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Simultaneous substitution of forage and grain with sugar beet pulp in finishing lambs: impacts on feed efficiency, ruminal fermentation, and chewing behavior

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Abstract Sugar beet pulp (BP) is a by-product rich in both non-fibrous carbohydrates and highly digestible neutral detergent fiber. This study evaluated the effects of simultaneously substituting forage (alfalfa hay) and grains (corn and barley) with increasing levels of BP on growth performance, digestibility, chewing behavior, ruminal fermentation, and blood metabolites in fattening lambs. Twenty-six male Lori lambs (body weight= 28.2±3.6 kg) were randomly assigned to one of four iso-nitrogenous and iso-energetic diets in a completely randomized design. Diets included 0% (BP0), 10% (BP10), 20% (BP20), or 30% (BP30) BP, with BP replacing equal proportions of both forage and grains. As BP inclusion increased, the forage-to-concentrate ratio declined from 25:75 to 10:90, dietary neutral detergent fiber (NDF) increased (28.8% to 31.3%), and starch (43.5% to 32.6%) and forage NDF (14.2% to 6.9%) decreased. Increasing BP levels linearly reduced dry matter (DM) intake, while NDF intake remained unchanged. Apparent digestibility of DM and NDF increased linearly, but crude protein digestibility was unaffected. Average daily gain (ADG) tended to decline linearly, whereas feed efficiency showed a quadratic response, peaking at BP10 and BP20. Carcass traits (dressing percentage, tail fat, offal weights), blood metabolites (glucose, urea nitrogen, cholesterol, triglycerides, total protein, β-hydroxybutyrate), urine pH, and ruminal pH were not influenced by treatment. However, ruminal acetate proportion and the acetate-to-propionate ratio increased linearly, while propionate decreased. Total rumination time and rumination per kilogram of DM or NDF intake declined linearly, with the lowest values observed in BP30-fed lambs. In conclusion, moderate inclusion of BP (10–20%) improved fiber digestibility and feed efficiency without compromising health or carcass characteristics, despite a slight reduction in DM intake. Inclusion at 30% may reduce intake and chewing activity, potentially limiting its practical utility at this level.

Keywords: beet pulp, growth performance, feeding behavior, fiber digestibility

Introduction

Indoor lamb fattening is a cornerstone of meat production systems in arid and semi-arid regions, where limited pasture availability necessitates reliance on energy-dense, concentrate-based diets. In such systems, feed costs account for more than70% of total production expenses, creating strong economic incentives to explore cost-effective alternatives particularly locally available agro-industrial by-products (Lanza et al., 2001; Okab et al., 2012). Sugar beet pulp (BP), a fibrous by-product of sugar extraction, is abundantly available in Iran. According to the Agriculture Statistics of Iran (2025), the country produces approximately 8.1 million metric tons of sugar beet annually, which is projected to yield about 506,000 metric tons of dehydrated BP (assuming 25% BP with 25% dry matter [DM]). BP contains both highly digestible neutral detergent fiber (NDF; 35-45%) and neutral detergent–soluble fiber, primarily in the form of pectin (25-32% DM; Omer et al., 2013; NRC, 2001). Unlike lignified forages, BP's NDF degrades rapidly due to its low lignin content (<2%), while pectin fermentation yields acetate and butyrate without significant lactate production (NRC, 2001). This metabolic profile helps stabilize ruminal pH and reduces the risk of subacute ruminal acidosis (SARA) a common challenge in high-concentrate feeding systems (Guo et al., 2013; Heydari et al., 2021).

Sugar BP has been widely used as a substitute for various feedstuffs, including cereal grains and forages, across ruminant species (Habeeb, 2024). In lambs, replacing barley with BP improved NDF digestibility and average daily gain (ADG; Cooper et al., 1996). In transition Zel ewes, partial replacement of barley with BP increased DMI, milk yield, and lamb birth weight (Kohestani et al., 2011). In dairy cows, BP substitution maintained milk yield while slowing ruminal starch degradation, potentially shifting starch digestion postruminally (Voelker and Allen, 2003; Hatew et al., 2015), and mitigated subacute ruminal acidosis in cows fed finely ground wheat (Guo et al., 2013). In beef cattle, partial substitution of corn with BP elevated ruminal acetate, enhanced populations of cellulolytic bacteria, and increased circulating insulin, and reduced serum non-esterified fatty acids (FA) without negatively affecting DMI, ADG, or feed efficiency (Jeong et al., 2022). These findings highlight BP's versatility in modulating ruminal fermentation and supporting productivity across production systems.

