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ARTICLE

Evaluating Physical and Qualitative Properties of Lamb Meat Fed Different Levels of Neutral Detergent Fiber

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Abstract This study investigates the impact of neutral detergent fiber (NDF) content in pelleted complete diets on the weight gain, carcass characteristics, and meat quality of lambs. A total of 72 lambs (12±1 weeks old) were randomly assigned to three dietary groups: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (32.82% NDF), with 8 replicates as the experimental unit. Weight gain parameters were recorded over 84 days. At the end of the trial, carcass characteristics, body components, wholesale cuts, fat depot metrics, and physical separation were evaluated. In addition, the physical, chemical, and fatty acid profiles of the meat and the qualitative meat characteristics were assessed. All data were analyzed using one-way ANOVA and regression analysis. Lambs fed Diet 2 exhibited superior overall weight gain and improved carcass characteristics, including higher slaughter weight, empty weight, hot carcass weight, cold carcass weight, and carcass compactness index. The amounts of back fat, omental fat, mesenteric fat, meat percentage, and trimmings were also higher in Diet 2 than in the other groups. In terms of meat quality, Diet 2 resulted in lower shear force and a higher myofibril fragmentation index, indicating higher tenderness, along with substantially reduced cooking loss indicating improved meat quality. In addition, lambs fed Diet 2 had higher crude protein and polyunsaturated fatty acids content, while saturated fatty acid content decreased. In conclusion, these findings suggest that an NDF level of 28.23% in lamb diets optimizes weight gain, improves carcass characteristics, and enhances meat quality.

Keywords lamb, neutral detergent fiber, carcass, meat quality, fatty acids

Introduction

Globally, the increasing production of lamb is crucial for red meat consumption, substantially contributing to the protein supply (Juárez et al., 2021). However, the demand for high-quality meat is rising in international markets, leading to a continuous improvement in optimal lamb production practices (Ding et al., 2024). To achieve this goal, several strategies must be implemented, including genetic selection, nutrition management, health management, and sustainable practices. As part of nutritional management, diet formulation is considered one of the key aspects to achieve optimal production practices and improve meat quality by evaluating diets in terms of weight gain, carcass characteristics, and meat quality (Kotsampasi et al., 2024).

Dietary fibers are essential for both human and animal diets. They serve as an important substrate for rumen bacteria, provide the necessary structure for growth and improve overall rumen function (Abdelrahman et al., 2018). Neutral detergent fiber (NDF) consists of plant cell wall components, including cellulose, hemicellulose, and lignin, which remain insoluble when treated with neutral detergent solutions. NDF accurately measures fiber content and affects feed intake, passage rate, and nutrient digestibility (Grabber et al., 2009). Rumen bacteria utilize NDF as an energy source through fermentation and produce volatile fatty acids, which are important for the metabolism of lambs (Zhao et al., 2023). However, the digestibility of NDF varies depending on its physical properties and source (Macdonald et al., 2021).

Pelleted complete diets containing both roughage and concentrates, are a common feeding method for lambs. This method has several benefits: it prevents selective feeding, reduces the risk of metabolic disorders such as acidosis, and ensures a consistent intake of nutrients (Alhidary et al., 2016). However, the pelleting process plays a critical role in increasing the digestibility of diet ingredients by altering their physical structure, which can potentially affect NDF utilization (Bertipaglia et al., 2010). Moreover, pellets reduce feed waste compared to lambs fed roughage and grain (Zhong et al., 2018). In this context, the NDF content in pelleted complete diets is considered a critical factor that may influence various aspects of lamb meat production and quality (Karimizadeh et al., 2017).

Studies suggest that the optimal NDF level in pelleted diets may play a crucial role in lamb weight gain. Research indicates that reducing the NDF content in the diet (22%–26%) can increase average daily gain and improve feed efficiency by increasing energy availability from easily digestible dietary components (Godínez-Olmedo et al., 2022; Mirzaei-Alamouti et al., 2021). Lambs-fed pellets with an NDF content of 30% demonstrated better overall growth and feed efficiency (Alhidary et al., 2017). Additionally, lambs fed diets with an NDF content of 15% showed higher weight gain and carcass yields (Gallo et al., 2019).

On the other hand, several studies have reported that the minimum NDF requirement for lambs ranges between 20% and 24.5%, and a 20% reduction in NDF content leads to a decline in rumen fermentation activity (Kozloski et al., 2006; Pereira et al., 2016). Conversely, very high NDF levels have a low energy density and, consequently, reduce feed intake, leading to poor weight gain (Asadollahi et al., 2017; Chibisa et al., 2020). However, lower NDF level has been associated with improved meat quality, higher dressing percentage, and increased carcass weight (Moura et al., 2019). In another study, most carcass characteristics of lambs fed different levels of NDF showed no significant changes (Santos-Silva et al., 2019). However, fat deposition was found to be influenced by the type and source of NDF in the diet (Awawdeh et al., 2019).

Based on the findings of previous studies on different NDF levels and their effects on lamb meat production, further research under controlled conditions with completely pelleted diets are needed. In addition, the specific effects of optimal NDF levels on the physiochemical and qualitative properties of red lamb meat is area that needs to be explored. Therefore, this study investigates the influence of NDF content in pelleted complete diets on overall meat production weight gain, carcass traits, meat quality, and fatty acid composition of meat.

Materials and Methods

Animals, design, and management

Ethical approval for this study was obtained from the Scientific Research Ethics Committee of King Saud University, Saudi Arabia (approval number: KSU-SE-22-26). All animal husbandry, feed formulation, sampling and analyzes were performed in accordance with these guidelines and ARRIVE guidelines.

During the experimental growth period, which lasted 84 days, a group of 72 Awassi lambs of similar age (12±1 weeks old) and initial weight (23.61±0.10 kg) were used. Upon arrival, all animals were acclimatized to the environmental conditions, including diet and housing, for 10 days and continuously monitored to ensure that they were free of disease. Subsequently, the lambs received a single subcutaneous vaccination against common diseases in the study area, including internal and external parasites (1 mL), peste des petits ruminants (1 mL), septicemia, and enterotoxaemia (2 mL). All vaccines were from Ebreez Company, SA, and were approved by the Animal Resources Board of the Ministry of Environment, Water, and Agriculture. The experimental lambs were randomly allocated into three dietary groups with 8 replicates each (24 lambs per group, 3 lambs per replicate), using a completely randomized design. They were housed in group pens with sufficient space (3.5 m^2 per pen) to allow movement and natural behavior, with each pen (three lambs) serving as an experimental unit. Fresh water was provided throughout the 84-day (12-week) trial, and proper ventilation and hygiene were maintained.

