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Feed Intake, Ingestive Behavior, and Metabolic Parameters of Ewes Fed Fully Extruded Diets with Different Forage Levels Compared to Corn Silage

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ABSTRACT

The objective of this study was to evaluate dry matter intake (DMI), dry matter digestibility (DMD), ingestive behavior, and blood parameters in ewes fed extruded diets with increasing forage levels compared with fresh corn silage. Twenty adult, non-pregnant crossbred ewes (Dorper × Santa Inês; 4 ± 0.5 years old) with an initial body weight of 65.17 ± 10.45 kg were housed in metabolic cages for 20 days in a completely randomized design and assigned to one of the following treatments: fresh corn silage, extruded diet containing 52.5%, 60.0%, 65.0%, or 70.0% forage based on *Urochloa* spp. grass fiber. Data were analyzed using mixed models after testing for normality and homogeneity of residuals. Orthogonal contrasts were used to evaluate the effects of forage type and increasing forage levels. Glucose concentrations were analyzed as repeated measures over time, and the covariance structure was selected based on the corrected Akaike information criterion. Statistical significance was declared at $p \leq 0.05$. Extruded diets increased DMI, water intake from the drinker, fecal score, idling time (IT), chewing efficiency (CE), rumination efficiency (RE), and serum urea concentrations compared with corn silage ($p < 0.05$); however, no effect was observed on DMD. Increasing forage levels in the extruded diets promoted a positive quadratic effect on DMI and rumination time up to 65.0% forage inclusion, whereas negative quadratic responses were observed for IT, CE, and RE. Blood glucose concentration showed a quadratic response to forage inclusion, reaching a maximum at 60.0% forage, while serum urea concentrations decreased linearly as dietary forage levels increased ($p < 0.05$). In conclusion, fully extruded diets improved feed intake, water consumption, and ingestive efficiency in ewes without affecting DMD, even at higher forage inclusion levels. Forage inclusion levels between 60.0% and 65.0% optimized intake and rumination activity, while promoting greater stability in blood glucose concentrations.

***Keywords:** digestibility; glucose; rumination; ruminants; serum urea*

INTRODUCTION

Dietary fiber is utilized by ruminal microorganisms as an energy source (Hall & Mertens, 2023) and plays a fundamental role in maintaining gastrointestinal health. Beyond its nutritional contribution, fiber provides the physical stimulation required for proper rumen function by promoting chewing activity and saliva secretion (Schmitz-Esser, 2021; Zhang *et al*., 2025). The type and level of fiber used in production systems must consider feed cost and availability, as well as their effects on digestive physiology and animal performance, because diets with high fiber content or a predominance of long fiber particles may limit nutrient intake in sheep (Faryabi *et al*., 2023).

Numerous studies have demonstrated that feed processing, particularly grain processing, can reduce anti-nutritional factors and decrease the resistance of grains to ruminal fermentation (Risyahadi *et al*., 2023). Zhong *et al*. (2018) reported increased feed intake, improved growth performance, modulation of ruminal fermentation, enhanced gastrointestinal development, and beneficial effects on cholesterol metabolism and animal health in sheep fed pelleted forage-based diets compared with those fed non-pelleted diets.

Nevertheless, additional processing strategies associated with pelleting may further enhance these effects and optimize dietary fiber utilization. Extrusion is widely used to increase the exposure of starch granules in grains to ruminal fermentation and digestion (Risyahadi *et al*., 2023) by subjecting feed ingredients to high pressure, moisture, and temperature.

However, limited information is available regarding the application of extrusion in high-forage

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diets for small ruminants, particularly those based on tropical forages, which are characterized by greater fiber complexity and stronger physical limitations to feed intake and digestion. In addition, previous studies evaluating processed diets in sheep have primarily focused on growing or feedlot animals (Zhong *et al*., 2018). Recent studies using extruded tropical forages in sheep diets have demonstrated promising effects on feed intake and digestibility (Silva *et al*., 2023). However, information remains scarce, especially in systems with high forage inclusion levels. The thermal and mechanical effects of extrusion may represent a viable strategy to alter the structural organization of fibrous feed components (Brand *et al*., 2023; Ghorbani *et al*., 2020; Gjorgjievski *et al*., 2022), thereby enhancing fiber intake, microbial colonization, and ruminal digestion and potentially improving nutrient utilization in high-fiber diets.

