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Effects of different feeding regimes on growth performance, intake, digestibility, and ruminal metabolic and morphological characteristics in Awassi lambs

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Abstract

The aim of this research was to investigate the effects of different feeding regimes on the growth performance, nutrient intake, apparent digestibility, and ruminal metabolic and morphological characteristics of Awassi lambs. A total of 96 lambs (initial age: 10 ± 1 weeks; mean body weight: 23.62 ± 0.01 kg) were divided into four dietary groups in a completely randomised design (eight replicates/diet, three lambs/replicate). The four diets were as follows: control (CON: 50% barley grain, 50% long lucerne/alfalfa hay), diet 1 (D1: 100% complete pelleted feed), diet 2 (D2: 40% concentrate pellets, 60% long lucerne hay), and diet 3 (D3: 60% concentrate pellets, 40% roughage pellets). The lambs were fed the four diets for 84 days, and growth performance indicators were assessed twice (every 42 days) during this period. After 84 days, all target parameters, including morphometry, fermentation indicators, and bacterial activity in the lambs' rumens, were assessed. The primary findings indicated that treatments D2 and D3 led to increased body weights, weight gains, and feed intakes. Lambs fed D2 had a higher dry matter intake and nutrient digestibility, along with increased papilla height, density, and total surface area. Specific fibre-degrading bacteria were more prevalent in D1, D2, and D3 than in the CON lambs. The higher total volatile fatty acid concentrations measured in the rumens of the D1, D2, and D3 lambs signified an improved fermentation profile. In conclusion, these results highlight the potential of complete diets and concentrate pellets with roughage sources to optimise performance, rumen health, and nutrient utilisation in lambs.

Keywords: bacterial activity, fibre source, production, rumen fermentation, sheep

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Introduction

Sheep have a unique digestive system that enables them to extract nutrients from forage (Ata, 2016; Yang *et al*., 2022). The Awassi is a prolific indigenous breed from the Middle East that adapts well to harsh environments and efficiently utilises low-quality forages (Lafi *et al*., 2009). Nonetheless,

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providing a balanced diet that meets their nutritional requirements is still essential for improving growth performance (Alshamiry *et al*., 2023). In Saudi Arabia, Awassi sheep are mainly distributed in the northern and eastern regions, which are among the hottest areas in the country and receive little rainfall, and thus experience water scarcity. This has led to a shift from traditional grazing to intensive feeding systems based on grains and roughage (Alhidary *et al*., 2016). This shift in feeding systems requires a deeper understanding of how these diets affect lambs at the physiological level. Specifically, the metabolic and morphological characteristics of the rumen are critical determinants of subsequent growth and the successful utilisation and uptake of nutrients (Li *et al*., 2022). Rumen bacteria are essential for fermenting dietary components, such as cellulose and hemicellulose, and converting them into volatile fatty acids, which are primary energy sources for the animal (Cunha *et al*., 2011; Liu *et al*., 2022). Crucially, the production of volatile fatty acids in the lamb rumen contributes to rumen health, nutrient intake, and overall animal performance (Henderson *et al*., 2015). However, the physical form and composition of the diet directly affect rumen fermentation characteristics and the digestive process (Karimizadeh *et al*., 2017). In addition, the integrity of the rumen wall and the development of the papillae (rumen histomorphology) are key indicators of the lamb's absorptive capacity and digestive efficiency (Sohail *et al*., 2022). Dietary manipulation significantly influences these characteristics, including papilla length and surface area, as well as rumen fermentation profiles, such as the volatile fatty acid composition and pH (Wang *et al*., 2022).

The processes of microbial activity and fermentation within the rumen may be influenced by different factors related to the animal's physiological state and diet composition, including the physical form of the forage (Pazoki *et al*., 2017). Each stage of animal growth requires a different percentage of forage, concentrate, or supplement to meet the animal’s nutritional requirements (Aguayo-Ulloa *et al*., 2013). The use of various feed sources results in different amounts of energy, protein, fibre, and other essential nutrients, and these are critical for an optimal, balanced diet that promotes efficient nutrient utilisation and growth (El-Nomeary *et al*., 2021). However, the type and amount of forage and concentrate ingested has a significant impact on the composition and activity of the rumen microbes, affecting the production of volatile fatty acids, the rumen pH, and nutrient digestibility (Khateri *et al*., 2017; Li *et al*., 2019).

Claffey *et al*. (2018) reported that increasing the ratio of concentrate to roughage benefits lambs by improving their growth rate and feed efficiency. However, excessive concentrate intake can impair rumen fermentation, ultimately resulting in a decrease in the rumen pH and reduced fibre digestibility (Arjmand *et al*., 2022). Consequently, determining the optimal concentrate-to-roughage ratio is critical for achieving maximal growth performance, enhancing nutrient digestibility, and supporting ruminal metabolic and morphological development (Trottier, 2020; Chen *et al*., 2021). Previous research by Tripathi *et al*. (2007) found that feeding lambs a 49% concentrate diet resulted in optimal rumen pH and improvements in nutrient digestibility, rumen health, and growth indicators.

In addition, the particle size of the forage provided (e.g. hay or pellets) also influences rumen function and digestibility (Ishaq *et al*., 2019). Combining concentrate pellets with forages such as hay or straw provides a balanced nutritional approach, and this strategy can improve feed intake, digestibility, and growth performance compared to feeding concentrate pellets alone (Li *et al*., 2021). Moreover, pelleted complete feeds offer benefits such as improved feed intake and growth rate (Nagi *et al*., 2012), while longer green forages such as hay stimulate chewing, saliva production, and rumen buffering capacity (Khurshid *et al*., 2023). While some studies have investigated these factors individually, there is a notable gap in understanding the combined effects of the concentrate-to-forage ratio and the physical form of the diet in Awassi lambs (Beigh *et al*., 2017; Baldi *et al*., 2019). This study fills this critical gap by systematically evaluating the interaction between these two key dietary factors. Specifically, we investigate how different combinations of concentrate-to-forage ratio and forage form (long hay versus pelleted forage) affect growth indicators, nutrient digestibility, and overall rumen health in Awassi lambs.

The results of this research could provide novel and practical information for lamb producers in arid regions. By identifying the most effective and efficient feeding regimes, it provides a scientific basis for optimising feed formulations and increasing the productivity of Awassi lambs in Saudi Arabia. Therefore, this research aimed to investigate the growth performance parameters, nutrient intake, apparent digestibility, rumen fermentation characteristics, and rumen morphology of Awassi lambs fed under different feeding regimes.

Materials and methods

The research protocol received ethical approval from King Saud University through the Standing Committee on Scientific Research Ethics, specifically the Animal Care and Use Committee (ethical approval number: 22-26).

Animals and experimental design

Ninety-six male Awassi lambs, aged 10 ± 1 weeks and with similar initial body weights (23.62 ± 0.01 kg), were used in the 84-day experiment. The study was conducted at the King Saud University experimental farm, where semi-closed housing pens (4 × 3 m), each equipped with dedicated feeders and drinkers, were used. The lambs were randomly allocated to 32 pens (replicates), with each pen containing three lambs. This resulted in eight replicates (pens) and 24 lambs per feeding group, following a completely randomised design. All the lambs were offered feed *ad libitum* once a day, and water was always available. The lambs were adapted to the different treatment diets for 14 days after arrival, once they had been examined and confirmed to be free of health problems and parasites. They were then vaccinated against endemic diseases, including peste des petits ruminants, septicaemia, plague, enterotoxaemia, and foot-and-mouth disease (vaccines manufactured by the Ibriz Company, Kingdom of Saudi Arabia).

