THE EFFECT OF FEED PROCESSING AND NUTRIENT DENSITY LEVEL ON THE GROWTH RATE, FEED CONVERSION, RUMEN FERMENTATION PARAMETERS AND ECONOMY OF FINISHING LAMBS.

by

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Declaration

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Abstract

The primary objective of this study was to investigate the influence of feed processing on lamb performance, feedlot profitability and rumen fermentation parameters and the interaction of feed pelleting effects with nutrient density in the diet. In the first trial a total of 64 S.A. Mutton Merino male lambs were randomly allocated to 8 pens. The pens were randomly assigned to 2 treatment blocks of either high nutrient density (HD) or low nutrient density (LD). Within each treatment block, the control group was offered a total mixed ration (TMR) containing coarse grain, protein, additives and chopped roughage (Groups L0 and H0). Three treatment groups within each block were offered a complete pelleted ration (CPR) with pellet sizes of 4mm (L4 and H4), 6mm (L6 and H6) and 8mm (L8 and H8) diameter. Over an experimental period of 7 to 8 weeks, the dry matter intake (DMI), average daily gain (ADG), feed efficiency (FCR) and feedlot economy were measured for the different groups. The average DMI of the H4 group was significantly ($P < 0.05$) lower than the average DMI of all the other groups except for the L0 group. The ADG of lambs that received the L0 diet was significantly lower ($P < 0.05$) than the ADG of all the other groups. The lambs receiving the H6 diet achieved the highest ADG (0.305 kg/d ± 0.04). The ADG of the H6 group was significantly higher ($P < 0.05$) than the ADG of lambs on the H4 diet. Pelleting increased ADG in the low-density diets by an average of 44% (195g/d versus 281g/d; $P < 0.01$), while no significant ADG response of pelleting was observed in lambs fed the high-density diets. The least effective feed conversion rate (FCR) was achieved by the L0 group (6.9 kg ± 0.90), which also differed significantly ($P < 0.05$) from all the other groups. Although not significant, the FCR of the high-density groups was numerically better than the FCR of the low-density groups. Within the LD and the HD groups, a tendency ($P < 0.10$) towards a better FCR with an increase in pellet size were established. The average dressing percentage (DP) of the lambs that received HD diets were significantly ($P < 0.05$) higher than the lambs on LD diets. The highest average gross profit (GP) was obtained by the H8 (R310/lamb) and the H0 (R283/lamb) groups and differed significantly ($P < 0.05$). At an average of R76/lamb, the L0 group returned the lowest GP of all the groups. The pelleting of the complete LD diet improves growth and economic performance of fattening lambs mainly due to an increase ($P < 0.05$) in DMI and a better FCR, while pelleting of a complete HD diet did not show any effect on lamb performance. The use of larger diameter pellets in a HD diet seems to be more beneficial to lamb performance than the use of smaller pellets.

The aim of the second study was to evaluate the effects of feed pelleting and feed nutrient density on the rumen fermentation parameters of sheep. A total of 8 mature S.A. Mutton Merino ewes were used in a change-over design with a repeated observation

experiment. The main treatment blocks were either high nutrient density (HD) or low nutrient density (LD) rations. Within each treatment block, the control group was offered a total mixed ration (TMR) containing coarse grain, protein, additives and chopped roughage (Groups L0 and H0). Three treatment groups within each block were offered a complete pelleted ration (CPR) with pellet sizes of 4mm (L4 and H4), 6mm (L6 and H6) and 8mm (L8 and H8) diameter.

The animals fed the LD diets resulted in significantly ($P < 0.05$) higher daily dry matter intake (DMI) compared to the HD diets. The average ruminal pH of the sheep dropped to a minimum at approximately 4 hours after feeding, after which the pH slowly returned to the initial values. The sheep that received both the L8 and L6 diets had the lowest average ruminal pH reading at 4 hours after feeding, while group H0 had the lowest reduction in ruminal pH ($P < 0.01$). The ruminal pH of sheep on all three of the LD pelleted diets, experienced a lower ruminal pH for a longer time after the meals than what was observed in the HD pelleted rations and was attributed to higher DMI. Sheep that was fed unprocessed feeds (H0 and L0), had a less significant drop and a slower recovery rate to the initial ruminal pH compared to the sheep on processed feeds. Concentrations of volatile fatty acids were higher in the LD groups than in the HD groups. Rumen ammonia nitrogen (RAN) measurements and methylene blue reduction (MBR) test results did not indicate to any association between nutrient density and level of processing of the diet. The faecal pH of the sheep at 6 hours after feeding followed the general trend of the ruminal pH findings, but no definite association with either feed nutrient density or level of processing could be established. The same was observed with the MBR test on the ruminal fluid at 6 hours after feeding. The observed differences in rumen fermentation parameters in sheep on high and low nutrient density diets, could be explained by higher DMI as well as rate of starch intake.

Opsomming

Die primêre doel van hierdie studie was om die invloed van voerprosessering deur verpilling en voerdigtheid op lamprestasie, voerkraalwinsgewendheid en rumenfermentasie parameters te ondersoek. In die eerste studie is 64 S.A. Vleis Merino ramlammers met 'n aanvangsmassa van 30-32 kg ewekansig aan 8 groepe toegeken. Die groepe is ook ewekansig aan twee behandelings blokke toegeken, naamlik ‘n hoë voedingsdigtheid (HD) voer en ‘n lae voedingsdigtheid (LD) voer. Binne elke behandelingsblok was die kontrolegroep 'n volledige rantsoen bestaande uit growwe graan, proteïen, bymiddels en gekerfde ruvoer (Groepe L0 en H0). Drie behandelingsgroepe binne elke blok het 'n volledige verpilde rantsoen ontvang met pil groottes van 4 mm (L4 en H4), 6 mm (L6 en H6) en 8 mm (L8 en H8). Gedurende die eksperimentele periode van 7 tot 8 weke is die droë materiaal inname (DMI), gemiddelde daaglikse toename (ADG), voeromsetdoeltreffendheid (FCR) en ekonomie vir die verskillende groepe gemeet.

Betekenisvol hoër ($P < 0.05$) daaglikse DMI is waargeneem by diere wat LD diete teenoor HD diete gevoer is. Die gemiddelde DMI van die H4-groep was betekenisvol ($P < 0.01$) laer as die gemiddelde DMI van al die ander groepe, met die uitsondering van die L0-groep. Die ADG van lammers wat die L0-dieet ontvang het (0,195 kg/d ± 0,03) was aansienlik laer ($P < 0.05$) as die ADG van al die ander groepe. Die lammers wat die H6-dieet ontvang het, het die hoogste ADG behaal en was was aansienlik ($P < 0.05$) hoër as die ADG van die lammers op die H4-dieet. Verpilling het die ADG van die lammers wat die LD diete ontvang het, met gemiddeld 44% verhoog (195 g/d teenoor 281 g/d; $P < 0,01$), terwyl geen noemenswaardige ADG-respons weens verpilling by lammers op die HD diete waargeneem is nie. Die swakste voeromsetdoeltreffendheid (FCR) is deur die L0-groep (6,9 kg ± 0,90) behaal, wat ook betekenisvol ($P < 0.05$) verskil het van al die ander groepe. Alhoewel nie-betekenisvol, was die FCR van die groepe wat die HD dieet ontvang het, numeries beter as die FCR van die groepe wat die LD diete ontvang het. Binne die LD- en die HD-groepe was daar 'n neiging ($P < 0.10$) na 'n beter FCR met 'n toename in pil grootte. Die gemiddelde uitslag persentasie (DP) van die lammers wat HD-diëte ontvang het, was betekenisvol ($P < 0.05$) hoër as die lammers op LD-diëte. Die H8 (R310/lam) en H0 (R283/lam) groepe het die hoogste bruto marge (GP) van alle groepe gerealiseer en was ook aansienlik beter ($P < 0.05$) as die GP van al die LD-groepe. Die L0-groep het die laagste GP van al die groepe gerealiseer, met ‘n gemiddeld van R76/lam. Die beter GP van die HD-groepe was hoofsaaklik toegeskryf aan die beter karkas opbrengs. Die gevolgtrekking van die proef is dat verpilling van die LD-diete die groei en ekonomiese prestasie van lamafronddiete verbeter hoofsaaklik weens verhoogde DMI en 'n verbeterde FCR. Verpilling van 'n volledige HD-diete het nie 'n beduidende

uitwerking op lamprestasie gelewer nie. Die gebruik van voerpille met ‘n groter deursnit in 'n HD-dieet is meer voordelig vir lamprestasie as die gebruik van kleiner pille.

Die doel van die tweede studie was om die effek van voerverpilling en voerdigtheid op die rumen fermentasie parameters van skape te evalueer. Altesaam 8 volwasse S.A. Vleis Merino-ooie is gebruik in 'n omskakelontwerp met 'n herhaalde waarnemings eksperiment. Die belangrikste behandelingsblokke was of die hoë voerdigtheid (HD) of lae voerdigtheid (LD) diete. Binne elke behandelingsblok het die kontrolegroep 'n volledige dieet ontvang wat growwe graan, proteïen, bymiddels en gekerfde ruvoer bevat (Groepe L0 en H0) het. Drie behandelingsgroepe binne elke blok het 'n volledige verpilde dieet ontvang met 4 mm (L4 en H4), 6 mm (L6 en H6) en 8 mm (L8 en H8) deursnit respektiewelik. Die gemiddelde ruminale pH van die skape het ongeveer 4 uur na voeding tot 'n minimum gedaal, waarna die ruminale pH stadig na die aanvanklike waardes teruggekeer het. Die skape wat beide die L8- en L6-diete ontvang het, het die laagste gemiddelde pH-lesing op 4 uur na voeding gehad, terwyl H0 groep die laagste ($P < 0.05$) daling in ruminale pH getoon het. Die ruminale pH van skape op al drie die LD-korrel-diete, het 'n laer pH vir 'n langer tyd na die maaltye getoon as wat in die HD-korrel-diete waargeneem is. Skape wat die ongeprosesseerde voere (H0 en L0) ontvang het, het 'n minder beduidende daling en 'n stadiger hersteltempo tot die aanvanklike ruminale pH ervaar as wat die geval met die skape wat die verpilde voer ontvang het was. Konsentrasies van vlugtige vetsure was hoër in die LD-groepe as in die HD-groepe. Rumen-ammoniak stikstof (RAN) metings en metileenblou reduksie (MBR) -toetsresultate het geen verband met voedingsdigtheid of die vlak van prosessering van die dieet getoon nie. Die fekale pH van die skape op 6 uur na voeding het ‘n soortgelyke tendens as die algemene neiging van die ruminale pH-bevindings getoon, maar daar kon geen definitiewe verband met voerdigtheid of vlak van prosessering bepaal word nie. Dieselfde is waargeneem met die MBR-toets op die ruminale vloeistof 6 uur na voeding. Die waargeneemde verskille in rumen fermentasie parameters by skape op hoë en lae voerdigthede, kan verklaar word deur hoër DMI en hoër tempos van styselinnames.

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Note

This thesis is presented as a compilation of 5 chapters. Each chapter is introduced separately and is written according to the style of the South African Journal of Animal Science.

List of Abbreviations

ADF:	Acid Detergent Fibre
ADG:	Average Daily Gain
BW:	Body Weight
CF:	Crude Fibre
CP:	Crude Protein
CPD:	Complete Pelleted Diet
CPR:	Complete Pelleted Ration
DE:	Digestible Energy
DM:	Dry Matter
DMI:	Dry Matter Intake
DP:	Dressing Percentage
DVFI:	Daily Voluntary Feed Intake
FCR:	Feed Conversion Rate
FE:	Feed Efficiency
FS:	Faeces Score
GIT:	Gastrointestinal Tract
GMD:	Geometric Mean Diameter
GP:	Gross Profit
HD:	High Nutrient Density
LD:	Low Nutrient Density
LW:	Live Weight
MBR:	Methylene Blue Reduction
ME:	Metabolic Energy
MP:	Metabolic Protein
N:	Nitrogen
NDF:	Neutral Detergent Fibre
NE:	Net Energy
NEg:	Net Energy Gain
NFC:	Non-fibre Carbohydrates
OM:	Organic Matter
PDI:	Pellet Durability Index
peNDF:	Physical Effective Neutral Detergent Fibre
R:	Rand
RAN:	Rumen Ammonia Nitrogen

RDP:	Rumen Degradable Protein
SAMM:	South African Mutton Merino
SARA:	Sub-acute Rumen Acidosis
SD:	Standard Deviation
SRNS:	Small Ruminant Nutritional System
TMR:	Total Mix Ration
VFA:	Volatile Fatty Acids
VFI:	Voluntary Feed Intake

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CHAPTER 1
GENERAL INTRODUCTION

1.1 Introduction

The intensification of livestock production for meat consumption has increased significantly over the past 50 years due to an ever-growing need for food security. Global meat production has quadrupled since 1961 with Asia accounting as the largest meat producer in 2018 for around 40-45% of total meat production and Africa around 5-6% (Ritchie and Roser, 2017). Small ruminant meat is one of the most stable livestock production systems globally, with the average per capita meat consumption being consistent over the past 50 years (± 1.91 kg per year) (Ritchie and Roser, 2017). South African sheep farmers produce lambs under a wide variety of climatic and management conditions, including both intensive and extensive systems (Coetzee, 2019). Although lamb finishing from pastures often have economic advantages, the variable composition of pastures, together with limitations on availability and parasite contamination, make pasture finishing a risky and unreliable proposition (MLA, 2020). Feedlot finishing provides a reliable and profitable alternative to lamb finishing, and in South Africa, the popularity of commercial and on-farm lamb feedlots have risen significantly (Coetzee, 2019). The practice of feedlotting can be summarised as the practice of purchasing young, weaner animals, improving their market value through intensive feeding and management to produce a carcass that meets the market specifications (Van der Merwe *et al.,* 2020). In terms of economic relevance, the most important input for intensive animal production is feed, and thus improvements in the proportion of money invested in this asset that is converted into income from meat has a direct and drastic consequence on profitability (Bach *et al.*, 2020). Considering current concerns regarding the sustainability of red meat production in a world with an increasing global demand for food of animal origin, there is a need for a better understanding of factors that influence the growth rate and feed conversion efficiency of animals on commercial farms *(*Lima *et al.*, 2020). Feeding components, such as type of processing and characteristics of the feed, are vital factors to take into consideration when feeding lambs for profit (Lawrence *et al.*, 1999). Advantages of pelleted versus un-pelleted feed for feedlot lambs include less feed selection (Malik *et al.*, 2021), less metabolic problems (Lailer *et al.*, 2005), higher DMI (Marsh and Lingham, 2011; Kelln *et al.*, 2019), less wastage, and possible increased digestibility (Bertipaglia *et al.*, 2010; Soltani *et al.*, 2020). Pelleting also allows the use of less palatable ingredients (Beigh *et al.*, 2017). Marsh and Lingham (2011) have shown clear benefits of 6 mm vs. 3 mm pellets when growth and intake of calf starter feeds were evaluated. These authors contributed the higher growth rates to a

higher DMI and better ruminal development (Marsh and Lingham, 2011). Diet density further plays a vital role towards the advantages of pelleted feeds as shown by the results of a study by Tetlow and Wilkins (1978), where different pellet sizes with different nutrient densities were fed to calves. The primary objective of this study was to look at the influence of feed processing (pelleting) on lamb performance, feedlot profitability and rumen fermentation parameters and the interaction of feed pelleting effects with nutrient density in the ration. Furthermore, this study aimed to:

- Determine if pellet size and pellet-quality affect lamb feedlot performance of high or low nutrient density diets.
- Identify differences in animal production performance between processed (pelleted) and non-processed feeds.
- Investigate the effect of different pellet sizes on animal production performance (growth rate and feed conversion).
- Focus on the effect of different rations (high and low nutrient density) and processing methods on rumen health through measuring changes in rumen pH and VFA concentration after feeding.
- Evaluate the economic viability of pelleting feedlot feed in intensive lamb production systems.

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CHAPTER 2
LITERATURE REVIEW

2.1 Feed Processing – definition and importance

Feed processing can be defined as means of altering the physical and/or chemical nature of feed commodities to improve the utilisation by animals and to enhance mixing and stability of the diet (Campabadal and Maier, 2021). The major components of any diet, roughage, and grain, are the feeds most likely to be processed. However, in some cases, the minor components of the diet (additives) are processed into pellets to help mixing and to maintain the stability of the diet (Forster, 2020). In South Africa, over a wide spectrum of farm animal species, commercial animal feeds are often provided in a pelleted form. The abundant advantages of feeding feedstuffs in pelleted form can be summarised as follows:

i. Pelleting prevents ingredient segregation and ensures the composition of the feed remains constant (Malik *et al*., 2021) while wastage is reduced because selective feeding of components is disallowed. This guarantees a balanced supply of nutrients throughout the feeding period (Zhong *et al.*, 2018).
ii. Pelleting improves feed preservation. Pellets are less subject to infestations by insects and moulds. Pelleting preserves vitamin A potency and ensures less storage losses and prevents disintegration of nutrients after the feed is mixed. Pelleting kills bacteria such as Salmonella (Himathongkham *et al.*, 2000; Munoz *et al.*, 2021) and *Escherichia coli* (Munoz *et al.*, 2021), if present in the feed mainly due to exposure to high temperatures associated with pelleting (Huang *et al*., 2015).
iii. Pelleting improves handling of feed because of better flow properties in conveying equipment, and better gravitational behaviour in silos. Pelleting increases the density which reduces storage and transport cost (Thomas and Van Der Poel, 1996; Adesogan *et al.*, 2020).
iv. Pelleting is beneficial in utilizing non-palatable feed ingredients, ensuring reduced costs especially where there is a high availability of low-quality roughages (Zhong *et al.,* 2018).
v. Pelleting improves production and efficiency, specifically in monogastric livestock feeding, but also in ruminants (Wanapat *et al.*, 2013). Normally it increases palatability and digestibility (Beigh *et al.*, 2017). Research has shown that animals fed with good-quality pellets have better growth performance and feed conversion than those fed with mash, reground pellets, or pellets with more fines (Svihus *et al.,* 2004; Mina-Boac *et al.,* 2006; Li *et al.,* 2021).

Pelleting also has its disadvantages. Pelleting requires expensive equipment, including bins, mixing equipment, pellet presses, and coolers. Most of the equipment requires additional costs in terms of high energy demand, for example a boiler to generate steam and conditioning equipment (Campabadal and Maier, 2021). Since the feed is already mixed and blended into a total mixed ration (TMR) before pelleting, additional costs for investment in pelleting equipment should be considered with respect to the gain that can be achieved due to incorporation of the pelleting process (Thomas and Van der Poel, 1996). Research has shown that in monogastric farm animals such as pigs and poultry, the heat, moisture, and mechanical pressure applied during conditioning and pelleting, may have beneficial or detrimental effects on feed components and gastrointestinal development (Kiarie and Mills, 2019). In ruminants, grinding of concentrates increases ruminal degradation rate of starch (Van Zyl, 2017) and may thereby increase the probability of rumen acidosis (Svihus *et al.*, 2005). This can result in a depression in dry matter intake (DMI), average daily gain (ADG) and feed conversion rate (FCR) of feedlot lambs which could lower feedlot profitability. As such, the main challenge in grain processing technologies for ruminants, is to promote animal performance and feed utilisation, but without impairing rumen and animal health (Humer and Zebeli, 2017; Van Zyl, 2017).

2.2 Effects of altering particle size during processing

Compound feed for pelleting will generally have an average particle size of approximately 0.5 to 0.7 mm, with no particles greater than 1.0 to 1.5 mm (Behnke, 2001). Particles greater than this will otherwise act as somewhat predetermined breaking point in the pellet (Behnke, 2001). Pelleting moulds mash diets to macro-particles in the form of pellets and simultaneously reduces the size of the micro-particles of the mash further while the rollers press the softened mash through the holes in a circular die. As a result the amount of coarse particles diminishes and the amount of fine particles increases (Svihus *et al.,* 2004).

Depending on the processing method used, ruminal degradation of starch differs among cereals. By grinding the grain, the pericarp breaks and exposes more of the endosperm, but also greatly increases the surface area of the material so that there is more exposure to the microbial enzymes (Rowe *et al*., 1999; Dehghan-banadaky *et al*., 2007). The rate of digestion of starch from grain in the rumen varies inversely with particle size of the grain (Svihus *et al*., 2005; Van Zyl, 2017; Shipandi, 2019).

In feedlot cattle it is known that the digestion of different grains respond differently to various methods of processing; with wheat and barley of least benefit, while maize and grain sorghum require the seed coat or pericarp to be disrupted before it can be digested (Richards and Hicks, 2007). Offner *et al.* (2003), clearly illustrated the variation between processing of

different cereals on fermentation in a study in rumen-cannulated Holstein male calves. In this experiment, maize and barley was provided either in ground or pelleted (6mm) form. The pelleted concentrates resulted in a lower acetic to propionic acid ratio and a more significant pH reduction after feeding and this effect was more noticeable in the maize pellets (Offner *et al.*, 2003). These results are in agreement to that of earlier work by (Ørskov, 1986) as shown in Table 2.1.

Table 2.1 The effect of processing of different cereals on rumen pH, proportion of acetic and propionic acid (Ørskov, 1986).

			Molar proportion of:	
Cereal	**Process**	**Rumen pH**	**Acetic acid**	**Propionic acid**
Barley	Whole	6.4	52.5	30.1
	Ground pelleted	5.4	45.0	45.3
Maize	Whole	6.1	47.2	38.7
	Ground pelleted	5.2	41.3	43.2
Oats	Whole	6.7	65.0	18.6
	Ground pelleted	6.1	53.2	37.5
Wheat	Whole	5.9	52.3	32.2
	Ground pelleted	5.0	34.2	42.6

It is therefore clear that the rate of starch digestion can be altered through grain processing (Rowe *et al.*, 1999; Table 2.1, Figure 2.1), which in turn can influence cattle or sheep performance (Richards and Hicks, 2007).

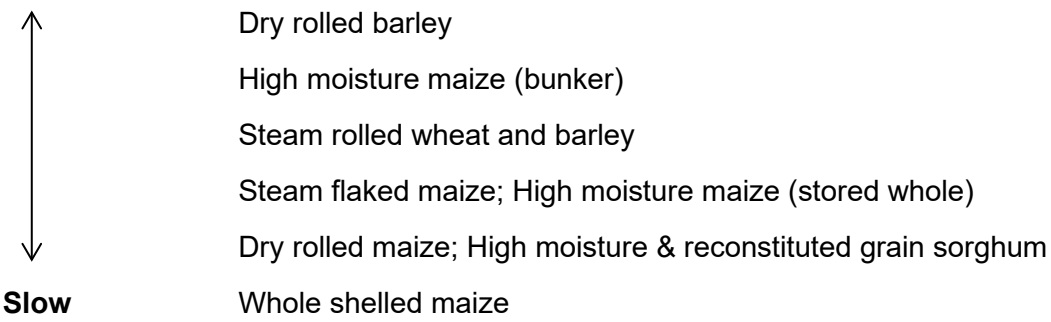

Figure 2.1 Grains categorized by rate of starch breakdown in the rumen of feedlot cattle (Richards and Hicks, 2007).

Elevations in rumen fermentation because of a decrease in particle size can lead to a more volatile ruminal pH which is likely to increase the risk of acidosis (See section 2.7.2). Castillo *et al.* (2006) performed a study where fermentation and production parameters in feedlot steers fed pelleted feed versus a meal were compared. Although not statistically significant, the pelleted fed steers showed the numerical highest ADG, DMI and FCR. The apparent improved efficiency in cattle fed highly processed grain was largely attributable to increased starch availability. The reduced DMI with the highly processed grain was attributed to high rates of acid production in the rumen due to the rapid fermentation of starch. Although the animals that received the pelleted feed showed a more stable acid–base balance over time compared to those fed a ground feed, they also showed higher levels of L-lactate and lower base excess and HCO^{-3} values. Thus, cattle fed pelleted grain reflect a greater risk of grain-acid overload (Castillo *et al.,* 2006).

A recent study in Spain (Andrés *et al.,* 2019) illustrated the effects of different grinding particle sizes of grains (2 mm vs. 6 mm) included in a complete pelleted diet (CPD) of fattening lambs. Animal performance (growth and feed efficiency) as well as carcass and meat quality were monitored. Although no differences were found in FCR or carcass characteristics, the lambs fed coarser diets (6 mm) were more ($P < 0.05$) efficient with less residual feed intake (RFI) than lambs fed the 2 mm CPD. Furthermore, higher levels of intramuscular fat and saturated fatty acids were seen in the lambs fed the 6 mm CPD.

The processing of cereal grains, by grinding, rolling, pelleting, tempering, steam rolling or steam flaking, breaks down refractory barriers such as the hull, pericarp, and protein matrix and allows microbes access to the starch situated within endosperm cells (Dehghan-banadaky *et al*., 2007). Additionally, these processes result in the reduction of particle size of the grain, increasing the surface area available for microbial attachment and colonization. Through combining these actions, the rate and extent of starch digestion escalates (McAllister *et al*., 1990; Firkins *et al*., 2001; McAllister *et al*., 2006). All methods of processing which accelerates the rate of degradation of starch, is likely to increase the extent of its digestion (Van Zyl, 2017) in the rumen, specifically with whole maize, which is highly resistant to microbial attack in the rumen (Campling, 1991).

2.3 Effects of pellet quality

Pellet quality can be defined as the pellet's resistance to disintegration and scarping during handling without dispersing and to reach feeders with minimal amount of fines (Briggs *et al.,* 1999; Rowe *et al*., 1999; Amerah *et al.,* 2007). The grinding of feed is generally required before pelleting, because of the impact on pellet quality. The general rule is that the finer the

grind, the better the pellet quality. This is mainly because grinding increases gelatinisation during conditioning which is essential for pellet quality (Behnke, 2001; Svihus *et al*., 2005).

One of the main parameters used to determine pellet quality is pellet durability index (PDI), which per definition specifies the percentage of pellets that remain intact after being processed by mechanical forces (Mina-Boac *et al*., 2006). Poor-quality pellets will fragmentise after transport and handling, which will result in a higher percentage of fines. Fine particles can negatively influence animal performance, because of the geometric mean diameter (GMD) of fine particles being lower or equal to that of mash diets, which may cause nutritional imbalance in feed chemical composition (Dehghan-Banadaky *et al*., 2007). Research has shown that weight gain and feed conversion in broilers are negatively correlated with the percentage of fines in their feed (Muramatsu *et al.,* 2015).

Research in monogastric animals in general indicates that animals fed high quality pellets have better growth performance and feed conversion compared to those fed with mash, reground pellets, or pellets with more fines (Mina-Boac *et al.,* 2006). High quality pellets result in homogenous feed, reduced wastage, reduced segregation, improved palatability and reduces time of consumption of their feed (Subramonian and Borregaard, 2017). Quentin *et al*. (2004) showed in broilers that diets with high PDI's and lower percentage fines result in significantly better feed efficiency. In pigs it is commonly known that by pelleting the diets, their growth performance improves (Rojas and Stein, 2017). However, it was also determined that if pellets have a low quality, with a high percentage of fines, the wastage of feed will be higher, palatability would be reduced, and feed intake would decreased (Vukmirović *et al.,* 2017). Behnke (1996) indicated that improvements in animal performance with high quality pellets have been attributed to decreased feed wastage, reduced selective feeding, decreased ingredient segregation, less time and energy expended for prehension, destruction of pathogens, thermal modification of starch and protein, and improved palatability.

Research in ruminants on the effect of pellet quality on animal performance is limited. Kertz *et al.* (1981) investigated the difference in consumption between fine pellets (4 cm diameter), coarse pellets (premix pellet with cracked maize), crumbed pellets and meal in dairy cows. It was found that cows consumed the pelleted feed more rapidly than the other forms of feed. Once feeding time is limited, such as in milking parlour feeding, the consumption rate may be the most limiting effect on milk production. A Canadian study, evaluated the effect of pellet size and durability on ruminal fermentation and total-tract digestibility of Hereford cross-bred heifers (Wood *et al.,* 2019). The results indicated that pellet size (3.96 mm vs 12 mm diameter) and binder inclusion did not affect forage or pellet intake, apparent total-tract digestibility, ruminal pH, or animal performance. However, pellet size and binder inclusion may modulate ruminal fermentation, specifically molar concentrations of acetate and propionate primarily (Wood *et al.,* 2019).

The inherent structure of feed can be affected by pelleting under different conditioning temperatures and times, and therefore may affect nutrient profiles and availability in livestock (Gardner *et al*., 1997). Huang *et al.* (2015) showed that the PDI of canola meal pellets was not affected by conditioning temperature but was positively affected by conditioning time. Different temperatures and time of conditioning during pelleting process significantly affected protein profiles without altering carbohydrate profiles. Molecular structure analyses also showed that pelleting altered inherent protein molecular structures of canola meal (Huang *et al.,* 2015). PDI may therefore influence production indirectly via its correlation with the conditioning process during pelleting of co-products from the bio-oil industry.

2.4 Effect of pellet size

Pellet size can have a significant influence on fermentation through larger relative surface area of smaller pellets or via the additional grinding effect of forcing feed through smaller dies, resulting in smaller particle sizes (Van Zyl, 2017). An in vitro study from Bertipaglia *et al.* (2010) concluded that higher gas production occurs during the first 6 h of incubation of a complete diet (0.9 : 0.1, concentrate : straw as fed) in the form of a meal compared to pellets with a 10 mm diameter. Intermediate values were recorded when the concentrate was pelleted to a 3.5 mm size. In contrast, when the compound feeds were incubated after milling to pass a 1 mm diameter mesh, the pelleted treatments produced more gas compared to the meal treatment. The researchers hypothesised that pelleting can alter fermentation kinetics and/or feeding behaviour and that pelleting at smaller sizes may increase the available surface area for microbial degradation and enhance substrate fermentation (Bertipaglia *et al.,* 2010).