Therefore, the present study addresses an important gap in the literature by evaluating extruded diets (DExt) containing high levels of tropical forage (*Urochloa* grass) in adult ewes under high-forage feeding systems (up to 70% forage inclusion) as a strategy to improve fiber utilization. This study evaluated the effects of DExt containing *Urochloa* grass on dry matter intake (DMI), dry matter digestibility (DMD), ingestive behavior, and serum metabolites compared with a non-extruded corn silage diet. It was hypothesized that extrusion would allow greater forage inclusion without impairing feed intake, digestibility, or metabolic status in adult ewes.

MATERIALS AND METHODS

Location, Animals, Experimental Design, And Diets

The study was approved by the Ethics Committee on Animal Use (CEUA) of the Federal University of Uberlândia (UFU) under protocol number 094/17 and conducted at the Small Ruminant Sector (SEPER/UFU), located in Uberlândia, Minas Gerais, Brazil, at an altitude of 863 m (18°87′79.6″ S, 48°34′46.9″ W). During the experimental period, the average temperature was 17.4 °C, the average relative humidity was 64.02%, and no precipitation was recorded (CLIMAUFU – ICIAG).

Twenty adult non-pregnant crossbred ewes (Dorper × Santa Inês), aged 4 ± 0.5 years and with an initial body weight (BW) of 65.17 ± 10.45 kg, were used. The animals were randomly assigned to individual metabolic cages equipped with a drinker, feed trough, salt feeder, slatted floor, and a feces and urine separation system. The experimental period lasted 20 days, consisting of 15 days of adaptation to the diets and facilities, followed by five days of data collection.

The animals were assigned to five diets differing in forage source and forage inclusion level: corn silage, DExt containing 52.5%, 60.0%, 65.0%, or 70.0% forage based on *Urochloa* grass. The extruded forage was composed of *Urochloa* grass, starch, minerals, and urea. All diets (Table 1) were formulated and balanced to meet the maintenance nutritional requirements of adult ewes according to the recommendations of the National Research Council (NRC, 2007). The particle size distribution of the corn silage was determined using the Penn State Particle Separator equipped with sieves of 19, 8, and 4 mm and a bottom pan (Lammers *et al*., 1996).

Dry Matter Intake, Dry Matter Digestibility, Water Intake, and Fecal Score

Animals were weighed at the beginning and end of the experimental period. Diets were offered twice daily at 08:00 and 16:00 h, with 50% of the daily feed allowance provided at each feeding. Feed refusals were recorded daily before the morning feeding to calculate intake and adjust feed supply, maintaining ad libitum intake with approximately 10% orts on an as-fed basis.

Water was available ad libitum throughout the experimental period. Water was supplied daily in buckets, and both the volume offered and refusals were measured daily. To estimate evaporation losses, a control bucket inaccessible to the animals was placed inside the barn, and water volume was recorded every 24 h. The difference in water volume between consecutive days was considered evaporative loss. Water intake from the drinker was calculated as the difference between the amount supplied and refusals, corrected for evaporation. Water volume was measured using 2-L graduated cylinders with a precision of 20 mL. Water intake from the diet was estimated based on feed

Table 1. Chemical composition of the experimental feeds and diets, and particle size distribution of corn silage used in diets for adult ewes fed fully extruded diets with different forage levels or corn silage

Nutritional composition (%)*	Experimental feed and diets				Corn silage
	52.5F	60F	65F	70F	
Dry matter	90.00	91.20	91.50	91.00	31.20
Crude protein	7.98	7.67	7.65	6.67	8.00
Neutral detergent fiber	47.46	50.33	53.59	64.44	57.11
Non-fibrous carbohydrates	38.24	35.96	32.62	23.67	36.17
Total digestible nutrients	66.00	65.81	63.91	64.44	62.52
> 19 mm[1]					39.54
8 - 19 mm[1]					45.85
< 8 mm[1]					14.61