Experimental diets

All four experimental diets were formulated to align with National Research Council (NRC, 2007) recommendations, ensuring that the nutritional requirements of the lambs were met throughout the 84-day trial period. The four feeding regimes tested in this study (Table 1) were as follows:

1. Traditional/control diet (CON): This diet consisted of 50% barley grain and 50% long lucerne/alfalfa (*Medicago sativa*) hay with no additional vitamin and mineral supplementation. The CON diet was included to mimic a traditional feeding practice common in the region, where barley grain and long lucerne hay are fed separately. This allows a direct comparison with the scientifically formulated experimental diets.
2. Complete pelleted diet (D1): Lambs were fed a 100% complete pelleted diet containing all necessary nutrients in a single homogeneous pelleted form to reduce forage sorting by the lambs.
3. Pelleted concentrate diet plus long lucerne hay (D2): Lambs were fed a combination of 40% concentrate pellets and 60% long lucerne hay, offered separately. This ratio was chosen to test the balance of nutrients required by the lambs from the concentrate pellets and fibre (long lucerne hay). It serves as a direct comparison to the traditional diet to determine whether the use of pelleted concentrates, while maintaining roughage in the form of hay, is beneficial.
4. Pelleted concentrate diet plus forage pellets (D3): Lambs received 60% concentrate pellets and 40% forage pellets, offered separately. In this group, the same concentrate pellets were used as in D2, but the long lucerne hay was replaced with forage pellets. The comparison between D2 and D3 is the key to understanding whether hay or pelleted forage is more favourable.

Growth performance

Each lamb was individually weighed to record its initial body weight. This procedure was then repeated at six-week intervals during the trial (on days 1, 42, and 84). Daily weight gain was calculated as the average for each experimental unit (three lambs in one pen), as previously described by Mousa *et al*. (2022):

$$Daily\ weight\ gain\ (g/day) = \frac{Final\ weight\ (g) - Initial\ weight(g)}{Days}$$

The body condition of each lamb was scored on a scale from 1 (very lean) to 5 (obese) by three experienced individuals, at the same time intervals as the lambs were weighed (Wang *et al*., 2022).

The daily feed intake was estimated for each pen (replicate) to determine the feed-to-gain ratio (Pereira *et al*., 2020):

$$Daily\ feed\ intake\ (g/day) = \frac{Feed\ offered\ (g) - Feed\ refused\ (g)}{Days}$$

$$Feed{:}\,gain\ ratio\ (g{:}\,g) = \frac{Daily\ feed\ intake\ (g)}{Daily\ weight\ gain\ (g)}$$

Table 1 Feed components and nutrient analysis of four different feeding regimes provided to Awassi lambs

	Feeding regimes						
	CON		D1	D2		D3	
	Barley grain	Long lucerne hay	Pelleted complete feed	Pelleted concentrate	Long lucerne hay	Pelleted concentrate	Pelleted forage
Inclusion (%)	50	50	100	40	60	60	40
Feed ingredients:							
Barley grain	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Lucerne hay	0.00	100.00	22.13	0.00	100.00	0.00	60.00
Maize grain	0.00	0.00	35.14	45.00	0.00	45.00	0.00
Wheat bran	0.00	0.00	18.00	25.00	0.00	25.00	0.00
Wheat straw	0.00	0.00	7.00	0.00	0.00	0.00	40.00
Soybean meal	0.00	0.00	9.80	22.09	0.00	22.09	0.00
Molasses	0.00	0.00	3.00	3.00	0.00	3.00	0.00
Limestone	0.00	0.00	3.00	2.58	0.00	2.58	0.00
Salt	0.00	0.00	0.83	0.83	0.00	0.83	0.00
Acid buffer	0.00	0.00	0.80	1.10	0.00	1.10	0.00
Vit+min premix[1]	0.00	0.00	0.30	0.40	0.00	0.40	0.00
Total	100	100	100	100	100	100	100

Nutrient analysis (%, unless otherwise indicated) on a dry matter basis[2]**:**

	CON	D1	D2	D3
Dry matter	94.48	94.63	94.74	94.62
ME (kcal/kg)	2890	2940	2950	2940
Crude protein	14.22	14.23	14.34	14.47
NDF	29.50	29.53	29.67	34.67
ADF	14.26	14.51	15.00	15.08
Lignin	3.28	3.41	3.45	3.54
Starch	24.43	25.61	25.67	25.77
Ether extract	1.34	2.49	2.55	2.57
Ash	6.38	8.32	8.17	8.33
Calcium	0.54	2.36	2.34	2.26
Total phosphate	0.21	0.46	0.48	0.47
Iron (ppm)	155	413	424	418
Copper (ppm)	3	10	11	11
Zinc (ppm)	22	140	145	146

ME: metabolisable energy, NDF: neutral detergent fibre, ADF: acid detergent fibre. [1] The vitamin and mineral premix contained 10 000 IU/kg vitamin A, 1000 IU/kg vitamin D, 20 IU/kg vitamin E, 300 mg/kg magnesium, 24 mg/kg copper, 0.6 mg/kg cobalt, 1.2 mg/kg iodine, 60 mg/kg manganese, 0.3 mg/kg selenium, and 60 mg/kg zinc. [2]The nutrient content of the diets was analysed using the methods described by the AOAC (2019).

Nutrient intake and apparent digestibility

After 84 days of the feeding trial, one lamb per pen was randomly selected (eight lambs per feeding group) and placed in a digestion cage (1.2 × 0.6 m) prepared with a feeder, a drinking trough, and a bowl to collect faeces for a digestibility trial. The daily feed intake was calculated as the difference between the feed offered and refused per lamb over four days as a sub-replicate, following a seven-day adaptation period. The amount of faeces excreted was also recorded daily. The nutrient concentrations in the diets and faeces were analysed in triplicate using standard AOAC (2019) methods: dry matter (method number 934.01), crude protein (Kjeldahl method, number 984.13, nitrogen percentage × 6.25), ether extract (Soxhlet method, number 920.39), and starch (enzymatic digestion followed by colorimetric tests, number 996.11). The neutral detergent fibre and acid detergent fibre were analysed using the Fibre Analyzer (ANKOM Technology, NY, USA), based on the Van Soest method (Van Soest *et al.,* 1991). The metabolisable energy content was estimated from the gross energy content by accounting for energy losses during digestion and absorption (digestible energy), then multiplying by 0.82 as a general correction factor (Neto *et al.,* 2023). The calcium, total phosphate, iron, copper, and zinc concentrations were determined using an atomic absorption spectrometer (PerkinElmer, MA, USA), following the method described by Pelegrin-Valls *et al.* (2020).

The daily intake of each nutrient was calculated by subtracting the amount excreted in the faeces from the amount of the respective nutrient in the feed consumed (Costa *et al*., 2021). The apparent nutrient digestibility of dry matter, crude protein, crude fat, neutral detergent fibre, and acid detergent fibre were calculated using the standard formula (Pelegrin-Valls *et al*., 2020):

$$Apparent\ digestibility\ (\%) = \frac{Nutrients\ ingested - Nutrients\ excreted}{Nutrients\ ingested} \times 100$$

Rumen tissue morphometrics

After 84 days of the trial, approximately 2 cm rumen tissue samples were taken from eight lambs per feeding group (one lamb per pen) immediately after slaughter. The tissue samples were fixed in 10% neutral buffered formalin for 72 hours and then processed using an automated tissue processor (Tissue-Tek VIP 5 Jr., Sakura, Japan). All samples were subsequently cut into two sections, each 5 µm thick, using a microtome (Leica Biosystems, Germany).

The tissue sections were stained with haematoxylin and eosin. For morphometric analysis, five randomly selected papillae per lamb were analysed from each tissue section. Several morphological parameters of the rumen were measured for each selected papilla using an image analyser (Leica Imaging Systems Ltd., Cambridge, UK) under a light microscope (Wang *et al*., 2021). The morphology of the ruminal tissue was assessed by recording the height, width, and density (the number of papillae per unit area) of the papillae. In addition, the thickness of the stratum corneum, epithelium, lamina propria, and submucosa was measured at three representative points on each section. The recorded height, width, and density data were then used to calculate both the individual and total papilla surface area for each lamb (Cui *et al*., 2019).

Rumen sampling and pH determination

On day 84 of the trial, rumen fluid was sampled from eight randomly selected lambs per dietary group (one lamb per pen) immediately before the morning feeding. Samples were collected using a specialised tube connected to a vacuum pump (KNF Neuberger, Freiburg, Germany). After collection, samples were filtered into sterile 25 mL tubes (Wu *et al*., 2022). The pH of the rumen fluid was immediately determined in duplicate using a portable pH meter (Sartorius PT-10, Germany). All the samples were spiked with 5 mL of 0.2 N hydrochloric acid and centrifuged at 5 °C (14 000 × g) for 10 minutes, and the solid and supernatant fractions were stored at −80 °C until the analysis of the ammonia nitrogen concentration, the volatile fatty acid concentrations, and the bacterial activity.