Dietary groups

The experimental diets were formulated in a pelleted complete form with different levels of NDF as follows: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF). The other nutritional requirements of the lambs, including protein, energy, vitamins, and minerals were met according to the standards for their age and growth stage based on the recommendations of the National Research Council (NRC, 2007). Diet ingredients were selected with varying NDF contents to achieve the target NDF levels in each diet. Feedstuff and nutrient analyze for each dietary group are presented in Table 1.

Overall weight gain measures

The average body weights of the lambs (initial and ultimate weights) and the feed provided were recorded for each replicate throughout the study period, from day 1 to day 84. Daily weight gain was determined by dividing the total weight gain (final weight minus initial weight) by the study duration (in days). This calculation was performed according to the method described by Mousa et al. (2022). Daily feed intake was calculated as the difference between feed offered and feed refused divided by the study duration, similar to the approach used by Atsbha et al. (2021).

The dry matter content of the diet was determined in triplicate in an oven (Sanyo Oven, Osaka, Japan) at 105℃ for 24 h throughout the study according to the methods of Association of Official Analytical Chemists (AOAC, 2012). Daily dry matter intake was calculated by multiplying the daily feed intake by the dry matter content and dividing by 100, as described by Atsbha et al. (2021). The feed conversion ratio was calculated for each group by dividing the daily feed intake by the daily weight gain (Wang et al., 2020). Finally, the growth rate was calculated using the formula: growth rate = 2 × (ultimate weight − initial weight) / (ultimate weight + initial weight) × 100 (Goiri et al., 2021).

Slaughter procedures and carcass measurements

After 84 days, one lamb from each replicate (8 lambs per group) was randomly selected for slaughter according to standard commercial procedures. Slaughter weight was determined immediately after 14 h of feed withdrawal, with water freely available to the lambs. The slaughter weight in this study corresponds to local market weights of Awassi lambs in intensive production systems. Lambs were skinned individually under standardized conditions, and the body components—including

Table 1. Feedstuffs and nutrients analysis of dietary groups

	Dietary groups		
	Diet 1	Diet 2	Diet 3
Feedstuffs (%)			
Corn	35.14	26.45	28.98
Molasses	3.00	3.00	3.00
Wheat bran	18.00	20.80	20.00
Alfalfa hay	22.13	21.08	13.53
Wheat straw	7.00	7.00	4.01
Soy meal hulls	0.00	7.87	18.21
Soybean meal	9.80	10.25	9.23
Limestone	3.00	1.95	1.40
Salt	0.83	0.50	0.54
Acid buffer	0.80	0.80	0.80
Vit. and Min. premix[1)]	0.30	0.30	0.30
Total	100	100	100
Calculated nutrients based on dry matter (%)			
Dry matter	95.88	95.79	95.86
Crude protein	14.68	14.67	14.66
NDF	20.98	28.23	34.82
ADF	14.53	14.55	14.54
Lignin	4.53	4.54	4.52
Fat	3.81	3.87	3.86
Ash	8.25	8.28	8.27
Ca	2.25	2.22	2.24
Available P	1.01	0.99	0.98
Mg	0.38	0.37	0.39
K	1.54	1.52	1.49
Na	0.34	0.33	0.32
Fe (ppm)	484	480	478
Cu (ppm)	10	11	10
Zn (ppm)	166	164	162
Net energy (Kcal/kg)	2,950	2,940	2,940

[1)] The vitamins and minerals per kg premix: vitamin A, 13,000 IU; vitamin D, 1,300 IU; vitamin E, 25 IU; magnesium, 400 mg; zinc, 70 mg; copper, 30 mg; manganese, 85 mg; selenium, 0.40 mg; cobalt, 0.80 mg.
NDF, neutral detergent fiber; ADF, acid detergent fiber.

head, liver, spleen, lungs, heart, kidneys, gut fill, genitals, stomach, intestine, and tail—were removed and weighed. The body components were expressed as a percentage of slaughter weight by dividing the weight of each component by the slaughter weight and multiplying by 100 (Atsbha et al., 2021). Empty body weight was calculated by subtracting the weight of the stomach and intestine from the slaughter weight (Goiri et al., 2021). Carcass weight was measured 30 min after slaughter (hot carcass weight) and then placed in cold storage at 4℃ for 24 h to determine cold carcass weight and chill shrink (the percentage difference between hot and cold carcass weights, divided by hot carcass weight; Salazar-Cuytun et al., 2022). Finally, the percentage was calculated as (hot carcass weight / slaughter weight) × 100, as described by Macías-Cruz et al. (2020).

Wholesale cuts and fat depots parameters

The carcasses were cut lengthwise and the right half was divided into standard cuts (shoulder, rack, loin, leg and foreshank with breast). The weight of each cut was recorded and expressed as a percentage of body weight, according to the method described by Avendaño-Reyes et al. (2011).

The thickness of subcutaneous fat was measured at two locations: over the eye muscle and along the body wall. The weights of pericardial, kidney knob, channel, omental and mesenteric fat were determined as a percentage of carcass weight (Bautista-Díaz et al., 2020).

Tissue composition of the cuts

Trained personnel separated the fat, meat, bone, and trimmings from the rack cut. The weight of the individual components was calculated as a percentage of the total weight of the rack cut (Almeida et al., 2022).

Evaluation of meat's physical and qualitative properties

At 30 min and 24 h after slaughter, pH and temperature were measured (duplicate per sample) in the *longissimus thoracis* muscle of the carcass and the meat sample using a pH meter (211, Hanna, Woonsocket, RI, USA) equipped with a puncture electrode and a thermometer (Macías-Cruz et al., 2020).