Despite these benefits, high BP inclusion may suppress DMI, likely due to its high water-holding capacity and bulk density, which increase rumen fill and promote physical satiety (Rouzbehan et al., 1994; Voelker and Allen, 2003). Moreover, the shift toward a higher acetate:propionate ratio may reduce glucogenic precursor supply and increase methane emissions per unit of volatile fatty acid (VFA) produced, potentially decreasing net energy availability and compromising feed conversion efficiency (Ungerfeld, 2008). When BP is used to replace traditional forages, it may dilute the concentration of physically effective NDF (peNDF), particularly the coarse particle fraction (>1.18 mm) essential for stimulating rumination, salivation, and rumen buffering capacity. When BP replaces traditional forages (corn silage or straw), it dilutes peNDF, particularly the coarse particle fraction essential for stimulating rumination and salivary buffering. In high-concentrate diets already low in long forage particles, such peNDF dilution may paradoxically heighten SARA risk, even with BP's intrinsic buffering properties (Naderi et al., 2016; Sharbafan-Mojaver et al., 2019).

Given this duality, the optimal application of BP may lie not in displacing grain or forage alone, but in the coordinated, simultaneous substitution of both. This integrative strategy could theoretically reduce dietary starch load while preserving fermentable fiber to support cellulolytic activity and maintain metabolic efficiency, a concept successfully demonstrated in heat-stressed dairy cows (Heydari et al., 2021). Nevertheless, this approach remains critically underexplored in fattening lambs fed high-concentrate diets. Therefore, the objective of this study was to evaluate the effects of incrementally substituting both alfalfa hay and cereal grains (corn and barley) with BP in finishing lambs. We hypothesized that moderate BP inclusion (10-20%) would improve nutrient digestibility and feed efficiency by favorably shifting ruminal fermentation and enhancing cellulolytic activity, without compromising growth performance, carcass traits, or metabolic status, while avoiding the DMI suppression and acidosis risks associated with inadequate fiber in high-concentrate systems.

Material and methods

Animals, diets, and experimental design

The experiment was conducted at the research farm of Isfahan University of Technology (Isfahan, Iran) using twenty-six male Lori lambs (body weight= 28.2 ± 3.6 kg). Lambs were randomly assigned to one of four dietary treatments in a completely randomized design, with 6 or 7 lambs per treatment. The experimental diets contained increasing levels of BP: 0% (BP0), 10% (BP10), 20% (BP20), and 30% (BP30) on a DM basis. In all treatments, BP simultaneously and proportionally replaced both cereal grains (corn and barley) and alfalfa hay, maintaining a balanced substitution of energy and fiber sources. Diets were formulated to be iso-nitrogenous and iso-energetic (metabolizable energy ≈ 2.75 Mcal/kg DM; crude protein ≈ 11.7% DM) based on NRC (2007) requirements for finishing lambs. Crude protein concentrations were equalized across treatments by adjusting the inclusion level of soybean meal; all other ingredients remained constant. The chemical composition and physical characteristics of the experimental diets are presented in Table 1.

Prior to the commencement of the 84-day trial, lambs were fed a common control diet for a 20-day adaptation period. During the experimental phase, total mixed rations (TMR) were offered ad libitum (at 110% of the previous day's intake) twice daily at 08:30 and 14:30 h. Lambs were housed individually in concrete-floored pens (1.8 m^2 each), each equipped with a dedicated feed bunk and water bucket. Fresh water was available at all times. Individual BW was recorded every two weeks before the morning feeding to monitor growth performance.

Table 1. Ingredients, chemical composition and physical characteristics of experimental diets (%, DM basis, unless otherwise stated) fed to finishing lambs with increasing levels of sugar beet pulp replacing both alfalfa hay and cereal grains.