Note: *Values provided by the manufacturer; 52.5F= extruded diet with 52.5% Urochloa grass; 60F= extruded diet with 60% Urochloa grass; 65F= extruded diet with 65% Urochloa grass; 70F= extruded diet with 70% Urochloa grass; [1]Penn State Particle Separator.

moisture content and individual feed intake. Total water intake was calculated as the sum of water intake from the drinker and water intake from the diet.

The digestibility trial was conducted during the last 5 days of the experimental period. Samples of feeds, refusals, and feces were collected for the determination of DM content, DMI, and DMD. Feces were collected by total fecal collection over 24 h using the metabolic cage system. DM content was determined according to the methodology described by Detmann *et al*. (2021). Samples were pre-dried in a forced-air oven at 55°C for 72 h and subsequently ground using a knife mill equipped with a 1-mm sieve. Thereafter, the samples were oven-dried at 105°C for 24 h for final DM determination. Fecal consistency was visually assessed throughout the fecal collection period according to the scoring system proposed by Dickson and Jolly (2011): 1 = dry, hard feces; 2 = firm feces close to normal consistency; 3 = partially softened feces forming a soft pile; 4 = loose feces forming a soft heap; and 5 = watery feces, including diarrhea.

Ingestive Behavior

Ingestive behavior was evaluated on days 16 and 17 of the experimental period by continuous visual observation over 24 h at 5-min intervals, recording the eating time (ET), ruminating time (RT), and idling time (IT) according to Fischer *et al*. (1988). Total chewing time (TCT) was calculated as the sum of ET and RT. Feeding efficiency (FE), rumination efficiency (RE), and chewing efficiency (CE) were calculated as the ratio between DMI and the time spent on each activity (Burger *et al*., 2000). Nocturnal observations were performed under artificial lighting, and the animals were adapted to the lighting conditions for 5 days before behavioral assessments.

Ruminal contractions were evaluated by auscultation and percussion-auscultation of the left flank using a stethoscope positioned between the 7th and 8th ribs at the costochondral junction (Dirksen, 1993). Complete ruminal contractions and incomplete ruminal contractions, characterized by lower amplitude and force, were recorded. Total ruminal contractions were calculated as the sum of complete and incomplete ruminal contractions. Assessments were performed on day 18 at 10:00 h using continuous recording for 5 min.

Blood Analysis

Blood samples were collected by jugular venipuncture using Vacutainer tubes on days 16, 18, and 20 of the experimental period to determine serum metabolites. All samples were collected at 08:00 h before the morning feeding. On day 20, additional blood samples were collected at 08:00 h (pre-feeding), 11:00, 14:00, 17:00, and 20:00 h to evaluate the glycemic curve using tubes containing sodium fluoride and ethylenediaminetetraacetic acid as a glycolytic inhibitor and anticoagulant, respectively. On this day, the second meal was offered only after the last blood collection (20:00 h).

Blood samples were centrifuged at 3,500 rpm for 15 min to obtain serum. Serum metabolites were analyzed using a semi-automatic biochemical analyzer (Bioplus® 2000) by the photoelectric colorimetric method with commercial kits (Labtest Diagnóstica S.A.®) to determine glucose, cholesterol, triglycerides, total protein, albumin, urea, and creatinine concentrations. Except for the glycemic curve analysis, results were expressed as the mean of the three sampling days (days 16, 18, and 20).

Statistical Analysis

Data were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC, USA). Residual normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test) were evaluated. When necessary, data were transformed using the Box–Cox procedure and/or analyzed assuming heterogeneous variances using the GROUP option in SAS.