Instrumental color values, including CIE L*, CIE a*, and CIE b* of the meat (*longissimus thoracis* muscle), were directly measured (duplicate per sample) at 30 min and 24 h after slaughtering using a digital colorimeter (CR-400, Konica Minolta, Osaka, Japan). Instrumental color values were used to determine color difference, chroma, hue angle, and the CIE b* to CIE a* ratio, as previously described by Wang et al. (2020).

The *longissimus thoracis* muscle was removed, cut into cubes, and packed in polyethylene bags to analyze the meat quality in two runs. A 100 g meat sample (27℃) was cooked on an electric grill (2321, Princess, Breda, The Netherlands), and the temperature was monitored with a thermal probe (Eco-Scan Temp JKT, Eutech Instruments, Singapore) until the internal temperature reached 70℃, indicating that cooking was complete. The meat samples were patted dry before weighing after cooking to remove surface moisture that could affect the weight. Cooking loss was calculated in duplicate for each sample as follows: Cooking loss% = [difference between starting and cooked weights (g) multiplied by 100] divided by the starting weight (g) (Cardoso et al., 2021).

The filter paper method described by Cardoso et al. (2021) was used to determine the water holding capacity. In this method, a weighed meat sample (2 g) was placed in duplicate between filter paper (25 microns) and pressed at 12 kg for 5 min using a specialized pressing machine, then the meat was carefully separated and weighed. Water holding capacity (%) = 100 − [(weight of meat before pressing) − (weight of meat after pressing)] / (weight of meat before pressing) × 100.

The myofibril fragmentation index was measured (in duplicate per sample) to assess the degree of muscle protein degradation in the samples (Yan et al., 2022). A homogeneous 4 g sample of *longissimus thoracis* muscle was prepared in 40 mL of cold buffer (4℃) to create a uniform suspension. The buffer (pH=7) consisted of 0.1 M potassium chloride, 25 mM potassium phosphate, and 1 mM ethylene glycol tetraacetic acid. The sample was then subjected to multiple washes about 3 times with 40 mL of cold buffer, and the absorbance at 540 nm for each 1.5 mL sample was measured using a Jenway spectrophotometer, model 6705, Stone, Staffs, UK. The absorbance value is directly proportional to the degree of myofibril fragmentation, with higher absorbance indicating greater fragmentation and, consequently, increased tenderness. The myofibril fragmentation index for each sample was determined by multiplying the absorbance value by a factor of 200.

The shear force and texture profile analysis parameters were determined in duplicate for each individual sample of *longissimus thoracis* muscle. Cooked, well-done samples were cut into square slices (2 cm^2) with the long axis parallel to the muscle fiber direction. The samples were cooled to 25℃ before testing (measured internally). Shear force and texture profile analysis were measured using a Texture Analyzer (Stable Micro Systems, Godalming, UK) fitted with a Warner-Bratzler attachment. The tests were performed at 26±2℃ at a test speed of 5 mm/min. The shear force and TPA procedure was generally performed as described by Almeida et al. (2022).

Analysis of the chemical and fatty acid composition of the meat

Duplicate 200 g samples of *longissimus thoracis* muscle was collected and stored in polyethylene bags at –20℃ until further analysis. The samples were crushed, dried to determine the dry matter content, and then ground to a fine powder. The moisture, ash, crude protein, and fat content were then analyzed according to the methods of the AOAC (2012).

Gas chromatography-mass spectrometry (Agilent Technologies, Santa Clara, CA, USA) was used to identify and quantify the individual fatty acids. This method allowed a detailed analysis of the fatty acid composition in the meat samples. The fatty acid profile was expressed as a percentage of total fat (Almeida et al., 2022).

Statistical data analysis

A normality test (skewness, kurtosis, and boxplot analysis) was conducted before data analysis. All results were analyzed using one-way ANOVA with general linear models in Statistical Analysis System 9.4 (SAS, 2008).

The formula for the statistical model was as follows: Observation (Yij) = general average (μ) + NDF levels (i = 20.98%, 28.23%, and 34.82%) + experimental error (eij).

The parameters of each dietary group were compared using Duncan's multiple range test at $p<0.05$. Additionally, a regression analysis was performed to evaluate the quadratic response between NDF levels and the dependent variable. The mean values of the individual parameters were presented, with the standard errors of the mean given as ±SEM.

Results

Overall weight gain measures

The evaluation of the overall weight gain of lambs fed NDF levels in pelleted complete diets is shown in Table 2. The results show that lambs fed Diet 2 (28.23% NDF) had higher ($p<0.05$) final body weight, total weight gain, daily gain, and growth rate than lambs fed Diet 1 (20.98% NDF), but there was no significant difference with Diet 3 (34.82% NDF).

In addition, lambs fed Diets 2 and 3 had a higher ($p<0.05$) daily feed intake and daily dry matter intake compared with those fed Diet 1. There was no significant difference ($p>0.05$) in feed conversion ratio by dietary groups. Furthermore, no quadratic effect of NDF content on overall weight gain parameters was observed ($p>0.05$).

Table 2. The evaluation of the overall weight gain measures of lambs fed pelleted complete diets with levels of neutral detergent fibers (NDFs) from day 1 to day 84

Parameters	Dietary groups[1)]			SEM	p-value	
	Diet 1	Diet 2	Diet 3		Groups	Quadratic
Body weight at 1 day (kg)	23.71	23.61	23.51	0.301	0.894	0.845
Body weight at 84 days (kg)	42.00^{b}	44.75^{a}	43.28^{ab}	0.796	0.046	0.163
Total weight gain (kg)	18.29^{b}	21.14^{a}	19.77^{ab}	0.555	0.001	0.179
Daily weight gain (g/day)	217.74^{b}	251.66^{a}	235.30^{ab}	6.613	0.001	0.232
Daily feed intake (g/day)	1,312^{b}	1,462^{a}	1,436^{a}	16.22	<0.0001	0.133
Daily dry mater intake (g/day)	1,262^{b}	1,382^{a}	1,376^{a}	14.50	<0.0001	0.229
Feed conversion ratio (g/g)	6.19	5.86	6.18	0.187	0.337	0.917
Growth rate (%)	55.60^{b}	61.98^{a}	59.30^{ab}	1.464	0.008	0.273

[1)] Dietary groups consisted of pelleted complete diets with varying NDF content: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF).