Item	Dietary treatments[1]				SE
	0BP	10BP	20BP	30BP	
Ingredients					
Concentrate:Forage:Beet pulp	75:25:0	70:20:10	65:15:20	60:10:30	-
Alfalfa hay, chopped	18.5	13.5	8.5	3.5	-
Wheat straw, chopped	6.5	6.5	6.5	6.5	-
Beet pulp	0	10	20	30	-
Corn grain, whole	35	32	29	26	-
Barley grain, whole	35	32	29	26	-
Soybean meal	3.5	4.5	5.5	6.5	-
Calcium carbonate	0.6	0.6	0.6	0.6	-
White salt	0.3	0.3	0.3	0.3	-
Ammonium chloride	0.4	0.4	0.4	0.4	-
Mineral vitamin premix[2]	0.2	0.2	0.2	0.2	-
Chemical compositions					
DM (% as-fed)	70.8	59.8	49.4	43.8	-
ME (Mcal/kg DM)	2.78	2.80	2.81	2.82	-
CP	12.2	12.3	12.4	12.4	-
EE	2.4	2.3	2.2	2.1	-
NDF	28.8	29.6	30.5	31.3	-
ADF	14.0	14.8	15.6	16.4	-
ADL	3.2	2.9	2.6	2.3	-
Forage NDF	14.2	11.7	9.2	6.9	-
NFC	53.2	52.4	51.5	50.7	-
Starch	43.5	39.9	36.2	32.6	-
Particle size distribution					
19 mm	3.0	2.3	1.2	1.2	0.35
8 mm	45.3^{a}	42.2^{a}	41.0^{ab}	36.7^{b}	1.10
1.18 mm	48.0^{c}	53.2^{bc}	56.4^{ab}	62.0^{a}	1.60
Pan	3.7^{a}	2.3^{ab}	1.4^{ab}	0.6^{b}	0.40
Mean particle size (mm)	6.44	6.21	6.00	5.88	0.10
Physically effective NDF>1.18 mm	27.3^{d}	28.3^{c}	29.2^{b}	30.5^{a}	0.80
Physically effective NDF>8 mm	13.7	12.9	12.5	11.6	0.30

[1]Diets included 0% (BP0), 10% (BP10), 20% (BP20), or 30% (BP30) BP, with BP replacing equal proportions of both forage and grains.
[2]Contained per kilogram of supplement: 1,300,000 IU of vitamin A, 360,000 IU of vitamin D, 1,200 IU of vitamin E, 16 g of Zn, 10 g of Mn, 0.8 g of Fe, 0.12 g of Co, 0.15 g of I, and 0.08 g of Se.
DM: Dry matter, ME: Metabolizable energy, CP: Crude protein, EE: Ether extract, NDF: Neutral detergent fiber, ADF: Acid detergent fiber, ADL: Acid detergent lignin, Forage NDF: Forage neutral detergent fiber, NFC: Non-fiber carbohydrates.
[a, b]: Within row, means with common superscript (s) do not differ (P>0.05).

Fecal and TMR sampling and chemical analysis

Feed samples were collected every other week throughout the experiment. Fecal samples were gathered during three collection periods (days 24-26, 54-56, and 82-84), each spanning 72 hours with sampling intervals of 9 hours. Fecal and feed samples were dried in a forced-air oven at 60 °C for 48 h to determine DM content. Subsequently, samples were ground to pass through a 1-mm screen and analyzed for crude protein (CP) using an automated Kjeldahl system (Kjeltec Auto 1030 Analyzer, Tecator, Sweden). NDF and acid detergent fiber (ADF) were determined using an ANKOM 220 Fiber Analyzer (Model A220, ANKOM Technology, USA) according to the procedures described by Van Soest et al. (1991), with the inclusion of heat-stable α-amylase during NDF analysis. Ether extract (EE) was analyzed only for feed samples. Apparent total-tract digestibilities of DM, CP, and NDF were estimated using acid-insoluble ash as an internal marker, following the methodology of Van Keulen and Young (1977).

Particle size distribution and chewing behavior

Particle size distribution of the diets was determined using the Penn State Particle Separator (PSPS) with three sieves, as described by Kononoff et al. (2003). Samples were analyzed in their as-fed form, and the material retained on each sieve was dried at 60 °C for 48 h to determine DM. The physically effective factor (pef) was calculated as the cumulative proportion of DM retained on the top three sieves. Physically effective NDF was then computed as the product of dietary NDF content and pef.

Chewing behavior was recorded visually for each lamb at 5-minute intervals over a 24-hour period on days 21, 49, and 77. Total time spent eating, ruminating, and chewing (eating + ruminating) was recorded, and activities were normalized per unit of nutrient intake specifically per kilogram of DM, NDF, and peNDF retained on the sieve with a pore size greater than 1.18 mm.

Rumen fluid and blood sampling

Rumen fluid was collected via an esophageal stomach tube at 3 h after the morning feeding on days 23, 51, and

79 of the experimental period. Immediately after collection, pH was measured using a portable digital pH meter (HANNA Instruments, Model HI 98103, Portugal; serial no. 137243), calibrated with standard buffers at pH 4.0 and 7.0. The fluid was then filtered through four layers of cheesecloth to remove solid particles. For VFA analysis, 5 mL of strained rumen fluid was mixed with 1 mL of 250 g/L metaphosphoric acid and kept frozen (−20°C) until analysis.