Orthogonal contrasts were applied considering the fixed effects of forage type (corn silage vs. DExt) and the linear and quadratic effects of forage levels within the DExt. Because forage inclusion levels in the DExt were not equally spaced (52.5%, 60.0%, 65.0%, and 70.0%), contrast coefficients were calculated based on the actual values to ensure orthogonality, according to Littell *et al*. (2006). The glycemic response curve was analyzed as repeated measures over time, considering diet, sampling time, and the diet × time interaction as fixed effects. Polynomial contrasts were applied to diet effects, whereas linear, quadratic, and cubic contrasts were applied to sampling time. The following covariance structures were tested: unstructured, compound symmetry, heterogeneous compound symmetry, first-order autoregressive [AR(1)], heterogeneous first-order autoregressive [ARH(1)], Toeplitz, heterogeneous Toeplitz, and first-order ante-dependence [ANTE(1)]. The covariance structure with the lowest corrected Akaike information criterion, based on the −2 log-likelihood, was selected as the best fit. Statistical significance was declared at $p \leq 0.05$, and trends were considered when $0.05 < p \leq 0.10$.

RESULTS

Extruded diets (DExt) increased BW, DMI (DMI, DMI%BW, and $DMI^{0.75}$), water intake from the drinker, and fecal score of ewes compared with corn silage-based diets ($p<0.05$) (Table 2). The DMI of animals fed corn silage represented only 42% of that observed in animals fed DExt. Both DMI ($p = 0.02$) and BW ($p = 0.04$) showed a quadratic response to increasing forage inclusion levels in DExt, with maximum values estimated at 65.0% forage inclusion. Water intake from the diet and total water intake (drinker + diet) were greater in animals fed corn silage ($p<0.01$). DMD was not affected by forage source or forage inclusion level ($p>0.05$) (Table 2).

ET, RT, TCT, and the number of ruminal movements were greater in animals fed corn silage than in those fed DExt, whereas IT, CE, and RE were greater in animals fed DExt, likely due to the higher DMI observed in these diets (p<0.04) (Table 3).

In addition, RT and TCT showed a quadratic response to increasing forage inclusion levels in DExt, with maximum values estimated at 65.0% forage inclusion (p<0.05). Conversely, IT exhibited an opposite quadratic response, decreasing up to 65.0% forage inclusion and increasing thereafter at 70.0% forage inclusion. CE and RE also showed a quadratic response, with minimum values estimated at 65.0% forage inclusion in DExt.

Serum concentrations of cholesterol, triglycerides, total protein, albumin, and creatinine were not affected by forage source or forage inclusion level in DExt (p>0.05) (Table 4). However, DExt increased serum urea concentrations compared with corn silage (p<0.01). Within the DExt, increasing forage inclusion levels promoted a linear reduction in serum urea concentrations (p<0.01). The serum glucose concentration was not affected by the forage source (p = 0.48); however, it showed a quadratic response to forage inclusion levels in DExt (p = 0.01), with the highest

Table 2. Dry matter intake and digestibility, fecal score, and water intake of ewes fed corn silage or fully extruded diets with different forage levels

Variables	Forage source					SEM	p value		
	Silage	52.5F	60F	65F	70F		SxF	L	Q
DMI, kg^{-1}	1.258^{b}	3.019^{a}	3.277^{a}	3.303^{a}	2.171^{a}	0.207	<0.01	0.03	0.02
DMI/BW, kg^{-1}	2.25^{b}	4.35^{a}	4.71^{a}	4.57^{a}	3.37^{a}	0.251	<0.01	0.23	0.13
DMI/BW$^{0.75}$	61.50^{b}	125.24^{a}	136.00^{a}	133.14^{a}	103.37^{a}	7.478	<0.01	0.14	0.07
BW, kg^{-1}	55.70^{b}	69.81^{a}	69.70^{a}	72.33^{a}	58.83^{a}	2.019	<0.01	0.12	0.04
DMD, %	63.24	62.68	64.64	62.10	61.51	0.623	0.72	0.36	0.37
FS	2.00^{b}	2.20^{a}	2.45^{a}	2.20^{a}	2.35^{a}	0.069	0.05	0.66	0.53
WId, L^{-1}	2.891^{b}	4.085^{a}	4.078^{a}	4.098^{a}	3.489^{a}	0.255	0.05	0.54	0.70
WIf, L^{-1}	2.775^{a}	0.335^{b}	0.288^{b}	0.307^{b}	0.253^{b}	0.232	<0.01	0.08	0.99
WIt, L^{-1}	5.833^{a}	4.420^{b}	4.147^{b}	4.404^{b}	4.445^{b}	0.305	<0.01	0.95	0.78