Castrillo *et al.* (2013) investigated the effect of feeding a compound feed as a meal or as small (3.5 mm) and large (10mm) pellets on feed intake patterns and rumen fermentation in growing calves. Compound feeds were fed *ad libitum* with barley straw to rumen cannulated calves. Compared to unprocessed mash, pelleting at 3.5 mm increased ruminal fermentation rate, and resulted in lower ($P < 0.05$) pH values (Castrillo *et al*., 2013). Increased ruminal fermentation in response to pelleting was confirmed by the higher concentration of total VFA's, together with the lower acetic: propionic ratio and the decreased ammonia concentration in the rumen fluid. Increasing the pellet diameter to 10 mm decreased the rate of fermentation through a more homogeneous daily intake pattern, without affecting total DMI (Castrillo *et al.*, 2013). Significant benefits (permitting earlier weaning and reducing calf rearing cost) when feeding a 6mm calf starter pellet compared to a 3 mm were observed by Marsh and Lingham, 2011. Research on the effect of pellet size on the performance of growing lambs is however limited.

2.5 Interaction of processing effects and ration composition

2.5.1 Roughage processing (Low nutrient density diets)

The inclusion of roughages in the diets of ruminants are necessary to maintain good rumen function and prevent digestive disorders. Roughages do not only supply energy but impart certain physical properties which make the rations acceptable to the animals (Hale, 1980; Suárez *et al.,* 2007).

Research at the University of Illinois more than 60 years ago (Esplin *et al.,* 1957), indicated that pelleting of high roughage rations is of significant value to lambs. A relative high roughage diet (47.5% lucerne hay, 47.5% maize, 5% molasses) was fed to feedlot lambs. Lambs fed the pelleted diet gained weight faster (36 g/day) compared to those fed an un-pelleted ration (Table 2.2). Feed efficiency was similar between the two groups; however, DMI was higher for lambs fed the pelleted diet (Esplin *et al.,* 1957). According to the latter researchers, pelleting rations with more than 60% roughage should result in similar ADG as observed with feeding high-concentrate rations; however, feed efficiency will be poorer compared to lambs fed a high concentrate finishing diet. This study confirmed the importance of comparing the costs of pelleting to the advantages expected in ADG as DMI.

Table 2.2 Influence of pelleting on lamb performance (Esplin *et al.,* 1957).

Group	Pelleted	Mash
ADG (g/d)	236	200
FCR	7.50	7.60
DMI (kg)	1.68	1.50

Early research from the University of Stellenbosch in South Africa (Vosloo and Du Plessis, 1966) showed that one of the most common problems in the effective utilisation of low-grade roughage is wastage, and that this problem can be overcome by pelleting. Pelleting of straw will significantly increase the stocking rate of farms in the wheatbelt areas of the Western Cape. It was found that the growth rate of pre-weaned lambs increased by 146% when their mothers received pelleted compared to chopped lucerne hay. Francisco *et al.* (2020) investigated the effect of lucerne particle size and starch content on the intake and animal performance of growing lambs. Grounded lucerne allowed higher DMI (16.8%; $P < 0.001$) of crude protein (25.5%; $P < 0.001$), starch (7.5%; $P = 0.009$) and NDF (21.6%; $P < 0.001$), compared to chopped lucerne. The growth of lambs fed ground lucerne was 10.4% higher ($P < 0.001$) compared to chopped lucerne, although FCR was not affected by

treatments. Blanco *et al.* (2014) studied the effect of forage in different forms on the rumen fermentation and production parameters of light-weight Merino lambs (Table 2.3).

Table 2.3 Effect of forage form on production and rumen fermentation parameters of Merino lambs (Blanco *et al.,* 2014).

	Feeding system				
	Control[1]	**B05[2]**	**B15[2]**	**B25[2]**	**Lusern[3]**
Total DMI	817	791	916	1056	887
Concentrate (%DM)	96.7	95	85	75	47.6
ADG (g/day)	299	279	339	353	194
FCR (g/g)	2.76	2.89	2.74	3.03	4.84
Rumen pH	5.77	5.24	5.56	5.69	6.94
Acetate/Propionate	1.99	1.82	1.9	1.65	3.32

[1]Ad libitum barley straw in long form + concentrate pellets

[2]T B05 – 5% inclusion of barley straw; B15 – 15% inclusion; B25 – 25% inclusion

[3]Ad libitum long stem lucerne hay + restricted concentrate pellets

Lambs receiving a complete pelleted ration (CPR) with 25% barley straw (Group B25), although being fed a relatively high fibre ration, had a lower rumen pH compared to lambs receiving long stem roughage (Control and lucerne groups). The authors concluded that this could be explained by the small particle size of the roughage decreases the physical effective fibre, thereby reducing saliva production and buffering capacity in the rumen. The long stem forage-based diets were as expected associated with slow fermentation rates, low VFA production, and a high acetate to propionate ratio in the rumen. But although the pelleted diets did not have positive effects on rumen fermentation parameters, the inclusion of up to 25% barley straw in the TMR in a pelleted form was associated with improved DMI and growth rates (Table 2.3). So, this study confirmed the positive effect of pelleting of poor-quality roughage on production of feedlot lambs primarily due to an increase in DMI.

The positive effect of pelleting of low energy diets on animal performance can therefore be explained by the reduced forage particle size that will increase DMI, decreases digestibility, and decreases retention time of solids in the rumen. Diets that have a smaller forage particle size enter the rumen at a smaller size after initial chewing and swallowing; therefore, they leave the rumen faster (Blanco *et al.,* 2014). The result is an increase in the fractional turnover rate of ruminal dry matter (DM) and increased DMI (Haselmann *et al.,* 2019). Pelleting therefore arguably does not change the nutritive value of the feed but improves performance due to a decrease in ruminal retention time and by forcing the lambs to constantly eat the grain

and roughage in the proportions required. Diets which include poor quality roughage when pelleted lead to heavier animals, more efficient weight gains, and with better carcass classification compared to mash diets with poor quality roughages (Van der Merwe *et al.,* 1962; Petersen, 1962; Fluharty *et al.,* 2017).

2.5.2 Grain processing (High nutrient density diets)

In contrast to the persistent positive effects of pelleting of roughages on ruminant performance, research indicated that processing high energy density diets will only increase lamb performance slightly or in some studies may even negatively affect lamb performance (Vosloo and du Plessis, 1966; Hejazi *et al.*, 1999; Zietsman, 2008; Tag Eldin *et al*., 2011). Fontenot and Hopkins (1965) investigated the effect of the physical form of hay, the concentrate and complete lamb fattening diet on feedlot performance, incidence of rumen parakeratosis and digestibility of ration components. The latter authors reported that by pelleting the hay, the rate of weight gain increased significantly ($P < 0.05$). Pelleting the concentrate portion however consistently resulted in a depression in DMI, with no effect on ADG. Furthermore, they concluded that the pelleted feeds resulted in an increased ($P < 0.01$) incidence of rumen parakeratosis.

In an early Canadian study (Tait and Bryant, 1973), the processing effects of barley and wheat were compared in all-concentrate rations for lambs weaned at 8 weeks of age. Cereal grains were fed in different forms, namely whole, rolled, and pelleted. The main effects of the type of grain and the method of processing on ADG, FCR, and DMI are summarised in Table 2.4. No significant ($P > 0.05$) difference between the ADG of the wheat- and barley-fed groups were observed (Tait and Bryant, 1973). Processing in contrast had a significant ($P < 0.05$) effect on lamb performance, with whole grains resulting in a faster rate of weight gain compared to pelleted grains. Rolled grains resulted in an intermediate rate of weight gain that was not significantly different from either the whole or pelleted forms (Table 2.4). These authors concluded that the processing of cereal grains for lambs may be unnecessary when digestibility was considered and would appear to be detrimental to growth rate and feed conversion efficiency.

Table 2.4 Lamb performance as influenced by wheat and barley processing (Tait and Bryant, 1973).

Cereal	Processing	**ADG (g)**	**FCR**	**DMI**
Barley	Whole	292[a]	3.85	88
	Rolled	251[abc]	4.43	84
	Pelleted	219[c]	3.98	66

Wheat	Whole	269[ab]	4.22	87
	Rolled	249[abc]	4.20	78
	Pelleted	208[c]	4.34	70

*[abc] Means followed by different letters are significantly different (P < 0.05).

Multiple research documented in the literature indicate little or no benefit of processing (steam rolling, grinding, pelleting or dry rolling) when compared with feeding barley whole in forage or concentrate diets for sheep (Lardy and Redden, 2013). Table 2.5 summarizes research trials related to barley processing and the effects on lamb performance.

Table 2.5 Influence of barley processing on growth rate and feed efficiency of sheep fed high-grain diets. (Adapted from Lardy & Redden, 2013).

Processing Method	**ADG (g/d)**	**FCR (kg feed/kg gain)**
Whole	181-290	3.85-7.53
Ground	218-318	5.63-6.61
Rolled	250	4.43
Pelleted	168-390	3.98-7.76

Compared to grounded barley, pelleted-barley diets resulted in higher ADG's, higher DMI's and similar feed efficiencies in lambs (Erickson *et al.*, 1987). Research in the USA (Hatfield, 1994) showed no differences in lamb performance between whole and pelleted barley diets. Cost of gain was lower with whole-barley diets because of processing cost. Lardy and Redden (2013) concluded that extensive processing of barley does not appear to be necessary for optimum utilization in sheep diets. In contrast, the same does not seem to be true for maize as lambs fed whole barley showing significantly better feed conversions compared with whole maize (Lardy and Redden, 2013). Lambs fed grounded maize also resulted in significantly higher ADG's compared with lambs fed whole maize (Lardy and Redden, 2013).

Gallo *et al.* (2014) could not find any negative effects of the feeding of a whole maize diet on the growth performance, carcass quality and ruminal papillae development of lambs. It was concluded that compared to processed grain, whole grain feeding of lambs will improve feed efficiency, increases average daily gain, and lower overall feed costs per kilogram of gain (Gallo *et al.*, 2014). According to Umberger (2009), the feeding of whole, non-processed grain is the most profitable feeding program that can be used for grain-based finishing of feedlot lambs.

According to Beretta and Kirby (2004), the primary purpose of processing grain is to improve the utilisation of cereal starch by microbial fermentation or to reduce particle size to increase surface area for amylolytic attack. However, the whole-tract digestibility of cereal starch by sheep approaches 100 per cent for common feed grains so there is limited potential for increasing the efficiency of digestion of grains (Table 2.6). There is little response in either starch digestibility or dry matter digestibility when cereal grains are processed prior to feeding to sheep.

Table 2.6 Digestion of starch in whole or minimally processed cereal grains by sheep (Beretta and Kirby, 2004).

Cereal	Treatment	Whole tract digestibility of starch (% of intake)	Starch fermented in rumen (% of intake)	DM digestibility (%)
Barley	Whole		95	84
	Processed	100	93-97	88
Maize	Whole	97		81-86
	Processed	100	96	81-84
Sorghum	Rolled	97	89	
	Processed	93-97	85	

It can therefore be concluded that the effect of pelleting low-density diets has a significant favourable effect on lamb feedlot performance, whereas in contrast pelleting high density diets have little positive to negative effects. These findings can mainly be attributed to fluctuations in the ruminal environment health of the animal. Processing high energy density diets, decreases the particle size of the feed and increases the surface area which enhances the risk of acidosis (Hernández *et al.,* 2014).

2.6 Ruminal health in feedlot lambs

2.6.1 Normal rumen function and homeostasis

The rumen acts as an anaerobic fermentation chamber in which rumen microbial communities synergistically interact with one another. Diverse and complex microorganisms are present in the rumen, such as populations of bacteria, ciliate protozoa, anaerobic fungi, bacteriophages, and methanogens (Matthews *et al.*, 2019). Bacterial populations are predominantly responsible for the modification and breakdown of plant fibre to short-chain

volatile fatty acids (VFA's), proteins and gasses (Matthews *et al*., 2019). VFAs are absorbed across the rumen epithelium to function as the primary energy source supporting animal maintenance and growth (Van Soest, 1994; Zeineldin *et al.,* 2018). These VFA include, in descending order of concentration, three single chain VFA's namely acetate, propionate, and butyrate, and three branched-chain VFA (isobutyrate, isovalerate, and valerate). The composition of the diet has a direct influence on relative VFA concentration (Storm *et al*., 2012). In feedlot lambs on high concentrate diets, the proportional concentration of propionate is expected to increase (Ellison *et al.,* 2017).

According to Schultheiss (2018), rumen microbial health is largely regulated by two aspects, namely the balance between rumen degradable protein (RDP) and non-fibre carbohydrates (NFC) of the diet and the resulting ruminal pH. An excess of RDP may lead to higher ammonia delivery to the liver which must be removed by urea formation. This added metabolic function by the liver is counterproductive and leads to a less effective intermediary metabolism. However, more applicable to feedlot lambs on high concentrate diets is a surplus of NFC, resulting in a rumen pH decrease, which is a less favourable environment for cellulolytic bacteria (Schultheiss, 2018). Cellulolytic bacteria are unable to multiply at a pH below 6.0 and their growth rate decreases by 1.4% per hour for each 0.1 pH unit drop between 6.5 and 6.0 (Schultheiss, 2018). Under normal conditions ruminal pH is maintained at 5.5 - 6.5, but the acids produced by fermentation are theoretically capable of reducing the ruminal pH to 2.5 - 3.0 (Mcdonald *et al.,* 2010).

2.6.2 Acidosis

Under normal circumstances, to maintain optimum rumen function, the environment within the rumen continually adapts to a particular diet. Ruminal acidosis can be defined as a metabolic condition during which rumen osmolality increases because of the accumulation of lactate, short-chain fatty acids and glucose (Meyer and Bryant, 2017). In feedlot animals, acidosis is mainly the result of an overconsumption of fermentable carbohydrates (Nagaraja and Lechtenberg, 2007). Ruminal pH decreases resulting in reduced feed intake and volatile fatty acid absorption by the animal (Meyer and Bryant, 2017). Acidosis can be categorized in several forms, which include acute and sub-acute rumen acidosis (SARA), also known as clinical and sub-clinical rumen acidosis, respectively (González *et al.,* 2012). Nagaraja and Titgemeyer (2007) characterize acute acidosis as being present when rumen pH is below 5.0, lactic acid concentration is above 50 mM/L and ruminal volatile fatty acids (VFA) concentration is less than 100 mM/L.

Although there is some discrepancy on the precise definition of SARA, the current definition is based on the pH of the rumen fluid (Plaizier *et al.,* 2008), with accepted values

depending on method of rumen fluid sampling. Duffield *et al*. (2004) proposed that the thresholds for abnormal pH indicating SARA should be 5.5, 5.8 and 5.9 when rumen fluid samples are collected by rumenocentesis, by means of a rumen cannula from the ventral sac, and by the use of an oral probe, respectively. Although acute ruminal acidosis can be fatal to the animal, sub-clinical ruminal acidosis is mainly responsible for economic losses in feedlots (González *et al.,* 2012). Financial losses due to SARA is predominantly via a reduction in DMI and a subsequent decreased average daily gain (ADG) (Britton and Stock, 1989; McCarthy *et al.*, 1989; Aldrich *et al*., 1993) as well as through an increase in treatment cost (Attia, 2016).

2.6.3 Monitoring rumen health

Examining the rumen fluid of the animal is one of the more effective methods used to investigate the health of the forestomach and distinction of diseases, including types of vagal indigestion, ruminal acidosis, and potential intoxications. Several procedures of rumen fluid collection exist, namely via rumen cannulas, via orogastric or nasogastric intubation, or via percutaneous rumenocentesis (Nordlund and Garrett, 1994). During any of these procedures, it is imperative that proper restraint of the animal is exercised (Bayne and Edmondson, 2021). However, it is important to acknowledge that ruminal pH is not homogeneously distributed throughout the rumen and that different sampling techniques will produce different results (Nordlund and Garrett, 1994; Aschenbach *et al.,* 2011; De Assis Lage *et al.,* 2020).

The standardized sampling site for ruminal pH is the left ventricular ruminal sac, since the most active mixing of ruminal content occurs in this location (Aschenbach *et al.,* 2011). The ventral ruminal sac represents the most reliable information on the pH status of the whole rumen, being that motility is still intact (Aschenbach *et al.,* 2011).

2.7 Economy of lamb finishing

2.7.1 Economic importance of sheep meat

Global meat consumption has changed significantly over the past 40 years, with the broiler meat market increasingly incorporated into the expanding meat industry. On an international scale, the total per capita average yearly meat consumption has increased from 23 to 43 kg/year between 1961 and 2013 (Lundström, 2019). Internationally, the cattle meat production has more than doubled since 1961. Growing from 28 million tonnes per year to 68 million tonnes in 2014 (Ritchie and Roser, 2017). Production of poultry meat has expanded rapidly worldwide over the last 50 years, increasing more than 12-fold between 1961 to 2014 (Ritchie and Roser, 2017). Pig meat production has grown more steadily since 1961, increasing 4-5 fold to 112 million tonnes in 2014 (Ritchie and Roser, 2017). The global sheep

flock has increased nearly 17% over the past two decades to a record high of over 1.2 billion head of sheep (Ritchie and Roser, 2017). China holds the largest sheep flock at about 13% of the global flock but is also the top importer of sheep meat (Ritchie and Roser, 2017). A recent upswing in international sheep meat prices is mainly attributed to an increasing appetite for meat protein in the developing world, and a lower supply from the main export countries like Australia and New Zealand (Dalgleish, 2020).

In South Africa the gross income from animal products amounted to R142 964 million during 2017/2018 (DAFF, 2018). The poultry industry made the largest contribution, with income from poultry meat at R46 382 million (30.9%), cattle and calves slaughtered at R37 913 million (26.5%), and sheep slaughtered at R7 227 million (5.1%) (DAFF, 2018). Between 1999 and 2019 the national sheep flock decreased by 24%, amounting to +/-7 million animals (Maré, 2020). This decrease can mainly be attributed to economic factors, with predation, theft and droughts being major risk factors (Maré, 2020). In terms of domestic demand, the annual per capita consumption of sheep meat in South Africa (Figure 2.2), decreased during the past 3 decades by almost 50% (Maré, 2020). Although the South African mutton and lamb prices have recently followed the strong gains observed on the international market, the long-term pressure on the South African sheep farming industry emphasise the importance of optimum production practices and precision feeding in lamb production.

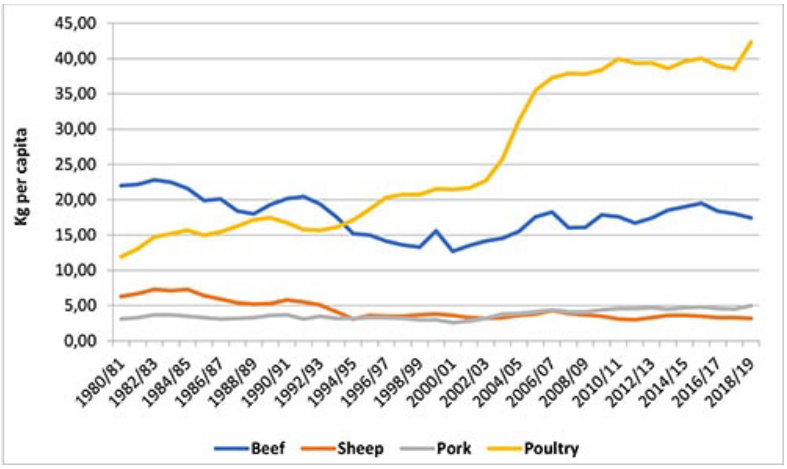

Figure 2.2 Per capita consumption of meat in South Africa from 1980/81 to 2018/19 (Maré, 2020).

2.7.2 Feedlot Profit Drivers

Former research in beef feedlots recognised six variables that explained more than 90 percent of the variability of steer feeding profits. Schroeder *et al.* (1993) reported that 70 to 80 percent of profit variability can be attributed to price margin (purchase and carcass prices),

and 6 to 16 percent was attributed to maize prices. Feed efficiency and average daily gain was responsible for less than 10 percent of variation in profits (Schroeder *et al.*, 1993). Langemeier *et al.* (1992) analysed a decade worth of feedlot data in the USA and concluded similar results to that of Schroeder *et al.* (1993). Lawrence *et al.* (1999) inspected 220 feedlots in the upper Midwest and confirmed these earlier reports that relatively few variables explain most of the difference in profits between pens of cattle. Purchase prices had a more significant impact on profitability at heavier starting weights as the total cost of the feedlot animal increases. Carcass price however seemed to be the most crucial factor determining cattle feeding returns (Lawrence *et al.*, 1999). Price margin described over 70 percent of the profitability for all groups except for lightweight heifers. Feed prices, feed efficiency, and interest rates become of more importance as the feeding period lengthens (Lawrence *et al.,* 1999). According to Small *et al.* (2010), factors that had the most influence on the profitability of cattle feedlots in Nebraska, USA, were (ranked from most to least important) the carcass price, price margin, weaner price and maize price, whilst other factors were not significant. It is therefore clear from all these studies that the purchase price of weaners and the carcass price of the finished animals are the most important factors that influence the profitability of beef feedlots.

Several studies showed that profit drivers in lamb feedlots do not differ significantly from beef feedlots. The main factors affecting feedlot profit margins include the purchase price of store lambs, the price of meat produced, along with the dressing percentage of the carcass, the price of feed consumed by the animal, as well as the efficiency of growth achieved (Lima *et al.,* 2017). An analyses of the profitability of grain-based lamb finishing operations in Australia (MLA, 2011) are defined by key profit drivers and in order of importance were:

- Purchase price
- Growth rate
- Carcass price
- Scale of the operation
- Shy feeders
- Mortality rate (1-5%)

A Western Australian report (Duddy, 2017) concluded that the profitability of finishing lambs is heavily influenced by:

- Price margin (purchase price vs carcass price). The purchase price impacts heavily on profitability with a 66 to 70 percentage contribution to total input costs, independent of finishing system (pasture or grain-fed).

- Throughput. Operations finishing lambs at or close to their maximum annual throughput had lower non-operating and fixed costs and greater profit margins.

The same study (Duddy, 2017) showed that profitability was influenced to a lesser degree by:

- Feed prices
- Establishment cost and
- Operational scale, with larger operations likely to return greater profits per lamb than smaller (5000-10 000) systems

2.7.3 Systems of lamb finishing

International literature on the economic evaluation of sheep production systems is limited, and most of the available papers deal with broader issues, or an economic analysis of specific procedures, and not with the calculation of production costs specifically. The economic outcome of sheep production in a competitive market environment depends on management of production costs and on economies of scale. In this context, knowledge of production costs is critical (Raineri *et al.,* 2015). When choosing a feeding system, it is important to remember that feed is the single largest cost centre in the lamb production operation, and flexibility in accommodating various ingredients for cost-effective diets is crucial (Wand, 2014). The ability to formulate the ration to meet nutrient demands is just as important to the finishing system as the cost of feed. When formulating the diet, the aim should be to meet the nutrient demands of the lamb by the most cost-effective means (MLA, 2020). Many producers will source feed based on cost per tonne, although this can be very ambiguous as it does not account for quality or inclusion rate in the diet. The quality of the feed is as important as the cost as it will have a significant impact on growth rate and hence profitability (MLA, 2011).

Feedlots vary from large outside lots with self-feeders to complete confinement pens on slotted floors. Equipment varies from automated feeders, bunk fence-line feeders, to self-feeders, to separate hay and grain feeders. There is no best ration for feedlot lambs, and optimum feeding programmes will differ according to place, time and circumstances (MLA, 2020). Rations are usually formulated conferring to available feedstuffs and price relationships, and can consist of numerous combinations of roughage and grain (Kott, 2010). Many on-farm lamb finishing in South Africa make use of a TMR system, where a mixer wagon is used to blend all dietary ingredients in such a way to prevent separation and selection. With TMR feeding the lambs have continuous free choice availability of a uniform feed, resulting in a more stable ruminal fermentation and in general higher production compared to what would

have been achieved if roughage and concentrates are being fed separately (Beigh *et al.,* 2017). The primary advantage of the latter system is that the producer has complete control over the nutritional specification of the diet by incorporating specific amounts of roughage, grain, and minerals into the mix. The ration sources are often locally sourced according to price and quality. However, the success of a TMR feeding system is dependent on optimising the diet to avoid selective feeding of the lambs, which may invalidate the advantages of a stable rumen environment (Beretta and Kirby, 2004).

In general, larger commercial feedlots in South Africa make use of complete pelleted rations (CPR) for lamb finishing, provided by a commercial feed provider (Van der Merwe *et al.,* 2020). From the producer's point of view, pelleted diets are more expensive to purchase compared to unprocessed grain. An Australian study ranked pelleted feed as the most expensive system of lamb finishing (MLA, 2011). However, pellets have the advantages over unprocessed grain of convenience, ease of handling and purchasing in most cases a well formulated ration. In order to assess the cost-benefit of feeding a pelleted diet, it is necessary to establish the expected growth rate and feed conversion rate of lambs in this feeding system (Beretta and Kirby, 2004).

2.8 Conclusion

The general practice in commercial lamb feedlots in South Africa is to make use of complete pelleted feeds, while on-farm feedlots often use whole grains as the basis of finishing rations. The main effect of processing is a reduction in the particle size of the feed. In pelleted feeds this effect may even be greater in smaller size pellets. In ruminants, a reduction in particle size will generally lead to an increase in degradation rate and a lower ruminal retention time. Animals on processed high roughage diets will generally show positive production responses mainly associated with higher feed intakes. Whereas animals that receive diets with high levels of readily fermentable carbohydrates, highly processed feed may negatively affect production associated with a lower rumen pH and poorer ruminal health. Research on the interaction between processing and nutrient density and the effects on production and economy of feedlot lambs under S.A. conditions is limited.

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CHAPTER 3
THE EFFECT OF FEED PROCESSING AND NUTRIENT DENSITY LEVEL ON THE GROWTH RATE, FEED CONVERSION AND PROFITABILITY OF FINISHING LAMBS.

3.1 Abstract

The objective of the trial was to evaluate the effects of feed pelleting and the interaction of nutrient density on the production performance and profitability of finishing lambs. After an adaptation period of 14 days, a total of 64 three-month-old S.A. Mutton Merino male lambs were used in a 2 x 4 factorial layout design. The lambs were randomly assigned to one of two nutrient density feeds, namely high nutrient density (HD) or low nutrient density (LD) feed. After allocating the lambs, they were further assigned to four different methods of processing within each nutrient density. The control group was offered a total mixed ration (TMR) containing whole grain, protein, additives and chopped roughage (Groups L0 and H0). Three treatment groups within each nutrient density were offered a complete pelleted ration (CPR) with pellet sizes of 4 mm (L4 and H4), 6 mm (L6 and H6) and 8 mm (L8 and H8) diameter. Over an experimental period of 7 to 8 weeks, the voluntary dry matter intake (DMI), growth rate, feed efficiency and feedlot economy were determined for the different groups. The average DMI of the H4 group was (P < 0.01) lower than the average DMI of all the other groups with the exception for the L0 group. Lambs that received the L0 diet resulted in the lowest ADG (0.195 kg ± 0.03) in comparison to and was significantly (P < 0.01) lower than the ADG of all the other treatments. The treatment that achieved the highest ADG were the lambs that received the H6 diet (0.305 kg ± 0.04), although the group had only a significantly (P < 0.05) higher growth performance than the lambs on the H4 diet. Pelleting increased ADG in the low-density diets by an average of 44% (195g/day versus 281g/day; P < 0.01), while no significant ADG response of pelleting was observed in lambs on the high-density diets. The worst feed conversion rate (FCR) was achieved by the L0 treatment (6.9 kg ± 0.90), which also differed significantly (P < 0.01) from all the other treatments. The FCR of the high-density treatments was significantly better than the FCR of the low-density treatments, and within the LD and the HD treatments, a tendency (P < 0.10) towards a better FCR with an increase in pellet size was observed. The average dressing percentage (DP) of the lambs that received HD diets (47.7%) were significantly (P < 0.05) higher than the lambs on LD diets (44.5%). Considering the margin and transport cost of the commercial feed company, the highest average gross profit (GP) was obtained by the H8 (R310/lamb) and the H0 (R283/lamb) treatments. The GP of these groups were also significantly (P < 0.05) better than the GP of all the LD treatments. At

an average of R76/lamb, the L0 treatment returned the lowest GP of all the groups. In conclusion, the pelleting of the LD TMR improved growth and economic performance of fattening lambs mainly due to an increase in feed intake and improved FCR, while pelleting of HD diets did not show any significant effects. The use of larger diameter pellets in HD diets seems to be more beneficial to lamb performance than the use of smaller pellets.

3.2 Introduction

Producing quality slaughter lambs year-round from extensive production systems is challenging due to many constraints, including variable composition of pastures combined with fluctuations in availability and the threat of parasite contamination. Pasture finishing is therefore often a risky and unreliable enterprise (Ponnampalam *et al.*, 2017). Feedlot or grain based diets have been shown to support high growth rates and carcass yields (dressing percentage) through a consistent supply of feed with suitable concentrations of crude protein (CP) and metabolizable energy (ME) (Ponnampalam *et al.*, 2017).

Various factors can have a significant impact on the profitability of a lamb feedlot and are considered as drivers of profit. In beef feedlots, the total cost of the final carcass involves the purchasing price of the weaner (53%), the feed price (37.4%), overhead costs (5.3%), mortality and morbidity (0.5%) and marketing (3.8%) (SAFA, 2003). Selling price (R/kg carcass) as well as dressing percentage further have significant effects on feedlot profitability (SAFA, 2003). Feed processing can be defined as the means of altering the physical structure of feed commodities to optimise the utilisation by animals (Coffey *et al.,* 2015; FutureBeef, 2020). Complete pelleted rations (CPR) are becoming more common because of the advantages it holds. Advantages include a decrease in nutrient losses during storage and feeding, as well as the prevention of raw material selection in the diet (Richards and Hicks, 2007). According to Zhong *et al.* (2018) additional advantages includes lower transportation costs, easier storage and utilization of non-palatable feed ingredients ensuring reduced costs and increased availability of roughage. The use of CPR further reduces wastage and allows feed supply automation (Zhong *et al.*, 2018).

Chemical and physical feed alternations is possible with the addition of heat (Dehghan-banadaky *et al.*, 2007), moisture and mechanical pressure during conditioning and pelleting (Rowe *et al.*, 1999). This can have either beneficial or unfavourable effects on the gastrointestinal development, feed components and animal performance (Zhong *et al.,* 2018). According to Ishaq *et al.* (2019), shorter or smaller diet particles can change the dynamics of digestion and increase gastrointestinal tract (GIT) passage rate which in turn increases dry matter intake (DMI). However, with the application of heat and pressure during pelleting which

promotes starch gelatinization, the potential fermentation and risk of acidosis will increase (Ørskov, 1986; Zhong *et al.,* 2018).

