.461**