Prior to analysis, frozen rumen fluid samples were thawed overnight and centrifuged at 10,000 × g for 20 min at 4°C. The supernatants were analyzed using a gas chromatograph equipped with a flame ionization detector. Volatile fatty acids were separated on a fused silica capillary column (0.25 × 0.32, 0.3 µm i.d., Model No. CP-9002 Vulcanusweg 259 a.m., Chrompack, Delft, the Netherlands), with crotonic acid used as an internal standard. The oven temperature was programmed from 100 to 150°C. Nitrogen served as the carrier gas, while hydrogen and compressed air were supplied to the FID as fuel and oxidizer, respectively.

Jugular venous blood samples were collected at 2 h post-morning feeding on days 24, 52, and 80. Blood was drawn into vacutainer tubes and centrifuged at 3,000 × *g* for 15 min at 4°C. The resulting serum was aliquoted and stored at –20°C until analysis. Serum concentrations of glucose, triglycerides, total cholesterol, blood urea nitrogen (BUN), total protein, and β-hydroxybutyrate (BHB) were measured using colorimetric commercial kits (Pars Azmun Co., Karaj, Iran) according to the manufacturer's instructions.

Slaughter procedure

Prior to slaughter, lambs were fasted for 18 h with free access to water to ensure complete evacuation of the digestive tract. Final BW was recorded immediately before slaughter, which was performed by exsanguination via jugular vein section in accordance with Halal guidelines. After bleeding, carcasses were skinned, eviscerated, and the hot carcass weight was recorded. The tail fat was separated and weighed individually. Additionally, the combined weight of the rumen and reticulum (as representative offal components) was recorded for each animal.

Statistical analysis

Data were analyzed using the PROC MIXED procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC, USA) according to a completely randomized design with unequal replication (6 to 7 lambs per treatment). The following linear mixed model was fitted:

$$Y_{ij} = \mu + T_i + L_j + \beta(\mathrm{BW})_j + e_{ij}$$

where Y_{ij} is the observed response variable, μ represents the overall mean, T_i is the fixed effect of dietary treatment i (0%, 10%, 20%, or 30% BP), L_j> denotes the random effect of lamb j, β is the regression coefficient for birth weight included as a continuous covariate, and e_{ij} is the random residual error. Orthogonal polynomial contrasts were applied to evaluate linear and quadratic dose-response effects of increasing BP inclusion levels. Degrees of freedom were estimated using the Kenward-Roger approximation to improve inference accuracy for the unbalanced design. Statistical significance was declared at $P \leq 0.05$, and tendencies were reported at $0.05 < P \leq 0.10$.

Results

Diet nutrients, intakes, and digestibility

As designed, dietary metabolizable energy (~2.8 Mcal/kg DM) and CP (~12.2–12.4% DM) remained relatively constant across treatments (Table 2). However, increasing BP inclusion from 0% to 30% with proportional replacement of both alfalfa hay and barley/corn grains resulted in a linear increase in dietary NDF (from 28.8% to 31.3% DM) and peNDF (from 27.3% to 30.5% DM), while starch concentration decreased linearly (from 43.5% to 32.6% DM).

Table 2. Feed and water intake, and apparent total-tract digestibility of nutrients in finishing lambs fed diets with increasing levels of sugar beet pulp (BP) replacing both alfalfa hay and cereal grains

	Dietary treatments[1]					*P*-value		
Item	0BP	10BP	20BP	30BP	SEM	Linear	Quadratic	Cubic
Intake (kg/d)								
DM	1.228[a]	1.168[ab]	0.975[b]	1.067[ab]	0.030	0.02	0.23	0.14
NDF	0.469	0.457	0.401	0.467	0.013	0.59	0.12	0.14
Water	2.15	3.00	3.10	3.00	0.17	0.09	0.32	0.83
Apparent total tract digestibility (%)								
DM	78.4	78.3	79.1	80.4	0.43	0.08	0.41	0.77
NDF	68.4[c]	73.4[b]	74.8[b]	80.3[a]	1.0	<0.01	0.83	0.12
CP	69.7	66.8	67.3	67.9	0.53	0.31	0.11	0.49

[1]Diets included 0% (BP0), 10% (BP10), 20% (BP20), or 30% (BP30) BP, with BP replacing equal proportions of both forage and grains.
DM: Dry matter, CP: Crude protein, NDF: Neutral detergent fiber.
[a, b]: Within row, means with common superscript (s) do not differ (P>0.05).