Ammonia nitrogen analysis

The concentration of ammonia nitrogen was determined to evaluate the level of protein degradation and nitrogen availability to rumen microbes. It was analysed using the phenol-hypochlorite reagent method with a spectrophotometer (PerkinElmer, MA, USA), after pre-treating the samples with 0.5 mL of hydrochloric acid (0.1 N), according to the previously described procedure (Broderick & Kang, 1980; Adejoro *et al*., 2020).

Estimation of rumen volatile fatty acids

The volatile fatty acid concentrations (acetic acid, propionic acid, and butyric acid) in the rumen fluid were quantified using gas chromatography–mass spectrometry (Agilent, Series 1260, Palo Alto, CA, USA) to evaluate the rumen fermentation patterns of the lambs, as previously described (Prathap *et al*., 2023). Aliquots (5 mL) of rumen fluid (supernatant) were mixed with 1 mL of 25% metaphosphoric acid and centrifuged at 5 °C for 10 minutes (14 000 × g) to remove the solid fraction. The supernatant fraction (1 mL) was filtered and transferred to a glass chromatography vial (Agilent). All internal standards were purchased from Dr. Ehrenstorfer (Augsburg, Germany). The results for individual volatile fatty acids were expressed as percentages of the total volatile fatty acid concentration (Li *et al*., 2023).

Bacterial activity in the rumen

Total microbial DNA was extracted from the solid fraction of the rumen fluid using a tissue homogeniser and a commercially available extraction kit (Qiagen, Germantown, MD) according to the manufacturer's protocol. The purity and yield of the isolated DNA were verified by using a Nanodrop spectrophotometer (Thermo Scientific, 2000, MA, USA) to measure the 260/280 nm absorbance ratio. Dilutions of the extracted DNA from each sample were prepared to obtain the same DNA concentration (50 ng/µL) in all samples. The quantities of the selected rumen bacteria (total bacteria, *Butyrivibrio fibrisolvens*, *Fibrobacter succinogenes*, *Streptococcus bovis*, *Ruminococcus albus*, and *Ruminococcus flavefaciens*) were measured using Power SYBR Green Master Mix kits (Qiagen, Valencia, CA, USA), with a quantitative real-time polymerase chain reaction (7300 RT-PCR System, Applied Biosystems). Table 2 shows the specific primer sequences used. The results were expressed as absolute quantities ($\log_{10}$ colony-forming units [CFU] per 1 mL of rumen fluid), based on a standard curve for each target gene generated using a serially diluted pool of bacterial DNA (Tian *et al*., 2023).

Table 2 Forward and reverse primer sequences used for real-time quantitative polymerase chain reaction assay

Target gene	Primer sequence (5′ → 3′)	Size (bp)	Reference
Total bacteria	F: CGGCAACGAGCGCGAACCC R: CCATTGTAGCACGTGTGTAGCC	130	Delgadillo-Ruiz *et al*., 2022
Butyrivibrio fibrisolvens	F: CGCATGATGCAGTGTGAAAAGCTC R: CCTCCCGACACCTATTATTCATCG	64	Mirzaei-Alamouti *et al*., 2021
Fibrobacter succinogenes	F: GTTCGGAATTACTGGGCGTAAA R: CGCCTGCCCCTGAACTATC	121	Delgadillo-Ruiz *et al*., 2022
Streptococcus bovis	F: ATTCTTAGAGATAGGGTTTCTCTT R: ACCTTATGATGGCAACTAACAATA	134	Mirzaei-Alamouti *et al*., 2021
Ruminococcus albus	F: CCCTAAAAGCAGTCTTAGTTCG R: CCTCCTTGCGGTTAGAACA	176	Tian *et al*., 2023
Ruminococcus flavefaciens	F: ATTGTCCCAGTTCAGATTGC R: GGCGTCCTCATTGCTGTTAG	173	Tian *et al*., 2023

Statistical analysis

All data were subjected to Shapiro–Wilk and Levene's tests to determine normality and homogeneity of variances. In addition, all experimental data for each parameter were analysed using a general linear model with a one-way analysis of variance (ANOVA). The analysis was conducted using SAS 9.4 software (SAS Institute, 2008).

For parameters measured at multiple time points (e.g. body weight, body condition score, daily weight gain, and daily feed intake), a repeated-measures analysis was performed to account for the correlation between measurements taken over time on the same experimental unit. The statistical model used was as follows:

$$Y_{ijk} = \mu + T_i + \mathrm{Time}_j + (T \times Time)_{ij} + Pen_k + e_{ijk}$$

where:
Y_{ijk}: observed value,
μ: overall mean,
T_i: effect of the feeding regime *i* (CON, D1, D2, or D3),
$Time_j$: effect of time of measurement,
$(T \times Time)_{ij}$: interaction effect,
Pen_k: random effect of the pen, and
e_{ijk}: random error.

This model considers the fixed effects of diet and time, their interaction, and the random effect of pen within diet, which is crucial because the lambs were fed in groups within pens. The experimental unit for this analysis was the pen, with each diet group having eight replicates (pens).

For the parameters measured only at the end of the study period, a one-way ANOVA model was used, as previously stated:

$$Y_{ij} = \mu + T_i + e_{ij}$$

where:
Y_{ij}: observed value,
μ: overall mean,
T_i: effect of the feeding regime *i* (CON, D1, D2, or D3), and
e_{ijk}: random error.

The experimental unit for this analysis was the lamb from each pen, with each feeding group having eight replicates (lambs).

Duncan's multiple range test was used to identify significant differences (P <0.05) between the feeding regimes. In all tables, results for each variable are reported as the mean ± the standard error of the mean (SEM).

Results and discussion

The current results highlight the valuable insights and potential benefits of complete feeds or pelleted concentrates, including the feed source and physical form of the forage, while emphasising the importance of tailored feeding strategies for optimal lamb production. The effects of the feeding regimes on the growth performance parameters of Awassi lambs are shown in Table 3. The results showed no significant differences (P >0.05) in body weight, daily weight gain, or feed-to-gain ratio between the lambs fed the different regimes during the initial period of the trial (1–42 days). However, the daily feed intake was highest in the D3 group (60% concentrate pellets + 40% forage pellets) during this phase (P <0.05). This finding is consistent with the results reported by Aguayo-Ulloa *et al.* (2013) and Herath *et al*. (2021), who found that body weight and early daily weight gain were similar in lambs regardless of whether they were fed a pelleted concentrate feed or barley grain with long lucerne hay. This suggests that the early growth phase in young lambs may be less sensitive to differences in concentrate-to-roughage ratios or the physical form of the diet, as rumen development and maturation are still ongoing.

In contrast to the early phase, significant differences emerged in the later period (43–84 days and 1–84 days). Lambs fed the pelleted diets (D1–D3) had higher body weights and daily weight gains than the CON group at 43–84 days and at 1–84 days (P <0.05). Lambs fed D3 showed the highest daily feed intake from 1 to 42 days (P <0.05). In contrast, lambs fed D2 had the highest (P <0.05) daily feed intake, followed by those in the CON group, then D3 and D1, from 43 to 84 days of age and for the overall 84-day period. The feed-to-gain ratio was also significantly improved (reduced) in all the pelleted groups (D1–D3), compared to the CON group, for the overall 84-day period (P <0.05).

These results support the conclusions of previous studies, which found that diets containing highly processed or pelleted components improved growth indicators and feed efficiency in growing lambs (Retnani *et al*., 2020; Yang *et al.,* 2022). Specifically, the finding that both the physical form of the diet (pelleting) and the proportion of concentrate significantly affect later growth aligns with the findings of Claffey *et al.* (2018), who noted that increasing the ratio of concentrates to roughage increased the growth rate and feed efficiency in lambs. Additionally, pelleted complete feeds can enhance feed intake, growth indicators, and feed conversion efficiency in lambs compared to traditional hay (Nagi *et al.,*

2012). Pelleted concentrates are also characterised by increased feed intake, reduced feed wastage, and reduced energy losses during feeding (Ojo *et al.,* 2019), thereby allowing lambs to consume more energy to meet their growing requirements, as reflected in the performance of the lambs in this study. In contrast, Costa *et al.* (2017) reported that feeding lambs a highly concentrated (75:25 concentrate:roughage) diet led to a decrease in growth performance parameters, whereas feeding lambs a diet with a 50:50 ratio had no significant effect (Francisco *et al.,* 2018).