Therefore, when farming animals in an intensive livestock production system, especially in feedlots, precise feeding of animals is crucial to prevent financial losses. Research concerning these topics on sheep are however limited. A study was therefore conducted at the University of Stellenbosch to:

- Determine if pellet size and quality affect lamb feedlot production parameters when high or low nutrient density diets are fed
- Identify differences in animal production parameters between processed (pelleted) and non-processed feeds
- Investigate the effect of different pellet sizes on animal production performance (growth rate and feed conversion)
- Evaluate the economic viability of pelleting of feedlot feed for feedlot lambs.

3.3 Material and Methods

Prior to commencement of the study, ethical clearance was obtained from the Stellenbosch University Animal care and ethics committee (ACU-2021-15156).

3.3.1 Animals, management, and experimental design

The study was designed as a 2 x 4 factorial layout design with two levels of nutrient density and four levels of different feed processing methods. The production trial consisted of 64 male Mutton Merino lambs with a mean initial body weight (BW) of 30 ± 1.31 kg. All experimental animals received a vaccine for active immunisation against *Clostridium* strains for the prevention of pulpy kidney, malignant oedema, tetanus, and black quarter. Additionally, the lambs also received an oral treatment for the protection against roundworms and tapeworms and were screened for any external parasites and treated if necessary.

Animals were ranked according to initial body weight and then divided into two comparable groups that received either a high or a low nutrient density diet. Subsequently, each of the two groups were then randomly allocated to one of four dietary processing treatments. The experimental design therefore consisted of eight treatment groups in a factorial layout where each of the nutrient density groups received all the processing treatments. The layout is presented in Table 3.1.

Table 3.1 Trial design.

Diet	Control[1]	Pellet size		
		4mm	6mm	8mm
HD[2]	8	8	8	8
LD[3]	8	8	8	8

[1]Unpelleted feed
[2] HD – High nutrient density feed
[3] LD – Low nutrient density feed

All the animals were housed individually indoors to exclude environmental influences. The housing was in a well-ventilated building with soft wood chippings as bedding. The measurements of the production trial pens were 1.75 m in length and 1.75 m in width (3.0 m^2). Pens were placed in a double, back-to-back, row with a common centre partitioning. Individual water troughs were fitted in the corners of each pen to ensure *ad libitum* water availability. Prior to commencement of the trial, the lambs had already been adapted to a creep feed with 60% grain content. A further period of seven days was used for adaptation to the treatment diets.

After adapting the lambs to their respective treatment diets, they were fed *ad libitum* making provision for between 1 and 5% refusals. The lambs were fed three times daily at 07h00, 11h00 and 16h00 to simulate commercial feedlot conditions. The justification for this increase in feed frequency, is based on a reduction of feed wastage and an increased DMI of the lambs (Keskin *et al.,* 2007). Refusals were weighed back daily at 7 AM. This allowed accurate measurements of the dry matter intake (DMI), average daily gain (ADG) and feed conversion rate (FCR).

3.3.2 Formulation of the diets

Nutrient requirements in terms of energy and protein were determined with the use of the Small Ruminant Nutritional System (SRNS) model for growing lambs (Tedeschi *et al.,* 2010). Hypothetical lambs with a live weight of 38 kg were used as a benchmark with target ADGs of 400 g/day and 250 g/day for the HD (high-density) and LD (low-density) groups, respectively. According to these parameters, lambs in the HD group will have a ME (Metabolizable Energy) requirement of 10.9 MJ ME/day and a MP (Metabolizable Protein) requirement of 156 g MP/day, whereas the LD group requirements would be 9.41 MJ ME/day and 122 g MP/day, respectively. The Pulina *et al.* (1996) model was used to predict the feed intake of the lambs. According to this model, a lamb in the LD group would have a daily DMI of 1550 g/day compared to 1400 g/day in the HD group. The ingredients and nutrient specifications of the two dietary treatments are shown in Table 3.2. Feed lime ($CaCO_3$) were used as a calcium source and a standard micro mineral and vitamin premix were used (Table

3.3). Other additives include monensin (ionophore) and ammonium chloride (urinary acidifier for calculi).

Table 3.2 Ingredient and chemical composition specifications of the experimental diets.

Ingredient, Kg/ton				
	LD		**HD**	
	Formulated	Actual	Formulated	Actual
Lucerne hay	150	150	100	100
Barley grain	100	100	100	100
Barley screenings	200	200	160	160
Barley straw	150	150	-	-
Maize whole	200	200	360	360
Lupins	100	100	100	100
Canola oilcake	-	-	16	16
Exstrublend 36[1]	-	-	16	16
Molasses meal[2]	120	120	100	100
Lime	8	8	10	10
Salt	10	10	10	10
Urea	5	5	10	10
Sheep premix micro pack[3]	3	3	3	3
Monensin	0.1	0.1	0.1	0.1
Ammonium chloride	5	5	5	5
Total	1051.1	1051.1	990.1	990.1
Nutrient (DM)				
DM (g/kg)	890	888	902	892
Ash (g/kg)	98	97	82	80
OM (g/kg)	900	902	910	920
N (g/kg)	21.5	23.5	27.2	26.2
CP (g/kg)	140	147	170	164
EE (g/kg)	32	27	37	26
Crude fibre (g/kg)	185	180	137	135
NDF	368	360	246	258
ADF	217	195	128	133
Starch (g/kg)	290	220	405	335

[1]DM = 89%, CP = 36%, RDP = 18%, CF = 9%, ME = 12 MJ/kg
[2]DM = 84%, CP = 4%, CF = 10%, ME = 10.5 MJ/kg
[3]See Table 3.3 for composition.

Table 3.3 Sheep premix micro pack.

Chemical Composition	
Item	Units
Vitamin E	100 IU/kg
Vitamin A	6000 IU/kg
Cobalt	0.2 mg/kg
Copper	6 mg/kg
Iodine	0.7 mg/kg
Manganese	20 mg/kg
Selenium	0.4 mg/kg
Zinc	40 mg/kg

3.3.3 Preparation of the experimental diets.

The composition of the LD and the HD diets are presented in Table 3.2. Before mixing, all roughages were ground in a hammermill to pass through an 8 mm sieve. The mixture of ingredients was performed by a mixer wagon (Seko Industries, Curtarolo, Italy). Both control (unprocessed diets H0 and L0) diets remained at the experimental site where mixing was done whereas the remaining feed was transported to a commercial feed manufacturing factory for pelleting into 4 mm, 6 mm and 8 mm pellets respectively.

3.3.4 Data recorded

Daily DMI was recorded for each lamb individually by subtracting refusals daily. The pellet quality of all the processed feeds was also predetermined prior to commencement of the trial at a commercial feed mill as described by Stelte *et al.* (2012). The lambs were weighed weekly (full belly) on the same day and time to determine the weekly growth rate. ADG and FCR were calculated weekly. The lambs were fed until the treatment group reached an average live weight of 45 kg, after which they were transported to a registered abattoir in Riversdale, Western-Cape (Hessequa Abattoir) to be slaughtered. Individual warm carcass weights, dressing percentages as well as classification of the carcasses were documented. Dressing percentage and cold carcass weight were successively calculated. Cold carcass weight was measured by subtracting 4% from the hot carcass weight (Hessequa Abattoir, 2020). The gross profit (GP) of each was calculated by subtracting the variable costs (purchase cost, feeding cost/lamb and lamb processing cost) from the gross income (carcass weight multiplied by carcass price). Two different scenarios were used to calculate mean GP in this study. In the first scenario, the cost of each diet was used excluding margin of the feed company or transport cost to the farm in consideration. A second scenario, that includes the

Gross Profit Margin (GPM), was also introduced. In this scenario, a R500/ton margin was added to the raw material cost price of all the pelleted treatments, which represented the profit and pelleting cost of the feed company as well as the transport cost to the farm. Furthermore, the faecal consistency of the animals was observed and documented for each lamb once every day until slaughter, using a scoring system as described by Le Jambre *et al.* (2007).

Table 3.4 Faecal consistency score (Le Jambre *et al.,* 2007). Illustrations by Sheep CRC (2020) and RAGFAR (2007).

Score	Description	Illustration
1	Normal formed pellets	
1.5	Pellets losing their form	
2	Faeces have no pellet form	
3	Faeces wet but do not run on a flat surface	
4	Watery faeces that run on a flat surface but maintain a depth >2 mm	
5	Watery faeces that run on a flat surface and do not maintain a depth >2 mm.	

3.3.5 Statistical analysis

The effect of feed density and feed processing on the performance and economy of feedlot lambs was statistically evaluated of the different treatments. Using a 2 x 4 factorial layout design with feed density and feed processing method as main effects (two levels of

feed density, four processing methods). The lambs were randomly assigned to one of two nutrient density feeds, namely HD or LD feed. After allocating the lambs, they were further assigned to four different methods of processing within each nutrient density so that there are eight replicants of each group. Parameters for DMI, ADG, FCR, carcass characteristics and economy data were analysed according to a main effects ANOVA with main effects being treatments (feed density and processing method as factors). SAS Enterprise Guide 7.1 was used for statistical analysis and significance and tendencies was be declared at $P < 0.05$.

3.4 Results and Discussion

Results of the trial are presented in Table 3.5, Table 3.6, and Table 3.7. Discussion of these results follow in the sections below.

Table 3.5 The effect of nutrient density in feedlot lamb diets on performance and economic parameters. Averages with SD presented.

	Feed Density	
Parameter	**LD**	**HD**
DMI total (kg)	59.6 ± 4.9	58.6 ± 4.8
DMI daily (g)	1216.7 ± 100.3	1194.9 ± 97.0
ADG (g)	0.258[a] ± 0.1	0.284[b] ± 0.1
FCR (kg)	5.69[a] ± 1.1	4.91[b] ± 0.7
DP[1] (%)	44.5[a] ± 2.0	47.7[b] ± 2.1
GP[2] (Rand)	156.58[a] ± 81.6	295.16[b] ± 118.0

[a,b]Means within rows with different superscripts differ ($P < 0.05$)
[1]Dressing percentage
[2]Gross profit

Table 3.6 The effect of method of feed processing in feedlot lambs on performance and economic parameters. Means with SD presented.

	Processing method			
Parameter	**Control**	**4mm**	**6mm**	**8mm**
DMI Total (kg)	55.7[a] ± 5.1	58.3[a] ± 5.1	61.2[b] ± 3.3	61.1[b] ± 3.6
DMI Daily (g)	1137.5[a] ± 103.3	1189.5[a] ± 105.0	1249.4[b] ± 68.2	1246.7[b] ± 72.9
ADG (g)	0.236[a] ± 0.1	0.270[b] ± 0.0	0.287[b] ± 0.1	0.295[b] ± 0.0
FCR (kg)	5.97[a] ± 1.3	5.24[b] ± 0.8	5.11[b] ± 0.8	4.89[b] ± 0.5
DP (%)	45.9 ± 2.5	45.6 ± 2.8	46.1 ± 2.4	46.7 ± 2.8
GP (Rand)	179.49[b] ± 147.7	205.68[b] ± 118.1	241.1[ab] ± 103.7	277.22[a] ± 101.1

[a,b]Means within rows with different superscripts differ ($P < 0.05$).

Table 3.7 The effect of the different treatments in feedlot lambs on the performance and economic parameters. Means with SD presented.

	Treatment							
Parameter	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
DMI W1 (g)	798.2^{ab} ± 106.7	884.7^{b} ± 53.1	874.8^{b} ± 39.4	904.8^{b} ± 28.0	877^{b} ± 61.7	717.9^{a} ± 30.2	876.9^{b} ± 38.3	864.9^{b} ± 38.6
DMI W7 (g)	1379.6^{ab} ± 172.9	1575.0^{b} ± 99.2	1548.3^{b} ± 74.6	1580.6^{b} ± 118.2	1480.3^{ab} ± 207.6	1386.9^{a} ± 83.6	1559.5^{b} ± 81.5	1494.3^{ab} ± 131.2
DMI W7[1] (%)	3.69^{bc} ± 0.39	3.78^{b} ± 0.18	3.82^{b} ± 0.17	3.84^{b} ± 0.26	3.65^{abc} ± 0.41	3.43^{ac} ± 0.21	3.65^{abc} ± 0.19	3.51^{c} ± 0.21
LW W8 (kg)	38.3^{a} ± 3.0	42.7^{bcde} ± 2.9	41.9^{bd} ± 0.8	42.9^{bcde} ± 1.9	41.9^{d} ± 3.6	42.2^{dc} ± 2.0	45.0^{ef} ± 2.0	44.4^{cf} ± 2.1
ADG (kg)	0.195^{a} ± 0.03	0.279^{bc} ± 0.05	0.270^{bc} ± 0.04	0.295^{bc} ± 0.03	0.277^{bc} ± 0.05	0.261^{b} ± 0.04	0.305^{c} ± 0.04	0.294^{bc} ± 0.04
FCR (kg DMI/kg gain)	6.07^{a} ± 0.79	4.79^{b} ± 0.88	4.78^{b} ± 0.67	4.40^{b} ± 0.48	4.44^{b} ± 0.78	4.43^{b} ± 0.56	4.22^{b} ± 0.63	4.20^{b} ± 0.48
DP (%)	44.68^{a} ± 1.61	43.90^{a} ± 2.26	44.91^{a} ± 2.39	44.48^{a} ± 1.94	47.14^{b} ± 2.77	47.32^{b} ± 2.22	47.31^{b} ± 1.89	48.99^{b} ± 1.29
GP (Rand)	75.97^{a} ± 49.44	151.27^{ab} ± 86.39	190.28^{bc} ± 45.68	208.79^{be} ± 75.11	283.00^{cef} ± 140.77	260.09^{cef} ± 125.11	291.92^{ef} ± 127.12	345.64^{f} ± 74.57
GPM[2] (Rand)	75.97^{a} ± 49.44	109.92^{a} ± 88.60	149.47^{ab} ± 46.39	169.14^{ac} ± 73.33	283.00^{e} ± 140.77	223.45^{bce} ± 124.37	254.89^{ce} ± 128.54	310.04^{e} ± 74.89

$^{a,b,c,d,e,f.}$Means within rows with different superscripts differ ($P < 0.05$)

[1]Average DMI at week 7 presented as a percentage of BW

[2]Gross profit after adding a R500/ton margin to raw material cost

3.4.1 Feed Intake

The results of the average DMI in grams as fed of the lambs over a 7-week period are summarised in Table 3.8 and illustrated in Figure 3.1.

Table 3.8 The mean DMI (g/week) of the lambs over a 7-week period for each treatment group. Means with SD are presented.

	Treatment							
Week	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
Week 1	798.2^{ab} ± 106.7	884.7^{b} ± 53.1	874.8^{b} ± 39.4	904.8^{b} ± 28	877^{b} ± 61.7	717.9^{a} ± 30.2	876.9^{b} ± 38.3	864.9^{b} ± 38.6
Week 2	881.6^{c} ± 110.5	1033.6^{a} ± 82.3	1034.6^{a} ± 61.3	1019.7^{a} ± 82.3	978.6^{abc} ± 147.5	886.6^{bc} ± 133.6	1055.6^{a} ± 55.7	1065.3^{a} ± 31.4
Week 3	1024.7^{c} ± 92.3	1183.8^{ab} ± 83.6	1107.1^{abc} ± 112.1	1162.6^{ab} ± 69.1	1086.3^{bc} ± 149.9	1044.8^{c} ± 107	1199.9^{a} ± 77.9	1179.1^{ab} ± 101.5
Week 4	1049.5^{d} ± 67.5	1305.2^{a} ± 89.9	1208.6^{ab} ± 107.9	1243.2^{ab} ± 131.7	1081.4^{cd} ± 150.9	1143.3^{bcd} ± 62.3	1289.9^{a} ± 76.7	1193.3^{abc} ± 164.9
Week 5	1223.9^{d} ± 91.3	1393.4^{ab} ± 108.6	1384.8^{ab} ± 80	1440.8^{a} ± 47.2	1327.3^{bc} ± 100.6	1256.3^{cd} ± 59.2	1387.3^{ab} ± 121.5	1351.7^{abc} ± 141.5
Week 6	1295.4^{c} ± 129.9	1517.1^{a} ± 83.5	1487.7^{a} ± 108.5	1524.6^{a} ± 77.4	1441.8^{a} ± 140.9	1324.2^{bc} ± 76.3	1476.5^{a} ± 116.2	1428.9^{ab} ± 167.9
Week 7	1379.6^{ab} ± 172.9	1575.0^{b} ± 99.2	1548.3^{b} ± 74.6	1580.6^{b} ± 118.2	1480.3^{ab} ± 207.6	1386.9^{a} ± 83.6	1559.5^{b} ± 81.5	1494.3^{ab} ± 131.2

$^{a,b,c,d.}$Means within rows with different superscripts differ ($P < 0.05$).

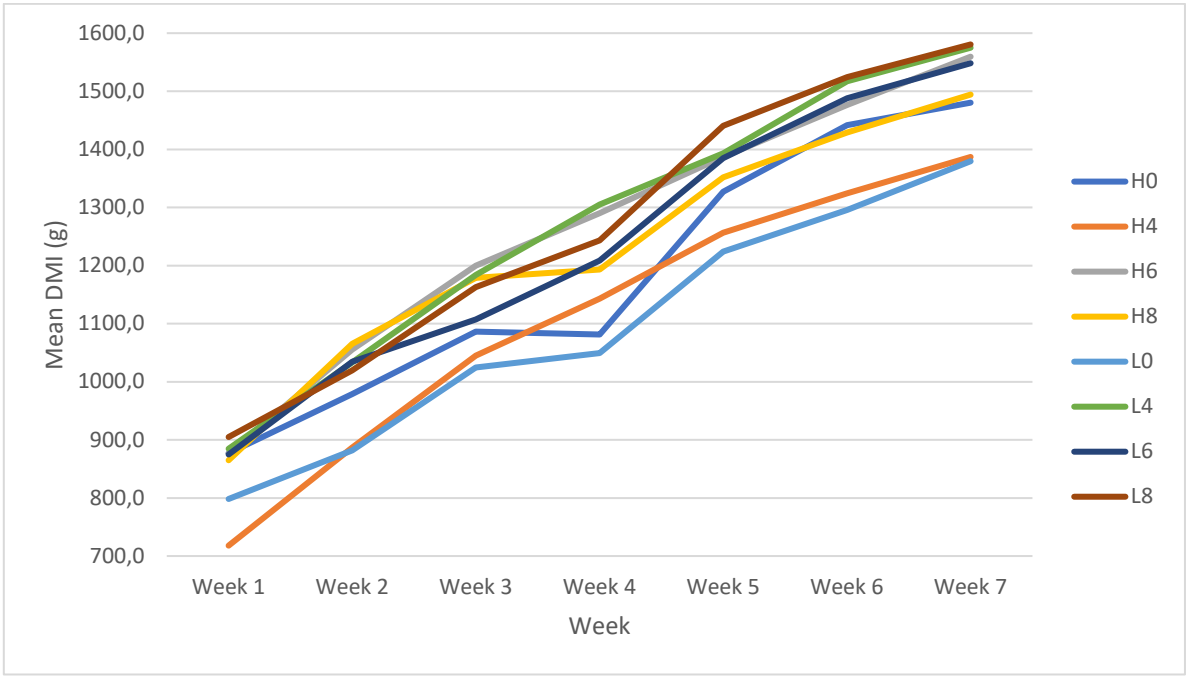

Figure 3.1 Mean DMI (g/week) of the lambs over a 7-week period for each treatment group.

The mean DMI of the lambs for each treatment group increased exponentially over the course of seven weeks. It appears (Figure 3.1) that over the trial period of 7 weeks, lambs that received the H4 and L0 diets, had a numerically lower relative DMI when compared to the other groups. For most of the groups, except for groups L4 and H6, a relative suppression in feed intake during week 4 of the trial was observed. This decrease in intake could partly be explained by the change of beddings of the lambs during that week. From week 5 to week 7 the exponential increase in feed intake continued with live weight of the animals. Even after the adaptation period of 7 days, it was already clear that during the first week of the trial, the lambs that had received the H4 diet already had the lowest DMI (717.9 g ± 30.2). This difference in feed intake was significantly ($P < 0.05$) lower than the average feed intake of the other treatment groups except for the L0 group (Table 3.7). Lambs that were fed the L8 diet showed the highest DMI (904.8 g ± 28.03) although the difference was only significant compared to the H4 group ($P < 0.05$).

The highest mean DMI was recorded during the last week of the trial (week 7) before the first animals were slaughtered. During this week, the lambs that received the L0 diet had the lowest DMI (1379.6 g ± 172.9), but no significant differences were found. The DMI of lambs that were fed the H4 diet (1386.9 g ± 83.6), was significantly lower ($P < 0.05$) than the DMI of all the other treatment groups except for the lambs on the L0, H0 and H8 diets (Table 3.7). Furthermore, the lambs that received the L8 diet had the highest DMI (1580.6 g ± 118.2) during week 7, although no significant differences could be established.

Table 3.9 Lamb performance and DMI at week 7 for each treatment group.

	Treatment							
Parameter	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
LW (kg)	36.9	41.2	40.1	40.6	40	40	42.2	42
ADG (g/day)	200	290	280	300	290	270	310	305
DMI (kg/day)	1.36	1.56	1.53	1.56	1.46	1.37	1.54	1.48
DMI (% of BW)	3.69	3.78	3.82	3.84	3.65	3.43	3.65	3.51

The mean DMI during week 7 as a percentage of BW (body weight) for each PTF group is illustrated in Table 3.9 and Figure 3.2. The group of lambs that were fed the H4 diet showed the lowest mean DMI (3.43% ± 0.21) and was significantly lower ($P < 0.05$) than the DMI of all the other low-density groups (Table 3.7). The group of lambs that were fed the H8 diet resulted in the second lowest mean DMI (3.51% ± 0.21) and was significantly lower ($P < 0.05$) than the L4, L6 and L8 group.

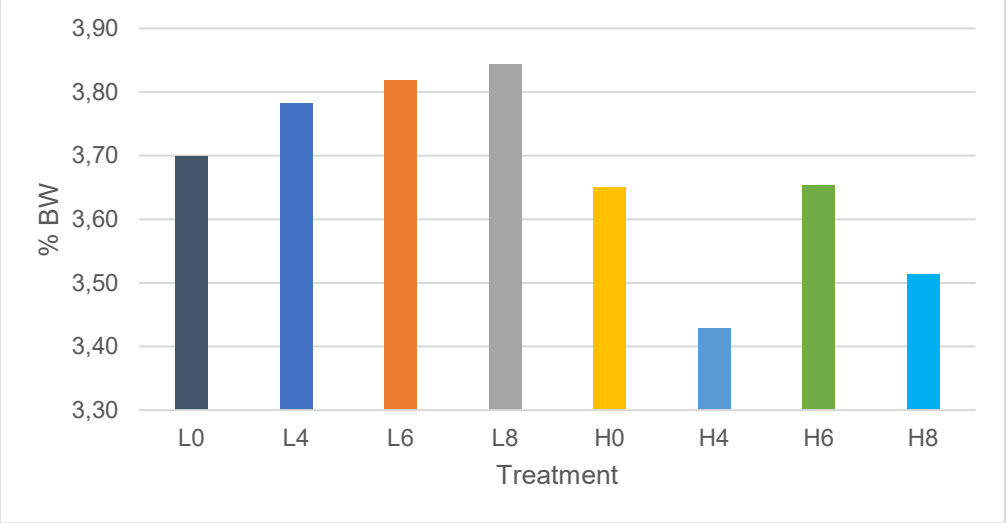

Figure 3.3 Mean DMI as a percentage of BW of the lambs at week 7 for all treatment groups.

Feed and energy intake control mechanisms in ruminants are complex and are integrated in feeding centres of the brain, with multiple signals that are working cohesively to determine feed intake. At a specific time, certain signals will dominate feed intake control, and these signals will vary across physiological states and diets. Feeding behaviour is therefore not only affected by physical, metabolic, and endocrine factors, but also managerial and environmental conditions (Allen and Piantoni, 2014).

In ruminants fed high roughage rations, feed intake is limited by physical means (Chen, *et al.,* 2021). Physical limitations of feed intake is partially a function of rate of digestion and therefore rate of passage of feed from the rumen (Pulina *et al*., 2013). If the rate of digestion can be increased, then the passage rate will most likely increase, which in turn allows the animal to consume more dry matter (Pulina *et al*., 2013). The overall filling effect is determined by forage NDF concentration, forage particle size, fragility of forage NDF (determined by forage type, e.g., proportion of legumes, perennial grasses, and annual grasses), and NDF digestibility within a forage family. Compared to other diet components, forage NDF is less dense, digests more slowly, and is retained in the rumen for longer periods, therefore increasing the diet forage NDF concentration can markedly reduce feed intake (Allen and Piantoni, 2014). Changing their physical form may be a possible mitigation strategy to overcome the limitations of bulky feeds. In ruminants, when a forage is chopped or ground there is usually an increase in voluntary feed intake due to a faster rate of passage of material from the rumen (Garnsworthy and Cole, 1990). According to Lammers *et al*. (1996), reduced forage particle size increases DMI, decreases digestibility, and decreases retention time of solids in the rumen. Diets that have a smaller forage particle size enter the rumen at a smaller size after initial chewing and swallowing; therefore, they leave the rumen faster. The end result is an increase in the fractional turnover rate of ruminal DM and increased DMI (Lammers *et*

al., 1996). Smaller forage particles spend less time in the rumen for microbial digestion, thereby decreasing digestibility, particularly fibre digestion (Lammers *et al.,* 1996). Since there is a limit to the amount of time a ruminant can spend ruminating (10–11 h/day), intake tends to be limited in sheep more than in cattle by the particle size of diets containing long hay. This combined with the lower fermentative capacity of sheep, explains why processing often increases the intake of forage and why the response is stronger in sheep compared to cattle (Cannas, 2004). According to an comprehensive review by Kott (2010), pelleting of bulky diets in feedlot lambs will increase feed consumption and consequently increased rate of gain.

In agreement to previous published research, the observed increase in feed intake and DMI due to pelleting observed among lambs in the current trial of the low feed density groups (Figure 3.1; Figure 3.9), may therefore be explained by a lower ruminal retention time and a higher ruminal content passage flow. Pelleting in general, especially 6 mm, appears to be sufficient in decreasing ruminal retention time and rumen fill, which allows greater feed intake to reach satiety (Table 3.6). Pellet size in the LD rations, however, did not have a significant influence on DMI.

As digestible energy content is increased, for example under typical lamb feedlot circumstances, metabolic control becomes the dominant factors limiting intake. The point of maximum total DMI (e.g., passage from physical to metabolic control of ingestion) for sheep fed pellets is estimated at about 10.3 MJ/kg of DE or 8.5 MJ/kg ME (Pulina *et al*., 2013). Under most commercial lamb feedlot conditions, DMI would therefore be under metabolic control and not limited by physical fill (Pulina *et al*., 2013). Chemoreceptors in the rumen reading VFA's and hepatic gluco-receptors send powerful satiety signals to the brain. Propionate, the main fermentation product from soluble carbohydrates, is considered as the most potent anorexic metabolite produced in the rumen. However, after an adaptation period, feed preferences are always governed by an inclination toward optimum rumen function (Faverdin, 1999). When feeding highly processed feed, propionate influx to the liver would increase resulting in an increase in hepatic energy status and satiety, while decreasing meal size and DMI. Diets with greater ruminal starch fermentability can therefore depress feed and energy intakes (Allen and Piantoni, 2014). Amongst the groups receiving high energy density diets, it was expected that the treatment with the smallest pellet size (H4 group), would also have the highest rate of fermentation. This may explain the lower feed intake of lambs receiving the H4 diet.

For comparisons of DMI of animals of different live bodyweights (BW), a reference scaling unit is used to achieve comparability, because relative to BW, large animals will usually eat less than small ones. Thus, different scaling factors have been applied to compare feed intake among ruminants of various sizes. Traditionally, in Europe, metabolic body size ($BW^{0.75}$) is used for feed intake comparisons (Riaz *et al*., 2014). Concerning feed factors, as shown above, the most important physical factors that limit the DMI are the fibre content of feeds and

fibre digestibility kinetics in the rumen, whereas the main limiting physiological factor is the content of soluble carbohydrates (Pulina *et al*., 2013). The use of diet energy concentration to predict intake therefor describes the combined effects of physical and metabolic controls on appetite (NRC, 1987). Pulina *et al*. (2013) used metabolic body weight and growth rate as predictors of feed intake of lambs. This equation was first used by Cannas *et al.* (2009) after an experiment carried out in South Africa with two local breeds (Cannas *et al.,* 2009). Osorio *et al.* (2015) used body weight, NDF and protein composition as predictors of feed intake of lambs on high carbohydrate diets. This formula was first proposed by Lee *et al.* (2011).

Considering DMI as % of BW (Table 3.9 and Figure 3.2), results of this trial confirm previously reported research that more energy dense rations are associated with lower DMI's. There is also clear trend from Table 3.9 that pelleting of LD diets showed a positive effect on DMI (3.69% of BW for L0 group versus 3.82% of BW for LD pelleted diets). The increased feed intake can at least partly explain the improved growth performance of lambs on pelleted LD rations.

Pelleting did not improve DMI amongst the lambs fed HD diets, with average DMI amongst the pelleted groups of 3.53% of BW, compared to the 3.65% of BW of the unpelleted group. No significant positive effect of pelleting high concentrate diets was also illustrated by Vosloo and du Plessis (1966), Hejazi *et al*. (1999) and Zietsman (2008). However, this finding is contrary to other experiments that did find positive intake effects of pelleting relatively high grain diets (Bowen *et al*., 2006; Zhong *et al*., 2018; Zhang *et al*., 2019; Li *et al*., 2021).

The H4 group of lambs attained the lowest average DMI of all the lambs. This result may be explained by the small particle size of the 4mm pellets, thus increasing the surface area which enhances the risk of acidosis (Hernández *et al*., 2014) and lowers DMI (Meyer and Bryant, 2017).