Particle size distribution was also affected by BP inclusion. The proportion of dietary DM retained on the 19-mm and 8-mm sieves decreased with increasing BP, indicating a reduction in coarse and medium particle fractions. Conversely, the proportion retained on the pan (<1.18 mm) decreased linearly (from 3.7% to 0.1% DM). The geometric mean particle size (GMPS) declined from 6.44 mm (BP0) to 5.88 mm (BP30), reflecting the finer physical structure of BP compared with chopped alfalfa hay or grains.

Nutrient intake and digestibility data are presented in Table 2. DMI decreased linearly (P=0.02) with increasing BP, reaching its lowest value in the BP20 group (975 g/d). Similarly, DMI expressed as a percentage of BW also decreased linearly (P=0.04). In contrast, NDF intake was unaffected by treatment. Water intake tended to increase linearly (P=0.09) with BP inclusion.

Apparent total-tract digestibility of DM showed a tendency to increase (P=0.08), while NDF digestibility increased linearly (P<0.01) from 68.4% (BP0) to 80.3% (BP30). CP digestibility remained similar across all diets.

Growth performance and carcass characteristics

Growth and carcass data are shown in Table 3. Initial and final BW did not differ among treatments. ADG tended to decrease linearly (P=0.09), with the lowest values observed in BP30 (182 g/d) and BP20 (193 g/d) compared to BP0 and BP10 (222 g/d). Feed conversion ratio (FCR; feed:gain) exhibited a quadratic response (P=0.03), with the lowest values in BP10 (5.29) and BP20 (5.05), and the highest value in BP30 (5.88).

Hot carcass weight (23.4-25.8 kg) and dressing percentage (52.3-56.2%) were unaffected by dietary treatment. Similarly, weights of tail fat and reticulorumen as percentages of BW showed no significant differences.

Table 3. Growth performance, feed conversion ratio, and carcass characteristics of finishing lambs fed diets with 0 to 30% sugar beet pulp replacing both forage and grain

	Dietary treatments[1]					*P*-value		
Item	0BP	10BP	20BP	30BP	SEM	Linear	Quadratic	Cubic
BW measurements								
Initial BW (kg)	28.3	28.3	28.0	28.2	0.72	0.92	0.96	0.91
Final BW (kg)	47.0	47.0	44.2	43.5	1.22	0.25	0.87	0.67
ADG (g/d)	222	222	193	182	10.0	0.09	0.78	0.59
Feed conversion ratio	5.55[ab]	5.29[b]	5.05[b]	5.88[a]	0.13	0.35	0.03	0.31
Carcass characteristics								
Carcass (kg)	25.8	24.4	24.7	23.4	0.88	0.29	0.99	0.59
Carcass (%)	54.7	52.3	56.2	53.7	0.01	0.90	0.96	0.17
Tail fat (%)	11.8	11.0	12.4	10.8	0.39	0.59	0.59	0.11
Reticulorumen (%)	1.93	1.67	1.84	1.72	0.05	0.23	0.41	0.08
Liver (%)	1.51	1.50	1.38	1.38	0.04	0.28	0.93	0.62

[1]Diets included 0% (BP0), 10% (BP10), 20% (BP20), or 30% (BP30) BP, with BP replacing equal proportions of both forage and grains.
ADG: Average daily gain.
[a, b]: Within row, means with common superscript (s) do not differ (P>0.05).

Rumen fermentation and blood metabolites

Rumen and blood parameters are summarized in Table 4. Rumen pH (6.19-6.61) and total VFA concentration (70.0-83.8 mM) were not affected by treatment. However, molar proportion of acetate increased linearly (P<0.001) from 32.6% (BP0) to 45.0% (BP30), while propionate decreased linearly (P=0.04) from 28.3% to 19.1%. Consequently, the acetate-to-propionate (A:P) ratio increased linearly (P<0.01), rising from 1.33 (BP0) to 2.36 (BP30).

Butyrate proportion exhibited a cubic effect (P<0.01), with higher values in BP10 (14.1%) and BP30 (14.3%) compared to BP0 (7.04%) and BP20 (8.15%). Urine pH remained stable across treatments. Serum concentrations of glucose, BUN, total protein, and BHB were all unaffected by dietary BP inclusion.