This research provides new, specific evidence for Awassi lambs regarding the combined effects of the concentrate-to-roughage ratio and the physical form of the forage. All diets that included pelleted components (D1–D3) consistently resulted in superior growth performance, compared to the traditional 50:50 mixed ration of barley grain and long hay (CON). Within the pelleted diets, the D2 group (40% concentrate pellets + 60% long lucerne hay) achieved the best overall daily weight gain and the most efficient feed-to-gain ratio in the later stage of growth. This indicates that, for Awassi lambs to grow optimally, it is best to move away from a 50:50 ratio by slightly lowering the proportion of concentrates and maintaining a higher proportion of long hay. The lambs provided with this diet (D2) performed better than those fed the complete pelleted diet (D1) or the higher concentrate + pelleted forage diet (D3). There were no significant differences (P >0.05) in the body condition scores of the lambs in the different feeding groups at any time point from day 1 to 84 of the trial. This lack of difference in body condition scores suggests that while feed efficiency and growth rate were improved by pelleting, overall subcutaneous fat and muscle mass deposition remained similar, indicating that the differences were primarily in the rate of gain rather than the overall body composition.

Table 3 Effects of four feeding regimes on the growth performance indicators of Awassi lambs

Variables	Feeding regimes[1]				SEM[2]	*P*-value
	CON	D1	D2	D3		
Body weight (kg)						
1 day	23.61	23.63	23.63	23.63	0.009	0.417
42 days	31.90	32.25	33.80	32.87	0.567	0.145
84 days	40.76^{b}	42.72^{ab}	44.72^{a}	43.38^{a}	0.512	0.001
Body condition score						
1 day	3.02	3.10	3.25	3.27	0.098	0.268
42 days	3.80	3.75	4.02	3.94	0.108	0.294
84 days	3.93	4.10	4.11	4.12	0.076	0.311
Daily weight gain (g/day)						
1–42 days	0.210	208	239	220	10.21	0.192
43–84 days	209^{b}	249^{a}	260^{a}	250^{a}	10.23	0.020
1–84 days	201^{b}	229^{a}	249^{a}	236^{a}	5.788	0.001
Daily feed intake (g/day)						
1–42 days	1186^{b}	1173^{b}	1237^{ab}	1291^{a}	20.82	0.007
43–84 days	1688^{ab}	1582^{b}	1826^{a}	1629^{b}	44.99	0.011
1–84 days	1437^{ab}	1377^{b}	1532^{a}	1461^{ab}	25.12	0.007
Feed-to-gain ratio (g:g)						
1–42 days	5.67	5.68	5.23	5.88	0.246	0.341
43–84 days	8.13^{a}	6.42^{b}	7.04^{b}	6.55^{b}	0.413	0.048
1–84 days	7.15^{a}	6.05^{b}	6.16^{b}	6.21^{b}	0.161	0.001

$^{a–b}$ Superscript values within each row highlight significant differences at P <0.05 between the feeding regimes for each variable. [1] CON: 50% barley grain + 50% long lucerne hay, D1: 100% pelleted complete feed containing 1 mm lucerne hay, D2: 40% concentrate pellets + 60% long lucerne hay, D3: 60% concentrate pellets + 40% forage pellets. [2] SEM: standard error of the mean.

The effects of the feeding regimes on the nutrient intake and apparent nutrient digestibility in the Awassi lambs are presented in Table 4. The daily dry matter intake was higher (P <0.05) in the lambs fed the D1 diet than in those fed the other diets. This could be due to several factors, including the finely ground nature of the pelleted complete feed, which may have facilitated easier absorption and faster passage through the digestive tract, as well as possibly stimulating the lambs' appetites (Andrés *et al*., 2018). The D1–D3 feeding regimes had higher (P <0.05) crude protein intakes than the CON. This aligns with the expectation of a higher protein content in a pelleted complete feed or concentrate diet than in the CON diet, which was solely based on barley grain and long lucerne hay. In addition, lambs fed D2 had a higher (P <0.05) fat intake than the CON group, which may be related to the specific ingredients in each feed formulation. However, there were no significant differences (P >0.05) in the intakes of organic matter, neutral detergent fibre, or acid detergent fibre between the different feeding regimes.

Lambs fed the D2 diet showed significantly higher apparent dry matter and fat digestibility (P <0.05) than those fed the CON diet, with no notable differences observed between the other feeding regimes. This may indicate that the dry matter and fat intake were higher in the D2 lambs than in the lambs fed barley grain and long lucerne hay (CON group). This could be attributed to several factors, such as a more balanced nutrient profile, more readily available energy sources, or improved rumen fermentation in response to the concentrate ingredients. The apparent digestibility of organic matter and protein was higher (P <0.05) in the lambs fed the pelleted feeding regimes (D1–D3) than in the CON group, suggesting more efficient utilisation of digestible energy and protein. This concurs with previous research showing that feeding lambs a combination of concentrate pellets and forage (hay or straw) provides a balanced nutritional approach, and consequently improves feed intake, digestibility, and growth performance compared to feeding concentrate pellets alone (Li *et al*., 2021). Tripathi *et al*. (2007) reported that lambs fed a 49% concentrate diet had better nutrient digestibility, and previous research has investigated several methods to obtain the optimal forage-to-concentrate ratio for improved nutrient digestibility (Trottier, 2020).

Table 4 Effects of four feeding regimes on nutrient intake and apparent nutrient digestibility in Awassi lambs

Variables	Feeding regimes[1]				SEM[2]	*P*-value
	CON	D1	D2	D3		
Daily nutrient intake (g/day)						
Dry matter	1313.63^{b}	1626.12^{a}	1302.64^{b}	1276.07^{b}	87.49	0.047
Organic matter[3]	1255.39	1485.32	1188.62	1163.67	81.03	0.058
Crude protein	140.75^{c}	208.63^{a}	225.93^{a}	187.15^{b}	12.57	0.002
Ether extract	30.74^{b}	38.86^{ab}	46.24^{a}	37.90^{ab}	2.572	0.009
Neutral detergent fibre	425.68	415.09	333.52	360.18	24.79	0.064
Acid detergent fibre	149.93	182.61	153.07	166.95	10.34	0.155
Apparent nutrient digestibility (%)						
Dry matter	77.66^{b}	80.35^{ab}	82.51^{a}	80.73^{ab}	1.047	0.044
Organic matter[3]	82.06^{b}	90.94^{a}	88.40^{a}	89.90^{a}	1.319	0.002
Crude protein	64.39^{c}	73.87^{b}	80.82^{a}	77.90^{ab}	1.581	<0.0001
Ether extract	78.55^{b}	82.13^{ab}	92.07^{a}	85.36^{ab}	1.945	0.002
Neutral detergent fibre	61.62	56.75	67.25	66.87	2.502	0.036
Acid detergent fibre	42.71^{b}	49.77^{ab}	63.48^{a}	61.26^{a}	3.501	0.003

$^{a–b}$ Superscript values within each row highlight significant differences at P <0.05 between the feeding regimes for each variable. [1] CON: 50% barley grain + 50% long lucerne hay, D1: 100% complete pelleted diet containing 1 mm lucerne hay, D2: 40% concentrate pellets + 60% long lucerne hay, D3: 60% concentrate pellets + 40% forage pellets. [2] SEM: standard error of the means. [3] Organic matter = 100 − ash concentration.

Lambs fed D2 and D3 had higher (P <0.05) apparent acid detergent fibre digestibility values than those in the CON group. However, they did not significantly differ from the lambs fed diet D1. This could indicate that the inclusion of specific forage sources in these diets (such as long lucerne hay or forage pellets) promoted microbial activity in the rumen and the degradation of recalcitrant fibre fractions. No significant differences in the digestibility of neutral detergent fibre were observed between the different feeding regimes (P >0.05). Previous research suggests that the presentation of the forage (hay versus pellets) can influence rumen function and digestibility (Ishaq *et al*., 2019). Heat during the pelleting process can also lead to the degradation of proteins and antinutritional substances, which may have a positive effect on digestibility (Soltani *et al*., 2020).