[a,b] Superscripts represent significant differences (p<0.05) between dietary groups for each parameter within a row.

Carcass characteristics measurements

The carcass traits measures of lambs fed different levels of NDF in pelleted complete diets are shown in Table 3. Lambs fed Diet 2 (28.23% NDF) had significantly higher (p<0.05) carcass properties, including slaughter weight, empty body weight, hot carcass weight, cold carcass weight, and carcass compactness index, compared with the other dietary groups. Additionally, the dressing percentage was higher (p<0.05) in lambs fed Diet 2 and Diet 3 than in those fed Diet 1. In contrast, there was no significant difference (p>0.05) in chill shrink by groups. A quadratic effect of NDF content on all carcass properties (p<0.05) was observed, except for dressing percentage, which was not affected (p>0.05).

The relative weights of body components, including liver, heart, kidneys, gut fill, and stomach, were not affected by diet (p>0.05). In contrast, the relative weights of head and lungs were significantly higher (p<0.05) in lambs fed Diet 1 than in lambs fed Diet 3, while no significant difference was observed in lambs fed Diet 2. The relative weights of spleen and intestine were significantly lower (p<0.05) in lambs fed Diet 2 than in lambs fed Diet 1, but did not differ from those fed Diet 3.

In lambs fed Diet 2, the relative weight of the genitals was significantly higher (p<0.05) than in the other diet groups. In addition, the relative weight of the tail was significantly higher (p<0.05) in lambs fed Diets 2 and 3 than in lambs fed Diet 1. A quadratic effect of NDF content on spleen, genitals, and tail was observed (p<0.05), while other body components were not affected (p>0.05).

Wholesale cuts and fat depot parameters

The evaluation of the primary wholesale cuts of lambs fed different levels of NDF in pelleted complete diets is shown in Table 4. The primary wholesale cuts, including shoulder, rack, loin, leg, foreshank, and breast, were not affected by the diet groups or quadratic effects (p>0.05). In contrast, lambs fed Diet 2 had significantly higher half carcass weight compared to the other groups (p<0.05). There was also a quadratic effect of NDF content on half carcass weight (p<0.05).

The evaluation of the body fat depot components of lambs fed different levels of NDF in pelleted complete diets is shown in Table 5. Back fat content was higher in lambs fed Diet 3 than in the other groups (p<0.05). The relative weights of

Table 3. The evaluation of the carcass traits measures of lambs fed pelleted complete diets with levels of neutral detergent fibers (NDFs)

Parameters	Dietary groups[1)]			SEM	p-value	
	Diet 1	Diet 2	Diet 3		Groups	Quadratic
Carcass properties						
Slaughter weight (kg)	42.36[b]	45.64[a]	41.30[b]	1.03	0.019	0.006
Empty body weight (kg)	35.94[b]	39.89[a]	35.12[b]	1.08	0.012	0.003
Hot carcass (kg)	18.84[b]	21.34[a]	19.31[b]	0.54	0.008	0.002
Cold carcass (kg)	18.24[b]	20.77[a]	18.73[b]	0.52	0.006	0.001
Chill shrink (%)	3.22	2.63	2.99	0.23	0.215	0.107
Dressing (%)	44.56[b]	46.72[a]	46.73[a]	0.66	0.047	0.200
Carcass compactness index (kg/cm)	0.25[b]	0.29[a]	0.27[b]	0.01	0.002	0.0008
Body components (%)						
Head	3.413[a]	3.334[ab]	3.247[b]	0.003	0.021	0.935
Liver	1.70	1.61	1.65	0.040	0.328	0.231
Spleen	0.15[a]	0.11[b]	0.13[ab]	0.011	0.035	0.019
Lungs	1.13[a]	1.02[ab]	0.86[b]	0.066	0.035	0.815
Heart	0.31	0.31	0.31	0.009	0.929	0.916
Kidneys	0.30	0.28	0.27	0.008	0.056	0.860
Genitals	0.91[b]	1.27[a]	0.96[b]	0.071	0.004	0.001
Tail	4.33[b]	6.39[a]	6.43[a]	0.319	0.0001	0.018
Gut fill	15.21	12.62	15.00	1.325	0.327	0.140
Stomach	3.51	3.36	4.03	0.285	0.242	0.258
Intestine	3.19[a]	2.59[b]	2.63[ab]	0.165	0.031	0.129

[1)] Dietary groups consisted of pelleted complete diets with varying NDF content: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF).

[a,b] Superscripts represent significant differences ($p<0.05$) between dietary groups for each parameter within a row.

Table 4. The evaluation of the primary wholesale cuts of lambs fed pelleted complete diets with levels of neutral detergent fibers (NDFs)

Parameters	Dietary groups[1)]			SEM	p-value	
	Diet 1	Diet 2	Diet 3		Groups	Quadratic
Half carcass weight (kg)	7.88[b]	8.74[a]	7.96[b]	0.179	0.004	0.001
Shoulder (%)	31.25	32.37	31.93	1.145	0.787	0.586
Rack (%)	7.36	8.31	7.27	0.343	0.080	0.056
Loin (%)	12.68	11.89	12.96	0.406	0.179	0.075
Leg (%)	34.70	33.98	33.40	0.585	0.310	0.919
Foreshank and breast (%)	14.01	13.45	14.43	0.645	0.566	0.339

[1)] Dietary groups consisted of pelleted complete diets with varying NDF content: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF).

[a,b] Superscripts represent significant differences ($p<0.05$) between dietary groups for each parameter within a row.