Table 4. Rumen fermentation profile, blood metabolites, and urine pH in finishing lambs fed increasing levels of sugar beet pulp replacing both alfalfa hay and cereal grains

	Dietary treatments[1]				SEM	*P*-value		
Item	0BP	10BP	20BP	30BP		Linear	Quadratic	Cubic
Rumen pH	6.41	6.43	6.19	6.61	0.09	0.65	0.28	0.66
Urine pH	7.78	7.88	7.87	7.77	0.04	0.81	0.51	0.59
Volatile fatty acids								
Total (mM)	70.0	83.8	73.4	79.5	2.42	0.38	0.41	0.07
Acetate (%)	32.6[b]	41.5[a]	40.2[a]	45.0[a]	1.33	<0.01	30.0	0.08
Propionate (%)	28.3	25.6	23.3	19.1	1.61	0.04	0.79	0.88
Butyrate (%)	7.04[b]	14.1[a]	8.15[b]	14.3[a]	0.83	0.44	0.64	<0.01
Isovalerate (%)	0.90	1.11	0.51	0.77	0.13	0.39	0.93	0.18
Valerate (%)	1.08[ab]	1.36[a]	1.22[a]	0.70[b]	0.10	0.12	0.04	0.97
A:P ratio	1.33[b]	1.71ab	1.74[ab]	2.36[a]	0.11	<0.01	0.50	0.24
Blood metabolites								
Glucose (mg/dL)	68.9	77.3	78.2	70.3	4.3	0.90	0.38	0.97
BHBA (mg/dL)	0.424	0.505	0.391	0.493	0.04	0.81	0.91	0.30
BUN (mg/dL)	19.7	28.3	21.0	22.0	1.7	0.98	0.28	0.13
Total protein (g/dL)	6.09	6.18	6.48	6.12	0.14	0.77	0.43	0.65

[1]Diets included 0% (BP0), 10% (BP10), 20% (BP20), or 30% (BP30) BP, with BP replacing equal proportions of both forage and grains.
A:P: Acetate: Propionate ratio, BHBA: β-Hydroxybutyrate, BUN: Blood urea nitrogen.
[a, b]: Within row, means with common superscript (s) do not differ (P>0.05).

Chewing behavior

Chewing behavior is presented in Table 5. Total ruminating time decreased linearly (P<0.01) from 438 min/d (BP0) to 276 min/d (BP30). This reduction was also evident when expressed per kilogram of DMI (P=0.03) or per kilogram of NDF intake (P<0.01). Eating time and total chewing time (eating + ruminating) were not significantly affected by treatment (P=0.07).

Table 5. Chewing behavior (eating, ruminating, and total chewing time) in finishing lambs fed diets with increasing levels of sugar beet pulp replacing both forage and grain

	Dietary treatments[1]					*P*-value		
Item	0BP	10BP	20BP	30BP	SEM	Linear	Quadratic	Cubic
Eating								
min/d	234	180	180	252	18.0	0.75	0.12	0.26
min/kg DMI	186	138	174	234	18.0	0.27	0.16	0.22
min/kg NDFI	11.9	9.40	13.1	13.8	0.68	0.19	0.56	0.45
Ruminating								
min/d	438[a]	378[ab]	354[ab]	276[b]	21.6	<0.01	0.73	0.11
min/kg DMI	360[a]	356[a]	372[a]	258[b]	15.6	0.03	0.31	0.56
min/kg NDFI	924[a]	924[a]	912[a]	594[b]	42.6	<0.01	0.31	0.55
Total chewing								
min/d	672	558	534	528	27.0	0.07	0.31	0.45
min/kg DMI	558	522	558	498	19.2	0.42	0.75	0.48
min/kg NDFI	1422	1362	1350	1134	53.4	0.07	0.38	0.10

[1]Diets included 0% (BP0), 10% (BP10), 20% (BP20), or 30% (BP30) BP, with BP replacing equal proportions of both forage and grains.
min/kg DMI: minutes per kilogram of dry matter intake, min/kg NDFI: minutes per kilogram of neutral detergent fiber intake.
[a, b]: Within row, means with common superscript (s) do not differ (P>0.05).

Discussion

The simultaneous replacement of both cereal grains and forages with BP represents a novel nutritional strategy aimed at balancing energy supply, rumen health, and feed efficiency in ruminants. Unlike conventional approaches that substitute BP for only one dietary component, our dual-substitution model was based on the hypothesis that coordinated replacement would mitigate the risk of acidosis by reducing dietary starch while concurrently supplying highly fermentable and digestible fiber. This approach was designed to support favorable ruminal fermentation and stimulate cellulolytic bacterial activity without compromising animal growth performance.