The effects of the feeding regimes on the rumen morphometrics of the Awassi lambs are presented in Table 5. Lambs fed D2 had the highest (P <0.05) papilla height and density, and the lowest (P <0.05) stratum corneum thickness. Papilla width was higher (P <0.05) in lambs fed D3 than in those fed CON and D2, but did not differ between D3 and D1. The papilla surface area in the lambs fed D3 and the total surface area of the papillae in the lambs fed D2 and D3 were higher (P <0.05) than in the CON group, but did not differ from the other dietary groups. The results indicate that lambs fed concentrate pellets with long lucerne hay (D2) showed better rumen morphological development. This finding is consistent with those of Wang *et al*. (2022), who found that concentrate-based diets improve rumen wall integrity and papilla development, thereby promoting fermentation and nutrient absorption. In addition, D2 resulted in a reduced stratum corneum thickness, which could facilitate nutrient exchange through the rumen wall, as suggested by Böck *et al.* (2023). The thickness of the epithelium increased in lambs fed D2 and decreased in those fed D3, compared to the other dietary groups (P <0.05). Furthermore, the lambs fed D2 had thicker (P <0.05) submucosa than the CON group, followed by those fed D3 and D1. This suggests a faster turnover of epithelial cells and a higher capacity for nutrient uptake (Na, 2022). An optimal forage-to-concentrate ratio has been found to lead to improved morphological characteristics in the rumen (Chen *et al.,* 2021).

Table 5 Effects of four feeding regimes on the rumen morphometrics of Awassi lambs

Variables	Feeding regimes[1]				SEM[2]	*P*-value
	CON	D1	D2	D3		
Papilla height (mm)	1.90^{b}	1.87^{b}	2.45^{a}	2.04^{b}	0.103	0.001
Papilla width (mm)	0.26^{b}	0.30^{ab}	0.25^{b}	0.32^{a}	0.013	0.002
Papilla surface area (mm)	1.53^{b}	1.77^{ab}	1.93^{ab}	2.04^{a}	0.118	0.023
Papilla density (n/cm^2)	61.67^{b}	61.67^{b}	84.00^{a}	68.58^{b}	3.853	0.0004
Total surface area of papillae (mm^2/cm^2)	57.97^{b}	67.37^{b}	101.84^{a}	88.34^{a}	4.844	<0.0001
Stratum corneum thickness (mm)	0.037^{a}	0.038^{a}	0.029^{b}	0.039^{a}	0.001	0.0005
Epithelium thickness (mm)	0.062^{b}	0.071^{b}	0.151^{a}	0.034^{c}	0.006	<0.0001
Lamina propria thickness (mm)	0.09^{c}	0.11^{bc}	0.13^{ab}	0.15^{a}	0.007	<0.0001
Submucosa thickness (mm)	0.14^{c}	0.20^{b}	0.25^{a}	0.23^{ab}	0.008	<0.0001

$^{a–b}$ Superscript values within each row highlight significant differences at P <0.05 between the feeding regimes for each variable. [1] CON: 50% barley grain + 50% long lucerne hay, D1: 100% complete pelleted diet containing 1 mm lucerne hay, D2: 40% concentrate pellets + 60% long lucerne hay, D3: 60% concentrate pellets + 40% forage pellets. [2] SEM: standard error of the mean.

The rumen ecosystem, comprising rumen microorganisms, rumen pH, and volatile fatty acids, is influenced by numerous factors, with the most significant being the type of feeding regime used (Chen *et al*., 2021). The rumen bacteria play a crucial role in fermenting feed components into volatile fatty acids, which contribute to rumen health, nutrient intake, and overall animal performance (Cunha *et al*., 2011; Henderson *et al*., 2015; Liu *et al*., 2022). The effects of the four feeding regimes on the bacterial activity (absolute $\log_{10}$ CFU/mL) in the rumens of the Awassi lambs are presented in Table 6.

The absolute quantification of total bacteria was higher (P <0.05) in the lambs fed diets D2 and D3, compared to the lambs fed the other diets, which may indicate improved rumen fermentation and nutrient degradation. In the lambs fed D1, *S. bovis* was less prevalent (P <0.05) than in the lambs fed

D2, but did not differ from lambs fed D3. *Fibrobacter succinogenes, R. albus*, and *R. flavefaciens* were more prevalent (P <0.05) in the lambs fed D1–D3 than in the CON group. This may indicate that complete and concentrated feeds with roughage sources promote efficient fibre digestion. The feed composition and physical form of the forage have previously been found to significantly influence rumen microbial activity and fermentation processes (Karimizadeh *et al*., 2017; Pazoki *et al*., 2017). However, there was no effect of diet (P >0.05) on the abundance of *B. fibrisolvens*.

Table 6 Effects of four feeding regimes on rumen bacterial activity (absolute $\log_{10}$ CFU/ml) in Awassi lambs

Variables	Feeding regimes[1]				SEM[2]	*P*-value
	CON	D1	D2	D3		
Total bacteria	6.01[b]	5.96[b]	7.27[a]	6.95[a]	0.218	0.002
Butyrivibrio fibrisolvens	5.40	5.84	5.51	6.20	0.281	0.229
Fibrobacter succinogenes	4.12[b]	5.23[a]	5.30[a]	4.94[a]	0.192	0.003
Streptococcus bovis	6.44[a]	5.02[b]	6.10[a]	5.93[ab]	0.251	0.002
Ruminococcus albus	4.52[b]	4.93[a]	4.59[a]	4.75[a]	0.222	0.002
Ruminococcus flavefaciens	6.29[b]	7.22[a]	7.47[a]	7.55[a]	0.230	0.002

[a–b] Superscript values within each row highlight significant differences at P <0.05 between the feeding regimes for each variable. [1] CON: 50% barley grain + 50% long lucerne hay, D1: 100% complete pelleted diet containing 1 mm lucerne hay, D2, 40% concentrate pellets + 60% long lucerne hay, D3: 60% concentrate pellets + 40% forage pellets. [2] SEM: standard error of the mean. CFU: colony-forming unit.

The effects of the feeding regimes on the rumen fermentation profiles of Awassi lambs are reported in Table 7.

Table 7 Effects of four feeding regimes on the rumen fermentation profiles of Awassi lambs

Variables	Feeding regimes[1]				SEM[2]	*P*-value
	CON	D1	D2	D3		
Rumen pH	6.19	6.19	6.69	6.57	0.169	0.095
Ammonia nitrogen (mg/100 ml)	5.35[d]	7.23[c]	9.62[a]	8.28[b]	0.215	<0.0001
Volatile fatty acids						
Acetic acid (%)	58.01[a]	51.43[a]	56.32[a]	41.42[b]	1.632	<0.0001
Propionic acid (%)	32.20[b]	27.98[b]	36.20[a]	40.83[a]	1.858	0.004
Butyric acid (%)	9.79[b]	20.68[a]	7.78[b]	17.74[a]	0.722	<0.0001
Total volatile fatty acids (mg/ml)	4.51[b]	5.86[a]	6.31[a]	6.01[a]	0.191	0.001

[a–b] Superscript values within each row highlight significant differences at P <0.05 between the feeding regimes for each variable. [1] CON: 50% barley grain + 50% long lucerne hay, D1: 100% complete pelleted diet containing 1 mm lucerne hay, D2: 40% concentrate pellets + 60% long lucerne hay, D3: 60% concentrate pellets + 40% forage pellets. [2] SEM: standard error of the mean.