Note: Means in the same row with different superscript differ significantly (p<0.05); 52.5F= extruded diet with 52.5% Urochloa grass; 60F= extruded diet with 60% Urochloa grass; 65F= extruded diet with 65% Urochloa grass; 70F= extruded diet with 70% Urochloa grass; DMI= dry matter intake, kg; DMI/BW= dry matter intake relative to body weight, kg; DMI/BW0.75= dry matter intake relative to metabolic body weight. BW= body weight; DMD= dry matter digestibility; FS= fecal score; WIb = water intake via drinking trough, L; WIf= water intake via diet, L; WIt= total water intake (drinking trough + diet), L; SxF= silage versus extruded diets with different forage levels; SEM= standard error of the mean; L= linear effect; Q= quadratic effect.

Table 3. Ingestive behavior of ewes fed corn silage or fully extruded diets with different forage levels

Variables	Forage source					SEM	p value		
	Silage	52.5F	60F	65F	70F		SxF	L	Q
ET, min^{-1}	315.0^{a}	221.25^{b}	273.75^{b}	221.25^{b}	212.5^{b}	17.636	0.04	0.70	0.36
RT, min^{-1}	418.75^{a}	91.25^{b}	127.50^{b}	300.0^{b}	177.50^{b}	30.671	<0.01	<0.01	<0.01
IT, min^{-1}	706.25^{b}	1127.5^{a}	1038.75^{a}	918.75^{a}	1050.0^{a}	42.226	<0.01	0.14	0.05
TCT, min^{-1}	733.75^{a}	312.50^{b}	401.25^{b}	521.25^{b}	390.0^{b}	42.226	<0.01	0.14	0.05
RM	7.00^{a}	5.50^{b}	5.50^{b}	6.25^{b}	5.75^{b}	0.178	<0.01	0.21	0.35
CE	1.739^{b}	10.549^{a}	8.175^{a}	6.524^{a}	7.108^{a}	0.865	<0.01	0.21	0.05
RE	3.029^{b}	31.921^{a}	34.438^{a}	11.488^{a}	14.617^{a}	3.826	<0.01	0.12	0.05

Note: Means in the same row with different superscript differ significantly (p<0.05); 52.5F= extruded diet with 52.5% Urochloa grass; 60F= extruded diet with 60% Urochloa grass; 65F= extruded diet with 65% Urochloa grass; 70F= extruded diet with 70% Urochloa grass; ET= eating time; RT= rumination time; IT= idling time; TCT= total chewing time; RM= ruminal movements; CE= chewing efficiency; RE= rumination efficiency; SxF= silage versus extruded diets with different forage levels; SEM= standard error of the mean; L= linear effect; Q= quadratic effect.

Table 4. Blood metabolites of ewes fed corn silage or fully extruded diets with different forage levels

Variables	Forage source					SEM 52.5F	p value		
	Silage	52.5F	60F	65F	70F		SxF	L	Q
GLU. mg dL^{-1}	39.75	41.50	50.25	39.75	36.50	1.478	0.48	0.06	0.01
CHOL. mg dL^{-1}	31.50	36.92	34.50	32.42	41.75	2.183	0.28	0.69	0.39
TRIG. mg dL^{-1}	16.17	15.00	13.75	14.92	14.00	0.577	0.20	0.70	0.76
TP. g dL^{-1}	4.95	5.20	4.68	4.62	4.69	0.129	0.60	0.16	0.17
ALB. g dL^{-1}	3.98	4.01	3.54	3.95	3.51	0.143	0.50	0.38	0.70
UREA. mg dL^{-1}	18.19^{b}	44.91^{a}	33.45^{a}	32.93^{a}	29.88^{a}	2.405	<0.01	<0.01	0.13
CREA. mg dL^{-1}	0.91	0.91	0.84	0.92	0.86	0.027	0.67	0.70	0.76