3.4.2 Live Weight and Growth

The mean LW of all the treatment groups during the eight weeks of the trial is summarised in Table 3.10 and Fig. 3.4. Mean LW of the treatment groups at week 8 is further illustrated in Fig. 3.3.

Table 3.10 The mean LW (in kg) of the lambs for all treatment groups during the trial. Means with SD presented.

	Treatment							
Week	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
Week 1	29.5 ± 1.4	29.9 ± 1.2	29.6 ± 1.4	29.3 ± 1.1	29.0 ± 1.0	30.2 ± 2.0	30.2 ± 1.3	29.8 ± 1.1
Week 2	30.2^{a} ± 1.9	31.6^{ab} ± 1.6	31.7^{ab} ± 1.1	31.1^{ab} ± 1.2	30.9^{ab} ± 1.8	31.0^{ab} ± 1.8	31.9^{b} ± 1.6	31.7^{ab} ± 1.0
Week 3	31.3^{c} ± 2.4	33.4^{ab} ± 2.0	32.7^{abc} ± 0.7	32.1^{bc} ± 1.5	32.3^{abc} ± 2.0	31.9^{bc} ± 1.7	34.0^{a} ± 1.8	33.1^{ab} ± 1.1
Week 4	31.9^{c} ± 2.3	34.9^{ab} ± 2.0	33.6^{bc} ± 1.0	33.3^{bc} ± 1.7	33.6^{bc} ± 2.2	33.3^{bc} ± 1.8	35.9^{a} ± 1.6	34.6^{ab} ± 1.4
Week 5	33.4^{c} ± 2.6	36.6^{ab} ± 2.2	35.1^{bc} ± 0.8	35.0^{bc} ± 1.4	35.1^{bc} ± 2.3	35.2^{bc} ± 1.7	37.1^{a} ± 1.7	36.3^{ab} ± 1.6
Week 6	35.3^{c} ± 2.6	39.3^{ab} ± 2.3	37.9^{b} ± 0.9	38.0^{b} ± 1.7	38.0^{b} ± 2.3	38.1^{b} ± 1.5	40.3^{a} ± 1.7	39.5^{ab} ± 1.9
Week 7	36.9^{c} ± 2.3	41.2^{ab} ± 2.2	40.1^{b} ± 1.1	40.7^{ab} ± 1.6	40.0^{b} ± 2.8	40.0^{b} ± 1.9	42.2^{a} ± 1.1	42.0^{ab} ± 2.2
Week 8	38.3^{d} ± 3.0	42.7^{abc} ± 2.9	41.9^{c} ± 0.8	42.9^{abc} ± 1.9	41.9^{c} ± 3.6	42.2^{bc} ± 2.0	45.0^{a} ± 2.0	44.4^{ab} ± 2.1

$^{a,b,c,d.}$Means within rows with different superscripts differ ($P < 0.05$).

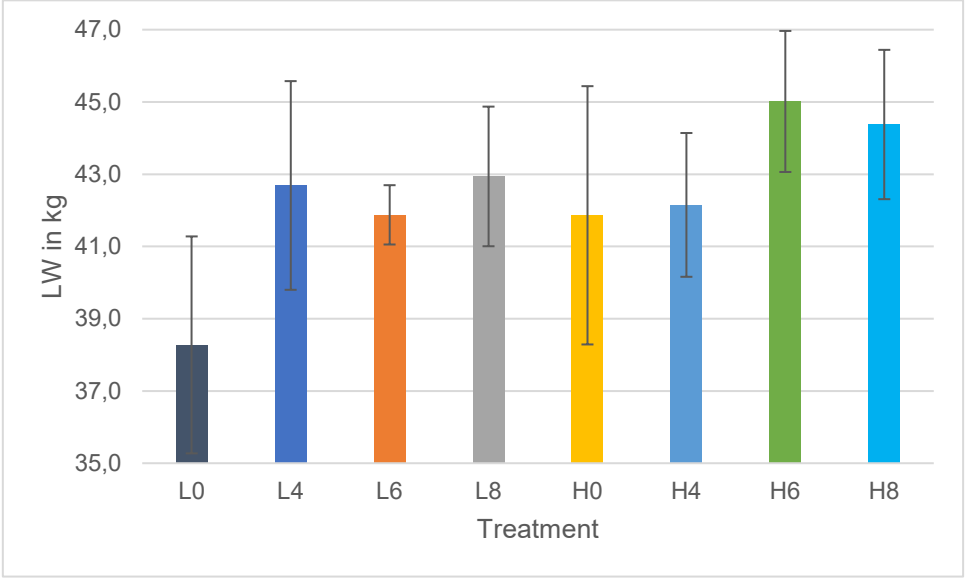

Figure 3.4 Mean LW (kg) of the lambs at week 8 of all treatment groups.

The lowest measured mean LW during week 8 was measured in the L0 group (38.3 kg ± 3.00), while the H6 (45.0 kg ± 2.0) and the H8 group (44.4 kg ± 2.1) finished with the highest mean LW (Table 3.7). It is clear from Figure 3.3 that the mean LW for the LD groups at week

8 was lower than the high-density groups. The mean LW of the L0 group was significantly lower ($P < 0.05$) than for all the other treatments. The only treatment groups that did not significantly ($P < 0.05$) differ from the H6 group, was treatments H8, L8 and L4. As illustrated in Figure 3.4 and Table 3.10, LW changes in an exponential curve over the 8 weeks of the trial. Fig. 3.4 clearly shows that the L0 group had the lowest mean LW during the whole trial period, whilst the H6 group had the highest mean LW.

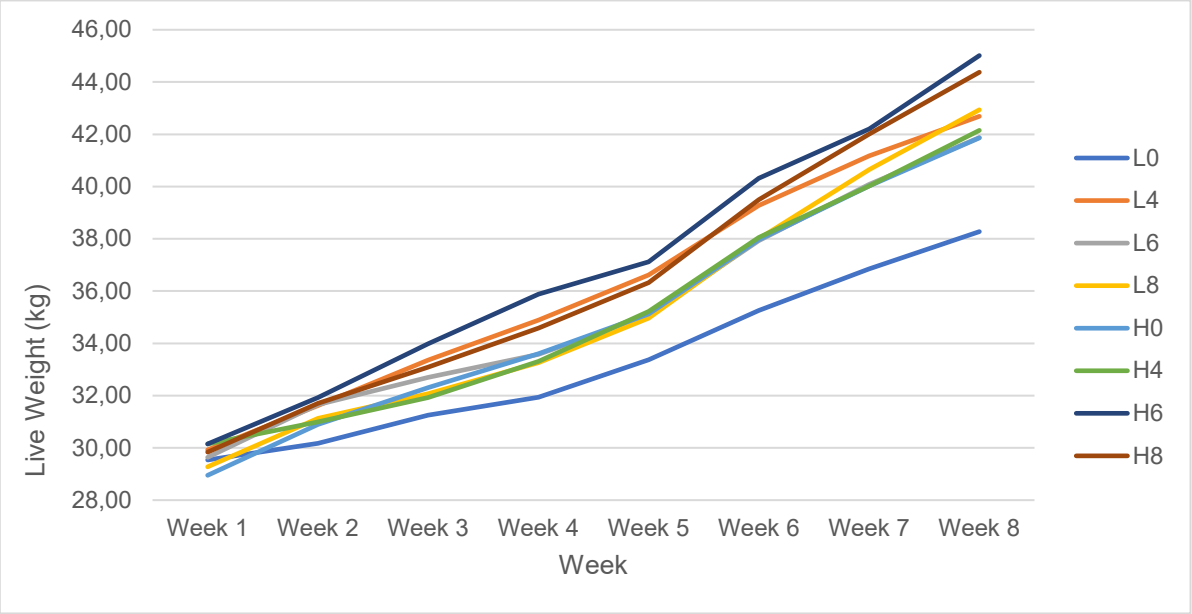

Figure 3.5 Mean LW (in kg) of the lambs for all treatment groups during the trial.

The mean daily gain (ADG) of all the lambs of each treatment group over the 7-week period is illustrated in Figure 3.5. The ADG of the LD feed groups were overall significantly lower ($P < 0.05$) than the HD groups (Table 3.5). Table 3.6 illustrates that the ADG of the unpelleted or control feed of the LD and the HD group combined were significantly lower ($P < 0.05$) than the pelleted feed groups. Lambs that received the L0 diet resulted in the lowest ADG (0.195 kg ± 0.03) and was significantly ($P < 0.05$) lower than the ADG of all the other treatment groups (Table 3.7). The group that achieved the highest ADG were the lambs that received the H6 diet (0.305 kg ± 0.04) and were also significantly higher ($P < 0.05$) than the H4 group (0.261 ± 0.04).

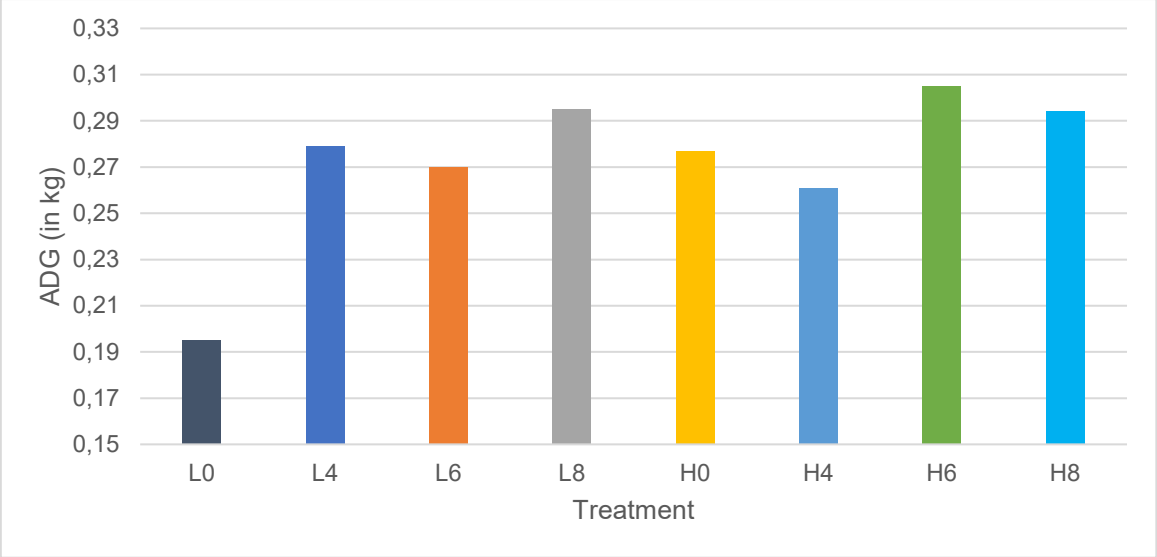

Figure 3.6 Average daily gain for the lambs over a 7-week period for each treatment group.

3.4.3 Growth Rate

The lamb's growth potential is genetically determined, with a heritability of approximately 10 – 15% (Burfening and Carpio, 1993). Other than genotype, growth rate of feedlot lambs is also affected by factors such diet composition, feed intake, feed conversion efficiency, past nutritional history, past exposure to grain, social interaction, age, sex, LW and disease (Lôbo *et al*., 2009). Non-genetic factors account for most of the variability in growth rate, while the degree to which genetic potential is reached depends on environmental conditions (Mathis and Ross, 2000). According to Van de Vyver (2014), nutrition is the most significant and manageable factor. According to Coetzee (2004), for profitable production in South Africa, producers often aim for an ADG of 300 g/day and a FCR of 5.0 kg feed/kg weight gain, depending on the breed and type of feed used in the finishing system. Anderton (2005) confirmed that weight gain of lambs in feedlots must exceed 300 g/lamb per day in order to be profitable, depending on the price of feed and meat. Where lower growth rates occur, it will result in an increase in costs, lowering the overall profit (Coetzee, 2004; Anderton, 2005). The observed growth rates in the current study, especially amongst the HD diets, was lower than the expected growth rates. Finishing diets of the HD groups was formulated for a projected maximum growth rate of 400 g/day, much higher than the average ADG of approximately 300 g/day for these lambs. Apart from group L0, the observed growth rate of the LD groups was better than the anticipated 200 g/day of the formulated rations. The reasons for the lower-than-expected HD growth rates could be due to environmental conditions as the trial was conducted during the winter. The higher-than-expected results of the LD treatments was unexpected and could not be explained.

3.4.3.1 High density versus low density diets

More nutrient dense rations (e.g. grain-based concentrates) are often used in lamb finishing to support high growth rates, shorten the time to slaughter, increase dressing percentage, and improve carcass quality (De Brito *et al*., 2017; Jaborek *et al*., 2017; Ponnampalam *et al*., 2017; Van Der Merwe *et al*., 2020). However, in this study, except for the L0 group of lambs, no significant differences were observed in ADG between lambs of the high and lambs of the low nutrient density groups (Table 3.7). This observation can be partly explained by differences in growth tissue partitioning (see dressing percentage). However, the trivial differences between the HD and LD groups of 6 mm and 8 mm pellets could not be explained considering the significant difference in total nutrient intake between lambs of the HD rations and lambs on the LD rations while DMI between these groups did not differ significantly (Section 3.4.1). In order to drive tissue protein synthesis, energy supply is the major nutrient of importance in the diet of fast-growing lambs, and it is generally accepted that the higher the energy level in the diet, the faster the growth rate and the better the level of feed efficiency (Jolly & Wallace, 2007; Kott, 2010). The ME requirements of finishing lambs increase exponentially with growth rate (NRC, 2007), and energy intake under most feedlot circumstances is considered to be the most limiting dietary factor in growth performance of lambs where the diet contains a minimal concentration of 15% CP (Ríos-Rincón *et al*., 2014). Nevertheless, because of the impact of dressing percentage, the differences in carcass growth of lambs were not reflected by the insignificant differences in growth rate between groups of lambs (except for group L0).

3.4.3.2 Processing effects in low nutrient density diets

The significant effect of pelleting on feed intake of the LD rations (Table 3.8), was also reflected in the pronounced effect on the growth of these lambs. Pelleting increased ADG in the LD diets by an average of 44% (195 g/day versus 281 g/day; $P < 0.01$). This result agrees with the general scientific consensus of improved ruminant production through processing of high roughage feedstuffs. The processing of the ruminant feed as well as the physical form can affect palatability, rumen fermentation, and nutrient digestibility (Huntington, 1997), thereby affecting animal feed consumption and growth (Khan *et al*., 2016). This result is in accordance with early research at the University of Illinois (Esplin *et al*., 1957) and at the University of Stellenbosch (Van der Merwe *et al*., 1962; Vosloo and Du Plessis, 1966), indicating that pelleting of high roughage diets is of significant value to lambs. Esplin *et al.* (1957) reported that lambs that were fed a pelleted high roughage ration (47.5% lucerne hay)

showed significantly ($P < 0.05$) higher ADG's compared to animals fed an un-pelleted ration. Van der Merwe *et al.* (1962) also showed that the grinding and pelleting of a relatively poor quality hay had a more pronounced effect on digestibility, feed intake and growth response than good quality hay. In all these studies, including the current study and the trial by Blanco *et al*. (2014), the improved lamb feedlot performance in terms of ADG due to pelleting can largely be attributable to an increase in feed consumption. Other benefits of pelleting that may have played a role is the elimination of wastage and the reduction of bulk (Blanco *et al*. (2014).

The interaction of roughage type (long versus short fibre; high versus low quality), level of roughage in the ration and production responses of processing is still unknown. In the current trial the pelleting of a ration with high quality lucerne roughage at 10% inclusion rate (HD diets), had no effect on lamb production, while the pelleting of medium quality roughage (50:50 lucerne and barley straw) at 30% inclusion rate (LD diets) however had a significant ($P < 0.05$) effect. In the current study, all roughages were ground with a hammermill to pass through an 8mm openings in the sieve. A recent study of Zhong *et al*. (2018) used a 29% inclusion rate of short fibre peanut shell and barley malt as roughage sources. Production parameters in finishing lambs were compared between rations in the form of a complete pelleted diet (CPR) or a loose total mixed diet (TMR). Feeding CPR increased ADG (223 vs 176 g/day) compared to TMR, and this was attributed to a 23.8% increase in DMI and associated improvements in gastrointestinal tract development and rumen fermentation characteristics (Zhong *et al*., 2018). A study where poor-quality roughage was fed to lambs (Stanton and Levalley, 2014) also showed that CPR gave more rapid and efficient gains and produced better classed carcasses compared to a TMR. In accordance with the current recommendations and research, the current trial supports the theory that pelleting is recommended in finishing rations with a relative high roughage inclusion or diets where poor-quality roughage is used mainly due to a positive effect on DMI.

3.4.3.3 Processing effects in high nutrient density diets

In contrast to the observed positive production response of pelleting in the LD diets, in the current study no significant positive production impact of pelleting was observed with lambs fed the HD diets (Table 3.7). This agrees to numerous studies comparing production responses of lambs fed high-concentrate TMR's and high-concentrate CPR's. An early South African study (Vosloo and Du Plessis, 1966) reported that the improved lamb performance through pelleting that was observed in low grain diets, could not be repeated when the bulk of the diet contained grains (maize, oats and barley). The main reason may be that processing of grains modifies starch degradation by increasing both gelatinization and degradability (Zebeli *et al*., 2010). An early Canadian study (Tait and Bryant, 1973) also showed that

processing cereal grains (barley and wheat) in early weaned lambs is unnecessary when digestibility is considered and would appear to be detrimental in growth rate and feed conversion efficiency. Gallo *et al*. (2014) could not find any negative effect in the efficiency of a whole maize grain diet on the growth performance of lambs, carcass quality parameters or ruminal papillae development. The latter study concluded that compared to processed grain, whole grain feeding of lambs improves feed efficiency, increases average daily gain, and lowers overall feed costs per kilogram of gain. Later research at different locations also indicated little or no benefit to processing (steam rolling, grinding, pelleting or dry rolling) when compared with feeding barley whole in forage or concentrate diets for sheep (Lardy and Redden, 2013). Better feed efficiency and growth rates were however observed when maize was processed compared to with whole maize (Lardy and Redden, 2013). In the current study, the high-density diet contained 10% barley and 36% maize respectively (Table 3.1).

Although the general recommendation for sheep is that high concentrate diets (> 50%) does not have production advantages in pelleted form compared to a TMR (Kott, 2010), other research does indicate benefits with the feeding of high nutrient density rations in a pelleted form. In most of these trials, the concentrate levels could however be defined as in the intermediate range (50 - 30%) (Zhong *et al*., 2018; Zhang *et al*., 2019; Li *et al*., 2021). Australian research (Bowen *et al*., 2006) also reported higher growth rates in lambs receiving a CPR (158 g/day; $P < 0.05$) compared to lambs being fed a TMR (138 g/day). In the latter study, the grain in the commercial feed pellets used were however in the form of grain sorghum, a type of grain with well-known processing advantages (Kott, 2010). Pelleting may also influence rumen development via the effect on starch degradability and VFA concentration. Chinese research (Li *et al*., 2021) indicated that the physical form of lamb starter feed as well as the processing does affect the performance of lambs over the weaning transition period. In this study, coarse textured feed (TMR) was more beneficial to lambs over the weaning transition than pelleting feed in promoting gastrointestinal development, intestinal enzyme activities, nutrient digestibility, and growth performance. The greater rumen wall weight and papillae length in this study suggest that the physical form of the starter feed had effects on gastrointestinal tract morphology and development over weaning transition. In contrast however, Zhong *et al*. (2018) reported that compared to a TMR, a CPR increased rumen papillae development and rumen fermentation. Although there seems to be contrasting results in the literature regarding the advantages of pelleting in high nutrient density diets, other factors such as the concentrate to roughage ratio, the degradability of the grains used and the use of other additives like rumen buffers may all have played a role.

3.4.3.4 Effects of different pellet sizes

It is clear from Table 3.7 and Figure 3.5 that feed pellet size did not have any significant impact on performance in the low-density diets, although the lambs on the L8 diet numerically had a 9.3% better ADG than the L6 group and a 5.7% better ADG than the L4 group of lambs. In the high-density diets however, the H6 group significantly (ADG = 305 g/d; *P = 0.04*) and the H8 group numerically (ADG = 294 g/d; *P = 0.12*) outperformed the H4 group (ADG = 261 g/d). No differences in ADG were observed between H6 or H8 (Table 3.7). The significant difference between the H4 and H6 group correlates with a significant lower feed intake (1557 g/d vs 1751g/d; *P = 0.02*) of the H4 group of lambs (Table 3.7).

From a feed manufacturing point of view, smaller pellet sizes may be beneficial when pellet quality is considered as it normally results in better pellet quality with less fines (Muramatsu *et al*., 2015). This is because smaller pellets require more force through the smaller dies, with associated higher temperatures; resulting in better genitalization (Muramatsu *et al*., 2015). From a ruminant production perspective, larger pellets may however, have advantages. It is possible that the smaller pellet size used in the H4 group of lambs may have influenced rumen fermentation via the larger relative surface area of the smaller macro-particles (Gardner *et al*., 1997). Additionally, micro-particles of the H4 diet may have been smaller because of the grinding effect of forcing the feed through the smaller dies. In the LD groups where the ration contained lower levels of fermentable carbohydrates, the negative impact of a likely higher fermentability and a lower rumen pH was not observed (Rowe *et al*., 1999; Dehghan-banadaky *et al*., 2007). This hypothesis agrees with an in vitro study of Bertipaglia *et al*. (2010), who found that when compared to a meal, pelleting leads to higher gas production during the first 6 h of incubation. The researchers concluded that smaller pellet sizes may increase the available surface area for microbial degradation and enhance substrate fermentation. Castrillo *et al*. (2013) came to the same conclusion when comparing the effect of different pellet sizes on rumen fermentation in calves. Increasing the pellet diameter from 3.5mm to 10 mm decreased the rate of fermentation through a more homogeneous daily intake pattern, although in contrast to the current results, DMI was not affected.

Although research on pellet size effects in sheep nutrition is lacking, research on early weaning calves carried out at Harper Adams University College in the U.K (Marsh and Lingham, 2011), supported the notion that larger pellets may improve animal performance. Compared to calves receiving 4mm pellets, calves fed a 6mm pellet had higher feed intakes and were 6.5kg heavier at 12 weeks of age (Marsh and Lingham, 2011). No differences in feed efficiency were however observed (Marsh and Lingham, 2011).

3.4.4 Feed Efficiency

The feed efficiency of the lambs was measured by determining FCR. For the current trial FCR was defined as the ratio between feed intake (kg DM) and liveweight gain (kg). Figure 3.6 demonstrates the differences in average FCR of the lambs over the 7-week period for each treatment group. The L0 group achieved the highest average FCR (6.9 kg ± 0.90) and was significantly higher ($P < 0.05$) than any other treatment group (Table 3.7). Lambs that received the H8 diet resulted in the lowest average FCR (4.77 kg ± 0.54). Considering diet density as a main effect, the high-density groups (4.91 kg) were significantly ($P < 0.05$) more efficient than the low-density groups (5.69 kg) (Table 3.5). When processing was considered all pelleted treatments significantly ($P < 0.05$) outperformed non-pelleted treatments (Table 3.6), however no differences were observed between pellet sizes (Table 3.6).

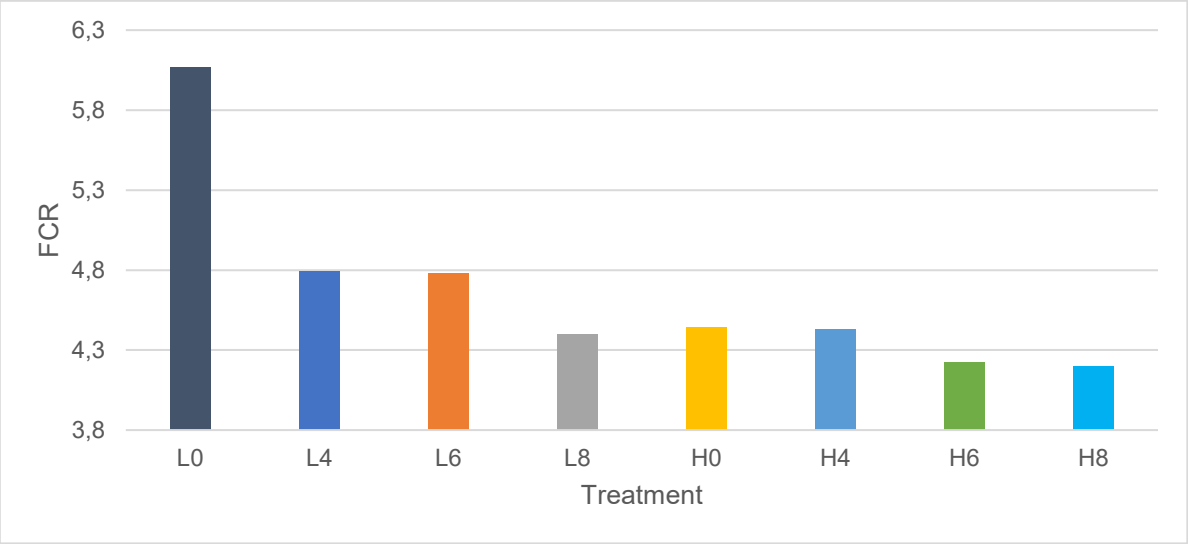

Figure 3.7. Mean FCR of the lambs over a 7- week period for each treatment group.

3.4.4.1 Measuring feed efficiency

An increase in profitability of lamb production is dependent on reducing input costs and/or increasing production output (Snowder and Van Vleck, 2003). Under feedlot circumstances, the cost of feed is an important economic input factor whereas lamb growth rate is an important economic output factor. Any change in feed efficiency without compromising growth rate or carcass quality can therefore have a substantial economic impact on lamb production (Snowder and Van Vleck, 2003). The most common method of measuring feed efficiency (FE) is via the use of feed conversion ratio (FCR) (Kerley, 2012). This is defined as the ratio between gain output and feed input and is also commonly expressed as gain-to-feed ratio (Kerley, 2012). In meat producing animals, the output meat, or the body weight gained by the animal, represented either in the final weight of the animal

or the weight of the dressed output. Animals that have a low FCR are considered efficient users of feed. Live weight is also a very rough measurement of growth because of the dramatic impact of gastrointestinal fill as prices are based on hot carcass weights and it is therefore important to take dressing percentage into account (Erickson, 2010). For the current trial, feed intake was calculated on a DM basis (88% DM), which is the general standard and dressing percentage was not incorporated and live full-belly weight was used.

3.4.4.2 Feed conversion standards

In the current trial, FCR varied from 6.07 kg DMI/kg gain for the L0 group to 4.20 kg DMI/kg gain for the H8 group (Table 3.7). These results are in accordance with published research. According to the NRC (2007), the FCR for lambs is often in the range of about 4 to 5 on high-concentrate diets, 5 to 6 on some forages of good quality, and more than 6 on feeds of lesser quality. The feed conversion ratio tends to be higher for older lambs (e.g. 8 months) compared to younger lambs (e.g. 4 months) (NRC, 2007). A report from MLA (Meat & Livestock Australia) showed significant variation in feed efficiency between individual lambs, with FCR ranging from the most efficient being 2.5:1 to the least efficient of approximately 14:1 (Male, 2012). A survey by Jolly and Wallace (2007) of intensive lamb finishers in Australia revealed an average FCR between 5:1 and 6:1 with only 17% of small operations experiencing an average FCR of greater than 7:1. South African Mutton Merino (SAMM) lambs average FCR were reported between 4:1 and 5:1 from several research trails (Sheridan *et al*. 2003; Brand *et al*., 2017; Swart, 2012).

3.4.4.3 Growth rate and FCR: Effect of processing LD diets

Although feed efficiency has a genetic basis, heritability estimates of ≈0.26 for feed conversion ratio (Snowder and Van Vleck, 2003), indicate the important role of other non-genetic factors. The significant ($P < 0.05$) poorer feed efficiency of the L0 group was expected due to the significant ($P < 0.05$) lower average growth rate of the group. Growth rate is a good indicator of efficiency because a higher growth rate is associated with a lower maintenance requirement and thus a saving in feed costs. A strong negative correlation (-0.61 to -0.95) exists between growth rate and the FCR (Retallick and Faulkner, 2012). A decrease in FCR in higher ADG animals can be accomplished through dilution of the proportion of nutrients diverted toward maintenance of the animal (Cannas *et al.,* 2004). Because nutrient requirements for maintenance are to a large extent fixed, nutrients supplied above these fixed requirements are then partitioned among different functions (in this instance growth) (Cannas *et al.,* 2004; Bach *et al*., 2020). The lambs in the H0 group therefore required a longer feeding period and utilized relatively more total feed for maintenance than the other groups. This result

is in support to the findings from *Esplin et al*. (1957), Van der Merwe *et al*. (1962) and Blanco *et al*. (2014a).

3.4.4.4 Nutrient density and FCR

Although not significant, there is a tendency ($P < 0.10$) amongst lambs receiving HD pelleted rations to have an increased FCR than lambs receiving the LD rations (average FCR = 4.65 vs 4.28) was observed. Several research indicates that the feeding of higher nutrient density diets will result in improved FCR (Kott, 2010). By comparing low, medium, and high-energy diets given to lambs in a feedlot with similar ADG's, Malik *et al*. (1996) showed that the lambs receiving the high-energy diet attained a FCR that was superior to those receiving the low or medium energy diets respectively. The influence of energy density on FCR was also illustrated in a study where SAMM lambs were fed two diets with different energy concentrations (Sheridan *et al*., 2003). In the latter study, the lambs receiving the high ME (12.1 MJ/kg DM) diet resulted in a significantly ($P < 0.05$) higher ADG and were more efficient (FCR of 5.56 vs. 9.40 than lambs fed a low ME (9.9 MJ/kg DM) diet. The absence of FCR differences of the current study can be attributed to the use of LW growth data. The use of carcass data would have resulted in more pronounced differences between HD and LD groups.