Nutrient intakes and digestibility

The linear reduction in DMI with increasing BP inclusion aligns consistently with findings in ruminants fed high-concentrate diets (Voelker and Allen, 2003; Nichols et al., 2014). In the present study, this response can be mechanistically attributed to the combined effects of increased dietary NDF, elevated water content of the TMR, and higher drinking water intake. As BP replaced both alfalfa hay and cereal grains, dietary NDF rose from 28.8% to 31.3% (DM basis), while the DM content of the TMR declined markedly from approximately 70% in the control diet to 40% in the 30% BP diet. Specifically, at a 30% BP inclusion level, the overall dietary DM percentage declined to below 50%. This reduction in dietary DM content is one of the factors that likely contributed to the observed decrease in feed intake, as diets with less than 50% DM can negatively affect voluntary intake. Concurrently, water intake increased numerically from ~2.1 L/d to ~3.0 L/d. Given BP's exceptionally high water-holding capacity (Rouzbehan et al., 1994), this combination likely intensified ruminal fill and distension, triggering satiety via stretch receptors in the rumen wall (Allen, 2000). Interestingly, while Yousefi et al. (2025) reported increased DMI in lambs fed TMR with elevated moisture (up to 30%), their moisture was added as free water rather than bound water from a highly hydratable fiber source like BP. In contrast, BP increases effective rumen fill through water retention within its fibrous matrix, which may activate stretch receptors more potently than free water alone (Voelker and Allen, 2003). Indeed, Voelker and Allen (2003) demonstrated that DMI depression in dairy cows fed pelleted BP was directly linked to increased rumen digesta mass and water retention not to changes in NDF pool size. In our lambs, which were adapted to a high-concentrate (25:75 forage:concentrate) the introduction of a highly hydratable, fibrous ingredient like BP may have exerted a strong physical filling effect.

Contrary to its suppressive effect on DMI, BP inclusion exerted a beneficial effect on nutrient digestibility particularly for NDF. This improvement was accompanied by stabilization of ruminal pH across the treatments, a finding that underscores the favorable modulation of the rumen environment. Unlike lignified forages, BP contains a highly digestible NDF fraction with very low lignin content, along with a substantial pool of pectic substances (Naderi et al., 2016; Nemati et al., 2020). Pectin fermentation proceeds more gradually than starch hydrolysis, with minimal lactate production and a reduced acid load. This metabolic profile mitigates sharp pH fluctuations but also fosters a stable and supports the proliferation and activity of cellulolytic bacteria. Indeed, the maintenance of ruminal pH within the normal physiological range despite a marked reduction in dietary starch reflects BP's intrinsic buffering capacity, attributed to its high potassium content and cation exchange properties (Jasaitis et al., 1987). This stabilized environment aligns with the mechanism proposed by Silva and Ørskov (1988), who suggested that BP stimulates the growth of fiber-degrading microbes. Our results are further corroborated by Jeong et al. (2022), who reported increased populations of *Fibrobacter succinogenes* and *Ruminococcus albus* in Korean steers fed BP, directly linking microbial shifts to enhanced NDF digestibility. In our lambs, the linear increase in NDF digestibility with BP inclusion without compromising ruminal pH provides compelling evidence that BP not only serves as a highly fermentable fiber source but also actively promotes a rumen ecosystem conducive to efficient fiber breakdown.

Based on the *in situ* data reported in Kahyani et al. (2019), the NDF digestibility (NDFD) of BP was approximately 72% at 24 h and near-complete (>95%) by 48 h, whereas alfalfa hay exhibited NDFD values of roughly 42% at 24 h and about 58% at 48 h (Kahyani et al., 2019).

Growth performance and carcass characteristics

The maintenance of ADG despite reduced DMI at 10-20% BP inclusion resulted in a quadratic improvement in feed efficiency an economically important outcome in lamb finishing systems. This likely reflects the combined benefits of enhanced fiber digestibility and a more stable ruminal environment, which support efficient energy harvest from feed even at lower intakes. However, ADG tended to decline at the 30% BP level, suggesting a threshold beyond which physical fill and reduced starch availability may limit growth.