Note:Means in the same row with different superscript differ significantly (p<0.05); 52.5F= extruded diet with 52.5% Urochloa grass; 60F= extruded diet with 60% Urochloa grass; 65F= extruded diet with 65% Urochloa grass; 70F= extruded diet with 70% Urochloa grass; GLU= glucose; CHOL= cholesterol; TRIG= triglycerides; TP= total protein; ALB= albumin; CREA= creatinine; SxF = silage versus extruded diets with different forage levels; SEM = standard error of the mean; L = linear effect; Q = quadratic effect.

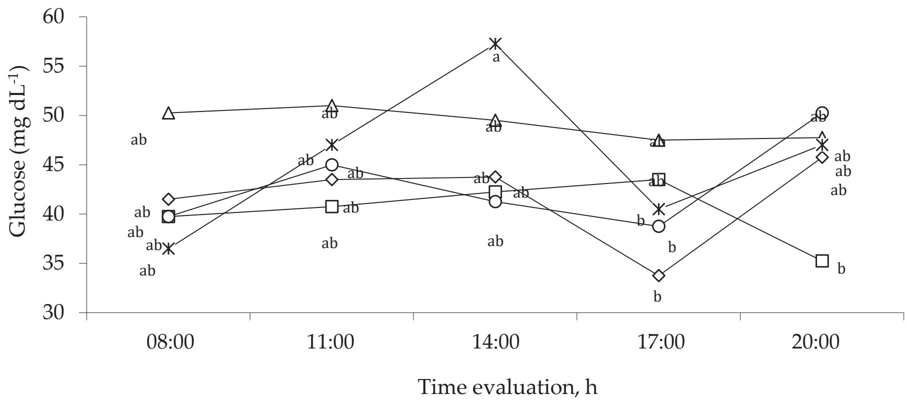

Figure 1. Glycemic curve of adult ewes fed corn silage or fully extruded diets with different forage levels. Note: —□— SIL, —◇— 52.5F, —△— 60F, —○— 65F, —✳— 70F

concentration observed in the diet containing 60.0% forage (50.25 mg dL^{-1}).

Regarding the glycemic response curve, the DExt containing 70.0% forage induced a glucose peak at 14:00 h, corresponding to 6 hours after feeding. Corn silage reduced blood glucose concentrations compared with DExt throughout the day ($p<0.05$). However, the decline in blood glucose concentration occurred only at 20:00 h in animals fed corn silage, whereas the reduction was observed at 17:00 h in animals fed DExt containing 52.5%, 65.0%, and 70.0% forage (Figure 1).

DISCUSSION

The high proportion of long particles in the corn silage used in the present study likely stimulated particle selection during feed intake (Malik *et al*., 2021), whereas this behavior was minimized in the DExt because of the uniform pellet size. After ingestion, mastication of the pellets may have further accentuated the differences in particle size between diets because *Urochloa* forage particles were reduced to 2 mm before extrusion. The increased intake of fine particles from DExt has been associated with reduced chewing activity and increased digesta passage rate (Findeisen *et al*., 2021), which may contribute to greater feed intake rates and increased DMI, as observed in the present study. This phenomenon occurs because smaller particles exit the rumen more rapidly, thereby reducing the physical limitations imposed by ruminal fill on the gastrointestinal tract (Dufreneix *et al*., 2019). Furthermore, Malik *et al*. (2023) reported that pelleted diets reduce the rumen-filling effect because of their smaller particle size and compact physical form, which supports the greater DMI observed in animals fed DExt in the present study.