3.4.4.5 Processing HD feed and FCR

In contrast to the positive effect of processing on the FCR of the LD rations, pelleting did not produce any significant positive effect on the FCR of the HD lambs (Table 3.7). This is in accordance with most research indicating that in sheep, other than in growing cattle, the processing of grains or high energy diets will not improve the feed efficiency (FE). Campling (1991) illustrated that the processing of whole grain in mixed diets for feedlot cattle have led to approximately a two-fold increase in starch digestibility of cattle compared with the feeding of whole grains. Nevertheless, sheep are much better utilisers of whole grain than cattle (Rowe *et al*., 1999), and early research on the effects of processing on rumen fermentation parameters and feed efficiency in sheep demonstrated that feed utilization is not improved by processing the various cereals (Ørskov *et al*., 1974) (Table 3.11). A later review concluded that any processing of grain given to sheep is likely to be of no value and may even have a negative effect as it can give rise to carcass quality problems, acidosis and the inhibition of cellulose digestion (Ørskov, 1979).

Table 3.11 The effects of processing on rumen pH, volatile fatty acid proportions in the rumen, ADG and FCR in sheep (Ørskov *et al.,* 1974).

Cereal	Form	Rumen pH	Acetic acid: Propionic acid	ADG (g/d)	FCR (kgDM/kg gain)
Barley	Whole loose	6.4	1.74:1	340	2.75
	Ground pelleted	5.4	0.99:1	347	2.79
Maize	Whole loose	6.1	1.22:1	345	2.52
	Ground pelleted	5.2	0.96:1	346	2.62
Oats	Whole loose	6.7	3.49:1	241	3.07
	Ground pelleted	6.1	1.42:1	238	3.33
Wheat	Whole loose	5.9	1.62:1	303	2.97
	Ground pelleted	5.0	0.80:1	323	2.56

3.4.5 Dressing Percentage

The average DP of the lambs that received HD diets were significantly higher ($P < 0.05$) than the DP of lambs on LD diets (Table 3.5). There were no significant differences found among the groups within groups of the same density diet (Table 3.6). The average dressing percentage (DP) of the lambs for each treatment group is presented in Figure 3.7. Lambs that received the H8 diet numerically had the highest average DP (48.99% ± 1.29) and were found to be significantly ($P < 0.05$) higher than the DP of all the other low-density groups (Table 3.7). Furthermore, the L4 group resulted in the lowest dressing percentage (43.90% ± 2.26), which was significantly ($P < 0.05$) lower than the DP of all the high-density feed groups.

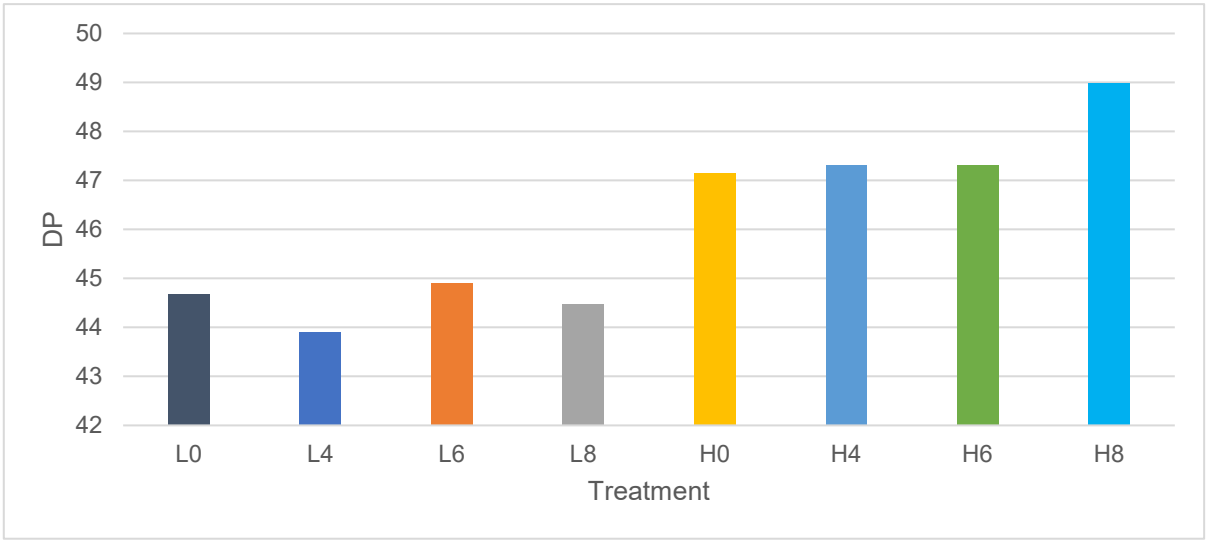

Figure 3.8 Mean dressing percentage of the lambs for each treatment group.

DP can be defined as the ratio between the hot carcass weight and the live weight of the animal, and therefore is of considerable economic importance (Kirton *et al.,* 1984). Dressing percentage is highly inconsistent in sheep and can vary from 36% to 60% and depends on many factors, e.g., age or weight at slaughter, husbandry system, breed, and sex (Corazzin *et al.*, 2019). The result of the current study illustrates that nutrient density has a significant influence on DP and composition of LW growth of lambs. This in turn might influence the profitability of finishing between the LD and the HD groups of lambs, because carcass weight and not LW determines product value. From Table 3.5 the average DPs of the lambs that received HD diets (47.7%) were significantly ($P < 0.05$) higher than the lambs on LD diets (44.5%). A South African study on lamb growth characteristics in commercial feedlots of SAMM feedlot lambs, showed that the average DP ranges between 44.2% and 48.9% (Brand *et al*., 2017).

The higher DP of lambs fed higher levels of concentrates (HD groups vs LD groups) agrees with earlier studies by Black and Chestnutt (1992), Chestnutt (1994), Jaborek *et al*. (2017) and Claffey *et al*. (2018). One of the most important factors influencing the DP in lambs is the weight of the gut at weighing, with gut fill that may vary between 10% and 22% of pre-fast live weight (Litherland *et al*., 2010). Feeding lambs high levels of bulky forages which are slow to digest can lead to an increased digestive tract size and weight. As a result, the gastrointestinal tract is greater in mass and thus has a negative effect on the DP of lambs (Litherland *et al*., 2010). Majdoub-Mathlouthi *et al*. (2013) showed that the DP of lambs increased ($P < 0.01$) by 2.7% when the concentrate level increased from 300 g/day to 600 g/day while Papi *et al*. (2011) reported a 4.9% increase in DP when concentrate proportion went from 30 to 50%. Higher DP with concentrate feeding has also been illustrated in cattle. Feedlot steers fed higher levels of roughage, resulted in significantly lower DP's at similar live weights (62.8 vs 65.9 and 65.3% for steers fed diets composed of 75, 30, and 14% maize silage respectively in high-moisture maize diets (Gill *et al*., 1976).

Previous studies involving different nutrient densities have demonstrated inconsistent results with respect to DP in lambs, and a lower DP is not a consistent finding with higher levels of roughage in the diet of lambs. A Mexican study (Fimbres *et al*., 2002) reported that although carcass weight decreased with increased levels (0 - 30%) of hay in the diet, dressing percentage ($P > 0.05$) was not affected by the percentage of hay in the diet. An earlier study in Canada (Petit and Castonguay, 1994) also did not find any effect of diet composition on DP. Various other trials also showed that nutrient density level in high energy finishing diets of lambs had small effects on DP of lambs (Beauchemin *et al*., 1995; Kumari *et al*., 2012; Ríos-Rincón *et al*., 2014).

From the current results the LW of the animals at slaughter was not well correlated with the quantity of saleable product. Differences in digestive tract fill and LW body

composition render full-belly BW alone imprecise as an indicator of growth and feed efficiency (Owens *et al*., 1993).

3.4.6 Profitability

The effect of feed density and feed processing on GP, is graphically illustrated in Figure 3.8 while means, SD and significance are presented in Tables 3.5, 3.6 and 3.7. Both the pelleted LD and pelleted HD groups of lambs tended to show an increase in GP as pellet size increased. Mean GP for the LD groups was R156.58/lamb, or R138.58/lamb (88%) lower than the mean GP of R295.16/lamb that was achieved by the HD groups (Table 3.5). The mean GP of the lambs fed on the 8 mm diets, were the highest (R277.22 ± 101.1) and was significantly ($P < 0.05$) higher than either the control or 4mm feed groups. The lambs that received the L0 diet resulted in the lowest mean GP (R75.97 ± 49.44) and were found to be significantly ($P < 0.05$) lower than the GP of other treatment groups except for the lambs fed the L4 diet (Table 3.7). Furthermore, lambs that received the H8 diet achieved the highest mean GP (R345.64 ± 74.57) and were significantly ($P < 0.05$) higher than the GP of all the LD groups. The mean GP of the lambs that received the H0, H4 and H6 diets were significantly ($P < 0.05$) higher than the GP of the L0 and L4 groups. Although just not significant ($P = 0.08$), the mean GP of the H8 group was R85.55/lamb or 33% higher than the mean GP of the H4 group.

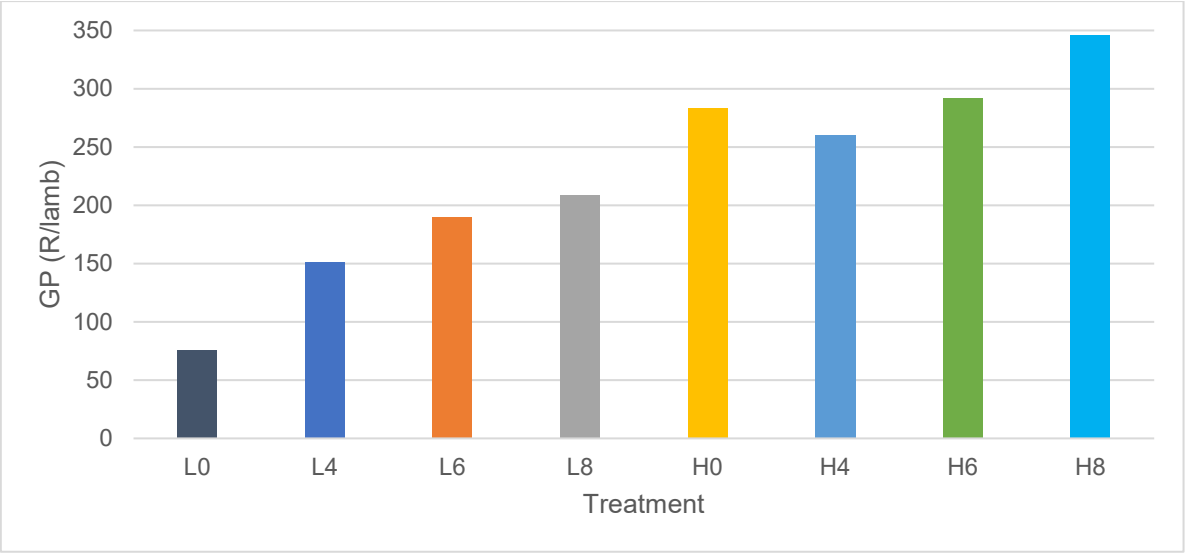

Figure 3.9. Mean GP (R/lamb) of the lambs for each treatment group.

Table 3.12 illustrates the total feed cost (Rand/kg) as well as the proposed feed selling price used for second scenario to calculate the GPM. The average GP calculated with the incorporated R500 margin of the pelleted feed is presented in Table 3.7 and Figure 3.9.

Table 3.12 Feed cost of the different treatments.

Treatment	Feed (R/kg)	Mix & Mill (R/kg)	Pelleting Cost R/kg	Total Processing Cost (R/kg)	Total Feed Cost (R/kg)	Selling Price[1] (R/kg)
L0	2.75	0.21	-	0.21	2.97	2.97
L4	2.75	0.43	0.07	0.50	3.25	3.75
L6	2.75	0.43	0.07	0.50	3.25	3.75
L8	2.75	0.43	0.06	0.49	3.24	3.74
H0	3.20	0.21	-	0.21	3.42	3.42
H4	3.20	0.43	0.07	0.50	3.70	4.20
H6	3.20	0.43	0.07	0.50	3.70	4.20
H8	3.20	0.43	0.06	0.49	3.69	4.19

[1]Estimated margin feeding price

Considering scenario 2, the GP of H0 exceeds that of the H6 group and this income is also significantly higher ($P < 0.05$) than that of the L6 and L8 groups (Table 3.7 and Figure 3.9). Under scenario 2, the GP of the L0 group does not differ significantly anymore from the GP of the other low-density feed groups (Table 3.7).

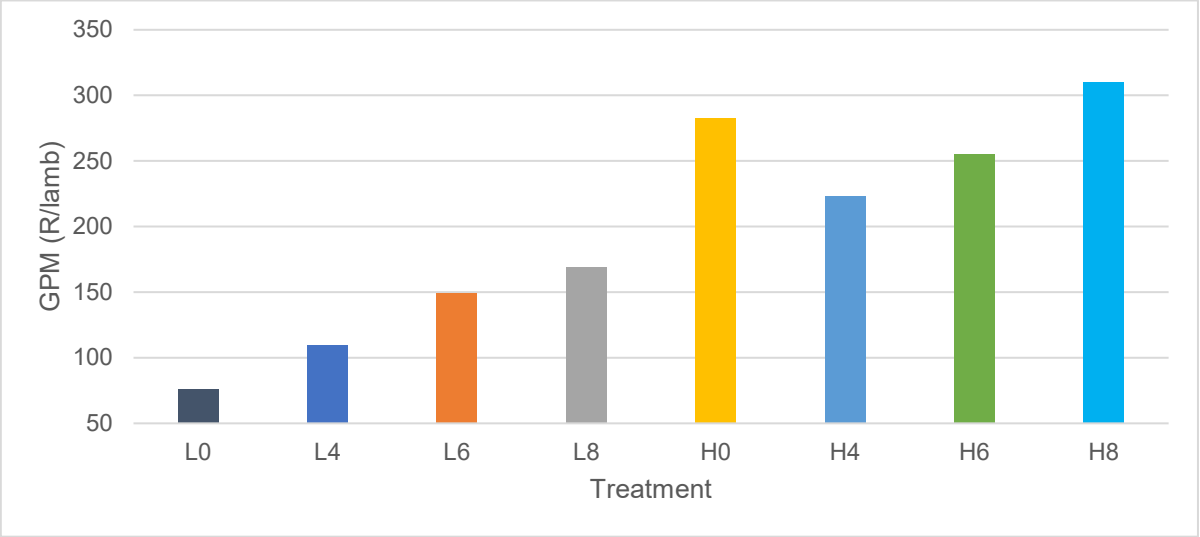

Figure 3.10 GPM (R/lamb) of the lambs for all treatment groups.

3.4.6.1 Profitability in the feedlot

Research regarding the cost-effectiveness of feedlots has revealed that many factors play a role in determining the profit, including ADG (Spies, 2011), FCR (Lima *et al.*, 2017),

purchase price (Van Zyl, 2021), carcass income (Oosthuizen, 2016), dressing percentage (Coyne *et al.,* 2019), feeding costs (Retallick, 2012) and mortality rate (Johnsen and Pendell, 2017). Profitability will be improved if these factors can be successfully managed (Lombard and Maré, 2015). Lima *et al*. (2017) confirmed that the main factors affecting feedlot profit margins include the purchase price of store lambs, the carcass price along with the dressing percentage of the carcass, the price of feed consumed by the animal, as well as the efficiency of growth achieved. The ability of the feedlot operator to manipulate the exact level of several of these profit drivers is very limited, since most of them are driven by economic and market forces (Oosthuizen, 2016). Although the price margin (purchase and carcass price) has a larger influence on the gross profit, feeding cost represents the largest proportion of the cost allocated to the amount of weight gained, and maximum efficiency is essential to ensure profitability in the feedlot (Maré *et al*., 2010).

3.4.6.2 Influence of nutrient density

Although the increase in nutrient density in the current study did not result in significant higher growth rates, the higher DP in the HD groups of lambs increased carcass value to these lambs with consequential superior profitability. The efficiency of carcass weight gain was therefore found to be higher in the HD groups of lambs, leading to better profitability (Table 3.5). The result of the current study therefore supports commercial industry standards that, from a profitability perspective, HD diets are preferred over LD diets. The main reasons include:

i. When compared with grazed or harvested forages, concentrate diets usually provide net energy for gain (NEg) at a lower cost (Owens, 2015). The efficiency with which metabolizable energy (ME) is converted to nett energy (NE) is referred to as the efficiency constant, k (Kaasik, 2010). When it comes to growth, k_g would apply. Because more of the ME in high-forage diets are lost to heat, k_g would be lower in low-density diets and growth is not expected to be equal to iso-caloric high concentrate diets (Weiss, 2010)**.** When comparing high roughage vs. high concentrate-based diets, a factor that may contribute to a lower k_g value is the higher ratio of acetate: propionate in ruminal fluid with lower nutrient density diets (NRC, 2007). Diets with increasing levels of concentrates decrease the acetate: propionate ratio in the rumen (Wang *et al.,* 2020). The ratio of the heat increments of the individual volatile fatty acids (VFA) produced in the rumen are 1.8:1.2:1.0 for acetic acid, propionic acid, and butyric acid (Jaborek *et al*., 2017). Therefore, the net energy content of the longer carbon chain VFA's, propionate and butyrate, are greater than for acetate. Mixtures of VFA with a

lower acetate: propionate ratio were therefore more energetically efficient and allowed for more energy to be retained by the sheep for growth (Jaborek *et al*., 2017). Further, concentrate-based diets are more digestible, have a greater rumen flow rate and have a lower ruminal methane production (Pereira *et al*., 2010).

ii. The extent and rate of body weight gain (in the current trial, carcass weight gain) is greater with concentrate when compared to roughage-based diets. Increasing the level of concentrate in the diet is known to increase the rate of gain of lambs (Jaborek *et al*., 2017). Baldwin and McLeod (2000) reported that lamb performance, as measured by DMI, ADG, and efficiency of gain, was greater ($P < 0.005$) when lambs consumed pelleted diets of 75% concentrate compared to pelleted diets with 75% forage. Two separate Brazilian studies (Bueno *et al*., 2004; Moreno *et al*., 2010) observed that increasing the amount of concentrate in the diet from 40% to 60%, improved daily weight gain in lambs. De Sousa *et al*. (2012) observed an interaction of feed conversion, carcass dressing yield and gross margin in feedlot lambs, resulting in lambs on 97% concentrates being more profitable than lambs receiving 50% concentrates.

iii. High concentrate diets can be transported more readily, handled, and processed and therefore result in less indigestible waste than forage-based diets (Owens, 2015). The result is that although roughages contain less energy than concentrates, when priced on an energy basis; roughages are much more expensive than concentrates (Homm, 2007). In the current trial, the as fed diet cost (R/kg) for the L0 and H0 formulated feed were R3.42/kg and R2.97/kg respectively, a 13.2% difference. Nevertheless, the costs in R/MJ ME differed by only 1% (R0.302/MJ for the H0 diet and R0.299/MJ for the L0 diet respectively).

iv. Pelleting cost of roughage-based diets is higher than concentrate based rations. Although pelleting of roughages by a feed mill has the advantages of expanding the potential sources of ingredients and saving of storage space and labour costs (Zhong *et al*., 2018), the grinding process is more expensive for concentrates than for roughages. Operating costs associated with pelleting include the production of steam for conditioning and electrical energy to operate the pellet mill. Electrical energy is typically considered the most important variable cost to monitor (Fahrenholz, 2012). In diets with higher bulk density (e.g., high roughage diets), an excess amount of energy is required in the mill to compress the material before it can be extruded through the die (Behnke, 1996). Normally, grinding of feed is required before pelleting as this step improves pellet quality and the general rule is that the finer the grind, the better the pellet quality (Butler, 1958). This is mainly because grinding increases gelatinisation during conditioning, which is essential for pellet quality (Muramatsu *et al.,* 2014).

Generally, compound pelleted feeds would have an average particle size of approximately 0.5 to 0.7 mm, with no particles > 1.0-1.5 mm (Behnke, 2001). Particle sizes below 1mm required less energy to pellet and produced pellets with a higher compressive strength (Behnke, 2001). The energy consumption for the milling process, depends primarily on the degree of particle size reduction and the type of feedstuff (Nielsen *et al*., 2020). Roughages thus require more energy and require a hammer mill for grinding, while a roller mill can be used for the grinding of concentrates. The energy cost (R/kWh) of a roller mill is 15 to 85% less per hour for the same tonnage (CPM, 2021). Besides lower energy consumption, quality of pellets will also be better when using a roller mill instead of a hammer mill (Vukmirović *et al*., 2016).

3.4.6.3 Processing effects on profitability

Compared to a TMR, pelleting requires additional costs due to high energy demand and capital for equipment including bins, grinding mills, pellet presses and conditioning equipment (CPM, 2021a). Because the feed is already mixed and blend into a TMR before pelleting, additional costs for investment in pelleting equipment should be considered with respect to economic advantages that can be achieved by pelleting (Thomas and Van der Poel, 1996). The operational cost of a feed pellet mill is evaluated on the energy consumption and wear rate of the dies and rollers (CPM, 2021a). The energy consumptions for swine and poultry feeds are estimated at 8-12 kWh/t and for roughage (lucerne) pellets at 26.5-33 kWh/t (Nielsen *et al*., 2020). In 2014, pelleting cost of broiler feeds in South Africa amounted to approximately R70 per ton (Louw and Einkamerer, 2014). Total processing cost for diets in the current study was an estimated R500 per ton (Table 3.9), which contributed to between 13.5% and 15% of the total feed cost. A conservative R500/t was budgeted for feed delivery and feed mill profit.

In the current study, pelleting did not have an unconditional or direct effect on profitability, but an interaction was observed between nutrient density and processing. This was expected given the significant effect of pelleting on the FCR and growth rate of the lambs on LD rations, while no such effects were observed in lambs fed the HD diets. Even with the added profit of the feed company, pelleting of the LD diets was still considered a more economic option (Figure 3.9; Table 3.7). In addition, other positive effects of pelleting e.g. the prevention of ingredient segregation and reduced selective feeding and wastage (Behnke, 2001; DKP, 2020), appears to be more pronounced in the LD diets compared to the HD diets.

3.4.6.4 Effect of pellet size on profitability

Although not significant, the trend of a better feed efficiency with an increase in pellet size, was also reflected in the gross margin analysis (Table 3.7). Compared to the 4 mm size pellets, the 8 mm size pellets gave in both the LD and HD groups the highest gross margin, increasing gross profit by 38.0% and by 32.9% respectively. Research on economic implications of pellet size of feedlot lambs is limited, and further investigations under a wider field of circumstances is needed before any definite deductions can be made.

3.4.7 Faecal score (FS)

The change in mean FS of the lambs for each treatment group is illustrated in Figure 3.10 and Figure 3.11. No significant differences were found between the treatment groups. Mean FS as well as variation in FS decreased over time in the feedlot (Figure 3.11). In both the LD and HD groups, lambs on the 4 mm pellets showed the lowest numerical mean FS, while the L8 group showed the highest numerical mean FS of all the treatment groups (Figure 3.10).

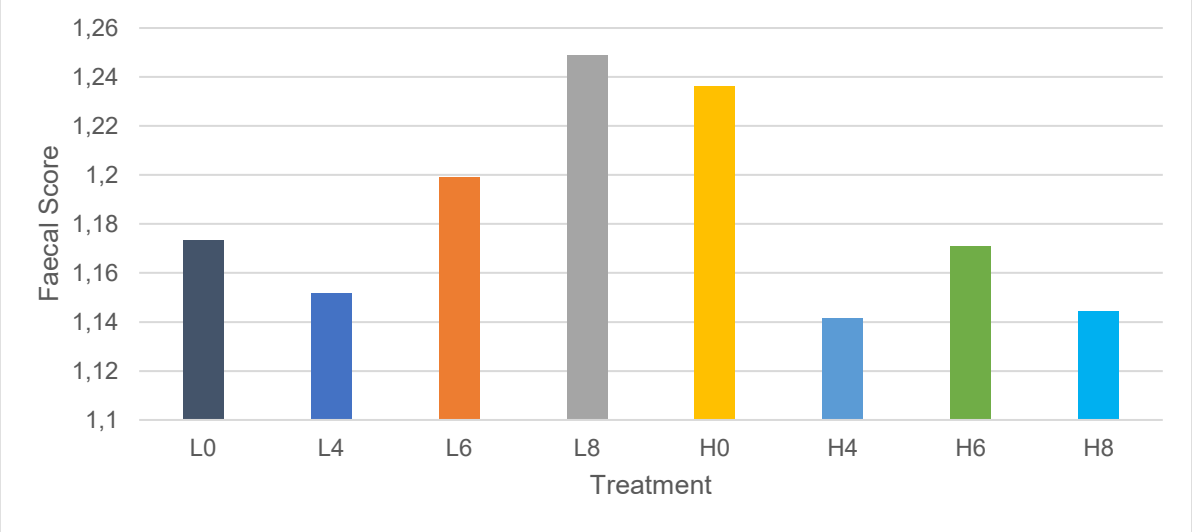

Figure 3.11 Mean FS of the lambs for each treatment group.

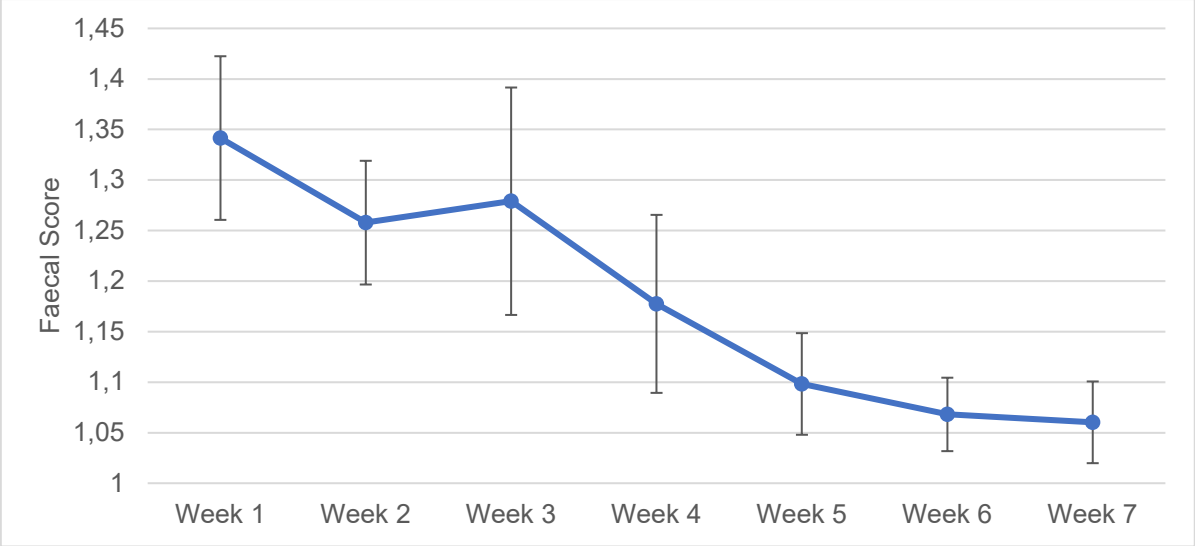

Figure 3.12 Change in mean and standard error FS of the lambs in all the groups over a 7-week period.

Although diet form (pellets vs. TMR) and particle size (pellet size) could also have a significant impact on gastrointestinal functionality (Celi *et al*., 2017), in the current study no significant differences in faecal consistency (FC) could be established between treatment groups. Figure 3.11 however indicates a downward trend of both FS and FC variation over time in the feedlot. The only exceptions were during weeks 3 and 4, which could be explained by bedding challenges during week 3 to 4. Gradual introduction of grain facilitates the development of a stable bacterial population that is able to utilise the new substrate and metabolise lactic acid (Bowen *et al*., 2006). Although the adaptation of the microbial environment has been reported to take approximately ten days in sheep (Warner, 1962) with the efficacy increasing each week (Dirksen *et al*., 1985). The decreasing trend recorded in FC values (Figure 3.11) was expected and could be explained by the better adaption over time. Considerable diversity in the ability of animals to cope with ingested cereal grain is evident, and a portion of this diversity may relate to the maintenance of protozoal populations (Brown *et al*., 2006). In sheep, the number of animals struggling to adapt to high starch diets may even be more pronounced, and it is considered normal to experience at least 5% shy feeders in the feedlot (Kirby *et al*., 2004). Effective functionality of the gastrointestinal tract (GIT) and its health are important factors in determining animal performance *(Celi et al*., 2017). However, while gut health is an increasingly important topic in animal nutrition, a clear scientific definition is still lacking although it has been used repeatedly in animal health (Kogut and Arsenault, 2016).

Although faecal consistency scoring is a subjective measurement, manure evaluation in dairy cows may provide valuable information regarding the site and extent of both digestion

and fermentation of consumed feeds. The consistency of manure is a function of the feed moisture content and the mean retention time of the feed in the digestive tract of the animal (Heinrichs and Varga, 2016). Ireland-Perry and Stallings (1993) evaluated dietary treatment effect on FC in dairy cattle. Results of the latter study indicated that lower dietary fibre reduced faecal pH and FC. However, FC varied among cows on the same diet, and FS and faecal DM were not related positively in all situations. Thus, according to the author, cows consuming a high roughage diet (higher in crude fibre and lower in DM), excreted faeces with a lower FC score (harder).

Under feedlot circumstances, Da Silva *et al*. (2012) evaluated the effects of high concentrate diets on faecal indicators of Nellore bulls. Results indicated that diets with lower physical effective neutral detergent fibre (peNDF) content showed lower faecal consistency and lower levels of faecal NDF. Cunha *et al*. (2021) using data of 15 commercial beef feedlots also reported that faecal DM was lower ($P < 0.05$) for animals fed diets where peNDF ≥ 20%. This finding was explained by a positive effect of higher fibre on chewing activity, saliva and sodium bicarbonate secretion and subsequent improved rumen health (Cunha *et al*., 2021). In feedlot cattle with mild or subacute ruminal acidosis, loose manure are commonly present with manure often smeared across their hindquarters (soiling) (Meyer and Bryant, 2017).