There was no effect of diet (P >0.05) on the rumen pH of the lambs. Rumen pH is a crucial indicator of rumen stability (Wang *et al*., 2023); therefore, it was stable for all the diets tested in this study. Ammonia nitrogen is an essential source of nitrogen for rumen microorganisms (Hua *et al*., 2011), and the lambs fed D2 had the highest (P <0.05) ammonia nitrogen concentration in the rumen, followed by D3 and D1, compared to the CON group. The increased ruminal ammonia nitrogen levels in the D2 lambs could be attributed to the enhanced digestibility of the crude protein in this diet. However, a decrease in the ammonia nitrogen concentration in the rumen is a crude predictor of the efficiency of the rumen microbiome at converting feed nitrogen to microbial nitrogen. Therefore, it may be beneficial

to consider strategies that lower rumen ammonia nitrogen concentrations, such as adjusting the protein content of the diet or supplementing the diet with specific feed additives to optimise rumen health. While ammonia is essential for microbial growth, excessive levels can lead to nitrogen losses (Dewhurst & Newbold, 2022).

Lambs fed D3 had a lower acetic acid concentration (P <0.05) than those on the other feeding regimes, whereas the propionic acid concentration was highest (P <0.05) in the lambs fed D2 and D3. The butyrate concentration was higher (P <0.05) in the lambs fed D1 and D3 than in the CON and D2 lambs. However, the total volatile fatty acid concentration was higher in the lambs fed D1–D3 than in the CON group (P <0.05). The type and amount of forage and concentrates influence the composition and activity of the rumen microbes, thereby affecting the production of volatile fatty acids (Khateri *et al*., 2017; Li *et al*., 2019). Volatile fatty acids are products of rumen fermentation and are considered essential energy sources for growing lambs (Mahboubi *et al*., 2022). The higher total volatile fatty acid concentrations in the lambs fed the novel feeding regimes may be related to the higher fermentation rates and improved nutrient digestibility in these lambs.

Based on these results, future research should investigate the effects of these diets over a longer duration, evaluate their effects on carcass composition and meat quality, and include metagenomic analysis. Further studies could also examine different forage-to-concentrate ratios and alternative feed sources in pelleted diets to optimise growth performance, rumen health, and nutrient utilisation. In addition, it would be beneficial to investigate interactions between these feeding regimes and other variables, such as environmental conditions and lamb age, sex, and breed.

Conclusions

The results showed that Awassi lambs fed concentrate pellets with roughage sources (long or pelleted) had significantly improved performance, particularly in the later growth phase, compared to lambs fed a traditional diet based on barley grain and long lucerne hay. This improvement was related to enhanced apparent nutrient digestibility, which was reflected in rumen morphology, including increased papilla height, density, and total surface area. In addition, the microbial population in the rumen, especially the fibre-degrading bacteria, was positively affected, resulting in more efficient fermentation and higher volatile fatty acid concentrations. These results highlight the potential of complete diets and concentrate pellets with roughage sources to optimise growth performance, rumen health, and nutrient utilisation in Awassi lambs. Nevertheless, further studies are needed to determine the long-term effects, the metagenomic implications, and the interactions of these feeding regimes with other variables, such as environmental conditions and lamb age, sex, and breed.

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Authors' contributions

A.S.A. and A.A.A.: Data curation, investigation, review, and editing. I.A.A.: Conceptualisation, visualisation, investigation, editing, project administration, and writing (review). H.H.A.-B.: Methodology, formal analysis, and writing (original draft). B.M.A.: Formal analysis and software. The final version of this manuscript was read, reviewed, and approved by all the authors.

Conflict of interest declaration

The authors have not disclosed any conflicts of interest.

References

Adejoro, F.A., Hassen, A., Akanmu, A.M., & Morgavi, D.P., 2020. Replacing urea with nitrate as a non-protein nitrogen source increases lambs' growth and reduces methane production, whereas acacia tannin has no effect. *Animal Feed Science and Technology*, 259:114360. DOI: https://doi.org/10.1016/j.anifeedsci.2019.114360

Aguayo-Ulloa, L.A., Miranda-De, L., Lama, G.C., Pascual-Alonso, M., Fuchs, K., Olleta, J.L., Campo, M.M., & María, G.A., 2013. Effect of feeding regime during finishing on lamb welfare, production performance and meat

quality. *Small Ruminant Research*, 111(1–3):147–156. DOI: https://doi.org/10.1016/j.smallrumres.2012.09.011

Alhidary, I.A., Abdelrahman, M.M., & Khan, R.U., 2016. Comparative effects of direct-fed microbial alone or with a traces mineral supplement on the productive performance, blood metabolites and antioxidant status of grazing Awassi lambs. *Environmental Science and Pollution Research*, 23:25218–25223. DOI: https://doi.org/10.1007/s11356-016-7684-z

Alshamiry, F.A., Alharthi, A.S., Al-Baadani, H.H., Aljumaah, R.S., & Alhidary, I.A., 2023. Growth rates, carcass traits, meat yield, and fatty acid composition in growing lambs under different feeding regimes. *Life*, 13(2):409. DOI: https://doi.org/10.3390/life13020409

Andrés, S., Jaramillo, E., Bodas, R., Blanco, C., Benavides, J., Fernández, P., & Giráldez, F.J., 2018. Grain grinding size of cereals in complete pelleted diets for growing lambs: Effects on ruminal microbiota and fermentation. *Small Ruminant Research*, 159:38–44. DOI: https://doi.org/10.1016/j.smallrumres.2017.12.009

AOAC, 2019. Official Methods of Analysis of AOAC International (21st edition), volume 1. Ed: Latimer, G.W., AOAC International, Gaithersburg, Maryland, USA.

Arjmand, M., Kiani, A., Azizi, A., Fadayifar, A., Azarfar, A., & Ponnampalam, E.N., 2022. Effects of dietary concentrate level and feeding length on nutrient digestibility, rumen hydrolytic enzymes activity, intermediary metabolites, and feeding behavior in growing fat-tailed lambs: Iranian feedlot system. *Small Ruminant Research*, 217:106832. DOI: https://doi.org/10.1016/j.smallrumres.2022.106832

Ata, M., 2016. Effect of hydroponic barley fodder on Awassi lamb's performance. *Journal of Biology, Agriculture and Healthcare,* 6:60–64.

Baldi, G., Chauhan, S.S., Linden, N., Dunshea, F.R., Hopkins, D.L., Rossi, C.S., & Ponnampalam, E.N., 2019. Comparison of a grain-based diet supplemented with synthetic vitamin E versus a lucerne (alfalfa) hay-based diet fed to lambs in terms of carcass traits, muscle vitamin E, fatty acid content, lipid oxidation, and retail colour of meat. *Meat Science,* 148:105–112. DOI: https://doi.org/10.1016/j.meatsci.2018.10.013

Beigh, Y.A., Ganai, A.M., & Ahmad, H.A., 2017. Prospects of complete feed system in ruminant feeding: A review. *Veterinary World*, 10(4):424. DOI: https://doi.org/10.14202/vetworld.2017.424-437

Böck, M.J., Simões, R.R., Rici, R.E.G., de Carvalho, S., do Santos Roberts, J.V., & de Morais-Pinto, L., 2023. Morphological aspects of rumen papillae of lambs fed agroindustrial wastes. *Animal Science Journal*, 94(1):13897. DOI: https://doi.org/10.1111/asj.13897

Broderick, G.A. & Kang, J.H., 1980. Automated simultaneous determination of ammonia and total amino acids in ruminal fluid and *in vitro* media. *Journal of Dairy Science*, 63(1):64–75. DOI: https://doi.org/10.3168/jds.S0022-0302(80)82888-8

Chen, H., Wang, C., Huasai, S., & Chen, A., 2021. Effects of dietary forage to concentrate ratio on nutrient digestibility, ruminal fermentation and rumen bacterial composition in Angus cows. *Scientific Reports*, 11(1):17023. DOI: https://doi.org/10.1038/s41598-021-96580-5

Chen, Y., Gong, X., Yang, T., Jiang, M., Wang, L., Zhan, K., & Zhao, G., 2021. *Ginkgo biloba* L. residues partially replacing alfalfa hay pellet in pelleted total mixed ration on growth performance, serum biochemical parameters, rumen fermentation, immune function and meat quality in finishing Haimen White goats. *Animals*, 11(11):3046. DOI: https://doi.org/10.3390/ani11113046

Claffey, N.A., Fahey, A.G., Gkarane, V., Moloney, A.P., Monahan, F.J., & Diskin, M.G., 2018. Effect of forage to concentrate ratio and duration of feeding on growth and feed conversion efficiency of male lambs. *Translational Animal Science*, 2(4):419–427. DOI: https://doi.org/10.1093/tas/txy071