Conversely, the ingestion of larger fiber particles promotes ruminal fill, increases digesta retention time, and enhances masticatory activity for the mechanical breakdown of feed particles (Singer *et al*., 2024), as observed in the silage-based diets, which showed increased RT, TCT, and ruminal movements. This physical distension promoted by the long fiber particles likely acted as the primary limiting factor for ingestive capacity, explaining the lower DMI observed in silage-fed ewes. Despite the lower DMI, ewes fed corn silage exhibited greater total water intake. This finding is a direct consequence of the substantial difference in DM content between diets (approximately 31% vs. 91% DM for corn silage and DExt, respectively). The high moisture content of corn silage supplied a considerable amount of water through the feed, thereby offsetting the lower voluntary water intake from the drinker. In this context, dietary moisture content is a key factor influencing feed intake patterns and ingestive behavior, including water intake dynamics (Havekes *et al*., 2020).

Diets with higher DM content improved FE and intake dynamics, as evidenced by the greater FE and RE observed in DExt, while also increasing IT and nutrient flow available for BW gain (Wondater & Ayanie, 2023), corroborating the BW responses observed in the study. The ET pattern observed herein is consistent with the findings of Li *et al*. (2021), who reported a greater feeding frequency associated with increased DMI in lambs fed pelleted diets.

Although DExt presented a similar particle size distribution, intake responses were more closely associated with forage inclusion level than with particle size per se. High forage inclusion increases neutral detergent fiber concentration and promotes rumen fill, which may limit feed intake, as observed in diets containing 70.0% forage (Faryabi *et al*., 2023). Conversely, the progressive increase in DMI observed in DExt up to 65.0% forage inclusion and 53.59% neutral detergent fiber likely allowed greater fiber intake by the animals, resulting in increased RT (Zhang *et al*., 2025) and reduced CE and RE, since diets with lower forage inclusion required less time spent ruminating.

However, despite the lower IT and FE observed in diets containing 65.0% forage, these diets increased BW compared with the other DExt, likely due to the greater nutrient supply promoted by the higher DMI. This response is consistent with the findings of Oliveira *et al*. (2025), who reported that the physical structure of extruded pellets modulates chewing dynamics and RE in lambs.

The increase in DMI observed in animals fed DExt was accompanied by greater water intake from the drinker, reflecting the well-established relationship between feed intake and water consumption

(Akinmoladun *et al*., 2019; Silva *et al*., 2024). By contrast, corn silage diets supplied a substantial amount of water through the feed because of their high moisture content, which explains the lower voluntary water intake from the drinker. In the present study, the increase in water intake from the drinker observed in DExt occurred in response to the greater DMI. However, considering the approximately threefold higher water content of corn silage, total water intake was approximately 1.5 L day^{-1} greater in ewes fed corn silage. These findings confirm that the physical form and moisture content of the diet are major determinants of water intake partitioning between drinking water and feed-derived water (Golher *et al*., 2021).

Considering the water intake requirement of 2.78 L day^{-1} per kg of DMI recommended by the National Research Council (NRC, 2007), corn silage increased total water intake by approximately 57%, whereas DExt reduced total water intake by approximately 50% relative to NRC (2007) recommendations.

Commonly, an increase in passage rate, which likely occurred in the DExt evaluated in the present study, negatively affects nutrient digestibility because of the reduced retention time of digesta in the gastrointestinal tract (Zhang *et al*., 2019; Malik *et al*., 2023). On the other hand, thermal processing may enhance nutrient availability, particularly through protein denaturation and improved enzymatic digestion (Oliveira *et al*., 2020; Risyahadi *et al*., 2023). Although increased DMD has been reported for DExt (Risyahadi *et al*., 2023), this effect was not observed in the present study, likely because the diets had similar protein concentrations and high forage inclusion levels, which may have limited the contribution of improved protein digestibility to overall DMD. Additionally, the longer fiber particles in corn silage may have increased ruminal retention time, contributing to the similar digestibility observed among diets. The similar fecal score values, which remained within the range indicative of normal gastrointestinal function (Dickson & Jolly, 2011), further support the absence of major differences in digestive efficiency among treatments.