Table 5. The evaluation of the body fat depots components of lambs fed pelleted complete diets with levels of neutral detergent fibers (NDFs)

Parameters	Dietary groups[1)]			SEM	p-value	
	Diet 1	Diet 2	Diet 3		Groups	Quadratic
Back fat (mm)	3.25[b]	3.49[b]	4.94[a]	0.347	0.004	0.167
Body wall fat (mm)	5.99[ab]	4.38[b]	6.30[a]	0.541	0.044	0.014
Pericardial fat (%)	0.18	0.19	0.18	0.012	0.956	0.935
KKCF (%)	0.41	0.44	0.33	0.053	0.357	0.300
Omental fat (%)	0.50[b]	0.75[a]	0.66[ab]	0.047	0.004	0.008
Mesentery fat (%)	0.68[b]	0.96[a]	0.67[b]	0.079	0.043	0.014

[1)] Dietary groups consisted of pelleted complete diets with varying NDF content: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF).
[a,b] Superscripts represent significant differences ($p<0.05$) between dietary groups for each parameter within a row.
KKCF, kidney knob and channel fat.

pericardial fat and kidney knob and channel fat were not affected by diet ($p>0.05$). Body wall fat was significantly lower and mesenteric fat higher in lambs fed Diet 2 than in lambs fed Diet 3 ($p<0.05$), but no significant difference was found between Diets 1 and 2 on body wall fat. In addition, omental fat was higher in lambs fed Diet 2 than in lambs fed Diet 1 ($p<0.05$), but no significant difference was found between Diets 2 and 3. A quadratic effect of NDF content on body wall fat, omental fat and mesenteric fat was observed ($p<0.05$), whereas other parameters were not affected ($p>0.05$).

Tissue composition of the cuts

The evaluation of the tissue composition of the cuts of lambs fed different levels of NDF in pelleted complete diets is shown in Table 6. Lambs fed Diets 2 and 3 had lower fat content in the rack than lambs fed Diet 1, with a quadratic effect of NDF content ($p<0.05$). In addition, meat content in the rack of lambs fed Diet 2 and meat trimmings in the rack of lambs fed Diets 2 and 3 were significantly higher ($p<0.05$) than in the other groups, with a quadratic effect of NDF content ($p<0.05$). In contrast, no significant differences ($p>0.05$) in cut weight or bone percentage between groups or quadratic effects observed.

Table 6. The evaluation of tissue composition of the cuts of lambs fed pelleted complete diets with levels of neutral detergent fibers (NDFs)

Parameters	Dietary groups[1)]			SEM	p-value	
	Diet 1	Diet 2	Diet 3		Groups	Quadratic
Cut (g)	681	630	591	42.46	0.343	0.908
Fat (%)	31.17[a]	18.29[c]	24.50[b]	1.107	<0.0001	0.001
Meat (%)	43.53[b]	52.09[a]	45.77[b]	1.482	0.001	0.005
Bone (%)	22.29	25.07	25.08	1.107	0.147	0.320
Trimmings (%)	3.00[b]	4.55[a]	4.65[a]	0.471	0.038	0.027

[1)] Dietary groups consisted of pelleted complete diets with varying NDF content: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF).
[a,b] Superscripts represent significant differences ($p<0.05$) between dietary groups for each parameter within a row.

Physical and qualitative parameters of meat

The physical and qualitative characteristics of the meat of lambs fed different levels of NDF in pelleted complete diets are shown in Table 7. The results show that the lambs in the different dietary groups showed no differences in pH and temperature (p>0.05) at 30 min and 24 h after slaughter. The color components of the meat (CIE L*, CIE a*, and CIE b*) were also not

Table 7. The evaluation of the physical and qualitative characteristics of the meat of lambs fed pelleted complete diets with levels of neutral detergent fibers (NDFs)

Parameters	Dietary groups[1)]			SEM	p-value	
	Diet 1	Diet 2	Diet 3		Groups	Quadratic
pH value						
At 30 min after slaughter	5.94	5.88	5.83	0.040	0.197	0.843
At 24 h after slaughter	5.78	5.79	5.78	0.024	0.919	0.685
Temperature (°C)						
At 30 min after slaughter	25.74	26.10	26.14	0.340	0.655	0.701
At 24 h after slaughter	15.38	15.01	15.17	0.412	0.819	0.607
Meat color components at 30 min after slaughter						
CIE L*	37.82	36.64	38.52	0.778	0.250	0.124
CIE a*	12.65	18.30	18.49	2.192	0.125	0.319
CIE b*	5.67	4.81	4.78	0.341	0.140	0.336
Meat color components at 24 h after slaughter						
CIE L*	41.82[a]	35.12[b]	36.37[ab]	1.774	0.033	0.081
CIE a*	14.76	14.85	14.43	0.444	0.788	0.646
CIE b*	10.27[b]	12.93[a]	12.47[a]	0.484	0.001	0.051
Meat color derivatives						
Color change	9.24	11.67	11.49	1.129	0.261	0.356
CIE b* to CIE a* ratio	0.70[b]	0.87[a]	0.86[a]	0.026	0.0002	0.130
Chroma	18.00	19.70	19.09	0.585	0.140	0.123
Hue angle	34.81[b]	41.00[a]	40.72[a]	0.942	0.0002	0.103
Meat quality properties						
Cooking loss (%)	36.94[b]	30.41[c]	40.66[a]	1.601	<0.0001	<0.0001
Water-holding capacity (%)	34.89	31.93	32.70	1.475	0.358	0.315
Myofibril fragmentation index	84.49[c]	118.31[b]	131.63[a]	11.32	0.021	0.046
Shear force (N/cm^2)	28.01[a]	21.46[b]	23.66[b]	0.690	<0.0001	<0.0001
Texture profile analysis						
Hardness (N)	10.70	10.04	8.07	0.891	0.119	0.557
Springiness ratio	0.68	0.71	0.68	0.021	0.525	0.277
Cohesiveness ratio	0.54[a]	0.52[a]	0.46[b]	0.013	0.001	0.298
Chewiness ratio	4.11	3.92	2.79	0.395	0.059	0.341

[1)] Dietary groups consisted of pelleted complete diets with varying NDF content: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF).

[a–c] Superscripts represent significant differences (p<0.05) between dietary groups for each parameter within a row.

influenced by the dietary groups or quadratic effects at 30 min after slaughter (p>0.05).

At 24 h after slaughter, CIE L* was lower (p<0.05) in lambs fed Diet 2 than in lambs fed Diet 1, but no significant difference between Diets 2 and 3. In contrast, CIE b*, CIE b* to CIE a* ratio, and the hue angle of the meat were increased (p<0.05) in lambs fed Diets 2 and 3 compared with those fed Diet 1. CIE a* color indicator, color change, and chroma were not influenced by diet groups (p>0.05). No quadratic effect of NDF levels was observed for any physical characteristics (p>0.05).