Although research on FC in lambs are very limited, it is well known that a low FC in lambs (diarrhoea) is a complex, multifactorial condition involving the animal's susceptibilities, the environment, nutrition, infectious agents, and management (Bayne and Edmondson, 2021). It has been ascribed to numerous factors such as intestinal pathogens and parasites, fungal endophytes, dietary composition, and water absorption (Mitchell and Linklater, 1983). For weaned lambs on pastures, gastrointestinal parasitic infestation and an increase in nematode egg counts are the most significant factors associated with a decrease in FC (Broughan and Wall, 2007). Nematodes are normally not a problem in confined (feedlot) animals, because grazing forages (pastures) play a crucial role in the life cycle of the parasites (Starkey and Pugh, 2021). It is therefore clear that more research is necessary to illustrate the associations between FC and rumen health, feed composition or other production parameters in feedlot lambs.

3.5 Conclusion

In conclusion, the pelleting LD diets improved growth and economic performance of fattening lambs mainly due to an increase in DMI and a better FCR, while pelleting of HD diets did not have similar positive effects on lamb performance. Compared to lambs on LD diets, the feeding of HD diets resulted in higher gross profits of feedlot lambs mainly due to the better carcass yield of these lambs. The feeding of a complete pelleted diet is a feasible strategy for

intensive lamb fattening operations, although the effect of pelleting on lamb performance will be greater with low density diets. From an economic point of view, the feeding of a high nutrient density TMR may also be advisable under specific circumstances, e.g., if mixing equipment is available on a farm. The use of larger diameter pellets in a HD diet seems to be more beneficial to lamb performance when compared to smaller diameter pellets. Further investigation into the interaction of nutrient density and pellet diameter is, however, needed. No association could be established between faecal consistency and either feed composition or feed processing, although FC score did indicate a downward trend over time in the feedlot.

3.6 References

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CHAPTER 4
THE EFFECT OF FEED PROCESSING AND NUTRIENT DENSITY LEVEL ON RUMEN FERMENTATION PARAMETERS OF SHEEP.

4.1 Abstract

The aim of this study was to evaluate the effects of feed pelleting, and nutrient density on the rumen fermentation parameters of sheep. A total of eight mature S.A. Mutton Merino ewes were used in a change-over design in a repeated observations experiment. The main treatment blocks were either high nutrient density (HD) or low nutrient density (LD) diets. Within each treatment block, the control group was offered a unpelleted total mixed ration (TMR) (L0 and H0). Three treatment groups within each block were offered a complete pelleted ration (CPR) with pellet sizes of 4 mm (L4 and H4), 6 mm (L6 and H6) and 8 mm (L8 and H8) diameter. The mean ruminal pH of the sheep decreased to a minimum at approximately 4 hours after feeding, after which the pH slowly returned to the initial values. The sheep that received both the L8 and L6 diets had the lowest average pH at 4 hours after feeding (5.15 pH ± 0.12; 5.15 pH ± 0.17), while group H0 showed the lowest reduction in pH (6.14 pH ± 0.41; $P < 0.01$). The ruminal pH of sheep on all three of the LD pelleted diets, experienced a lower ($P < 0.05$) pH for a longer time after the meals compared to what was observed in the HD pelleted diets. Sheep that were fed unpelleted feeds (H0 and L0), manifested a lower significant pH reduction and a slower recovery rate to initial pH than what had been seen in the sheep fed pelleted feeds. Concentrations of volatile fatty acids (VFA) were higher ($P < 0.05$) in the LD groups than in the HD groups. Rumen ammonia nitrogen (RAN) measurements and methylene blue reduction (MBR) test results did not indicate any association between nutrient density and level of processing of the diet. The faecal pH of the sheep at 6 hours after feeding did not show any definite association with either feed nutrient density or level of processing. The same was observed with the MBR test on the ruminal fluid at 6 hours after feeding. The observed differences in rumen fermentation parameters in sheep on HD and LD diets, could be explained by the higher feed intakes of sheep on the LD diets ($P < 0.05$), with an accompanying lower pH reduction and higher VFA concentrations of the ruminal fluid.

4.2 Introduction

In high-producing ruminants, highly fermentable diets are often used for improved production especially during the finishing of feedlots or peak lactation periods (Plaizier *et al.,* 2008). Diets containing excessive fermentable carbohydrates can however reduce ruminal pH and increase the risk of ruminal acidosis, especially sub-acute ruminal acidosis (SARA) (Nagaraja and Lechtenberg, 2007; Kleen and Cannizzo, 2012). Ruminal acidosis can be defined as a metabolic condition during which rumen osmolality increases because of the accumulation of lactate, short-chain fatty acids and glucose (Meyer and Bryant, 2017). Depression in ruminal pH results in reduced dry matter intake (DMI) and volatile fatty acid (VFA) absorption by the animal (Meyer and Bryant, 2017). This disorder affects rumen function, and can cause milk fat depression, rumen epithelium damage and laminitis in cattle, leading to unnecessary economic losses (Kleen and Cannizzo, 2012; Nejash*,* 2016).

Acidosis can be categorized in several forms, which include acute and sub-acute rumen acidosis (SARA), also known as clinical and sub-clinical rumen acidosis, respectively (González *et al.,* 2012). Nagaraja and Titgemeyer (2007) characterize acute acidosis as being present when rumen pH is below 5.0, lactic acid concentration is above 50 mM/L and ruminal VFA concentration is less than 100 mM/L. Although some discrepancy still exists on the precise definition of SARA (Nejash*,* 2016), the current definition is based on the pH of the rumen fluid (Plaizier *et al.,* 2008), with accepted values depending on method of rumen fluid sampling (Nejash*,* 2016). Duffield *et al*. (2004) proposed that the thresholds for abnormal pH indicating SARA should be 5.5, 5.8 and 5.9 when rumen fluid samples are collected by rumenocentesis, through a rumen cannula from the ventral sac, and using an oral probe, respectively. Although acute rumen acidosis can be fatal to the animal, sub-clinical rumen acidosis is mainly responsible for economic losses in the feedlot and dairy industry (González *et al.,* 2012). Considering the feedlot industry, financial losses due to SARA is predominantly via a reduction in DMI and a subsequent decreased average daily gain (ADG) as well as through an increased treatment cost (Attia, 2016).

A study was therefore conducted at the University of Stellenbosch to investigate the effect of different nutrient density diets and processing methods on the ruminal health of sheep by determining changes in ruminal pH, VFA and rumen ammonia nitrogen (RAN) concentration. A further objective was to evaluate the effects on faecal pH and rumen microbiota activity.

4.3 Materials and Methods

Prior to commencement of the study, ethical clearance was obtained from the Stellenbosch University Animal care and ethics committee (ACU-2021-15156).

4.3.1 Experimental Animals and Management

A change-over design with repeated measurements was used in this experiment and is illustrated in Table 4.1. Eight mature SA Mutton Merino ewes, two to three years of age, with an average initial BW of 80 kg ± 2.0 were used in the trial. Animals were blocked according to initial BW and randomly allocated in a pairwise fashion to treatments. The animals in each of the 4 runs were adapted for 14 days on the respective diets, whereafter the rumen fluid was collected. After the collection of rumen fluid, each pair were moved to an alternative treatment and this procedure was repeated until each of the four pairs had received all treatments resulting in eight replications per treatment. The same LD and HD diets and processing techniques described in Section 3.3.2 and 3.3.3 and Table 3.1 in Chapter 3 were used. All the animals were fed twice daily at 07h00 and 16h00 on an *ad lib* basis. *Ad libitum* water was supplied. On the days of rumen fluid collection, the animals were fed at 07h00 and 19h00.

Thirty days prior to commencement of the trial all animals were equipped with surgically inserted rumen microcannulas according to the method described by Miller and Maltby (1986) to allow for sufficient wound healing time (Komarek, 1981). The cannulas were surgically inserted with the use of local anaesthesia. The microcannulas formed a leak-proof seal between the rumen and abdominal walls while allowing access to the rumen and ensuring an anaerobic seal during non-sampling periods. Figure 4.1 Shows a cross section of the cannula inserted in the ruminal and abdominal walls. The ewes used in the trial were housed in a closed, well-ventilated building with slated floors. Feed troughs were secured in the middle of the pen as to avoid water contamination and cross feeding. The measurements of this study pens were approximately 3.0 m in length and 2.5 m in width (7.5 m^2).

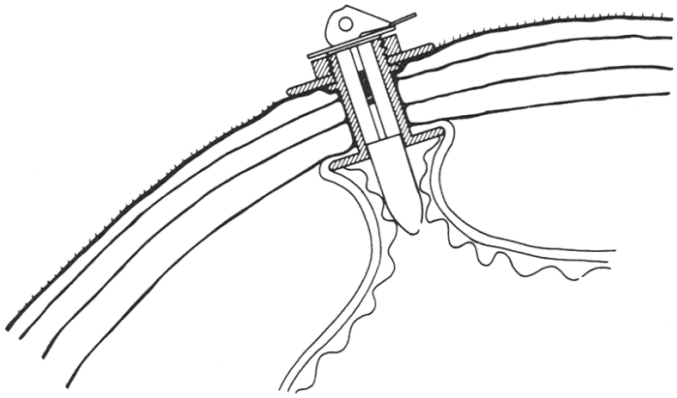

Figure 4.1 Cross section of a rumen cannula inserted through the ruminal and abdominal walls of a sheep (Komarek, 1981).

Table 4.7 The experimental design of the rumen fermentation trial.

	Control Diet		Processing type					
			Pellet size					
			4mm		6mm		8mm	
HD Group	14d Adaptation	Rumen fluid collection	14d Adaptation	Rumen fluid collection	14d Adaptation	Rumen fluid collection	14d Adaptation	Rumen fluid collection
LD Group	14d Adaptation	Rumen fluid collection	14d Adaptation	Rumen fluid collection	14d Adaptation	Rumen fluid collection	14d Adaptation	Rumen fluid collection

4.3.2 Measurements

The aim of this experiment was to evaluate diet density and processing method as main effects on the dynamic changes in rumen fermentation parameters over time, more specifically ruminal fluid pH, rumen ammonia nitrogen (RAN) and volatile fatty acids (VFA). On the day of sampling, ruminal fluid sample were collected via rumen cannulas at 0, 2, 4, 6, 8 and 12 h after feeding from the anterior ventral sac of the rumen. A methylene blue reduction test (MBR) was done on the rumen fluid samples at 6h after feeding. Methylene blue reduction is normally used as a rapid test to evaluate the quality of milk but can also be used to isolate the presence of anaerobic microorganisms including species of *Escherichia coli, Enterococcus, Streptococcus, Staphylococcus, Micrococcus, Bacillus, Corynebacterium* and *Lactobacillus* for bacteria and, *Mucor, Saccharomyces, Rhizopus, Fusarium, Geotrichum, Aspergillus* and *Penicillium* species of fungi (Braide *et al.,* 2015). The remaining rumen fluid was frozen in airtight plastic containers and stored at -20 ^{0}C for laboratory analyses, which included RAN and VFA analyses.

VFA's were determined using a modified procedure decribed by Siegfried *et al*. (1984). This procedure deproteinizes the rumen liquor samples as well as removing the sugars. This results in a clean solution of fermentation products to be analysed for VFA's via gas-liquid chromatography. Gas-liquid chromatography analyses were performed using a Thermo TRACE 1300 GC instrument, fitted with Thermo TriPlus RSH Autosampler and Thermo XCalibur software was used for analysis and processing of the data.

The Broderick and Kang (1980) recommendation of determining ammonia was used for RAN analysis. Rumen liquor samples were thawed and then diluted with deionized water to make a 4x dilution in Eppendorf tubes. The tubes were then centrifuged for 5 minutes at 6000 rpm, whereafter 50 µl are pipetted into 15 ml test tubes. Phenol reagent (2.5 ml) and Hypochlorite reagent (2 ml) were after the tubes were then placed in a water bath at 95 °C for 5 minutes. The tubes were then removed from the water bath and cooled in an ice bath for 5

– 7 minutes. The samples were then pipetted to a microplate, whereafter they were analysed using a spectrophotometer at 630 nm. Faecal pH was measured at 6 h after feeding after rectal collection of faeces. The pH was determined and recorded immediately after collection with the aid of a hand-held pH meter (Hanna pHep®, model HI98107, Smithfield USA).

4.4 Results and Discussion

4.4.1 Interpretation of results

This study was part of a larger feedlot trial. Although the same diets as in the feedlot trial were used (Table 3.2), the rumen fermentation parameters were measured using mature sheep. The data should therefore be carefully interpreted as an indication of rumen fermentation conditions in the feedlot lambs used during the first trial. The results of the key parameters that were focused on in this study are presented in Table 4.2, Table 4.3, and Table 4.4.

Table 4.2 The effect of feed density in sheep on the rumen fermentation parameters. Means with SD presented.

	Feed density	
Parameter	**LD**	**HD**
pH	5.98^{a} ± 0.04	6.4^{b} ± 0.04
Acetate (m/M)	44.7^{a} ± 0.01	28.6^{b} ± 0.01
Propionate (m/M)	29.0^{a} ± 0.00	16.7^{b} ± 0.00
Iso-Butyrate (m/M)	0.5^{a} ± 0.00	0.7^{b} ± 0.00
Butyrate (m/M)	7.6^{a} ± 0.30	5.6^{b} ± 0.30
Iso-Valerate (m/M)	0.57^{a} ± 0.00	0.07^{b} ± 0.00
Valerate (m/M)	2.2^{a} ± 0.09	1.3^{b} ± 0.09
RAN[1] (mg/dL)	2.1 ± 0.13	2.2 ± 0.13
MBR[2] (sec)	141.81^{a} ± 13.28	189.25^{b} ± 13.28
Faecal pH	6.92^{a} ± 0.05	7.48^{b} ± 0.05

[1]Rumen ammonia nitrogen.
[2]Methylene blue reduction test in seconds.
^{a,b}Means within rows with different superscripts differ ($P < 0.05$).

Table 4.3 The effect of feed processing in sheep on the rumen fermentation parameters. Means with SD presented.

	Processing method			
Parameter	**Control**	**4mm**	**6mm**	**8mm**
Rumen pH	$6.3^{a} \pm 0.06$	$6.3^{a} \pm 0.06$	$6.2^{a} \pm 0.06$	$6.0^{b} \pm 0.06$
Acetate (m/M)	$40.8^{a} \pm 0.02$	$33.7^{b} \pm 0.02$	$34.7^{b} \pm 0.02$	$37.3^{ab} \pm 0.02$
Propionate (m/M)	$20.7^{a} \pm 0.01$	$20.0^{a} \pm 0.01$	$21.4^{a} \pm 0.01$	$29.2^{b} \pm 0.01$
Iso-Butyrate (m/M)	$0.8^{a} \pm 0.00$	$0.6^{b} \pm 0.00$	$0.5^{c} \pm 0.00$	$0.5^{bc} \pm 0.00$
Butyrate (m/M)	$9.5^{a} \pm 0.4$	$4.6^{b} \pm 0.4$	$5.1^{b} \pm 0.4$	$7.4^{c} \pm 0.4$
Iso-Valerate (m/M)	$0.76^{a} \pm 0.00$	$0.26^{b} \pm 0.00$	$0.22^{b} \pm 0.00$	$0.05^{c} \pm 0.00$
Valerate (m/M)	$1.3^{a} \pm 0.12$	$1.5^{ab} \pm 0.12$	$1.7^{b} \pm 0.12$	$2.4^{c} \pm 0.12$
RAN (mg/dL)	$2.6^{a} \pm 0.19$	$1.2^{b} \pm 0.19$	$2.1^{a} \pm 0.19$	$2.6^{a} \pm 0.19$
MBR (sec)	$96.25^{a} \pm 18.78$	$175.19^{b} \pm 18.78$	$202.06^{b} \pm 18.78$	$188.63^{b} \pm 18.78$
Faecal pH	$7.0^{a} \pm 0.07$	$7.1^{a} \pm 0.07$	$7.4^{b} \pm 0.07$	$7.2^{ab} \pm 0.07$

[a,b,c.]Means within rows with different superscripts differ ($P < 0.05$).

Table 4.4 The effect of the different treatments in sheep on the rumen fermentation parameters. Means with SD are presented.

	Treatment							
Parameter	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
DMI (kg/day)	$2.54^{c} \pm 0.32$	2.72 ± 0.29	2.77 ± 0.37	$2.91^{a} \pm 0.25$	$2.27^{b} \pm 0.30$	$2.32^{b} \pm 0.33$	$2.33^{b} \pm 0.34$	$2.49^{c} \pm 0.38$
pH (at 4 hours)	$5.93^{a} \pm 0.22$	$5.34^{bc} \pm 0.26$	$5.15^{c} \pm 0.17$	$5.15^{c} \pm 0.12$	$6.14^{a} \pm 0.32$	$5.99^{a} \pm 0.51$	$5.98^{a} \pm 0.29$	$5.45^{b} \pm 0.29$
Acetate in m/M (at 2 hours)	$62.85^{ab} \pm 11.31$	$48.61^{bcd} \pm 12.23$	$64.06^{ac} \pm 29.02$	$71.14^{a} \pm 15.22$	$40.72^{d} \pm 9.12$	$43.47^{d} \pm 20.95$	$43.71^{d} \pm 10.49$	$33.72^{d} \pm 9.42$
Propionate in m/M (at 2 hours)	$31.12^{a} \pm 9.13$	$30.97^{a} \pm 7.72$	$44.6^{b} \pm 18.44$	$52.97^{b} \pm 11.09$	$17.49^{c} \pm 6.95$	$28.12^{ac} \pm 12.79$	$24.57^{ac} \pm 8.7$	$27.02^{ac} \pm 10.25$
RAN[1] in mg/dL (at 2 hours)	$7.124^{a} \pm 1.64$	$2.522^{bd} \pm 1.17$	$4.295^{c} \pm 1.50$	$7.786^{a} \pm 1.71$	$3.902^{cd} \pm 1.14$	$1.093^{b} \pm 1.20$	$6.616^{a} \pm 1.72$	$6.444^{a} \pm 1.62$
MBR[2] (sec)	$85.88^{c} \pm 47.31$	$217.13^{a} \pm 63.65$	$156.38^{abc} \pm 65.86$	$107.88^{bc} \pm 53.74$	$106.63^{bc} \pm 35.1$	$133.25^{abc} \pm 40.64$	$247.75^{abc} \pm 114.39$	$269.38^{ab} \pm 125.09$
Faecal pH	$6.90^{a} \pm 0.15$	$7.15^{ab} \pm 0.34$	$6.57^{c} \pm 0.21$	$7.04^{a} \pm 0.33$	$7.18^{acd} \pm 0.33$	$7.39^{bd} \pm 0.41$	$8.20^{e} \pm 0.24$	$7.14^{ad} \pm 0.24$

[a,b,c,d,e.]Means within rows with different superscripts differ ($P < 0.05$).

4.4.2 Rumen fermentation in feedlot lambs

Rumen microbiota fermenting feedstuffs into fermentation end-products, mainly VFA has been well documented (Barcroft *et al.,* 1944; Dijkstra, 1994). These compounds can then be absorbed across the gastrointestinal tract (Van Soest, 1994). These VFA include, in descending order of abundance, three single chain VFA's (acetate, propionate, and butyrate), and three branched-chain VFA (isobutyrate, isovalerate, and valerate) (Aluwong *et al.,* 2010). These VFA are known to differ in proportion by diet, with an increased proportional concentration of propionate, as seen in high concentrate feedlot lambs (Ellison *et al.,* 2017). Diet is the main determinant of rumen microbial composition and VFA molar concentration among cattle and sheep (Carberry *et al.,* 2012). Quantitatively, the proportions of ruminal VFA produced during fermentation usually range between 50 to 70% of the total VFA for acetate, 15 to 35% for propionate, and 10 to 12% for butyrate (Ghimire *et al.,* 2014). Generally the proportion of VFA is greatly influenced by diet (forage: concentrate ratio) and physical form of carbohydrate particles (Krehbiel, 2014).

4.4.2.1 Acidosis

Subacute ruminal acidosis (SARA) has commonly been attributed to an unbalance between acid production and acid elimination from the rumen, resulting in transitory periods of pH below particular physiological thresholds (Kleen, 2003). This reduction in pH drives the change in the volatile fatty acids (VFA) production profile towards more propionate and less acetate (Hernández *et al.,* 2014). When pH drops below 5.5, lactic acid accumulates (Calsamiglia *et al.,* 2012). Subacute ruminal acidosis derived from high concentrate feeding is not only a pH-dependent disorder, but it is also the result of changes in the microbial population secondary to the type of diet fed (Hernández *et al.,* 2014). Therefore, it has been proposed to re-name this type of subacute ruminal acidosis as a "high-concentrate syndrome" (Calsamiglia *et al.,* 2012).

In feedlot animals, the narrow C2 (acetate):C3 (propionate) ratio is however often desired in order to maintain the necessary body weight gain (Hernández *et al.,* 2014). It has to be managed carefully, because it is an unstable situation which may affect the DMI and therefore negatively influence growth rate (Kleen *et al.,* 2003). A recent Chinese study *(Li et al.,* 2017) indicate that a lower 2 - 4 h post feeding ruminal pH may not be a suitable indicator of SARA risk in finishing lambs. This study indicated that the risk of SARA was independent of DMI and dietary composition. There is some evidence that lactic acid is not the causal reason for the prolonged reduction in pH of the ruminal contents. Studies have shown only low lactate levels between 0.45 and 0.74 mmol/L in cows with suspected SARA (Aluwong *et*

al., 2010; Constable *et al.,* 2016). Excessive volatile fatty acid production may be a more important contributor to SARA in lactating dairy cows (Aluwong *et al.,* 2010; Constable *et al.,* 2016). According to Lean *et al.* (2013) both propionate and valerate are synthesized from lactic acid, and the removal of lactic acid from the rumen is an important safe method of maintaining rumen pH. Valerate is therefore a key indicator of ruminal change during grain challenge (Lean *et al.,* 2013).

In feedlot cattle SARA may show signs of colic and anorexia, and loose stools are commonly present. When an entire group of animals is affected, it is common to see a reduction in DMI (Eun *et al.,* 2014; Danscher *et al.,* 2015). Manure consistency of SARA affected animals will have a shiny appearance and are mostly liquid (Abdela, 2017). In addition, cattle commonly have an abnormal amount of manure smeared across their hindquarters. Mild or subacute acidosis is commonly seen during diet transitions, weather alterations, and mild feeding errors (Meyer and Bryant, 2017). Due to the insidious nature of subacute acidosis, it is often difficult to diagnosed in feedlot cattle (Abdela, 2017). Ruminal pH may be a good indicator of subacute acidosis, however a ruminal pH within the subacute acidosis range (5.0–5.5) may not reflect an acidotic state unless it is sustained (Nagaraja and Lechtenberg, 2007).

The chronic form of SARA affects mainly weaned lambs on large amounts of concentrates or cereal-rich diets. Lambs suffering from ruminal acidosis lose their appetite and display ruminal hypokinesia, delayed growth and, in some cases, symptoms of a chronic inflammatory reaction (Morgante, 2004). The acids produced by fermentation are theoretically capable of reducing the pH of rumen liquor to 2.5–3.0, but under normal conditions the pH is maintained at 5.5–6.5 (Mcdonald *et al.,* 2010). Generally, acute acidosis is defined by a pH below 5.0, while subacute acidosis is defined by a pH between 5.0 and 5.6 (McCann, 2018). Nevertheless, the definitions of SARA derived primarily from experiments using rumen cannulated animals, and upper pH thresholds (5.5, 5.6, or 5.8) may vary somewhat and a certain duration of time below this threshold may also be part of the definition (Gressley, 2014). Currently consensus is that SARA should be defined as a rumen pH (measured by rumenocentesis) of less or equal to 5.5 being sustained for at least 3 hours of each day (Nagaraja and Lechtenberg, 2007; Constable *et al.,* 2016).

4.4.2.2 Effects of nutrient density

It is commonly known that under feedlot conditions where energy is often the most limited nutrient for growth where high levels of easily fermentable carbohydrates with sufficient energy density are often being used. Soluble carbohydrates and starch are most effective in decreasing ruminal pH rapidly, whereas increasing the amount of physically effective fibre in

the diet is the most efficient nutritional measure to slow the pH decline after a meal (Aschenbach *et al.,* 2011). Acidotic conditions in the rumen are driven by the rapid production of organic acids from rumen fermentable carbohydrates and if production thereof exceeds the rate of absorption by the rumen wall, it will result in a depressed ruminal pH (McCann, 2018). Higher nutrient (energy) density diets will also change the ratios between volatile fatty acids (Hernández *et al.,* 2014). According to Fanning (2016), the acetate: propionate: butyrate ratio in ruminal fluid changes from 70:20:10 with a hay diet to 50:35:15 on a concentrate diet. Propionate is often produced in greater concentrations in ruminant animals that are fed a concentrate-based diet, and is not associated with the production of methane, while acetate and butyrate pathways often produce methane from CO^2 by-products (Van Soest, 1994). An earlier study by Raun *et al.* (1962) reported a narrowed acetate-propionate ratio, higher butyric acid levels, lower total volatile fatty acid levels and lower pH in lambs fed an 80% concentrate containing diet compared to lambs fed a 50% concentrate containing diet. Intensive feeding strategies is normally associated with high levels of readily fermentable carbohydrates and are therefore naturally linked to increased risk of both acute and sub-acute ruminal acidosis.

4.4.3 Ruminal pH

The mean ruminal pH over a 12-hour period after feeding is summarised in Table 4.5 and illustrated by Figure 4.2 and Figure 4.3 for the LD and HD treatments respectively.

Table 4.5 Mean ± SD pH of the sheep for each treatment at time intervals after feeding.

	Treatments							
Hours post-feeding	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
0	$6.49^{d} \pm 0.1$	$7.01^{ab} \pm 0.1$	$6.82^{bc} \pm 0.2$	$6.77^{c} \pm 0.2$	$6.97^{ab} \pm 0.3$	$6.92^{abc} \pm 0.2$	$7.03^{a} \pm 0.1$	$6.94^{abc} \pm 0.2$
2	$6.25^{b} \pm 0.1$	$5.31^{de} \pm 0.2$	$5.26^{e} \pm 0.2$	$5.52^{d} \pm 0.1$	$6.60^{a} \pm 0.1$	$5.83^{c} \pm 0.4$	$6.18^{b} \pm 0.3$	$5.51^{d} \pm 0.3$
4	$5.93^{a} \pm 0.2$	$5.34^{bc} \pm 0.3$	$5.15^{b} \pm 0.2$	$5.15^{b} \pm 0.1$	$6.14^{a} \pm 0.3$	$5.99^{a} \pm 0.5$	$5.98^{a} \pm 0.3$	$5.45^{c} \pm 0.3$
6	$5.79^{a} \pm 0.3$	$5.84^{bc} \pm 0.5$	$5.52^{c} \pm 0.3$	$5.39^{c} \pm 0.4$	$6.14^{a} \pm 0.4$	$6.40^{a} \pm 0.4$	$6.21^{a} \pm 0.3$	$5.88^{b} \pm 0.5$
8	$5.78^{d} \pm 0.3$	$6.26^{bc} \pm 0.3$	$5.99^{cd} \pm 0.2$	$5.84^{d} \pm 0.3$	$6.28^{bc} \pm 0.5$	$6.71^{a} \pm 0.4$	$6.54^{ab} \pm 0.3$	$6.07^{cd} \pm 0.4$
12	$6.26^{c} \pm 0.2$	$6.78^{abc} \pm 0.2$	$6.66^{c} \pm 0.2$	$6.56^{c} \pm 0.3$	$6.43^{bc} \pm 0.5$	$6.92^{a} \pm 0.3$	$6.91^{ab} \pm 0.2$	$6.45^{ab} \pm 0.4$

$^{a,b,c.}$Means within rows with different superscripts differ ($P < 0.05$).

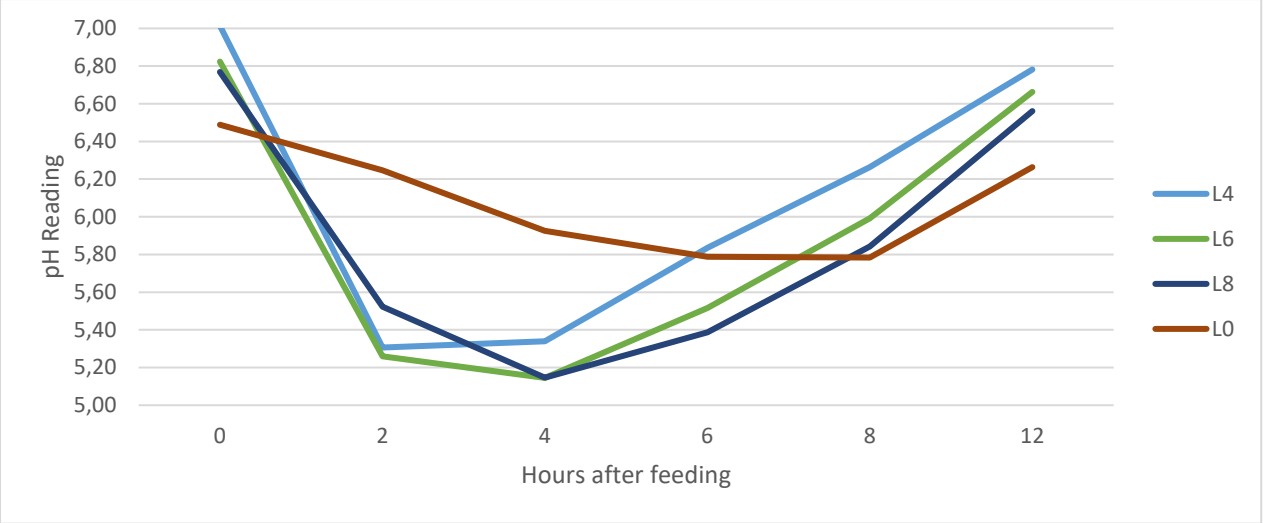

Figure 4.2 Mean pH readings of the sheep for the LD feed groups at different hours after feeding.