The lower DMI observed in animals fed corn silage likely reduced dietary protein intake, resulting in lower ruminal protein degradation and ammonia production (Chen *et al*., 2021). This may explain the lower serum urea concentrations compared with ewes fed DExt and is consistent with the findings reported by Zhong *et al*. (2018) for pelleted diets. The linear reduction in serum urea concentrations with increasing forage inclusion levels in DExt may be attributed to the lower protein concentration of diets with greater forage inclusion. In diets containing 70.0% forage, the lower dietary protein concentration combined with reduced DMI may have intensified the reduction in ruminal protein degradation and circulating urea concentrations. Nevertheless, the similarity in albumin, creatinine, and total protein concentrations indicates that protein metabolism was not impaired despite the reduction in protein turnover and urea metabolism.

Cholesterol and triglycerides are associated with short-chain fatty acid synthesis and the availability of energy substrates in the organism (Varanis *et al*., 2021). The diets evaluated in the present study had similar total digestible nutrient concentrations, suggesting that energy intake may have been more closely associated with differences in DMI. However, no evidence of energy deficiency was observed, as indicated by the similarity in energy-related metabolites among treatments, likely because of the use of adult ewes as the experimental model. All metabolites remained within the reference range for adult sheep (Varanis *et al*., 2021).

Zhong *et al*. (2018) also reported no differences in serum cholesterol concentrations in lambs fed pelleted versus non-pelleted diets, although high-density lipoprotein increased and low-density lipoprotein decreased under pelleted diets. In the present study, plasma lipoproteins were not evaluated, which limits conclusions regarding potential improvements in animal health associated with extruded or pelleted diets, as suggested by Zhong *et al.* (2018).

The glycemic profile may be associated with postprandial nutrient utilization because glucose metabolism in ruminants largely depends on hepatic gluconeogenesis from ruminal fermentation products rather than direct intestinal glucose absorption (Syperreck *et al*., 2023; Varanis *et al*., 2021). The higher glucose concentration observed at 14:00 h in the DExt containing 70.0% forage may be related to differences in nutrient availability and digestibility associated with DExt. By contrast, the more stable glycemic pattern observed in ewes fed corn silage may reflect the slower degradation of structural carbohydrates in non-extruded forage sources. Furthermore, the reduction in blood glucose concentrations after 17:00 h may be associated with lower feed intake and reduced nutrient availability throughout the day, consistent with the ingestive behavior observed in animals fed silage-based diets.

The increase in feed intake, IT, FE, RE, and serum urea concentrations observed in ewes fed DExt may be attributed to the extrusion and pelletization processes, which reduce particle size and increase the surface area available for ruminal microbial activity, particularly compared with the long-particle corn silage used in this study. Furthermore, the greater feed intake, RT, and blood glucose concentrations observed in diets containing 60.0% to 65.0% forage under extrusion highlight the potential of this processing method to support higher DMI even in diets with elevated forage inclusion levels.

CONCLUSION

Fully DExt enabled greater forage inclusion without impairing feed intake, DMD, or metabolic status in adult ewes. Compared with corn silage, DExt increased DMI, water consumption, feed efficiency, and serum urea concentrations, while DMD remained unchanged. Forage inclusion levels between 60.0% and 65.0% promoted greater DMI and water intake, as well as improved RE and higher early morning blood glucose concentrations. These findings indicate that DExt can be used as an alternative strategy to increase forage utilization in ruminant diets, allowing greater inclusion of high-fiber ingredients while maintaining animal performance and metabolic stability, which may contribute to more flexible feeding systems.

CONFLICT OF INTEREST

We certify that there are no conflicts of interest involving any financial, personal, or other relationships with individuals or organizations related to the material discussed in this manuscript.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

We certify that generative AI and/or AI-assisted technologies were not used in the writing of this manuscript, nor in the analysis, interpretation of data, or preparation of figures and tables.

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