Carcass traits, including dressing percentage and tail fat weight were unaffected by treatment. Although we did not measure intramuscular or subcutaneous fat composition, visual assessment indicated that carcasses from all groups exhibited soft adipose tissue, a common issue in lambs fed high-starch, high-concentrate diets. Starch-rich diets lower ruminal pH and alter microbial populations, promoting the production of *trans*-10 FA, which not only depress milk fat in dairy ruminants but may also influence adipose tissue firmness in lambs. Indeed, Normand et al. (2001) reported that lambs fed cereal-based concentrates had higher serum methylmalonate (a marker of propionate metabolism) and softer fat compared with those fed BP, though the effect on fat quality was not always significant. In our study, the use of BP may have mitigated ruminal acidosis and *trans*-10 formation, potentially improving fat firmness; however, since fat texture was not formally evaluated, this remains speculative. supplementation with trans-10, cis-12 CLA isomer reduced subcutaneous fat thickness (by 24.5%), subcutaneous and intermuscular fat in the hind leg (by 19.1% and 23.5%, respectively), and intramuscular fat in the Longissimus dorsi and Semitendinosus muscles (by 22.2% and 17.1%, respectively), without affecting ADG, carcass weight, or Longissimus dorsi dimensions (Bodkowski and Patkowska-Sokoła, 2013). Future work should assess adipose tissue FA profiles and physical properties to clarify the impact of dual substitution strategies on carcass quality.

Rumen fermentation and blood parameters

In the present study, ruminal pH remained stable across all levels of BP inclusion, despite a marked reduction in forage NDF from 14.2% in the control diet to only 6.9% in the BP30 diet. This finding is notable because forage NDF (not total NDF) is the primary dietary driver of ruminal pH and chewing activity (Zebeli et al., 2006). The pH stability likely resulted from our balanced dual-substitution strategy: by simultaneously reducing both grain (the main source of rapidly fermentable starch) and forage (the main source of peNDF), we mitigated the acidogenic load while preserving fermentable, digestible fiber from BP. The high pectin content and intrinsic buffering capacity of BP attributable to its elevated potassium concentration and high cation exchange capacity (Jasaitis et al., 1987) fostered a stable and uniform fermentation environment. This controlled fermentation pattern is essential for the successful integration of BP into high-concentrate finishing diets.

Notably, total VFA concentration increased with BP inclusion, a response that would typically predispose SARA. Yet, ruminal pH remained unchanged, suggesting enhanced VFA absorption and/or effective ruminal buffering. This metabolic resilience likely stems from the slower and more gradual fermentation of BP pectin compared with cereal starch, which minimizes abrupt acid accumulation (Nemati et al., 2020). The metabolic stability observed in the rumen was corroborated by blood parameters. Circulating concentrations of glucose, blood urea nitrogen, cholesterol, and total protein remained within normal physiological ranges and were unaffected by dietary treatment, confirming that lambs maintained metabolic homeostasis throughout the trial.

Particle size and chewing behavior

Simultaneous replacement of alfalfa hay and cereal grains with BP reduced the proportion of long particles (>8 mm), lowering peNDF >8mm a key driver of rumination (Zebeli et al., 2006). This directly explains the linear decline in total ruminating time and rumination per unit of DMI or NDF. Although GMPS of the TMR changed modestly, the critical factor was the loss of the longest particles needed to form a stable ruminal mat and stimulate mechanoreceptors (Mertens, 1997). Moreover, the decline in total rumination time with higher BP levels is consistent with Sharbafan-Mojaver et al. (2019), who observed no improvement in chewing activity when BP replaced grains in lamb starter diets, despite comparable NDF levels.

This reveals a key trade-off: while BP improves ruminal fermentation and pH stability, its fine physical structure provides insufficient mechanical stimulation for chewing and salivation. Unlike Mojtahedi and Mesgaran (2011) who observed increased rumination when BPreplaced barley in a very low-forage diet-our control contained moderate alfalfa hay. Thus, BP substitution here caused a net loss of peNDF. This underscores that BP's effect on chewing depends on baseline forage level. In high-concentrate lamb diets, retaining a minimum amount of long forage alongside BP may be necessary to sustain rumination and salivary buffering, fully leveraging BP's rumen health benefits.

Conclusion

In the simultaneous replacement of both forage and grain with BP in finishing lamb diets, moderate inclusion levels (10–20% of dietary DM) significantly enhanced fiber digestibility and shifted ruminal fermentation toward an acetate-dominant pattern without compromising growth performance or carcass quality. These changes resulted in improved feed efficiency, despite a modest reduction in DMI attributable to the high physical bulk and water-holding capacity of BP. Concurrently, the reduction in long forage particles decreased rumination time, which may compromise rumen health. Therefore, the key practical implication of this study is that BP can serve as a strategic substitute in high-concentrate lamb diets, provided that a minimum level of coarse forage is retained to sustain chewing behavior and salivary buffering.

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Conflict of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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