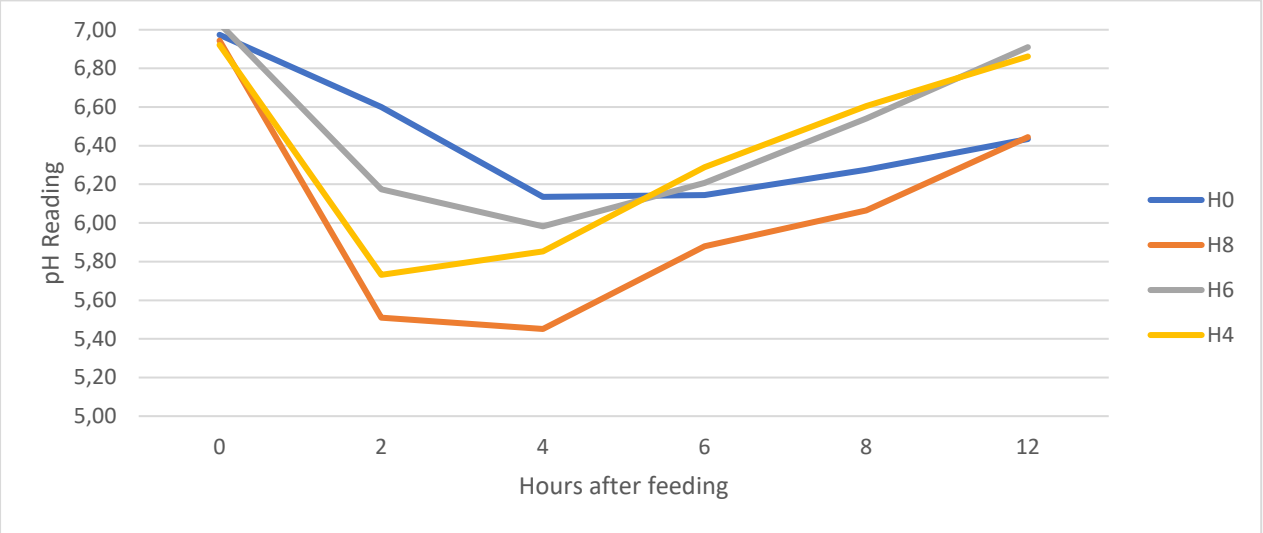

Figure 4.3 Mean pH readings of the sheep for the HD feed groups at different hours after feeding.

The mean ruminal pH of the sheep fed on the LD diets (5.98 ± 0.04) were significantly lower ($P < 0.05$) compared to the mean pH of the HD groups (6.4 ± 0.04) (Table 4.2). Amongst the different processed feeds, the sheep fed on the larger 8mm pelleted diet experienced the lowest mean ruminal pH (6.0 ± 0.06) and was significantly lower ($P < 0.05$) than all the other processed feeds which did not differ from each other (Table 4.3). The ruminal pH of the animals fed on most treatment groups decreased significantly ($P < 0.05$) up until approximately 4 hours after feeding after which it reaches an asymptote (Table 4.6). Table 4.4 shows that the sheep that received both the L8 and L6 diets recorded the lowest average pH reading at

4 hours after feeding (5.15 pH ± 0.12; 5.15 pH ± 0.17), while the sheep receiving the control (group H0) had the lowest reduction in pH (6.14 pH; ± 0.41). This difference was significant ($P < 0.05$). Amongst the HD groups, the animals in group H0) also had the lowest drop in pH at 4 hours after feeding, although this recording (pH = 6.14) was only significantly higher ($P < 0.05$) than the H8 reading (Table 4.4). An indication towards a lower and a slower recovery rate to the initial ruminal pH with unprocessed feeds (L0 and H0) was observed when compared to what was seen in the sheep fed processed feeds. Duration of ruminal pH less than 5.5 of different groups are illustrated in Table 4.6. Amongst the sheep that received the pelleted diets, the animals on HD diets in general resulted in higher pH values at 4 hours after feeding compared to animals on LD diets ($P < 0.05$). The only exception was between the H8 and the L4 group which did not differ (Table 4.4).

Amongst the pelleted diets used during this study, no association between higher nutrient density diets and length or extent of pH depression was observed. In fact, the ruminal pH of sheep on all three of the LD pelleted diets, experienced a lower pH for a longer time after the meals. The same trend was observed for the sheep on the control diets, with the ruminal pH of the L0 group being lower for a longer period of time than the pH of the H0 group ($P < 0.05$) until 8 hours after feeding whereafter it remained similar (Table 4.5). Given the current definition of SARA of a ruminal fluid pH of less than 5.5 for at least 3 hours per day Duffield *et al*. (2004), the sheep on the pelleted LD diets would qualify to be subclinical acidotic (Table 4.6). Of the HD groups, only group H8 had a mean pH drop of less than 5.5 (Figure 4.2).

Subacute acidosis is probably the most prevalent form of acidosis in feedlots and is difficult to diagnose because of its insidious nature. The only sign of subacute acidosis may be decreased feed intake. Dietary factors can have a significant impact on DMI and therefore on the incidence of acidosis. Grain type (high-moisture maize more than dry rolled maize or sorghum) and amount of grain, grain processing (particularly steam flaking), type and amount of roughage, and feed additives (such as ionophores and virginiamycin) influence intake patterns and subacute acidosis. Grains such as barley, wheat, and high-moisture maize that have fast rates of ruminal starch digestion generally cause the most acidotic problems (Nagaraja *et al.,* 1998).

The results of this study indicate that the ruminal pH of the sheep that was fed unprocessed feeds (H0 and L0), had a less significant drop and a slower recovery rate to the initial pH than for sheep receiving processed feeds (Figure 4.2 and Figure 4.3). This result is in accordance with findings reported by various other authors. Increased pelleted barley fed to sheep or lambs was associated with reduced ruminal fluid pH (Luther and Trenkle, 1967; Mann and Orskov, 1975; Fanning, 2016). In dairy cows it was found that feeding lucerne hay in the pelleted form instead of the chopped form could induce acidosis (Khafipour *et al.,* 2009),

although the pelleted feed was associated with an increase in ruminal acetic acid concentration.

In the current study, the expected effect of pellet diameter on rumen fermentation via the larger relative surface area of the smaller macro-particles and micro-particles of the smaller pellets (Castrillo *et al.,* 2013) were not observed. Table 4.6 illustrates that the rumen pH of sheep on larger pellets stays for longer periods under the 5.5 level compared to the pH of sheep on smaller pellets. The same general observation was true for VFA concentrations (Table 4.7). The observed response of pellet size on rumen fermentation could be explained in terms of a significant ($P < 0.05$) higher DMI of the larger pellets (Table 4.4), which is in agreement with observations on dairy calves (Marsh and Lingham, 2011). Table 4.4 further indicate significantly ($P < 0.05$) higher DMI when LD diets are compared against HD diets. The resulting higher DMI could have resulted in higher starch levels in the rumen despite the lower starch content of the LD diets (Table 3.1). These higher starch intakes could possibly explain the unexpected pH differences.

Both the grinding of whole grains and the pelleting process reduce the particle size of whole grains (Behnke, 2001). But whilst pelleting moulds mash diets to macro-particles in the form of pellets, it simultaneously reduces the size of the micro-particles of the mash further while the rollers press the softened mash through the holes in a circular die. The number of coarse particles diminished and the number of fine particles increased as a consequence of pelleting (Svihus *et al.,* 2004). Any form of processing of grains will increase the surface area available for microbial attachment and colonization and will in the process increase the rate and extent of starch digestion (Campling, 1991; McAllister *et al.,* 2006). Additionally, the rate of digestion of starch from grain in the rumen varies inversely with particle size of the grain (Svihus *et al.,* 2005). This comprehensive review also concludes that gelatinisation may not have a marked effect on either ruminal starch digestibility or physical quality of the feeds, but that particle size reduction is the process responsible for the effect that pelleting has on digestion and performance of ruminants.

Compared to processed grain, coarse grain promotes greater time for chewing and rumination, and consequently will produce greater amounts of saliva that will help stabilize the ruminal pH (Van Soest, 1994). Compared to processed grain, coarse grain therefore is fermented more slowly and consequently results in a higher rumen pH (Beretta and Kirby, 2004). Other factors that may play a role is this finding is the dynamics of particle flow through the tract (Rowe *et al.,* 1999) and the ability of sheep to chew the grain into smaller particles (Van Soest, 1994). The smaller physical size of the reticulo-omasal orifice in sheep will prevent unmasticated coarse grains to pass from the reticulo-rumen into the abomasum. So coarse grains are retained within the reticulorumen and subjected to further mastication during rumination (Cerrilla and Martínez, 2003). The effect of processing on fermentation was clearly

illustrated in a study on rumen-cannulated Holstein male calves (Offner *et al.,* 2003). In this experiment, the effect of maize and barley given either ground or pelleted (6mm) showed that the pelleted concentrates resulted in a lower acetic to propionic ratio and a more noticeable pH drop after feeding, but this effect was more pronounced in the maize pellets.

In agreement, a Chinese study (Bo Trabi *et al.,* 2019) found that the ruminal pH of high grain feedlot lambs was significantly lower in a complete pelleted (CPR) group as compared to total mixed ration (TMR) group (*P = 0.012*). The concentrations of lactate (*P = 0.024*) and valerate (*P = 0.001*) were significantly higher in the CPR group compared to the TMR group. The concentrations of acetate, propionate, isobutyrate, butyrate and total VFA were not significantly different between groups, and similarly, acetate: propionate ratio was not significantly affected.

Table 4.6 Approximate duration of pH less than 5.5 of the ruminal fluid.

	Treatments							
Parameter	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
Hours with pH < 5.5	0	3	4	4.5	0	0	0	2

4.4.4 VFA production

The mean ruminal fluid concentration (m/M) of the six different VFA's at different hours after feeding is summarised in Table 4.7. The change in concentration (m/M) over time is only illustrated for acetate (Fig. 4.4 and Fig. 4.5) and propionate (Fig. 4.6 and Fig. 4.7).

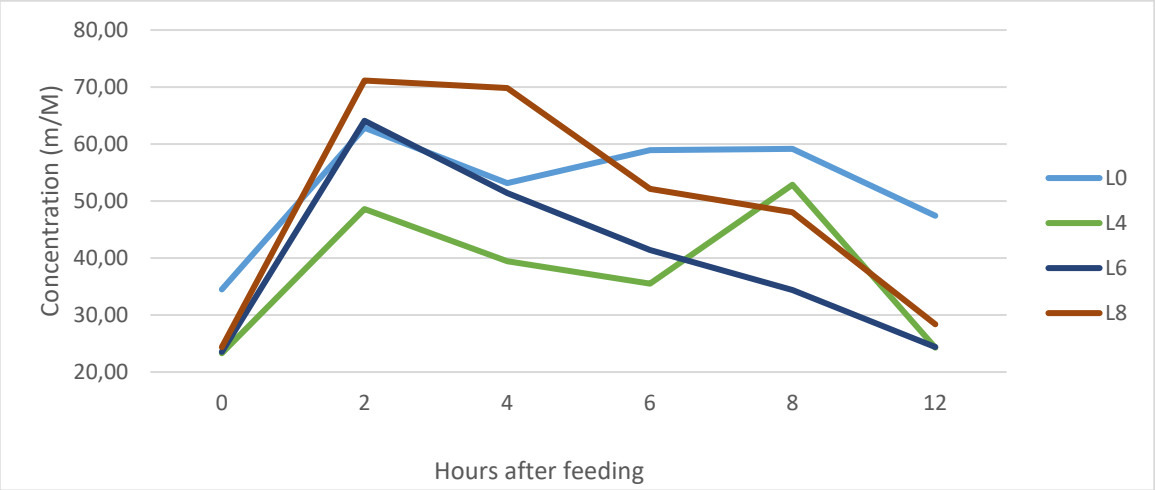

Figure 4.4 Mean acetate concentration (m/M) changes over time after feeding for LD feed groups.

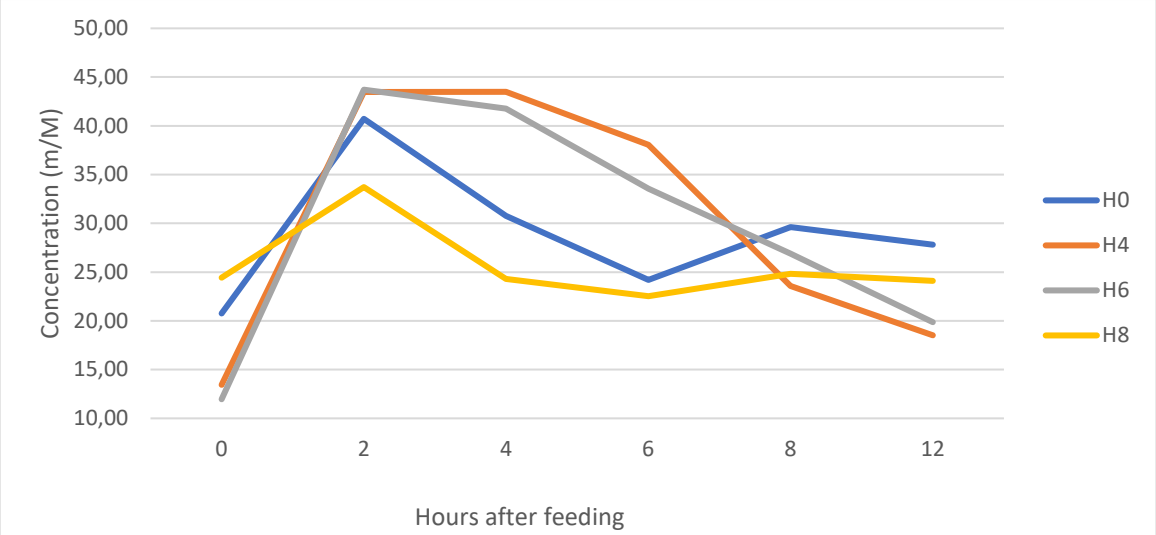

Figure 4.5 Mean acetate concentration (m/M) changes over time after feeding for HD feed groups.

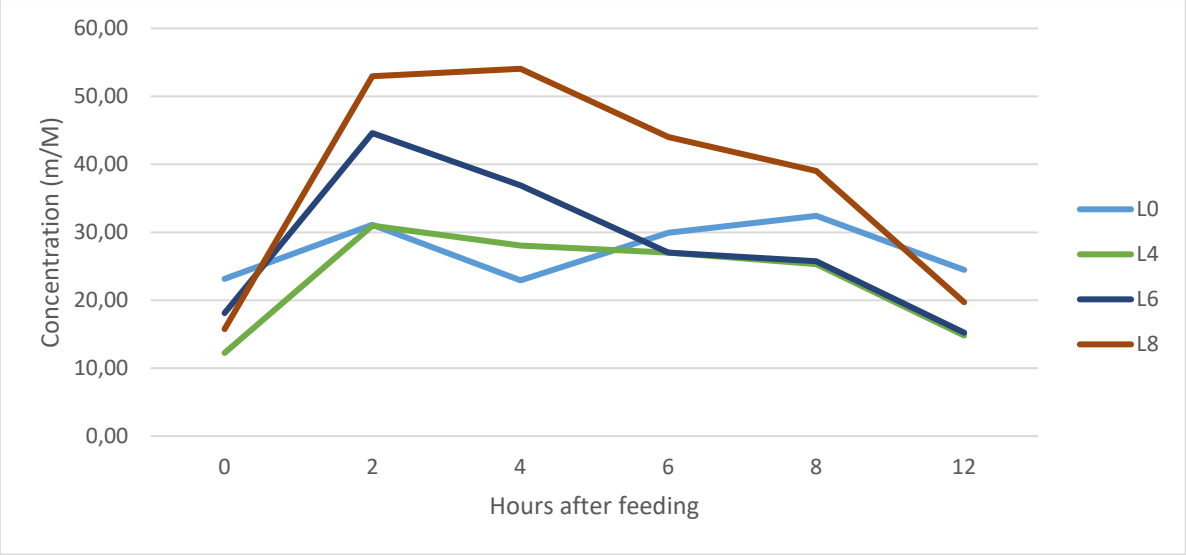

Figure 4.6 Change in mean propionate concentration (m/M) of the sheep over time after feeding for LD feed groups.

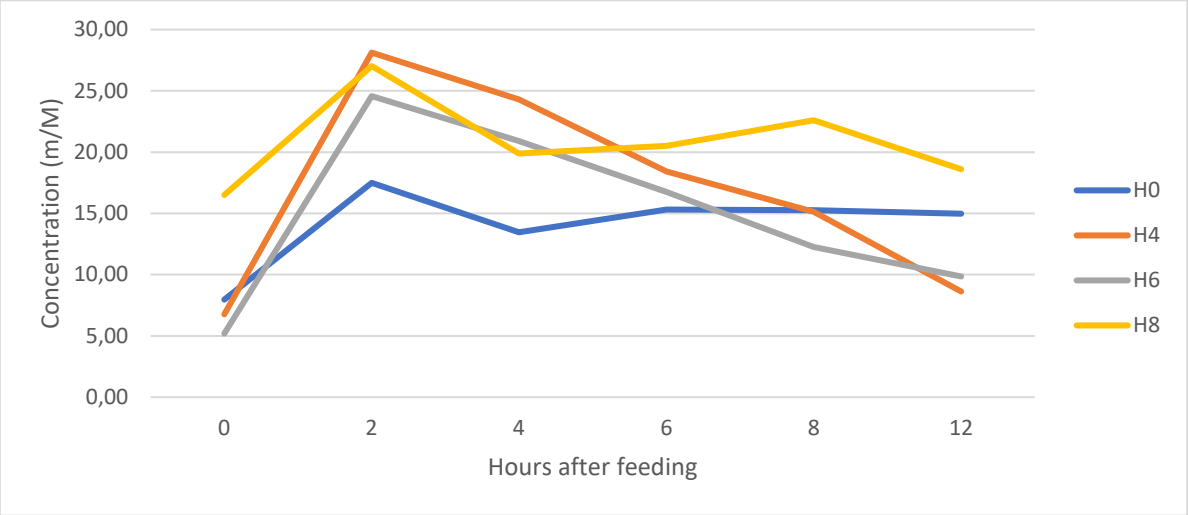

Figure 4.7 Change in mean propionate concentration (m/M) of the sheep over time after feeding for HD feed groups.

Table 4.7 Mean concentrations in M/m of the different VFA's for each treatment group at different hours after feeding. Mean with SD presented.

Parameter	Hours post-feeding	Treatments							
		L0	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
Acetate (m/M)	**0**	$34.5^{a} \pm 4.4$	$23.3^{b} \pm 6.3$	$23.5^{b} \pm 9.9$	$24.4^{b} \pm 10.3$	$20.8^{bc} \pm 4.2$	$13.4^{c} \pm 2.5$	$12.0^{c} \pm 3.5$	$24.4^{b} \pm 19.6$
	2	$62.9^{ab} \pm 11.3$	$48.6^{bc} \pm 12.2$	$64.1^{ab} \pm 29.0$	$71.1^{a} \pm 15.2$	$40.7^{c} \pm 9.1$	$43.5^{c} \pm 21.0$	$43.7^{c} \pm 10.5$	$33.7^{c} \pm 9.4$
	4	$53.2^{acf} \pm 12.2$	$39.4^{abcefg} \pm 7.2$	$51.4^{cf} \pm 16.6$	$69.8^{d} \pm 24.0$	$30.8^{efg} \pm 12.6$	$43.5^{acef} \pm 18.7$	$41.8^{abcf} \pm 13.0$	$24.3^{g} \pm 5.8$
	6	$58.9^{b} \pm 20.3$	$35.5^{bc} \pm 10.3$	$41.4^{b} \pm 25.6$	$52.1^{a} \pm 13.7$	$24.2^{cd} \pm 9.7$	$38.1^{bc} \pm 19.8$	$33.6^{bc} \pm 10.8$	$22.5^{d} \pm 9.2$
	8	$59.2^{a} \pm 9.4$	$52.9^{ab} \pm 64.4$	$34.4^{abc} \pm 15.6$	$48.0^{abc} \pm 10.9$	$29.6^{bc} \pm 13.4$	$23.6^{c} \pm 7.1$	$26.9^{c} \pm 9.5$	$24.8^{c} \pm 6.5$
	12	$47.4^{a} \pm 8.3$	$24.3^{c} \pm 7.6$	$24.4^{bc} \pm 10.1$	$28.4^{b} \pm 7.1$	$27.8^{c} \pm 10.5$	$18.5^{c} \pm 7.2$	$19.9^{c} \pm 7.4$	$24.1^{c} \pm 7.6$
Propionate (m/M)	**0**	$23.2^{a} \pm 8.9$	$12.2^{bcd} \pm 4.5$	$18.1^{ab} \pm 12.3$	$15.8^{abc} \pm 7.1$	$8.0^{cd} \pm 1.5$	$6.8^{d} \pm 1.9$	$5.2^{d} \pm 2.6$	$16.5^{ab} \pm 15.7$
	2	$31.1^{b} \pm 9.1$	$31.0^{b} \pm 7.7$	$44.6^{a} \pm 18.4$	$53.0^{a} \pm 11.1$	$17.5^{c} \pm 6.7$	$28.1^{bc} \pm 12.8$	$24.6^{bc} \pm 8.7$	$27.0^{bc} \pm 10.3$
	4	$22.9^{abe} \pm 7.9$	$28.0^{bc} \pm 8.2$	$36.9^{c} \pm 10.0$	$54.1^{d} \pm 13.5$	$13.5^{e} \pm 6.7$	$24.3^{ab} \pm 17.6$	$20.9^{abe} \pm 8.3$	$19.9^{abe} \pm 5.8$
	6	$29.9^{cd} \pm 11.3$	$27.0^{bc} \pm 8.1$	$27.0^{b} \pm 8.9$	$44.0^{a} \pm 16.1$	$15.3^{d} \pm 12.4$	$18.4^{c} \pm 6.9$	$16.7^{cd} \pm 7.2$	$20.5^{cd} \pm 10.6$
	8	$32.4^{ab} \pm 11.8$	$25.3^{bc} \pm 10.8$	$25.7^{bc} \pm 10.0$	$39.0^{a} \pm 7.2$	$15.3^{de} \pm 13.3$	$15.1^{de} \pm 8.0$	$12.3^{e} \pm 4.7$	$22.6^{cd} \pm 9.6$
	12	$24.5^{ab} \pm 7.8$	$14.8^{bc} \pm 4.8$	$15.2^{bc} \pm 5.8$	$19.7^{a} \pm 6.1$	$15.0^{cd} \pm 12.2$	$8.6^{d} \pm 5.5$	$9.8^{d} \pm 3.4$	$18.6^{cd} \pm 8.1$
Iso-Butyrate (m/M)	**0**	$0.85^{abc} \pm 0.1$	$0.58^{bc} \pm 0.3$	$0.55^{c} \pm 0.3$	$0.86^{ab} \pm 0.4$	$1.13^{a} \pm 0.5$	$0.89^{ab} \pm 0.2$	$0.75^{bc} \pm 0.2$	$0.62^{bc} \pm 0.4$
	2	$0.92^{a} \pm 0.5$	$0.23^{d} \pm 0.1$	$0.24^{d} \pm 0.1$	$0.51^{bc} \pm 0.1$	$1.04^{a} \pm 0.3$	$0.58^{bc} \pm 0.2$	$0.65^{b} \pm 0.2$	$0.40^{cd} \pm 0.1$
	4	$0.75^{a} \pm 0.2$	$0.15^{b} \pm 0.1$	$0.20^{bc} \pm 0.1$	$0.43^{cd} \pm 0.3$	$0.68^{a} \pm 0.3$	$0.55^{ad} \pm 0.3$	$0.53^{ad} \pm 0.2$	$0.25^{bc} \pm 0.1$
	6	$0.69^{a} \pm 0.2$	$0.22^{d} \pm 0.1$	$0.15^{cd} \pm 0.1$	$0.26^{bc} \pm 0.1$	$0.59^{a} \pm 0.3$	$0.62^{ab} \pm 0.2$	$0.43^{ab} \pm 0.2$	$0.31^{cd} \pm 0.1$
	8	$0.94^{a} \pm 0.3$	$0.26^{e} \pm 0.1$	$0.28^{de} \pm 0.1$	$0.49^{cd} \pm 0.2$	$0.71^{b} \pm 0.3$	$0.96^{a} \pm 0.4$	$0.45^{cde} \pm 0.1$	$0.60^{bc} \pm 0.3$
	12	$0.9^{a} \pm 0.2$	$0.50^{d} \pm 0.2$	$0.52^{d} \pm 0.2$	$0.70^{cd} \pm 0.2$	$0.81^{ab} \pm 0.4$	$1.11^{a} \pm 0.3$	$0.74^{bc} \pm 0.3$	$0.68^{cd} \pm 0.3$
Butyrate (m/M)	**0**	$4.8^{b} \pm 1.4$	$2.9^{bcd} \pm 1.2$	$2.3^{cd} \pm 0.9$	$3.9^{bc} \pm 1.9$	$8.1^{a} \pm 4.8$	$2.0^{cd} \pm 0.6$	$1.9^{d} \pm 0.7$	$4.0^{bc} \pm 2.3$
	2	$8.6^{cd} \pm 2.2$	$8.9^{bcd} \pm 1.9$	$11.1^{bc} \pm 4.7$	$15.0^{a} \pm 4.2$	$12.2^{ab} \pm 5.2$	$6.2^{d} \pm 2.6$	$7.0^{d} \pm 2.5$	$6.7^{d} \pm 2.5$
	4	$9.4^{a} \pm 3.7$	$8.4^{a} \pm 1.7$	$9.9^{a} \pm 3.6$	$14.9^{c} \pm 5.0$	$10.8^{a} \pm 4.7$	$3.5^{b} \pm 1.2$	$4.7^{b} \pm 1.4$	$4.2^{b} \pm 1.9$
	6	$8.8^{b} \pm 6.1$	$6.5^{b} \pm 2.5$	$5.5^{b} \pm 2.3$	$9.3^{a} \pm 2.9$	$9.5^{b} \pm 4.5$	$3.0^{c} \pm 0.7$	$3.7^{c} \pm 0.8$	$3.9^{c} \pm 1.5$

	8	11.4^{a} ± 4.6	4.6^{b} ± 0.9	5.3^{b} ± 2.4	9.8^{a} ± 3.6	12.3^{a} ± 6.0	2.8^{b} ± 1.2	3.1^{b} ± 1.1	5.6^{b} ± 3.3
	12	8.8^{ab} ± 3.0	3.8^{c} ± 1.7	3.6^{c} ± 1.4	5.3^{b} ± 1.4	9.5^{a} ± 1.7	2.0^{d} ± 0.7	2.8^{cd} ± 1.1	6.2^{c} ± 4.6
Iso-Valerate (m/M)	**0**	1.0^{a} ± 0.5	0.66^{b} ± 0.6	0.35^{bc} ± 0.4	0.07^{c} ± 0.0	0.04^{c} ± 0.0	0.19^{c} ± 0.2	0.08^{c} ± 0.0	0.04^{c} ± 0.0
	2	1.2^{a} ± 0.8	0.21^{b} ± 0.2	0.25^{b} ± 0.2	0.05^{b} ± 0.0	0.04^{b} ± 0.0	0.17^{b} ± 0.2	0.10^{b} ± 0.1	0.04^{b} ± 0.0
	4	1.5^{b} ± 0.4	0.17^{a} ± 0.2	0.32^{a} ± 0.3	0.04^{a} ± 0.0	0.04^{a} ± 0.0	0.14^{a} ± 0.1	0.07^{a} ± 0.0	0.04^{a} ± 0.0
	6	1.3^{a} ± 0.8	0.3^{bc} ± 0.2	0.31^{b} ± 0.3	0.1^{c} ± 0.1	0.07^{c} ± 0.1	0.15^{bc} ± 0.1	0.06^{c} ± 0.0	0.05^{c} ± 0.0
	8	2.1^{a} ± 1.4	0.31^{b} ± 0.2	0.38^{b} ± 0.3	0.05^{b} ± 0.0	0.04^{b} ± 0.0	0.13^{b} ± 0.1	0.05^{b} ± 0.0	0.05^{b} ± 0.0
	12	1.9^{a} ± 1.2	0.57^{b} ± 0.4	0.58^{b} ± 0.5	0.05^{c} ± 0.0	0.08^{c} ± 0.1	0.14^{c} ± 0.1	0.06^{c} ± 0.0	0.06^{c} ± 0.0
Valerate (m/M)	**0**	0.9^{bcd} ± 0.3	0.7^{bcd} ± 0.3	0.7^{cd} ± 0.2	1.4^{a} ± 0.7	1.2^{ab} ± 0.9	0.5^{d} ± 0.3	0.4^{d} ± 0.2	1.0^{abc} ± 0.4
	2	1.6^{c} ± 0.9	2.7^{bc} ± 0.8	4.0^{ab} ± 2.8	4.5^{a} ± 1.7	2.0^{c} ± 1.1	2.8^{bc} ± 2.0	2.2^{c} ± 1.0	2.2^{c} ± 1.0
	4	1.3^{a} ± 0.6	3.0^{b} ± 0.5	4.3^{c} ± 1.8	5.5^{d} ± 1.8	1.4^{a} ± 0.9	1.2^{a} ± 0.8	1.4^{a} ± 0.7	1.4^{a} ± 0.4
	6	1.3^{d} ± 0.4	2.2^{c} ± 1.0	2.3^{b} ± 0.9	3.1^{a} ± 1.2	0.9^{d} ± 0.4	0.8^{d} ± 0.4	0.9^{d} ± 0.3	1.4^{d} ± 0.6
	8	1.4^{bc} ± 0.5	1.4^{bcd} ± 0.5	1.9^{b} ± 0.7	3.2^{a} ± 0.8	1.2^{cde} ± 0.7	0.8^{de} ± 0.6	0.6^{e} ± 0.1	1.9^{b} ± 0.7
	12	1.3^{cd} ± 0.6	1.2^{bc} ± 0.6	1.4^{b} ± 0.4	1.6^{a} ± 0.7	1.1^{de} ± 0.4	0.5^{e} ± 0.2	0.6^{e} ± 0.2	1.8^{bc} ± 0.8

$^{a,b,c,d,e,f,g.}$Means within rows with different superscripts differ ($P < 0.05$).

Table 4.2 shows that the acetate and propionate concentrations for the LD groups are significantly higher ($P < 0.05$) than the HD groups. The observed higher DMI in the LD groups (Table 4.4) may be partly responsible for this response. Acetate concentrations were highest in the control feed groups (40.8 m/M ± 0.02) and was significantly higher ($P < 0.05$) than the sheep fed on the 4mm and 6mm pelleted diets (Table 4.3). Sheep fed on the 8mm pelleted diets showed the highest propionate concentrations (29.2 m/M ± 0.02) and was significantly higher than all the other processing feed groups. This observation can also be explained by the significantly ($P < 0.05$) higher DMI observed with the 8mm groups.