Costa, E.D.S., Ribiero, C.V.D.M., Silva, T.M., Ribeiro, R.D.X., Vieira, J.F., Lima, A.D.O., & Oliveira, R.L., 2021. Intake, nutrient digestibility, nitrogen balance, serum metabolites and growth performance of lambs supplemented with *Acacia mearnsii* condensed tannin extract. *Animal Feed Science and Technology*, 272:114744. DOI: https://doi.org/10.1016/j.anifeedsci.2020.114744

Costa, M., Alves, S.P., Francisco, A., Almeida, J., Alfaia, C.M., Martins, S.V., & Bessa, R.J.B., 2017. The reduction of starch in finishing diets supplemented with oil does not prevent the accumulation of trans-10 18:1 in lamb meat. *Journal of Animal Science*, 95(8):3745–3761. DOI: https://doi.org/10.2527/jas.2017.1578

Cui, K., Qi, M., Wang, S., Diao, Q., & Zhang, N., 2019. Dietary energy and protein levels influenced the growth performance, ruminal morphology and fermentation and microbial diversity of lambs. *Scientific Reports*, 9(1):16612. DOI: https://doi.org/10.1038/s41598-019-53279-y

Cunha, I.S., Barreto, C.C., Costa, O.Y., Bomfim, M.A., Castro, A.P., Kruger, R.H., & Quirino, B.F., 2011. Bacteria and Archaea community structure in the rumen microbiome of goats (*Capra hircus*) from the semiarid region of Brazil. *Anaerobe*, 17(3):118–124. DOI: https://doi.org/10.1016/j.anaerobe.2011.04.018

Delgadillo-Ruiz, L., Bañuelos-Valenzuela, R., GallegosFlores, P., Meza-López, C., Echavarría-Cháirez, F., & Valladares-Carranza, B., 2022. Ruminal bacteria and protozoa present in sheep supplemented with probiotics identified by counting and PCR endpoint. *Abanico Veterinario*, 12:1–18. DOI: https://doi.org/10.21929/abavet2022.6

Dewhurst, R.J. & Newbold, J.R., 2022. Effect of ammonia concentration on rumen microbial protein production in vitro. *British Journal of Nutrition*, 127(6):847–849. DOI: https://doi.org/10.1017/S000711452100458X

El-Nomeary, Y.A., Abd El-Rahman, H.H., Shoukry, M.M., Abedo, A.A., Salman, F.M., & Mohamed, M.I., 2021. Effect of different dietary protein sources on digestibility and growth performance parameters in lambs. *Bulletin of the National Research Centre*, 45:1–11. DOI: https://doi.org/10.1186/s42269-021-00486-1

Francisco, A., Alves, S.P., Portugal, P.V., Dentinho, M.T., Jerónimo, E., Sengo, S., & Santos-Silva, J., 2018. Effects of dietary inclusion of citrus pulp and rockrose soft stems and leaves on lamb meat quality and fatty acid composition. *Animal*, 12(4):872–881. DOI: https://doi.org/10.1017/S1751731117002269

Henderson, G., Cox, F., Ganesh, S., Jonker, A., Young, W., & Janssen, P.H., 2015. Rumen microbial community composition varies with diet and host, but a core microbiome is found across a wide geographical range. *Scientific Reports*, 5(1):14567. DOI: https://doi.org/10.1038/srep14567

Herath, H.M., Pain, S.J., Kenyon, P.R., Blair, H.T., & Morel, P.C., 2021. Growth and body composition of artificially-reared lambs exposed to three different rearing regimens. *Animals*, 11(12):3370. DOI: https://doi.org/10.3390/ani11123370

Hua, W., Hai, J., & Wang, Q., 2011. Ruminal fermentation: A review of CNCPS research. *Animal Husbandry and Feed Science*, 32:31–33.

Ishaq, S.L., Lachman, M.M., Wenner, B.A., Baeza, A., Butler, M., Gates, E., & Yeoman, C.J., 2019. Pelleted-hay alfalfa feed increases sheep wether weight gain and rumen bacterial richness over loose-hay alfalfa feed. *PloS One*, 14(6):0215797. DOI: https://doi.org/10.1371/journal.pone.0215797

Karimizadeh, E., Chaji, M., & Mohammadabadi, T., 2017. Effects of physical form of diet on nutrient digestibility, rumen fermentation, rumination, growth performance and protozoa population of finishing lambs. *Animal Nutrition*, 3(2):139–144. DOI: https://doi.org/10.1016/j.aninu.2017.01.004

Khateri, N., Azizi, O., & Jahani-Azizabadi, H., 2017. Effects of a specific blend of essential oils on apparent nutrient digestion, rumen fermentation and rumen microbial populations in sheep fed a 50:50 alfalfa hay:concentrate diet. *Asian-Australasian Journal of Animal Sciences*, 30(3):370–378. DOI: https://doi.org/10.5713/ajas.15.0865

Khurshid, M.A., Rashid, M.A., Yousaf, M.S., Naveed, S., Shahid, M.Q., & Rehman, H.U., 2023. Effect of straw particle size in high grain complete pelleted diet on growth performance, rumen pH, feeding behavior, nutrient digestibility, blood and carcass indices of fattening male goats. *Small Ruminant Research*, 219:106907. DOI: https://doi.org/10.1016/j.smallrumres.2023.106907

Lafi, S.Q., Talafha, A.Q., Giadinis, N., Kalaitzakis, E., Pourliotis, K., & Panousis, N., 2009. Factors affecting the reproductive performance of Awassi sheep flocks in north-east of Jordan: An epidemiological study. *Tropical Animal Health and Production*, 41(8):1755–1764. DOI: https://doi.org/10.1007/s11250-009-9374-z

Li, B., Sun, X., Huo, Q., Zhang, G., Wu, T., You, P., & Song, B., 2021. Pelleting of a total mixed ration affects growth performance of fattening lambs. *Frontiers in Veterinary Science*, 8:629016. DOI: https://doi.org/10.3389/fvets.2021.629016

Li, C., Zhang, Q., Wang, G., Niu, X., Wang, W., Li, F., & Zhang, Z., 2022. The functional development of the rumen is influenced by weaning and associated with ruminal microbiota in lambs. *Animal Biotechnology,* 33(4):612–628. DOI: https://doi.org/10.1080/10495398.2020.1812618

Li, R., Teng, Z., Lang, C., Zhou, H., Zhong, W., Ban, Z., & Lou, Y., 2019. Effect of different forage-to-concentrate ratios on ruminal bacterial structure and real-time methane production in sheep. *PloS One*, 14(5):0214777. DOI: https://doi.org/10.1371/journal.pone.0214777

Li, Z., Wang, X., Wang, W., An, R., Wang, Y., Ren, Q., & Xuan, J., 2023. Benefits of tributyrin on growth performance, gastrointestinal tract development, ruminal bacteria and volatile fatty acid formation of weaned Small-Tailed Han lambs. *Animal Nutrition*, 15:187–196. DOI: https://doi.org/10.1016/j.aninu.2023.08.006

Liu, S., Shah, A.M., Yuan, M., Kang, K., Wang, Z., Wang, L., & Peng, Q., 2022. Effects of dry yeast supplementation on growth performance, rumen fermentation characteristics, slaughter performance and microbial communities in beef cattle. *Animal Biotechnology*, 33(6):1150–1160. DOI: https://doi.org/10.1080/10495398.2021.1878204

Mahboubi, A., Agnihotri, S., Uwineza, C., Jomnonkhaow, U., & Taherzadeh, M.J., 2022. Chapter 18 – Waste-derived volatile fatty acids for sustainable ruminant feed supplementation. In: Biomass, Biofuels, Biochemicals. Eds: Varjani, S., Pandey, A., Taherzadeh, M.J., Ngo, H.H., & Tyagi, R.D., Elsevier. pp. 407–430. DOI: https://doi.org/10.1016/B978-0-323-88511-9.00015-X

Mirzaei-Alamouti, H., Abdollahi, A., Rahimi, H., Moradi, S., Vazirigohar, M., & Aschenbach, J.R., 2021. Effects of dietary oil sources (sunflower and fish) on fermentation characteristics, epithelial gene expression and microbial community in the rumen of lambs fed a high-concentrate diet. *Archives of Animal Nutrition*, 75(6):405–421. DOI: https://doi.org/10.1080/1745039X.2021.1997539

Mousa, G.A., Allak, M.A., Shehata, M.G., Hashem, N.M., & Hassan, O.G., 2022. Dietary supplementation with a combination of fibrolytic enzymes and probiotics improves digestibility, growth performance, blood metabolites, and economics of fattening lambs. *Animals*, 12(4):476. DOI: https://doi.org/10.3390/ani12040476

Na, S.W., 2022. Understanding the role of rumen epithelial host-microbe interactions in cattle feed efficiency. *Animal Nutrition*, 10:41–53. DOI: https://doi.org/10.1016/j.aninu.2022.04.002

Nagi, P.R.S., Reddy, D.N., Nagalakshmi, D., Reddy, Y.R., & Raghunandan, T., 2012. Effect of particle size of paddy straw on physical characteristics and performance of lambs fed paddy straw based complete diets. *Animal Nutrition and Feed Technology*, 12:111–119.