Cooking loss was lowest in lambs fed Diet 2, followed by those fed Diets 1 compared with those fed Diet 3 (p<0.05). In addition, the myofibril fragmentation index was lower (p<0.05) in lambs fed Diet 1 followed by Diet 2 than in lambs fed Diet 3. In contrast, lambs fed Diets 2 and 3 had lower shear force values than those fed Diet 1 (p<0.05). A quadratic effect of NDF content was observed for cooking loss, myofibril fragmentation index and shear force (p<0.05).

Water holding capacity was not affected by dietary groups or quadratic effects (p>0.05). The texture profile analysis was also not influenced by the diet groups or the quadratic effects (p>0.05), with the exception of the cohesion ratio, which was lower in lambs fed Diet 3 than in the other groups (p<0.05).

Analysis of the chemical and fatty acid composition of the meat

The nutrient analysis of the meat and the fatty acid profile of lambs fed different levels of NDF in pelleted complete diets are shown in Table 8. The nutrient content of meat, including dry matter, organic matter and crude protein, was higher (p<0.05), while the moisture content was lower (p<0.05) in lambs fed Diet 2 than in the other groups. Fat content was lower (p<0.05) in lambs fed Diet 2 than in lambs fed Diet 1, but there was no significant difference between Diets 2 and 3. In addition, a quadratic effect of NDF content on dry matter, organic matter, crude protein, moisture content and fat was observed (p<0.05). In contrast, ash content did not differ significantly between dietary groups or quadratic effects (p>0.05).

The profile of fatty acid methyl esters in meat, including lauric acid, tetradecenoic acid, linoleic acid, linolenic acid, stearidonic acid, arachidonic acid, polyunsaturated fatty acids, omega-6, omega-3 and the ratio of polyunsaturated to saturated fatty acids, was higher in lambs fed Diet 2, while saturated fatty acids were lower in lambs fed Diet 2 than in those fed the other diets (p<0.05). In addition, capric acid decreased and myristioleic acid increased (p<0.05) in lambs fed Diets 2 and 3 than in lambs fed Diet 1. Conjugated linoleic acid was lower (p<0.05) in lambs fed Diet 2 than in lambs fed Diet 3, but there was no significant difference between Diets 1 and 2. In contrast, other components of the meat fatty acid profile were not influenced by diet (p>0.05).

In addition, a quadratic effect of NDF content was observed for capric acid, lauric acid, saturated fatty acids, tetradecanoic acid, linolenic acid and stearidonic acid (p<0.05), whereas other parameters were not affected (p>0.05).

Discussion

NDF is an important nutrient in the diet of ruminants and affects feed intake, nutrient digestibility and weight gain of animals. In this study, the effects of different NDF contents in pelleted complete diets on weight gain, carcass characteristics, and meat quality of lambs were investigated. Our results showed that the diet with an NDF content of 28.23% (Diet 2) improved body weight, total weight gain, average daily gain, and relative growth rate compared to the diet with an NDF content of 20.98% (Diet 1), but did not differ from the diet with an NDF content of 34.82% (Diet 3). This suggests that the benefits of increased NDF reach a plateau up to a certain point (as in Diet 2) and potentially diminish beyond that point.

Table 8. The evaluation of the meat nutrients analysis and fatty acid profile of lambs fed pelleted complete diets with levels of neutral detergent fibers (NDFs)

Parameters	Dietary groups[1)]			SEM	p-value	
	Diet 1	Diet 2	Diet 3		Groups	Quadratic
Nutrient content of meat (%)						
Moisture	73.80^{a}	71.53^{b}	42.78^{a}	0.392	0.0008	0.0002
Dry matter	26.20^{b}	28.47^{a}	19.65^{b}	0.392	0.0008	0.0002
Organic matter	21.62^{b}	23.59^{a}	17.58^{b}	0.464	0.0099	0.002
Ash	4.57	4.88	8.52	0.157	0.405	0.239
Crude protein	20.77^{b}	22.73^{a}	17.21^{c}	0.293	0.0001	0.0001
Fat	19.07^{a}	16.29^{b}	16.76^{ab}	0.695	0.022	0.002
Meat fatty acid methyl esters profile (%)						
Capric acid	0.74^{a}	0.20^{b}	0.17^{b}	0.051	<0.0001	0.0006
Lauric acid	0.22^{b}	0.43^{a}	0.27^{b}	0.018	<0.0001	<0.0001
Myristic acid	3.01	3.22	2.69	0.325	0.459	0.336
Pentadecanoic acid	0.77	0.72	0.73	0.087	0.913	0.784
Palmitic acid	22.79	21.77	22.73	0.786	0.601	0.324
Heptadecanoic acid	2.44	2.29	2.67	0.128	0.153	0.121
Stearic acid	20.01	16.95	18.18	1.143	0.205	0.151
Saturated fatty acid	49.03^{a}	45.58^{b}	47.28^{a}	0.775	0.027	0.018
Myristioleic acid	0.13^{b}	0.28^{a}	0.29^{a}	0.067	0.014	0.185
Tetradecenoic acid	0.21^{b}	0.30^{a}	0.20^{b}	0.021	0.001	0.0005
Palmitoleic acid	2.09	2.24	2.12	0.226	0.881	0.630
Oleic acid	35.19	38.44	38.15	1.101	0.110	0.214
Vaccinic acid	2.88	1.88	2.67	0.663	0.548	0.292
cis-6-Octadecenoic acid	1.36	0.88	1.16	0.179	0.205	0.106
Monounsaturated fatty acid	41.74	43.88	44.49	0.912	0.122	0.507
Hexadecenoic acid	0.74	0.64	0.82	0.059	0.141	0.077
Conjugated linoleic acid	0.45^{ab}	0.37^{b}	0.49^{a}	0.026	0.038	0.057
Linoleic acid	4.31^{b}	6.58^{a}	4.23^{b}	0.228	<0.0001	0.959
Linolenic acid	0.51^{b}	0.68^{a}	0.50^{b}	0.023	0.0002	0.0006
Stearidonic acid	0.43^{b}	0.66^{a}	0.43^{b}	0.037	0.001	0.001
Arachidonic acid	0.40^{b}	0.58^{a}	0.39^{b}	0.055	0.041	0.336
Polyunsaturated fatty acids	7.12^{b}	9.61^{a}	6.95^{b}	0.203	<0.0001	0.784
Omega–6	4.63^{b}	7.04^{a}	4.62^{b}	0.225	<0.0001	0.324
Omega–3	0.93^{b}	1.33^{a}	0.93^{b}	0.041	<0.0001	0.121
Omega–3/ Omega–6	0.21	0.19	0.20	0.011	0.689	0.137
Polyunsaturated/saturated fatty acids	0.15^{b}	0.21^{a}	0.15^{b}	0.005	<0.0001	0.185