A tendency that the acetate concentration of the sheep on all treatment groups reached a peak at 2 hours after feeding, whereafter the concentration gradually declines until 12 hours after feeding. Significant differences ($P < 0.05$) were found at 2 hours after feeding (Table 4.4). This rapid decline after 2 hours was not expected. The acetate concentration of the sheep fed the LD diets, were overall significantly ($P < 0.05$) higher for all time points after feeding (except L4) than the concentration observed amongst the sheep on HD diets (Table 4.7).

The change in propionate concentration after feeding follows the same trend as the acetate concentration. Propionate concentration reaches its peak overall at 2 hours after feeding, whereafter the concentration gradually declines. This trend was expected as the rate of fermentation of starch is known to be rapid and will lead to a relative quicker decline in propionate molar proportions (Calsagmiglia *et al*., 2008). With *in vitro* results Van Zyl (2017) showed that almost 70% of maize starch was degraded after 6 hours fermentation indicating rapid degradation and formation of propionic acid. Treatment groups L6 (44.6 m/M ± 18.44) and L8 (52.97 m/M ± 11.09) exhibited the highest propionate concentration and was found to be significantly higher ($P < 0.05$) than the other groups (Table 4.4). In contrast, the H0 group (17.49 m/M ± 6.95) had the lowest propionate concentration and was significantly lower ($P < 0.05$) than those observed in the low-density feed groups. This finding can also be explained by DMI differences as explained

The higher acetic acid concentration of the ruminal fluid of the LD rations is consistent with other studies who reported increased acetic acid concentration and is usually associated with an increased roughage concentration of the diet (Luther and Trenkle, 1967; Anderson and Butcher, 1975; Al-Mamun *et al*., 2009). However, the same general tendency was also observed in the ruminal propionate concentrations, and in the propionate: acetate ratios, with the animals fed LD diets showing higher concentrations of propionate and valerate and higher propionate: acetate ratios. This was not expected and might be related to difference in DMI. Results of the current study also showed higher butyrate ($P < 0.05$, except H0 and L0) and valerate ($P < 0.05$) concentrations of the pelleted LD diets compared to the pelleted HD diets (Table 4.7). This is in contrast to reports in previous sheep studies where an increased butyric acid concentration was associated with increased grain content of the ration (Luther and

Trenkle, 1967; Anderson and Butcher, 1975; Fanning, 2016). Most studies in literature reported that in both sheep (Fanning, 2016) and cattle (Keese et al., 2008) increased concentrates is associated with an increase in the valeric acid concentration of the ruminal fluid. The VFA concentration results in the current study was unexpected and can be explained by the significantly ($P < 0.05$) lower ruminal pH findings of the LD versus the HD diets while both these results could be partially explained by the significantly high DMI observed by the sheep fed LD diets compared to the HD diets. These results highlight the importance of DMI and not only diet density towards rumen fermentation parameters.

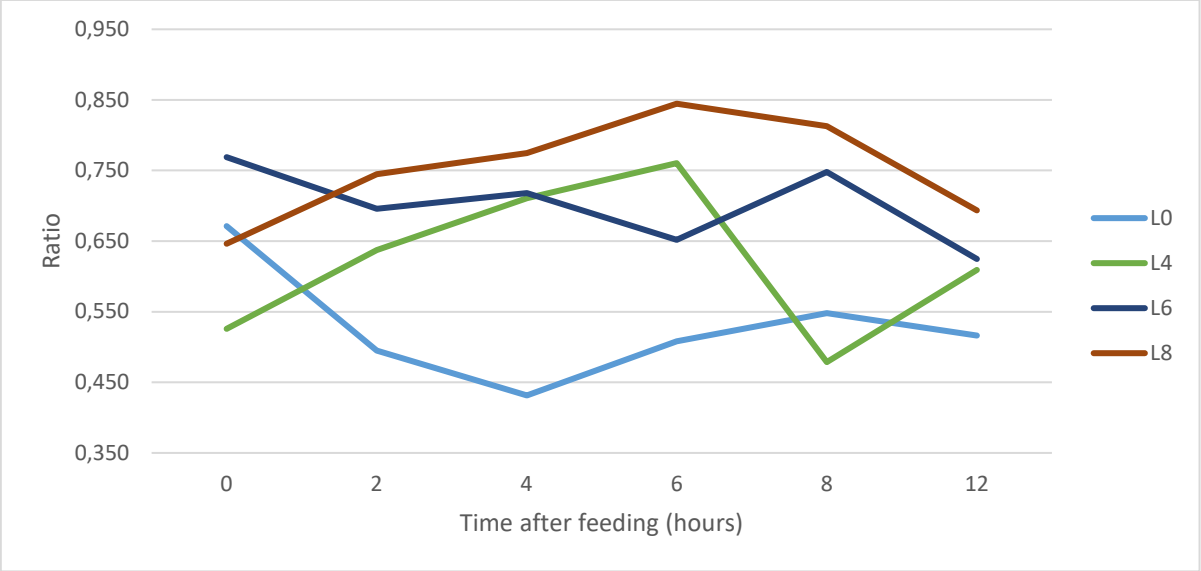

Figure 4.8 Change in mean ratio of propionate: acetate concentration over time after feeding for LD Feed groups.

Figure 4.8 and Figure 4.9 illustrates the change in ratio of propionate: acetate concentration of the low- and high-density feed groups respectively. The H8 group showed overall the highest ratio of all the treatment groups (almost 1:1 at 6 to 8 hours after feeding). Furthermore, no clear trend can be seen between the different processing feeds and density groups.

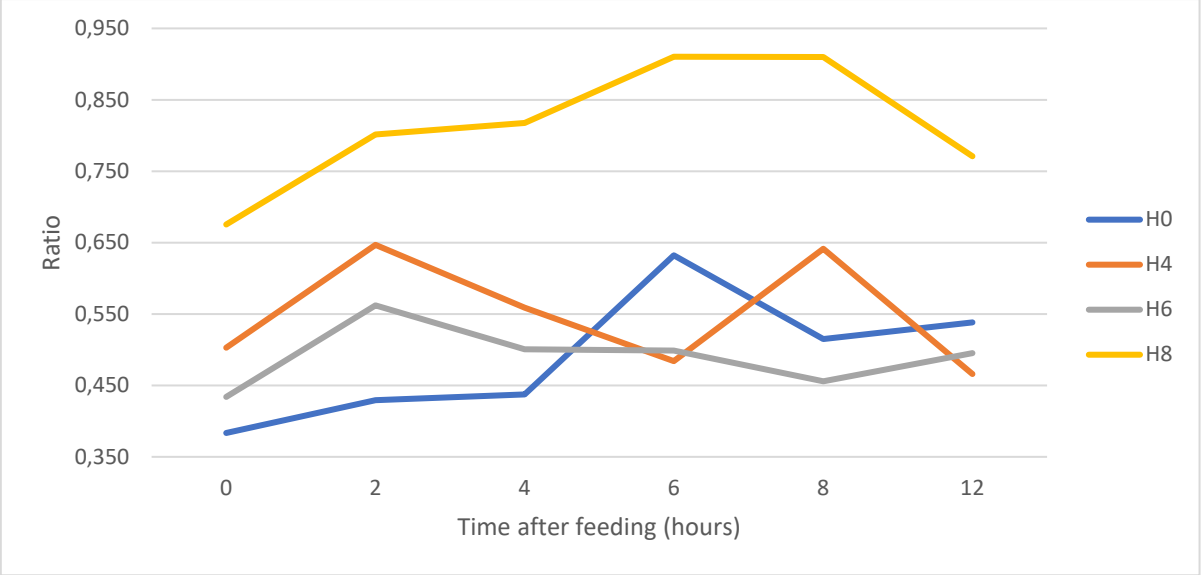

Figure 4.9 Change in mean ratio of propionate: acetate concentration over time after feeding for HD Feed groups.

4.4.5 Rumen ammonia nitrogen (RAN)

By measuring the ammonia nitrogen values in the rumen fluid, the efficiency of nitrogen utilization in the rumen can be assessed (Wohlt *et al.,* 1976). The change in mean RAN concentration over time of the LD group is illustrated in Figure 4.10 and for the HD groups in Figure 4.11. Table 4.8 summarises the average RAN concentration of the sheep at different hours after feeding for each treatment group.

There is a trend towards average RAN concentration of the sheep on each treatment (except H4) to peak at 2 hours after feeding, whereafter the concentration substantially declines until about 6 hours after feeding (Figure 4.10 and Figure 4.11) were observed. Grummer *et al*. (1984) reported the same observation in Holstein steers. In the latter study, four Holstein steers were fed a basal diet of urea supplemented maize and maize silage after which RAN concentration were documented after feeding. Rumen ammonia nitrogen concentrations ranged from 46 mg/dL at 1 hour after feeding to 3 mg/dL at 6 hours post feeding.

Table 4.8 Summary of the mean RAN concentration (mg/dL) of the sheep post-feeding for each treatment group. Mean with SD presented.

	Treatment							
Hours post-feeding	**L0**	**L4**	**L6**	**L8**	**H0**	**H4**	**H6**	**H8**
0	$2.0^{a} \pm 0.5$	$0.8^{c} \pm 0.5$	$0.8^{c} \pm 0.5$	$1.1^{bc} \pm 0.7$	$2.0^{a} \pm 1.0$	$1.6^{ab} \pm 0.9$	$1.8^{ab} \pm 0.5$	$1.9^{a} \pm 0.5$
2	$7.1^{a} \pm 1.6$	$2.5^{cd} \pm 1.2$	$4.3^{b} \pm 1.5$	$7.8^{a} \pm 1.7$	$3.9^{bc} \pm 1.1$	$1.1^{d} \pm 1.2$	$6.6^{a} \pm 1.7$	$6.4^{a} \pm 1.6$
4	$4.2^{a} \pm 1.5$	$0.7^{b} \pm 0.4$	$2.1^{c} \pm 0.7$	$3.1^{d} \pm 1.3$	$1.8^{c} \pm 2.0$	$2.7^{cd} \pm 1.7$	$3.5^{ad} \pm 1.5$	$3.5^{ad} \pm 1.4$
6	$2.3^{a} \pm 0.7$	$0.4^{d} \pm 0.3$	$0.7^{c} \pm 0.4$	$1.4^{abc} \pm 0.8$	$1.0^{cd} \pm 1.4$	$0.9^{bc} \pm 0.6$	$1.9^{ab} \pm 0.9$	$1.9^{ab} \pm 0.9$
8	$2.0^{a} \pm 0.6$	$0.6^{c} \pm 0.5$	$0.7^{c} \pm 0.5$	$1.0^{bc} \pm 1.1$	$1.2^{bc} \pm 1.1$	$1.1^{bc} \pm 0.6$	$1.4^{ab} \pm 0.6$	$1.5^{ab} \pm 0.6$
12	$2.2^{a} \pm 0.6$	$0.8^{c} \pm 0.4$	$0.7^{c} \pm 0.3$	$0.8^{bc} \pm 0.4$	$1.8^{b} \pm 1.4$	$1.3^{bc} \pm 0.6$	$1.0^{b} \pm 0.6$	$1.1^{b} \pm 0.5$

$^{a,b,c,d.}$Means within rows with different superscripts differ ($P < 0.05$).

Ammonia is a significant end-product of rumen microbial fermentation of nitrogen compounds as well as the major nitrogen source for microbial protein synthesis (Eschenlauer *et al.,* 2002). No clear pattern that the density of the diet may have influenced the RAN concentration after 2 hours after feeding could be established in the current study (Table 4.2). From Table 4.3, it seems more aggressive processing (4 mm) may lower RAN concentrations ($P < 0.05$). At two hours after feeding, the RAN concentration of the sheep that was fed the H4 diet, resulted in the lowest RAN concentration (1.1 mg/dL ± 1.2), whilst the sheep that received the L8 diet showed the highest concentration (7.8 mg/dL ± 1.7). Furthermore, significant differences ($P < 0.05$) were found between treatment groups at two hours after feeding, but no clear trend could be seen between the different nutrient density groups as well as within each of the nutrient density groups (Table 4.4). At 8 and 12 hours after feeding respectively, only minor changes in the RAN concentration were observed. Woyengo *et al*. (2004) found similar trends in Red Maasai sheep. Ammonia nitrogen levels increased initially post-feeding, whereafter concentration levels decreased (Woyengo *et al*., 2004).

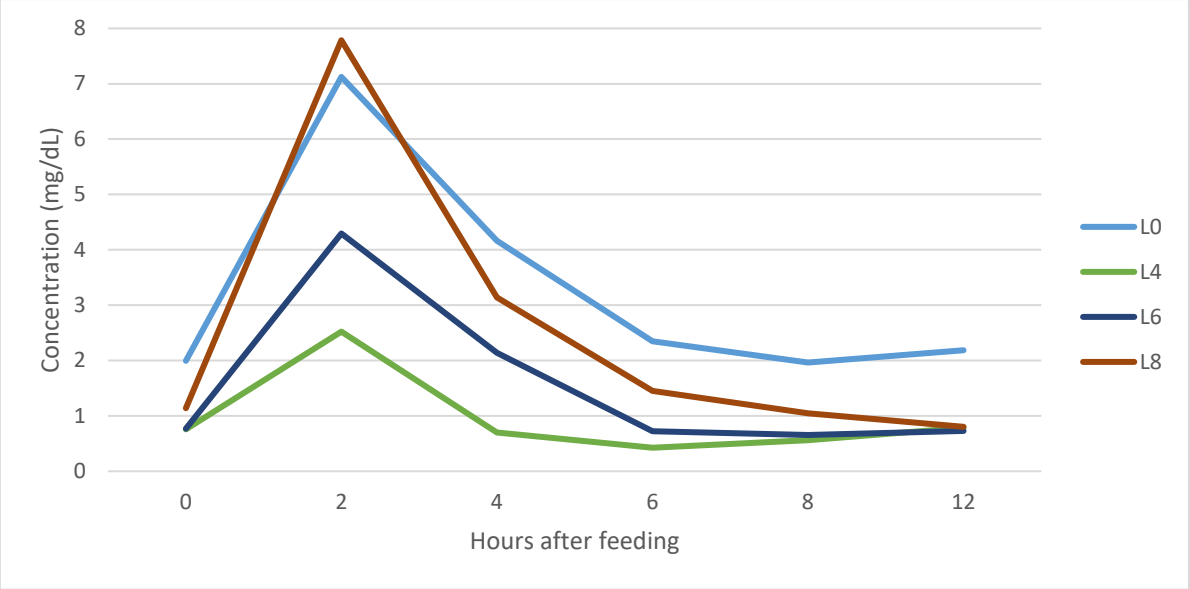

Figure 4.10 Change in mean RAN concentration (mg/dL) of the sheep over time for each treatment group.

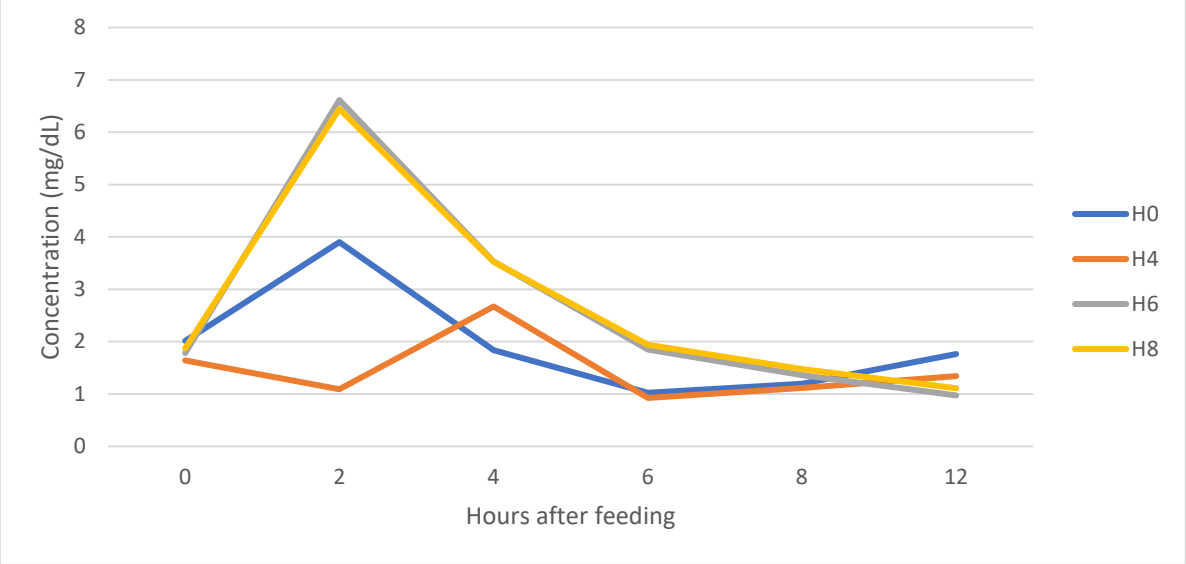

Figure 4.11 Change in mean RAN concentration of the sheep over time for each treatment group.

4.4.6 MBR Test

The MBR test reflects the activity of bacterial fermentation in the rumen (Bayne and Edmondson, 2021). In the current study the different feed densities did differ significantly ($P < 0.05$) (Table 4.2). Sheep fed the HD diets had numerically longer mean time (189.25 sec ± 13.28) than the LD diets (141.81 sec ± 13.28). Longer mean times were measured in sheep that were fed processed feeds (Table 4.3). Sheep fed the control diets (unprocessed feeds)

had the lowest mean time (98.25 sec ± 18.78) and was significantly (*P < 0.05*) lower than all the other processing methods. Although not significantly different, sheep fed larger pelleted diets tend to have longer mean times (Table 4.3). Table 4.4 and Fig. 4.12 illustrates the results of the MBR test of the sheep on the eight treatments groups. Sheep that received the H8 feed had numerically the longest mean time (269.38 sec ± 125.09), while the sheep that was fed the L0 feed had numerically the shortest mean time (85.875 sec ± 47.31). In the current study the time of the MBR test of the sheep that received the L4 feed, was significantly longer (*P < 0.05*) than the sheep fed on the L0, L8 and H0 feed. Literature regarding MBR tests on rumen fluid of sheep are however extremely limited.

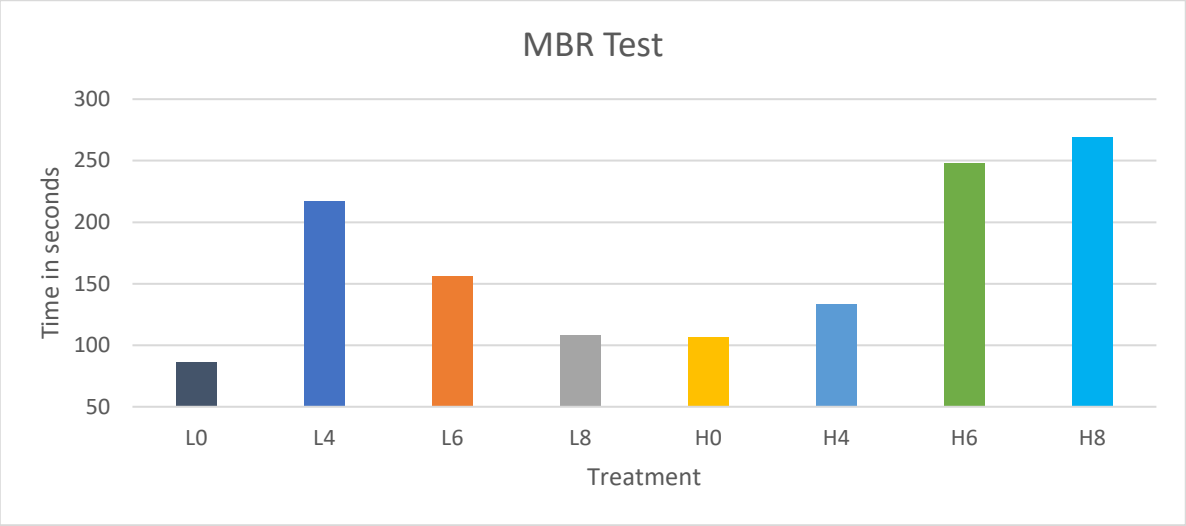

Figure 4.12 Mean time in seconds for the MBR test of the sheep for all treatment groups.

4.4.7 Hindgut fermentation

Overall, the mean faecal pH of the sheep that received the HD (7.48 pH ± 0.05) diets were higher than the LD (6.92 pH ± 0.05) diets (*P < 0.05*) (Table 4.2). Table 4.3 show that sheep fed the 6mm pelleted diets (7.4 pH ± 0.07), exhibited a higher mean faecal pH (*P < 0.05*) than the smaller pelleted (4mm) and unprocessed diets. The faecal pH of sheep receiving feed in the pelleted form did not differ significantly from faecal pH of sheep receiving a TMR ration. The results of the mean faecal pH of all the treatment groups are illustrated in Table 4.4 and Figure 4.13. Sheep that received the H6 diet resulted in the highest (*P < 0.05*) mean faecal pH (8.20 pH ± 0.24), while the sheep on the L6 diet had the lowest (*P < 0.05*) mean faecal pH that was recorded (6.57 pH ± 0.21).

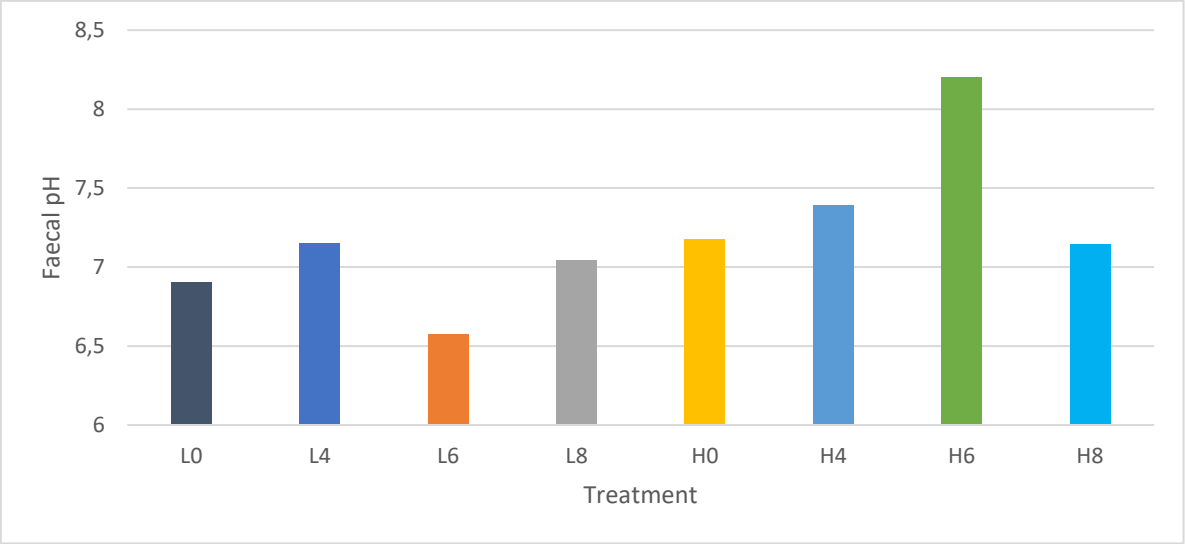

Figure 4.13 Means of different faeces pH readings for all the treatment groups.

Although the results of the faecal pH generally followed the results of the ruminal pH in this study, faecal pH is largely considered to be more associated with hindgut fermentation than with ruminal fermentation (Gressley *et al.,* 2011). However, conditions of excessive intake of fermentable carbohydrates may cause both ruminal acidosis and hindgut acidosis (Gressley *et al.,* 2011). The presence of hindgut acidosis implies that some of the fermentable carbohydrates consumed by the animal were passed through to the hindgut and where it was fermented (Oetzel, 2017). Hindgut acidosis is therefore characterized by increased rates of production of VFA's, decreased large intestine digesta pH, and damage to gut epithelium. Hindgut acidosis is thus more likely to occur in high-producing animals fed diets with relatively greater proportions of highly soluble carbohydrates and lesser proportions of forage (Gressley *et al.,* 2011). Additionally, feeding diets with smaller particle size, such as pelleted diets, can lower retention time of feed particles in the rumen, resulting in an increase in flow of fermentable substrates to the hindgut (Van Soest, 1994). DeGregorio *et al.* (1982) however, reported that whole grain maize and lower utilization of starch in the gastrointestinal tract leads to higher starch content in the faeces. Lin *et al.* (2021) found that pelleted high grain feed contributed to a lower impact on the colonic microbiome of sheep than high grain non-pelleted feed. In the current study the significantly higher DMI of the ewes on the LD diets may have been responsible for the lower ruminal pH as well as a lower faecal pH. This result is in support of Li *et al.* (2012) who reported reduced ruminal and faecal pH values in dairy cows when high intake of starch was high.

Research on the normal values of faecal pH in sheep is limited. The mean faecal pH of Nellore cattle on high concentrate diets was between 6.74 and 7.15 (Da Silva *et al.,* 2012).

Cunha *et al.* (2021) reported faecal pH values in feedlot steers between 6.60 and 6.31 for TMR rations with peNDF values below and above 20% respectively. Nagy and Gilbert (1968) reported mean faecal pH values of grazing sheep of 7.31 (range 7.10 - 7.48).

4.4.8 Possible explanation of the results

The unexpected results, in contrast to most studies on the effect of nutrient density on fermentation parameters, can be explained in the significant ($P < 0.05$) differences in DMI between sheep groups. It is also hypothesised that the increased rate of starch intake of the animals fed the LD diets also furthermore contributed to the unexpected results. It thus appears that the animals receiving LD diets, increased their DMI to such an extent that the ruminal pH was depressed to a greater extent and for a longer period of time than what was observed in the HD groups. The higher DMI in the LD groups also may have led to higher propionate levels and higher propionate: acetate levels. The faecal pH values observed also support this theory. The lower DMI of sheep on higher grain diets is generally supported by the literature, and diets with greater ruminal starch fermentability often depress feed and energy intakes (Allen and Piantoni, 2014). Most models used to predict feed intake in sheep also used energy concentration of the diet as a key indicator, with higher feed energy concentrations associated with lower DMI's (NRC, 1975; ARC, 1980; NRC, 1987; NRC, 2007).

4.4.9 General discussion on rumen fermentation findings

According to Calsamiglia *et al.* (2012) and Lean and Golder, (2018), the symptoms of SARA are not caused by a rumen pH depression alone, and that the diagnosis of SARA based solely on rumen pH values is not accurate. In contrast, no published study have definitely linked reduced production levels in sheep with subacute ruminal acidosis (Fanning, 2016). According to Plaizier *et al.* (2018), in dairy cows an accurate diagnosis of SARA requires a combination of clinical examinations of animals, as well as analyses of herd management and feed quality, including chemical and physical properties. Apart from rumen pH values, several blood, milk, urine, and faecal parameters, including respective pH values, have been proposed as indicators of SARA (Plaizier *et al*., 2018). Additionally, in practice both a reduction and an increase in daily variability in DMI have been used as indexes of subclinical acidosis (Kleen *et al.,* 2003). Discrepancies on the relationship between DMI and SARA do however exist. Under SARA conditions, the low rumen pH may not be the overriding factor that limits feed intake. This limits the usefulness of monitoring DMI for the diagnosis of SARA (Li *et al.,* 2012).

It is therefore clear that some degree of uncertainty still exists regarding the impact and prevalence of SARA in feedlot lambs. There has also been very little research on the economic importance of SARA in the sheep industry (Fanning, 2016). Due to the significant

interaction of DMI, diet composition and processing on the rumen fermentation parameters in animals of this study, little of the results could be interpreted and linked to the production results of lambs in the previous study.

4.5 Conclusion

In conclusion, the ruminal pH of sheep fed LD diets experienced a lower pH for a longer time after feeding compared to the observation in the HD diets. Sheep that were fed unpelleted feeds (H0 and L0), manifested a lower significant pH reduction and a slower recovery rate to initial pH than what had been seen in the sheep fed pelleted feeds. The concentrations of VFA's, specifically acetate and propionate, were higher in the LD groups than in the HD groups. Compared to pelleted diets, feed containing coarse grain promotes greater time for chewing and rumination and would be fermented slower and consequently results in a higher and more stable rumen pH. The confounding effect of DMI on fermentation, may have led to a more pronounced effect of LD feeds and of the diets containing larger pellet sizes on rumen pH and VFA concentrations.

4.6 References

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CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The substantial and continuous increase in cost of cereal grains in South Africa has highlighted the importance of the contribution of precision feeding to aid in profitability in intensive lamb production systems. The optimisation of both ruminal health and feed processing plays a crucial part in this regard. Results of the first trial showed that pelleting of a LD TMR improved the growth and economic performance of finishing lambs due to an increase in DMI and a better FCR. In contrast, pelleting of a HD TMR did not produce comparable beneficial effects on lamb performance. Lambs that received the HD diets exhibited higher GP compared to the lambs fed LD diets due to better carcass yields. On farms with available mixing equipment, the feeding of HD diets without any processing may be an economically viable option. Larger diameter pellets in a HD diet seemed to be more beneficial towards lamb performance compared to smaller pellets. Neither feed processing nor feed composition showed a significant effect on the faecal consistency of the lambs, although the FC score did show a downward trend over time.

The results of the second study were in contrast with most other research regarding the effect of feed density on rumen fermentation in sheep. The sheep that received the LD diets exhibited a lower ruminal pH and were lower for longer periods compared to the HD groups. Furthermore, the propionate and propionate: acetate levels were higher for the LD fed sheep compared to those fed the HD diets. This observation could mainly be explained by the significantly higher DMI that was observed in the sheep that were fed the LD diets.

5.2 Recommendations for future studies

Although the findings from this study are in accordance with the published literature with regards to low density diets, there is a need for additional research on the effects of processing of high-density diets in the lamb feedlot setting. Additionally, the confirmation of findings in this study regarding pellet size and general processing under a wider variety of circumstances is crucial prior to the publication of definitive guidelines in this respect.