Neto, A.B., Herbster, C.J.L., Geraseev, L.C., Junior, G.M., Nascimento, D.R., Rocha, A.C., & Pereira, E.S., 2023. Feed energy utilization by hair sheep: does the 0.82 conversion factor of digestible to metabolizable energy need to be revised? *The Journal of Agricultural Science,* 161(5):734–742. DOI: https://doi.org/10.1017/S0021859623000515

National Research Council (NRC), 2007. Nutrient requirements of small ruminants (1st edition). National Academy Press, Washington, DC, USA.

Ojo, V.O.A., Oyaniran, D.K., Ogunsakin, A.O., Aderinboye, R.Y., Adelusi, O.O., & Odusoga, F.S., 2019. Effects of supplementing herbaceous forage legume pellets on growth indices and blood profile of West African dwarf sheep fed Guinea grass. *Tropical Animal Health and Production*, 51(4):867–877. DOI: https://doi.org/10.1007/s11250-018-1767-4

Pazoki, A., Ghorbani, G.R., Kargar, S., Sadeghi-Sefidmazgi, A., Drackley, J.K., & Ghaffari, M.H., 2017. Growth performance, nutrient digestibility, ruminal fermentation, and rumen development of calves during transition from liquid to solid feed: Effects of physical form of starter feed and forage provision. *Animal Feed Science and Technology*, 234:173–185. DOI: https://doi.org/10.1016/j.anifeedsci.2017.06.004

Pelegrin-Valls, J., Serrano-Pérez, B., Villalba, D., Martín-Alonso, M.J., Bertolín, J.R., Joy, M., & Álvarez-Rodríguez, J., 2020. Effect of dietary crude protein on productive efficiency, nutrient digestibility, blood metabolites and gastrointestinal immune markers in light lambs. *Animals*, 10(2):328. DOI: https://doi.org/10.3390/ani10020328

Pereira, T.L., Fernandes, A.R.M., Oliveira, E.R., Cônsolo, N.R.B., Marques, O.F.C., Maciel, T.P., & Gandra, J.R., 2020. Serum metabolomic fingerprints of lambs fed chitosan and its association with performance and meat quality traits. *Animal*, 14:1987–1998. DOI: https://doi.org/10.1017/S1751731120000749

Prathap, P., Chauhan, S.S., Leury, B.J., Cottrell, J.J., Joy, A., Zhang, M., & Dunshea, F.R., 2023. Effects of feeding a commercial starch binding agent during heat stress on enteric methane emission, rumen volatile fatty acid contents, and diet digestibility of merino lambs. *Atmosphere*, 14(3):605. DOI: https://doi.org/10.3390/atmos14030605

Retnani, Y., Risyahadi, S.T., Qomariyah, N., Barkah, N.N., Taryati, T., & Jayanegara, A., 2022. Comparison between pelleted and unpelleted feed forms on the performance and digestion of small ruminants: a meta-analysis. *Journal of Animal and Feed Sciences*, 31(2):97–108. DOI: https://doi.org/10.22358/jafs/149192/2022

SAS Institute, 2008. SAS Users Guide: Statistics. SAS Institute Inc., Cary, NC, USA.

Sohail, M.A., Rashid, M.A., Habib, H.F., Malik, M.I., Yousaf, M.S., & Rehman, H., 2022. Effects of physical form and wheat straw level in the diet on growth performance, nutrient digestibility, rumen papillae morphometry, and carcass characteristics in Lohi lambs. *Animal Production Science*, 62(18):1805–1815. DOI: https://doi.org/10.1071/AN21559

Soltani, E., Naserian, A.A., Khan, M.A., Ghaffari, M.H., & Malekkhahi, M., 2020. Effects of conditioner retention time during pelleting of starter feed on nutrient digestibility, ruminal fermentation, blood metabolites, and performance of Holstein female dairy calves. *Journal of Dairy Science*, 103:8910–8921. DOI: https://doi.org/10.3168/jds.2020-18345

Tian, G., Zhang, X., Hao, X., & Zhang, J., 2023. Effects of curcumin on growth performance, ruminal fermentation, rumen microbial protein synthesis, and serum antioxidant capacity in housed growing lambs. *Animals*, 13(9):1439. DOI: https://doi.org/10.3390/ani13091439

Tripathi, M.K., Chaturvedi, O.H., Karim, S.A., Singh, V.K., & Sisodiya, S.L., 2007. Effect of different levels of concentrate allowances on rumen fluid pH, nutrient digestion, nitrogen retention and growth performance of weaner lambs. *Small Ruminant Research*, 72(2–3):178–186. DOI: https://doi.org/10.1016/j.smallrumres.2006.10.008

Trottier, K., 2020. Determining the ideal forage-to-concentrate ratio for finishing lambs. PhD thesis, University of Guelph, Canada.

Van Soest, P.J., Robertson, J.B., & Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science*, 74(10):3583–3597. DOI: https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Wang, L., Qi, W., Mao, S., Zhu, W., & Liu, J., 2022. Effects of whole corn high-grain diet feeding on ruminal bacterial community and epithelial gene expression related to VFA absorption and metabolism in fattening lambs. *Journal of Animal Science*, 100(3):56. DOI: https://doi.org/10.1093/jas/skac056

Wang, Q., Zeng, Y., Zeng, X., Wang, X., Wang, Y., Dai, C., & Yang, H., 2021. Effects of dietary energy levels on rumen fermentation, gastrointestinal tract histology, and bacterial community diversity in fattening male Hu lambs. *Frontiers in Microbiology*, 12:695445. DOI: https://doi.org/10.3389/fmicb.2021.695445

Wang, R., He, S., Huang, D., Wu, D., Peng, H., He, S., & Li, Q., 2023. The response of rumen pH, fermentation parameters and rumen bacteria to feeds of different concentrate to roughage ratios in buffalos. *Frontiers in Microbiomes*, 1:1053794. DOI: https://doi.org/10.3389/frmbi.2022.1053794

Wang, W., Patra, A.K., Puchala, R., Ribeiro, L., Gipson, T.A., & Goetsch, A. L., 2022. Effects of dietary inclusion of tannin-rich *Sericea lespedeza* hay on relationships among linear body measurements, body condition score, body mass indexes, and performance of growing Alpine doelings and Katahdin ewe lambs. *Animals*, 12(22):3183. DOI: https://doi.org/10.3390/ani12223183

Wu, Q.C., Wang, W.K., Zhang, F., Li, W.J., Wang, Y.L., Lv, L.K., & Yang, H.J., 2022. Dietary cysteamine supplementation remarkably increased feed efficiency and shifted rumen fermentation toward glucogenic propionate production via enrichment of *Prevotella* in feedlot lambs. *Microorganisms*, 10(6):1105. DOI: https://doi.org/10.3390/microorganisms10061105

Yang, Y., Wang, B., Li, H., Chen, B.Y., & Yu, Z., 2022. Effects of pelletized corn straw and alfalfa hay-based total mixed ration on growth performance, blood characteristics and rumen fermentation of small-tailed Han sheep. *Animal Nutrition and Feed Technology*, 22(3):469–480.