[1)] Dietary groups consisted of pelleted complete diets with varying NDF content: Diet 1 (20.98% NDF), Diet 2 (28.23% NDF), and Diet 3 (34.82% NDF).

[a,b] Superscripts represent significant differences (p<0.05) between dietary groups for each parameter within a row.

However, the effectiveness of NDF (28.23%) in improving lamb weight gain is likely related to its role in providing physical mass to the rumen, promoting microbial fermentation, and producing volatile fatty acids that provide energy to lambs. This is consistent with other studies by Abdelrahman et al. (2018), Alhidary et al. (2016), and Macdonald et al. (2021), who reported improved weight gains at around 28%–30% NDF, likely due to optimized rumen function and feed intake in lambs.

Our results showed that the diet with an NDF content of 20.98% (Diet 1) had lower daily feed and dry matter intake compared to both Diets 2 and 3, which could be due to insufficient rumen stimulation. This is consistent with studies that reported that a diet with an NDF content of 20.00% reduces rumen fermentation activity (Kozloski et al., 2006; Pereira et al., 2016). The results showed that feed intake and dry matter were higher in lambs fed Diets 2 and 3 than in those fed Diet 1. A higher NDF content generally stimulates feed intake by promoting regurgitation and saliva production, buffering rumen pH, and increasing microbial activity in lambs (Trottier, 2020). Excessive NDF content can lead to rumen filling and reduced digestibility, which ultimately limits the availability of energy for growth (Chishti et al., 2022). In Diet 3 (34.82% NDF), which stimulated feed intake, the additional fiber may have reduced overall digestibility enough to offset the increase in intake, resulting in similar weight gain parameters as Diet 1. In addition, the improved feed intake observed in Diets 2 and 3 suggests that the pelleted form of the diets, along with potentially highly fermentable NDF sources such as soy hulls. This is consistent with studies by Bertipaglia et al. (2010) and Zhong et al. (2018), who found that pelleting improved fiber utilization by altering fiber structure and improve feed intake. However, the lack of difference in feed conversion ratio between diets suggests that the increased feed intake in Diet 2 resulted in higher growth efficiency, while the increased intake in Diet 3 was likely offset by lower digestibility, resulting in no significant improvement in growth.

The effect of dietary NDF on carcass characteristics is one of the most important aspects of lamb nutrition (Ellison et al., 2022). The results of this study showed that lambs fed Diet 2 (28.23% NDF) had better carcass characteristics, including slaughter weight, empty body weight, hot and cold carcass weights, and carcass compactness index. In addition, the dressing percentage was higher in lambs fed Diets 2 and 3 than in those fed Diet 1. This is consistent with a previous study by Ozdogan et al. (2017), which found that diets with different NDF levels (15%, 20%, and 25% NDF) had effects on carcass characteristics. In contrast, lower NDF levels were associated with higher meat quality, higher dressing percentage and higher carcass weight (Moura et al., 2019). This discrepancy in the studies may be due to differences in breed, diet composition, and environmental conditions. Optimal NDF content improves rumen ecosystem activity and feed intake, which is reflected in higher growth rates and better carcass characteristics (Du et al., 2022). This suggests that the optimal NDF content in Diet 2 improved rumen activity and nutrient utilization, which was reflected in higher growth rates and improved carcass characteristics. The study suggests that the higher carcass weight in lambs fed Diet 2 was primarily due to muscle growth rather than water retention, as evidenced by the lack of effect on chill shrink. In addition, this study showed effects of dietary NDF on relative body component weights. Lambs fed 20.98% (Diet 1) NDF had higher relative weights of head and lung than Diet 3, while Diet 2 had intermediate values. The lower relative weights of the spleen and intestine in Diet 2 than in Diet 1 suggest a possible influence of NDF on intestinal health and immune function. Diet 2 also resulted in a higher relative weight of genitals, which could potentially be related to hormonal changes associated with improved growth performance. The higher relative tail weight in Diets 2 and 3 compared to Diet 1 should be investigated further, although its practical significance is probably limited. The different energy consumption patterns in these diets play a crucial role in explaining the observed differences in carcass characteristics and body components. Mengesha et al. (2017) point out that lambs achieve better carcass weights and yields when they fed a diet with a higher energy content.

The composition of the carcass, including the major cuts and fat deposits, is a decisive factor for the value of meat products

(Ekiz et al., 2013). The present results showed that an NDF content of 28.23% (Diet 2) improved half carcass weight without affecting the primary wholesale cut. The higher half carcass weight of lambs fed Diet 2 likely reflects the overall improved weight gains observed in these lambs, suggesting that optimal NDF levels promote efficient nutrient utilization for muscle and skeletal development. This aligns with previous studies indicating that NDF content primarily affects overall weight gain and carcass weight rather than drastically altering the proportions of major cuts of carcass (Jacques et al., 2011; Mirzaei-Alamouti et al., 2021). The changes observed in the distribution of fat depots are particularly interesting. While Diet 3 (34.82% NDF) resulted in increased backfat thickness compared to the other diets, suggesting a promotion of subcutaneous fat deposition. Backfat thickness is a commonly assessed carcass trait due to its influence on both carcass quality and consumer acceptance (Prache et al., 2022). The lower body wall fat and higher mesentery and omental fat in Diet 2 may indicate that 28.23% NDF influenced fat distribution within the carcass. This suggests that different levels of NDF may affect fat distribution within the carcass differently, possibly due to the affecting of metabolic pathways involved in lipogenesis. However, the lower fat content of the body wall in lambs fed 28.23% NDF indicates a different pattern of fat deposition, with less fat accumulating in the rib area than in the subcutaneous area (Carrillo-Muro et al., 2023). In another study, Mirzaei-Alamouti et al. (2021) reported that lambs fed low NDF (22.0%–24.5%) accumulated more body fat in certain fat depots, with the exception of backfat, which increased at high NDF levels.

The present study showed that the percentage fat content of lambs fed Diets 2 and 3 was lower compared to Diet 1, an important finding. This suggests that increasing NDF content within the range investigated in this study may influence fat deposition in the rack cut. Our results are consistent with the more general concept that fat content can be influenced by dietary fiber content, with NDF content potentially influencing the balance between muscle and fat accumulation (Gallo et al., 2019). At the same time, our results show that the percentage of meat was higher in lambs fed Diet 2 than in the other groups. This increase in meat percentage combined with the decrease in fat percentage suggests that Diet 2 (which likely represents the optimal NDF content) promotes a more favorable lean-to-fat ratio in the rack cut. This is a commercially desirable outcome as consumers often prefer leaner cuts of meat (Gurunathan, 2022). The higher percentage of trimmings in the racks of lambs fed Diets 2 and 3 supports this assumption and indicates a greater percentage of lean tissue available for processing and sale. Interestingly, we found no significant differences between the groups in terms of cut weight or percentage of bone in the racks. This observation suggests that the changes in meat and fat content are likely due to changes in the relative rates of muscle protein and fat synthesis and/or breakdown, rather than changes in skeletal growth or total tissue gain.

The fact that meat pH and temperature did not differ significantly between diet groups indicates that metabolic processes prior to slaughter were not influenced by NDF content. These factors have a significant influence on the subsequent biochemical and physical changes and are therefore essential for meat quality (Kim et al., 2020). At 24 h after slaughter, meat color showed an increase in CIE b* and a decrease in CIE L* in Diet 2, followed by Diet 3, which is not consistent with the expected color changes associated with metmyoglobin accumulation. Since metmyoglobin typically increases CIE b* and decreases CIE a*, these results suggest that other mechanisms may be responsible for the color differences observed in this study. However, future investigations should include more specific pigment analysis, muscle fiber type composition, and measurement of fat oxidation to confirm the mechanisms underlying the observed color changes in meat lambs fed different levels of NDF. The water holding capacity parameter was used to measure the water retention capacity of lamb meat (Almeida et al., 2022). However, the water holding capacity was not affected by the groups, which could be due to the fact that the ability of the meat to retain water was not affected. Cooking loss was lower in lambs fed Diet 2, followed by Diet 1, which could indicate improved water retention during cooking (Karaca et al., 2016). The higher cooking loss in Diet 3 may be due to reduced intramuscular fat. Lambs fed Diets 2 and 3 had lower shear force, indicating improved tenderness of the meat. The lower myofibril fragmentation index (a measure of muscle fiber breakdown) in these groups supports this conclusion (Bakhsh et al., 2019). The lower cohesiveness ratio in lambs fed Diet 3 indicates lower binding forces between the meat particles.

The higher dry matter, organic matter and crude protein content in combination with the lower moisture content in the meat of lambs fed Diet 2 indicates improved protein and water binding. These results are consistent with previous research demonstrating a positive relationship between dietary protein and meat quality (Saro et al., 2020). The lack of differences in ash content indicates that mineral composition was not significantly affected by NDF content.

The observed changes in the fatty acid profile of the meat illustrate the potential of dietary manipulation to influence meat quality (Sami et al., 2004). Of particular note was the increase in polyunsaturated fatty acids, including omega-3 and omega-6 fatty acids, in the meat of lambs fed Diet 2. These fatty acids are associated with numerous health benefits, and their inclusion in the human diet is recommended (Sun et al., 2020). Reducing saturated fatty acids and conjugated linoleic acid in the meat of lambs fed Diet 2 is also beneficial, as excessive intake of saturated fatty acids is associated with cardiovascular disease (Carneiro et al., 2021). Conjugated linoleic acid comprises several isomers and its content in meat is influenced by dietary factors (Torres et al., 2022). Specific changes in individual fatty acids, such as the increase in myristiolenic acid and the decrease in capric acid in the meat of lambs fed Diets 2 and 3, can also influence meat flavor and sensory characteristics (Costa et al., 2020).

Conclusion

In this study, investigated the impact of varying NDF content in pelleted complete diets on lamb weight gain measures, carcass characteristics, and meat quality. The results showed that an NDF content of 28.23% (Diet 2) optimized weight gain, carcass weight and muscle development compared to lower (Diet 1) and higher (Diet 3) NDF contents. Higher NDF levels stimulated feed intake but did not lead to a further increase in weight gain. Carcass analysis showed that Diet 2 improved meat tenderness, reduced fat content, increased meat content in the rack, and enhanced the fatty acid profile, with higher polyunsaturated and lower saturated fatty acids. These findings highlight the importance of optimizing the NDF content in lamb diets to improve production efficiency, carcass quality, and the nutritional value of the meat. However, further research is needed to elucidate the underlying mechanisms and determine the optimal NDF levels for specific production goals.

Conflicts of Interest

The authors declare no potential conflicts of interest.

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Author Contributions

Conceptualization: Alhidary IA. Data curation: Alharthi AS, Suliman GM. Formal analysis: Al-Ghamdi S, Al-Baadani HH. Methodology: Al-Ghamdi S, Al-Baadani HH, Alharthi AS, Suliman GM. Validation: Alhidary IA. Investigation: Alhidary IA. Writing - original draft: Al-Ghamdi S, Al-Baadani HH. Writing - review & editing: Al-Ghamdi S, Al-Baadani HH, Alharthi AS, Suliman GM, Alhidary IA.

Ethics Approval

All animal husbandry, feed formulation, sampling, and analyses were conducted following the guidelines of the Committee for Scientific Research Ethics of King Saud University, Saudi Arabia (approval number: KSU-SE-22-26).

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